Biomass Fly Ash Deposition in an Entrained Flow Reactor

Fly ash deposition on boiler surfaces is a major operational problem encountered in biomass-fired boilers. Understanding deposit formation, and developing modelling tools, will allow improvements in boiler efficiency and availability. In this study, deposit formation of a model biomass ash species (K2Si4O9) on steel tubes, was investigated in a lab-scale Entrained Flow Reactor. K2Si4O9 was injected into the reactor, to form deposits on an air-cooled probe, simulating deposit formation on superheater tubes in boilers. The influence of flue gas temperature (589 – 968°C), probe surface temperature (300 – 550°C), flue gas velocity (0.7 – 3.5m/s), fly ash flux (10,000 – 40,000g/m²h), and probe residence time (up to 60min) was investigated. The results revealed that increasing flue gas temperature and probe surface temperature increased the sticking probability of the fly ash particles, thereby increasing the rate of deposit formation. However, increasing flue gas velocity resulted in a decrease in the deposit formation rate, due to increased particle rebound. Furthermore, the deposit formation rate increased with probe residence time and fly ash flux. Inertial impaction was the primary mechanism of deposit formation, forming deposits only on the upstream side of the steel tube. A mechanistic model was developed for predicting deposit formation in the reactor. Deposit formation by thermophoresis and inertial impaction was incorporated into the model, and the sticking probability of the ash particles was estimated by accounting for energy dissipation due to particle deformation. The model reasonably predicted the influence of flue gas temperature and fly ash flux on the deposit formation rate.
Catalytic Hydropyrolysis of Biomass using Molybdenum Sulfide Based Catalyst. Effect of Promoters

Catalytic hydropyrolysis of beech wood was conducted in a fluid bed reactor at 450°C and a total pressure of 26 bar. The differences in hydrodeoxygenation activity, selectivity and the resulting product composition between sulfided Mo/MgAl₂O₃...
CoMo/MgAl₂O₄ or NiMo/MgAl₂O₄ catalysts have been investigated. The acidity and molybdate species in the oxide catalyst precursors were characterized with ammonia temperature programmed desorption and Raman spectroscopy. The spent sulfided catalysts were also extensively characterized by scanning electron microscopy (SEM) and by scanning transmission electron microscopy (STEM) coupled with energy dispersive X-ray spectroscopy (EDS). The catalytic hydropyrolysis of beech wood produced four kinds of products: Liquid organic and aqueous phases, solid char and gases. The solid char and aqueous phase yields were not affected by the type of catalyst. The sum of condensed organics and C₄+ gas yield varied between 24.3 and 26.4 wt.% on dry, ash free basis (daf) and was highest for the Mo catalyst and lowest for the NiMo catalyst. The NiMo catalyst had the highest hydrogenation, cracking, and de-carbonylation activity. The oxygen content in the condensed organic phase was between 9.0 and 12 wt.% on dry basis (db) and was lowest for the CoMo catalyst and highest for the Mo catalyst. The carbon recovery in the condensable organics was 39 % for both the CoMo and the Mo, and 37 % for the NiMo catalyst. These results indicate that the CoMo, due to its high deoxygenation activity and high carbon recovery, is the most suitable catalyst for catalytic hydropyrolysis. The carbon content on the spent CoMo was between 1.5 and 3.3 wt.% and between 0.9 and 3.1 on the spent NiMo catalyst, but between 5.0 and 5.5 wt.% on the spent Mo catalyst. The higher carbon content on the spent Mo catalyst was probably due to its lower deoxygenation and hydrogenation activity. Calcium particles and small amounts of potassium (≤1.5 wt.%) were detected on all spent catalysts using STEM-EDS, showing that alkali metals are transferred from the biomass to the catalyst, which potentially could lead to catalyst deactivation.
Effect of the catalyst in fluid bed catalytic hydropyrolysis

Catalytic hydropyrolysis of beech wood was conducted in a fluid bed reactor followed by a hydrodeoxygenation reactor with a sulfided NiMo/Al₂O₃ catalyst. In order to evaluate the effect of the catalyst in the fluid bed reactor, six different bed materials were tested. Conducting the hydropyrolysis using only the catalyst support materials MgAl₂O₄ or zeolite mixed with Al₂O₃ (H-ZSM-5-Al₂O₃) gave a high char and coke yield (18.7-21.1 wt.% dry ash free (daf)), CO and CO₂ (18.9 and 20.0 wt.% daf), and low yield of condensed organics and C₄+ gasses (17.8-20.4 wt.% daf). Using the supported catalysts CoMo/MgAl₂O₄ or NiMo/H-ZSM-5-Al₂O₃ significantly decreased the char yield to between 11.4 and 13.1 wt.% daf, while the condensed organics and C₄+ yield increased to 21.5 wt.% daf for the CoMo/MgAl₂O₄ and 24.0 wt.% daf for the NiMo/H-ZSM-5-Al₂O₃. As an alternative to the (commercial) supported catalysts, a cheap natural mineral bog iron was tested as catalyst and gave a condensed organics and C₄+ yield of 22.8 wt.% daf when pre-sulfiding the bog iron, while the yield was 24.7 wt.% daf when the bog iron was used un-sulfided, but reduced prior to the experiment. This indicates that bog iron is the most suitable catalyst in the fluid bed reactor.

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Impact of ZSM-5 Deactivation on Bio-Oil Quality during Upgrading of Straw Derived Pyrolysis Vapors

In this work, we provide detailed information on the change in product distribution and bio-oil quality during extended feeding of biomass derived fast pyrolysis vapors over ZSM-5. The effect of catalyst deactivation by coking on the resulting oil product characteristics was clarified in order to determine when the vapor upgrading should be stopped and the regeneration initiated. Obtaining a stable catalytic fast pyrolysis (CFP) oil while maintaining good energy recovery is important within the context of potential coprocessing of these oils with petroleum feedstocks via fluid catalytic cracking (FCC) or hydrotreatment of the whole CFP oil. Wheat straw derived fast pyrolysis vapors were upgraded in an ex-situ fixed bed reactor containing a steamed ZSM-5 catalyst at 500 °C. Oils were collected both for runs starting the upgrading over a fresh (or regenerated) catalyst and for runs which were continued over an increasingly coked zeolite. The oils were characterized for water content, elemental analysis, total acid number (TAN), chemical composition by gas chromatography mass spectrometry with flame ionization detection (GC-MS/FID), size exclusion chromatography (SEC), evaporation characteristics by thermogravimetric analysis (TGA), $^1$H nuclear magnetic resonance (NMR), $^{13}$C NMR, and two-dimensional heteronuclear single-quantum correlation (2D HSQC) NMR. With increasing biomass-to-catalyst mass ratio (B:C), the yield of deoxygenated hydrocarbons decreased, accompanied by a breakthrough of primary pyrolysis vapors leading to an increasing organic liquid yield. The oxygen content of the condensed, phase separated oil fraction increased and the molar O/C ratio of 0.05 and TAN of 6 mg KOH/g for oil collected during B:C = 0–1.1 increased to O/C = 0.18 and TAN = 14 mg KOH/g for oil collected during B:C = 3.6–6.2. Oil produced at 90% reduced catalyst amount and B:C = 0–6.5 and 0–12.9 increased the carbon recovery into the oil product to 23% and 27%, respectively but led to an increase in O/C ratio from 0.18 to 0.22, thus approaching the noncatalytic reference case (SiC bed at 500 °C) of O/C = 0.24. Clear differences in the evaporation behavior of the collected oils were observed, with a shift to more volatile fractions and less charring for products obtained at low B:C ratio. Characterization of the upgraded oils with $^{13}$C NMR and $^1$H NMR indicated a clear enhancement of thearomatics content and a reduction of sugar and aldehyde compounds. The concentration of carbon within carbonyl, carbohydrates, and methoxy/hydroxy groups was effectively reduced for oils obtained at low B:C ratios. Catalyst characterization was performed with X-ray fluorescence (XRF), ammonia temperature-programmed desorption (NH$_3$-TPD), N$_2$ and Ar-physisorption, transmission electron microscopy (TEM), and X-ray diffraction (XRD). After steaming and four repeated upgrading/regeneration cycles corresponding to an accumulated B:C ratio of 40, the zeolite’s concentration of strong acid sites measured by NH$_3$-TPD($T_{\text{des}} > 275 \, ^{\circ} \text{C}$) reduced from 0.43 mmol/g for the calcined version to 0.07 mmol/g and the Brunauer–Emmett–Teller (BET) surface area decreased from 468 to 385 m$^2$/g. The hot gas filter upstream of the zeolite bed was found effective in preventing accumulation of potassium on the catalyst.

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Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
KOH capture by coal fly ash

The KOH-capture reaction by coal fly ash at suspension-fired conditions was studied through entrained flow reactor (EFR) experiments and chemical equilibrium calculations. The influence of KOH-concentration (50–1000ppmv), reaction temperature (800–1450°C), and coal fly ash particle size (D_{50}=6.03–33.70μm) on the reaction was investigated. The results revealed that, at 50ppmv KOH (molar ratio of K/(Al+Si)=0.048 of feed), the measured K-capture level (C_K) of coal fly ash was comparable to the equilibrium prediction, while at 250ppmv KOH and above, the measured data were lower
than chemical equilibrium. Similar to the KOH-kaolin reaction reported in our previous study, leucite (KAlSiO$_4$) and kaliophilite (KAlSi$_2$O$_6$) were formed from the KOH-coal fly ash reaction. However, coal fly ash captured KOH less effectively compared to kaolin at 250ppmv KOH and above. Studies at different temperatures showed that, at 800°C, the KOH-coal fly ash reaction was probably kinetically controlled. At 900–1300°C it was diffusion limited, while at 1450°C, it was equilibrium limited to some extent. At 500ppmv KOH (molar ratio of K/(Al+Si)=0.481), and a gas residence time of 1.2s, 0.063gK/(g additive) and 0.087gK/(g additive) was captured by coal fly ash (D$_{50}$=10.20μm) at 900 and 1450°C, respectively. Experiments with coal fly ash of different particle sizes showed that a higher K-capture level were obtained using finer particle sizes, indicating some internal diffusion control of the process.
Aerodynamic and physical characterization of refuse derived fuel

Physical and aerodynamic characteristics of several refuse derived fuel (RDF) samples were studied. Each RDF sample was tested in a wind sieve to classify the particles into different fractions according to their terminal velocity. The individual particles from the wind sieve were then manually separated according to the material type and physically characterized by weight measurement and 2D photographing. For the tested samples, despite the overall weight distribution of the fractions from the wind sieve was similar, the material distribution of particles in each fraction was significantly different. It has been shown that regardless of the particle material, for each group of particles from the wind sieve test, the ratio of particle maximum projected area to particle mass lies in a narrow range. A new approach based on the particle maximum projected area was proposed to predict the terminal velocity of particles and was tested for each group of particles from the wind sieve experiment. The maximum deviation of the mass-based averaged terminal velocity predicted from the drag model compared to the mid-point wind sieve velocity was smaller than 14%. A procedure was proposed for physical characterization of RDF particles based on the wind sieve test and 2D imaging of particles. This characterization can be used as an input for Computational Fluid Dynamics (CFD) calculations of RDF-fired cement calciners and rotary kilns.
Biomass ash induced agglomeration in fluidized bed. Part 2: Effect of potassium salts in different gas composition

Agglomeration is one of the main challenges for combustion and gasification of biomass in fluidized beds. Bed agglomeration is related to K species present in biomass. Understanding the role of different types of K species on formation of agglomerates at different conditions can reveal the mechanisms of biomass ash induced agglomeration. Extensive experiments are conducted in a laboratory scale fluidized bed reactor, using mixtures of quartz sand and K species, including KCl, K₂SO₄ and K₂CO₃, to study the agglomeration mechanisms. The effects of gas composition, including air, H₂– and H₂O– containing gas are investigated. The morphology and elemental analyses of the agglomerate samples are examined by SEM/EDS analysis. Thermodynamic equilibrium calculations are performed for verifying the proposed mechanisms. The results show that the role of various forms of potassium salts on agglomeration in fluidized beds is different. Gas composition also has strong impact on the agglomeration tendency. In the air and H₂-containing gas, defluidization of KCl in a sand bed is caused by the melt of KCl. However, KCl reacts with SiO₂ to form K-silicates in the H₂O-containing gas, which results in a lower defluidization temperature. No defluidization is observed for K₂SO₄ in the presence of oxygen or water. However, K₂SO₄ decomposes and reacts with SiO₂ to form K-silicates, causing defluidization at 850°C in the H₂O-containing gas. In the air, H₂– or H₂O-containing gas, K₂CO₃ would react with SiO₂ to form potassium silicates and KOH may be additionally formed in the H₂– or H₂O-containing gas. The possible mechanisms of agglomeration of various potassium salts at different conditions are discussed.

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Combustion Behavior of Single Particles of Raw Wood and Pelletized Wood

What were our motivation and research objectives?
We present a single particle combustion (SPC) study examining the relationship between combustion behavior and particle density.
• There are limited data on the combustion behavior of raw and pelletized wood at suspension-fired conditions.
• Understanding the effect of pelleting conditions (temperature, pelleting pressure) on the combustion behavior of pine and beech pellets compared to raw wood in a SPC reactor.
• SPC studies allow to predict the particle combustion behavior in full-scale furnaces.

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Deposition Properties of Biomass Fly Ash
This study investigated deposit formation of biomass fly ash on steel tubes, in a lab-scale Entrained Flow Reactor. Experiments were conducted using model biomass fly ash, prepared from mixtures of K2Si4O9, KCl, K2SO4, CaO, SiO2 and KOH, as well as three different boiler fly ashes: a wood fly ash, a straw fly ash, and a straw + wood cofired fly ash. The fly ashes were injected into the reactor, to form deposits on an air-cooled deposit probe, simulating deposit formation on superheater tubes in boilers. The results revealed that increasing flue gas temperature, probe surface temperature, time, fly ash flux and fly ash particle size increased the rate of deposit formation. However, increasing flue gas velocity resulted in a decrease in the deposit formation rate. A mechanistic model was developed for predicting deposit formation in the reactor. Inertial impaction was the primary mechanism of deposit formation, when pure K2Si4O9, SiO2 or CaO was injected into the reactor, forming deposits only on the upstream side of the steel tube. However, feeding KCl, K2SO4 or KOH into the reactor resulted in deposit formation on both sides of the steel tube, via condensation, thermophoresis, and inertial impaction.

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Devolatilization of wood and torrefied wood with different apparent density: Experimental and modelling study
In this work, single particle combustion experiments on 3 mm raw and torrefied wood cubes of 5 different wood species with apparent density varying from 243 to 698 kg/m3 were conducted, under conditions (1256 °C, 2.8% O2, 27% H2O) simulating the local conditions in a pulverized fuel boiler. The devolatilization time was determined based on flame extinction time, which was measured by a chargecoupled device (CCD) camera [1]. The devolatilization process was modelled by a non-isothermal single particle model presented in a previous paper [2]. The modelling results are in good agreement with experimental data as shown in Fig. 1. Both experimental and modelling results show that the devolatilization time increases linearly with the particle mass, even though different wood species with different apparent density are used in the experiments. The reason is that the devolatilization process is dominated by heat transfer. When the particle size is the same, higher density particles results in lower heating rate, mainly due to the increased thermal capacity of the particles. The results suggest that under the studied conditions, particle mass is a primary parameter that influences the devolatilization time of biomass particles.

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Fremstilling af CO₂-neutral benzin og diesel: - ved katalytisk hydropyrolyse af biomasse - en spændende teknologi med mulighed for energilagring.

Siden 1965 er verdens energiforbrug mere end femdoblet og forbruget forventes at fortsætte med at stige i fremtiden. Imens mindskes reserverne af fossilt brændstof hastigt og CO₂-udledningen fra forbrændingen af fossile brændstoffer medfører global opvarmning. Vi har derfor brug for hurtigt at finde bæredygtige måder at producere flydende brændstoffer til transportformål, i særdeleshed til fly og lastbiler. En af de mest udbredte vedvarende energiteknologier er vindmøller. Vindenergi udgjorde 42% af Danmarks forsyning af elektricitet i 2015, men ulemper ved vinden er, at elproduktionen fluktuerer, hvilket allerede nu resulterer i, at der i perioder produceres mere strøm, end vi bruger, og i andre perioder ikke produceres nogen væsentlig mængde vindmøllestrøm. Andre vedvarende energikilder såsom sol- og bølgeenergi har samme ulempe. Der er derfor behov for nye effektive metoder til at lagre overskydende energi. En måde at lagre denne overskydende energi på er at bruge den i omdannelse af biomasse, såsom træ, halm og alger, til flydende kulbrinner der kan lagres og bruges i den eksisterende transportinfrastruktur. Dette kan gøres vedhjælp af katalytisk hydropyrolyse. Olieproduceret fra biomasse er i modsætning til fossil olie i udgangspunktet CO₂-neutrat, hvis den fremstilles fra bæredygtigt producerede skov- og landbrugsprodukter.

From Wood Chips to Pellets to Milled Pellets: the Mechanical Processing Pathway of Wood

We present a study focusing on the mechanical processing pathway of wood, including pellet feedstock size reduction, pelletization, and pellet comminution, because:
• Operators of wood suspension-fired power plants need information about the physical properties (i.e., size, shape, density) of milled pellet particles for optimizing particle burnout.
• An understanding of how pelletization and comminution affect the physical properties of wood is valuable for pellet producers, who want to produce pellets of desirable quality for power plants.
• Pellets after milling in coal mills are believed to show the original particle size distribution (PSD) before pelletizing.
• The effect of the size and shape of milled wood particles on the pelletizing process and pellet quality has hardly been studied.

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High Heating Rate Devolatilization Kinetics of Pulverized Biomass Fuels

Devolatilization kinetics for the biomass fuels miscanthus, leached miscanthus, and KCl-doped pinewood were determined at high heating rates (∼105 K s⁻¹), high peak temperatures (1405–1667 K), and short residence times (<70 ms). The particle temperature and residence time distribution were obtained from computational fluid dynamic simulations. The measured devolatilization rates, formulated in terms of single first-order reactions, were significantly faster than data reported in the literature. This difference was attributed partly to the fast heating rate/high-temperature conditions of the present study and partly to a more accurate estimate of the particle temperature. The current results indicate that neither the biomass type nor the alkali content of the biomass has a significant impact on the devolatilization rate under the investigated conditions. The development in the particle morphology was studied by electron microscopy as each fuel underwent partial to full conversion. The char yields ranged from 0.02 (leached miscanthus) to 0.11 (KCl-doped pinewood), indicating that even during fast heating, the biomass alkali content promotes char formation.
Hydrogen assisted catalytic biomass pyrolysis. Effect of temperature and pressure

Beech wood has been converted into a mixture of oxygen-free naphtha and diesel boiling point range hydrocarbons by using catalytic hydropyrolysis in a fluid bed reactor with a CoMoS/MgAl2O4 catalyst, followed by deep hydrodeoxygenation (HDO) in a fixed bed reactor loaded with a NiMoS/Al2O3 catalyst. The effect of varying the temperature (365–511°C) and hydrogen pressure (1.6–3.6MPa) on the product yield and organic composition was studied. The mass balance closed by a mass fraction between 90 and 101% dry ash free basis (daf). The yield of the combined condensed organics and C4+ varied between a mass fraction of 17 and 22% daf, corresponding to an energy recovery of between 40 and 53% in the organic product. The yield of the non-condensable gases varied between a mass fraction of 24 and 32% daf and the char yield varied between 9.6 and 18% daf. The condensed organics contained a mass fraction of 42–75% aromatics, based on GC×GC-FID chromatographic peak area, and the remainder was primarily naphthenes with minor amounts of paraffins. The condensed organics were essentially oxygen free (mass fraction below 0.001%) when both reactors were used. Bypassing the HDO reactor increased the oxygen concentration in the condensed liquid to a mass fraction of 1.8%. The results show that catalytic hydropyrolysis may be a viable way to process solid biomass into liquid and gaseous fuels.
Hydrogen assisted catalytic biomass pyrolysis for green fuels

Fast pyrolysis of biomass produces a high yield of bio-oil through well-established technologies [1]. To utilize this oil as liquid fuel the oxygen content must be reduced from 15-30 wt.% down to <1 wt.%, which increases heating value and stability and decreases acidity [1]. Upgrading bio-oil by catalytic hydrodeoxygenation (HDO) is challenged by severe polymerization and coking upon heating the oil. Alternatively, performing fast pyrolysis in high-pressure hydrogen atmosphere in a fluid bed reactor with a HDO catalyst as bed medium, could immediately stabilize reactive pyrolysis vapors [2]. An additional HDO reactor could ensure removal of oxygen down to <1 wt%. A schematic diagram for such a process is shown in Figure 1. A simplified bench scale setup has been constructed at DTU Chemical Engineering for proof-of-concept for the continuous conversion of solid biomass to low oxygen, fuel-grade bio-oil.

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Hydrogen assisted catalytic biomass pyrolysis for green fuels. Effect of cata-lyst in the fluid bed

1. Introduction
Fast pyrolysis of biomass is a well-known technology for producing bio-oil. However, in order to use the oil as transportation fuel the oxygen content must be decreased from approximately 40 wt.% to below 1 wt.% [1]. This can be achieved by catalytic hydrodeoxygenation (HDO). Unfortunately, deactivation due to coking of the cata-lyst is a severe problem for this technology [1]. The objective of the present work is to produce oxygen free gasoline and diesel from biomass by hydrogen assisted catalytic fast pyrolysis.

2. Experimental
Fast pyrolysis of beech wood (feeding rate: 270 g/h) has been performed in 26 bar hydrogen (flow: 55-90 NL/min) in a fluid bed reactor operated at 450 °C with several different catalysts as bed material followed by an additional vapor phase, fixed bed HDO reactor (operated at 370-400 °C) using a sulfided commercial Ni-Mo/Al2O3 catalyst. The time on stream varied between 0.75 and 3.5 h. The tested catalysts in the fluid bed include olivine sand (OS), MgAl2O4 (MgAl), CoMo/MgAl2O4 (CoMo), zeolite HZSM5 mixed with alumina (ZA), NiMo impregnated on zeolite mixed with alumina (NiMoZA), and a cheap and non-toxic catalyst (HYCP). The HYCP catalyst was tested both in reduced (HYCP-R) and sulfided forms (HYCP-S), while the other catalysts, with the exception of OS, were sulfided prior to the experiment.

3. Results and discussion
The product distribution for the experiments where the HDO reactor was used is shown in Figure 1. The obtained bio-oil from these experiments was essentially oxygen free and was in the diesel and gasoline boiling point range. Using MgAl
and ZA gave a high char yield and a lower yield of condensable organics compared to the supported active catalysts (CoMo and NiMoZA). Using the HYCP-R catalyst gave a condensable organic yield of 25 wt. % daf corresponding to the highest ob-tained energy recovery of 58 %. Using the HYCP-R catalyst in the fluid bed reactor and by-passing the HDO reactor decreased the C1-3 yield from 12 to 3 wt. % daf and increased the condensable organics yield from 25 to 34 wt. % daf. However, the oxygen concentration in the produced oil increased to 14 wt. % db. GC×GC−MS/FID showed that the oxygenates were mainly phenols (22 % FID-area) and oxygenated aliphatics (21 % FID area).

4. Conclusions

Our work indicates that hydrogen assisted catalytic pyrolysis is a feasible path for production of liquid renewable fuels. The presence of an active catalyst in the fluid bed is essential and has a significant impact on the product distribution. It is possible to obtain a high yield of condensable organics with the cheap HYCP catalyst, thus showing that it is not necessary to use expensive formulated catalysts. In our ongoing research the differences between CoMo, NiMo and Mo catalysts in the fluid bed is further investigated. Furthermore the effect of the metal loading and the effect of using different supports are also studied and the spent catalysts characterized by use of SEM and transmission electron microscopy (TEM).
which corresponds to an energy recovery up to 58%. Using MgAl and ZA gave a high char yield and a low yield of condensable organics compared to the supported active catalysts (CoMo and NiMoZa). Characterization of the spent catalyst with scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) showed a significant higher carbon content on the spent support materials (MgAl and ZA) compared to the supported catalysts (CoMo and NiMoZA) and the HYCP catalysts. Using the HYCP-R in the fluid bed reactor and bypassing the HDO reactor decreased the C1-3 yield from 12 to 3 wt. % daf and increased the condensable organic yield from 25 to 34 wt. % daf. However, the oxygen concentration in the produced oil increased to 14 wt. % db. GC×GC-MS/FID showed that the oxygenates were mainly phenols (22 % FID-area) and oxygenated aliphatics (21 % FID area). Our work indicates that hydrogen assisted catalytic pyrolysis is a feasible path for production of liquid renewable fuels. The catalyst in the fluid bed is essential and has a significant impact on the product distribution. It is possible to obtain a high yield of condensable organics with the HYCP catalyst, thus showing that it is not necessary to use expensive formulated catalysts. In our ongoing research the differences between CoMo, NiMo, Mo catalysts in the fluid bed is further investigated. Furthermore, the effect of the metal loading and the effect of using different supports are also studied and the spent catalysts characterized by use of SEM and transmission electron microscopy (TEM).

Figure 1. Effect of the catalyst in the fluid bed on the product distribution

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Measurements of the NOx precursors and major species concentrations above the grate at a waste-to-energy plant
Satisfactory results from modelling of NOx formation in CFD during combustion of Municipal Solid Waste (MSW) in grate-fired waste-to-energy plants is highly dependent on accurate descriptions of the temperature field in the free-board above the waste bed. Accurate modelling of the temperature field relies on an accurate determination of the boundary conditions; the species concentration, gas temperature and gas velocity from the waste bed into the computational domain. In this study the gas temperature and the gas concentration profiles of O2, H2O, CO, CO2, CH4, C2H2, C2H4, NH3 and HCN along the waste bed were measured. The measurements were performed on a 9 ton/h grate-fired waste-to-energy plant, Affald+ unit 4 in Denmark. The species concentration profiles were determined by gas extraction using a 6 m water cooled probe and FTIR spectroscopy, while the gas temperatures were determined by suction pyrometer. The major combustible gasses were determined to be CO, CH4 and C2H4, which are only found above the first half of the grate. Furthermore, it was determined that during grate-fired MSW combustion the majority of the NOx precursors are released as NH3; more than 80%. The influence of NOx precursor composition on the NOx formation was examined through CHEMKIN simulations. It was shown that for reliable modelling of the NO formation at high excess air ratios, \( \lambda > 1.1 \), it is important to determine the correct ratio between NH3 and HCN. The importance of an accurate precursor determination increases considerably with decreasing temperatures.

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Web of Science (2017): Impact factor 4.908
Web of Science (2017): Indexed yes
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BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.46 SJR 1.781 SNIP 2.123
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.14 SJR 1.634 SNIP 2.294
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BFI (2011): BFI-level 2
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BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.985 SNIP 2.27
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
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Scopus rating (2004): SJR 1.203 SNIP 1.864
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Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 1.065 SNIP 1.284
Scopus rating (2001): SJR 1.062 SNIP 1.269
Melting behaviour of raw materials and recycled stone wool waste

Stone wool is a widely used material for building insulation, to provide thermal comfort along with fire stability and acoustic comfort for all types of buildings. Stone wool waste generated either during production or during renovation or demolition of buildings can be recycled back into the stone wool melt production. This study investigates and compares the thermal response and melting behaviour of a conventional stone wool charge and stone wool waste. The study combines differential scanning calorimetry (DSC), hot stage microscopy (HSM) and X-ray diffraction (XRD). DSC reveals that the conventional charge and stone wool waste have fundamentally different thermal responses, where the charge experiences gas release, phase transition and melting of the individual raw materials. The stone wool waste experiences glass transition, crystallization and finally melting. Both DSC and HSM measurements indicate that the wool waste initiates melting at a lower temperature than the conventional charge. Also DSC measurements show that the wool waste requires less energy for heating and melting than the conventional charge, making stone wool waste recycling desirable both for environmental and for process purposes.

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Optimizing catalytic tar-deoxygenation of fast pyrolysis vapors

The concept of de-centralized smaller scale pyrolysis plants that locally valorize available biomass by densifying its energy content into a bio-crude is of increasing interest world-wide. Fast pyrolysis of biomass produces a high yield of bio-oil through well-established technologies at optimized temperature, pressure, and residence time of the liberated pyrolysis vapors\(^1\). Operating conditions and chemical transformations that reduce the oil’s oxygen content and acid number to stabilize the oil deserve prioritized attention\(^2\) and allow further processing in oil refineries. Deoxygenation can be obtained by catalytic upgrading oversolid acid catalysts. A close coupled process operating at similar temperature and atmospheric pressure conditions to those preferred for optimum yields of bio-oil potentially offers economic advantages for zeolite deoxygenation over high pressure hydrotreating\(^3\). To date, the medium pore size ZSM-5 zeolite yields a high aromatic yield and the least amount of coke\(^4\) in upgrading of pyrolysis vapors. However, coke formation in the reaction of pyrolysis vapors over the zeolites and steam dealumination still leads to rapid deactivation\(^5\)–\(^9\). Enhancement of ZSM-5 performance besides optimal Si/Al ratio and operating temperature is obtained by ethersynthesis modifications, or post-synthesis treatment. Incorporation of Ga to a ZSM-5 catalyst was shown to increase the aromatic yields considerably\(^10\), and the combination of several types of catalysts in order to exploit their unique advantages was demonstrated for physically mixing with mesoporous catalysts\(^11\) and dual beds comprised of solid acid and basic catalysts\(^12\). Despite promising laboratory results, long term experiments of pilot plants showing stable catalyst operation with multiple regeneration steps are needed to prove the economic attractiveness of bio-oil plants.
Performance of mesoporous ZSM-5 for the upgrading of straw derived pyrolysis vapors

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Performance of mesoporous ZSM-5 for the upgrading of straw derived pyrolysis vapors

In order to allow processing of biomass derived fast pyrolysis oils in oil refineries, reduction of the oil’s oxygen content and acid number is required [1]. Deoxygenation can be obtained by direct upgrading of the pyrolysis vapors over solid acid catalysts. A close coupled process operating at temperature and pressure conditions close to those for optimum liquid yields in pyrolysis units offers potential economic advantages over high pressure hydrotreating [2]. To date, the medium pore size ZSM-5 zeolite provides a high aromatic yield and the least amount of coke in upgrading of pyrolysis vapors [3]. However, the coke caused by reactive pyrolysis vapors causes a rapid decay in site accessibility and requires frequent regeneration to recover activity. In addition, irreversible dealumination can be caused by steam from the pyrolysis process, the dehydration reactions during upgrading and the steam produced during oxidative regeneration. We address the reversible deactivation due to coke by introducing an auxiliary mesopores network to improve the accessibility and prolong the zeolite’s active time on stream. In order to reduce the irreversible deactivation, the zeolites acid site strength and density have been balanced with modifications by phosphorous stabilization.

Performance of mesoporous ZSM-5 in deoxygenation of straw derived pyrolysis vapors

Fast pyrolysis of biomass produces a high yield of bio-oil through well-established technologies at optimized temperature, pressure, and residence time of the liberated pyrolysis vapors [1], [2]. In order to allow processing in oil refineries, further conversion that reduces the oil’s oxygen content and acid number deserve prioritized attention [3]. Deoxygenation can be obtained by catalytic upgrading over solid acid catalysts. A close coupled process operating at temperature and pressure conditions close to those for optimum liquid yields in pyrolysis units offers potential economic advantages for zeolite deoxygenation over high pressure hydrotreating [4]. To date, the medium pore size ZSM-5 zeolite provides a high aromatic yield and the least amount of coke [5] in upgrading of pyrolysis vapors. The coke caused by reactive pyrolysis vapors may form an envelope covering the zeolite crystals and block the pore mouth entries. The rapid decay in site accessibility requires frequent regeneration to recover activity. In addition, irreversible dealumination can be caused by steam from the pyrolysis process, the dehydration reactions during upgrading and the steam produced during oxidative regeneration. We address the reversible deactivation due to coke by introducing an auxiliary mesopores network to improve the accessibility...
and prolong the zeolite’s active time on stream. In order to minimize the irreversible deactivation, the zeolites acid site strength and density have to be carefully balanced with additional metal promoters or modification by phosphorous.

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**Potassium Capture by Kaolin, Part 1: KOH**
The reaction of gaseous KOH with kaolin and mullite powder under suspension-fired conditions was studied by entrained flow reactor (EFR) experiments. A water-based slurry containing kaolin/mullite and KOH was fed into the reactor and the reacted solid samples were analyzed to quantify the K-capture level. The effect of reaction temperature, K-concentration in the flue gas, and, thereby, molar ratio of K/(Al+Si) in reactants, gas residence time, and solid particle size on K-capture reaction was systematically investigated. Corresponding equilibrium calculations were conducted with FactSage 7.0. The experimental results showed that kaolin reached almost full conversion to K-aluminosilicates under suspension-fired conditions at 1100–1450 °C for a residence time of 1.2 s and a particle size of $D_{50} = 5.47 \mu m$. The amount of potassium captured by kaolin generally followed the equilibrium at temperatures above 1100 °C, but lower conversion was observed at 800 and 900 °C. Crystalline kaliophilite (KAlSiO$_4$) was formed at higher temperatures (1300 and 1450 °C), whereas, amorphous K-aluminosilicate was formed at lower temperatures. Coarse kaolin ($D_{50} = 13.48 \mu m$) captured KOH less effectively than normal ($D_{50} = 5.47 \mu m$) and fine ($D_{50} = 3.51 \mu m$) kaolin powder at 1100 and 1300 °C. The difference was less significant at 900 °C. Mullite generated from kaolin captured KOH less effectively than kaolin at temperatures below 1100 °C. However, at 1300 and 1450 °C, the amount of potassium captured by mullite became comparable to that of kaolin.

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Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
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Scopus rating (2015): CiteScore 3.34
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Potassium Capture by Kaolin, Part 2: K₂CO₃, KCl, and K₂SO₄

The reaction of kaolin powder with K₂CO₃, KCl, and K₂SO₄ under suspension-fired conditions was studied by entrained flow reactor experiments and equilibrium calculations. The influence of reaction temperature, K-concentration in the flue gas, molar ratio of K/(Al + Si) in the reactants, and gas residence time on the reaction was investigated. The results showed that the K-capture level (Cₖ) (g potassium reacted by per g kaolin available) of K₂CO₃ and KCl by kaolin generally followed the equilibrium predictions at temperatures above 1100 °C, when using a kaolin particle size of D₅₀ = 5.47 μm and a residence time of 1.2 s. This revealed that a nearly full conversion was obtained without kinetic or transport limitations at the conditions applied. At 800 and 900°C, the measured conversions were lower than the equilibrium predictions, indicating that the reactions were either kinetically or diffusion controlled. The measured Cₖ of K₂SO₄ by kaolin was much lower than the equilibrium predictions. Kaliphilite (KAISiO₄) product was predicted by the equilibrium calculations of the K₂SO₄ capture reaction; however the XRD results revealed that leucite (KAISi₂O₆) was formed. Compared with the Cₖ of KOH reacting with kaolin, the Cₖ of K₂CO₃ was similar, while the Cₖ values of KCl and K₂SO₄ were both lower.
Predicting Biomass Char Yield from High Heating Rate Devolatilization using Chemometrics

This study provides a simple model for biomass char yield obtained under conditions relevant for suspension firing. Using the multivariate data analysis methods, principal component analysis (PCA) and partial least-squares regression (PLS regression), an equation is presented, which predicts the char yield for wood and herbaceous biomass. The model parameters are heating rate (0.1–12 × 10^3 K/s), average particle size (0.13–0.93 mm), maximum temperature (873–1673 K), potassium content (from 0.02 wt %db and upward), and char yield (1–15 wt %daf). The model is developed based on wood biomass data and subsequently expanded to include straw and other herbaceous biomass. It is validated against experimental data from the literature, and in general, it exhibits the same characteristics. Independent data sets of wood are predicted with an average error (RMSEP) of 0.9 wt %point daf and straw with an RMSEP = 0.9 wt %daf for the model, when a slope/intercept correction is applied or RMSEP = 1.1 wt %daf otherwise. To include herbaceous biomass, the model introduces a potassium cut off level at 0.53 wt %db, because the catalytic effect of potassium on the devolatilization process levels off above this concentration. The model consists of one equation, making implementation into CFD and devolatilization models possible without adding to the computational costs.

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Reaction kinetics for biomass self-ignition at 150–230°C
Replacing coal with pelletized biomass on pulverized-fuel CHP-plants has led to an increased fire risk in storages and processing facilities. Accurate models to predict this behavior are scarce, mainly owing to a lack of reaction kinetic data for low temperatures.

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Reactive additives for alkali capture in biomass combustion

Biomass, as a renewable and CO₂ neutral fuel, is combusted in fluidized bed, grate and pulverized fuel-fired boilers for heat and power production. The gaseous alkali species released from biomass combustion, such as KCl and KOH, can cause several operation problems in the boilers, including ash deposition, corrosion, bed agglomeration, and deactivation of SCR catalysts. To address these problems, reactive additives that can convert the harmful gaseous alkali species to less harmful species, have been studied extensively through experiments and modelling. This paper aims to provide a discussion of the current understanding and applications of reactive additives for alkali capture in biomass combustion. The focus is on the thermodynamics, reaction mechanism, kinetics, and application aspects of sulfur based additives and Al-Si based additives.

Tensile Adhesion Strength of Biomass Ash Deposits: Effect of the Temperature Gradient and Ash Chemistry

Replacing coal with biomass in power plants is a viable option for reducing net CO₂ emissions and combating climate change. However, biomass combustion in boilers may exacerbate problems related to ash deposition and corrosion, demanding effective deposit removal. The tensile adhesion strength of model biomass ash deposits, containing mixtures of KCl, K₂SO₄, CaO, CaSO₄, and K₂Si₄O₉, has been investigated in this study. The deposits were prepared on superheater steel tubes and sintered in an oven. The superheater steel tube was cooled by air, incorporating a temperature gradient across the deposits. After sintering, the deposits were removed using an electrically controlled arm and the corresponding tensile adhesion strength was measured. The influence of the flue gas temperature (500–700 °C), steel surface temperature (500–650 °C), and deposit composition were investigated. The results revealed that increasing the flue gas temperature as well as the steel surface temperature led to a sharp increase in the tensile adhesion strength. The sharp increase was typically observed near the melting temperature (or deformation temperature) of the investigated model deposits. Furthermore, migration of molten/vapor species from the outer layer of the deposit to the deposit–tube interface, causing liquid-state sintering, was observed at high flue gas temperatures, leading to an increase in the tensile adhesion strength. Varying the ash chemistry of the model deposits revealed that the melt fraction of the deposit was highly influential in determining the deposit adhesion strength. The addition of compounds that increased the melt fraction of the deposit increased the tensile adhesion strength, whereas the addition of inert compounds with a high melting point, such as CaO, decreased the tensile adhesion strength. Moreover, the results suggested that the adhesion strength of the deposits was influenced by the corrosion occurring at the deposit–tube interface.
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Scopus rating (2017): CiteScore 3.55
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BFI (2016): BFI-level 2
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Web of Science (2016): Impact factor 3.091
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Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
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Scopus rating (2014): CiteScore 3.3
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Scopus rating (2013): CiteScore 3.52
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ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
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Web of Science (2008): Indexed yes
Web of Science (2007): Indexed yes
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Web of Science (2005): Indexed yes
Web of Science (2004): Indexed yes
Web of Science (2003): Indexed yes
Web of Science (2002): Indexed yes
Web of Science (2001): Indexed yes
Web of Science (2000): Indexed yes
The Role of Inorganic Matter in Biomass Self-Ignition

Solid biomass, such as wood pellets, can replace coal for heat and power generation in existing combined heat and power plants. This requires storing and processing such materials in large quantities, where they have shown a tendency to self-heat, and possibly spontaneously ignite. From a plant operator’s point of view, it is highly relevant to model and predict such behavior, ideally based on available fuel data. Inorganic matter present in biomass has been known to promote thermal conversion, both under oxidative and inert atmospheres. In this study, biomasses with different inorganic content and composition (pine, beech, wheat straw, sunflower husks) are screened in lab-scale fixed-bed heating experiments, and reaction rates for these materials are determined by thermogravimetric analysis. No clear connection between ash-forming elements naturally present in the biomass materials on one side, and reaction onset behavior or reaction rates at 150–230 °C on the other was found. However, adding KCl to pine wood increased reaction rates compared to the raw sample. The results presented here suggest that catalytic effects play a role, but across different materials, the low-temperature behavior is (likely) dominated the composition in terms of cellulose, hemicellulose, lignin, and extractives. Further research is necessary to confirm these findings.

Keywords: solid biofuel, reactivity, combustion, ashes, lignocellulose, low temperature

Transportation fuels from biomass fast pyrolysis, catalytic hydrodeoxygenation, and catalytic fast hydropyrolysis

This review presents and discusses the progress in combining fast pyrolysis and catalytic hydrodeoxygenation (HDO) to produce liquid fuel from solid, lignocellulosic biomass. Fast pyrolysis of biomass is a well-developed technology for bio-oil production at mass yields up to ~75%, but a high oxygen content of 35–50 wt% strongly limits its potential as transportation fuel. Catalytic HDO can be used to upgrade fast pyrolysis bio-oil, as oxygenates react with hydrogen to produce a stable hydrocarbon fuel and water, which is removed by separation. Research on HDO has been carried out for more than 30 years with increasing intensity over the past decades. Several catalytic systems have been tested, and we conclude that single stage HDO of condensed bio-oil is unsuited for commercial scale bio-oil upgrading, as the coking and polymerization, which occurs upon re-heating of the bio-oil, rapidly deactivates the catalyst and plugs the reactor. Dual or multiple stage HDO has shown more promising results, as the most reactive oxygenates can be stabilized at low temperature prior to deep HDO for full deoxygenation. Catalytic fast hydropyrolysis, which combines fast pyrolysis with catalytic HDO in a single reactor, eliminates the need for reheating condensed bio-oil, lowers side reactions, and produces a stable oil with oxygen content, H/C ratio, and heating value comparable to fossil fuels. We address several challenges, which must be overcome for continuous catalytic fast hydropyrolysis to become commercially viable, with the most urgent issues being: (i) optimization of operating conditions (temperature, H2 pressure, and residence time) and catalyst formulation to maximize oil yield and minimize cracking, coke formation, and catalyst deactivation, (ii) development of an improved process design and reactor configuration to allow for continuous operation including pressurized biomass feeding, fast entrainment and collection of char, which is catalytically active for side reactions, efficient condensation of the produced oil, and utilization and/or integration of by-products (non-condensable gasses and char), and (iii) long-term tests with respect to catalyst stability and possible pathways for regeneration. By reviewing past and current research from fast pyrolysis and catalytic HDO, we target a discussion of the combined processes, including direct catalytic fast hydropyrolysis. By critically evaluating their potential and challenges, we finally conclude, which future steps are necessary for these processes to become industrially feasible.
What were our motivation and research objectives?

• There are limited experimental data on 100% wood pellet comminution in full-scale coal vertical roller mills.
• To study if the grindability in roller mills and particle separation in dynamic classifiers were affected by the particle size distribution (PSD) of material within pellets.
• Understanding pellet quality properties that affect the milling performance will ensure efficient pellet milling and hence optimize the combustion process.

Wood Pellet Milling Performance in a Suspension-Fired Power Plant

This paper investigates the milling behavior of two industrial wood pellet qualities (designated I1 and I2 as per ISO 17225-2:2014) in large-scale coal roller mills, each equipped with a dynamic classifier. The purpose of the study was to test if pellet comminution and subsequent particle classification (i.e., the classifier cut size) are affected by the internal pellet particle size distribution obtained after pellet disintegration in hot water. Furthermore, optimal conditions for comminuting pellets were identified. The milling behavior was assessed by determining the specific grinding energy consumption and the differential mill pressure. The size and shape of comminuted pellets sampled from burner pipes were analyzed by dynamic image analysis and sieve analysis, respectively. The results showed that the internal pellet particle size distribution affected both the milling behavior and the classifier cut size. I2 pellets with coarser internal particles than I1 pellets required more energy for milling, led to a higher mill pressure drop and showed a larger classifier cut size. Comminuted pellet particles sampled from burner pipes were notably finer than internal pellet (feed) particles. At similar mill-classifier conditions, characteristic particle sizes of 0.50mm for comminuted I1 pellets (compared to 0.83mm for material within I2 pellets), respectively, were obtained. Pellet comminution at lower mill loads and lower primary airflow rates reduced the mill power consumption, the mill pressure drop, and the classifier cut size. However, this was at the expense of a higher specific grinding energy consumption. Derived 2D shape parameters for comminuted and internal pellet particles were similar. Mill operating changes had a negligible effect on the original elongated wood particle shape. To achieve the desired comminuted product fineness (i.e., the classifier cut size) with lower specific grinding energy consumption, power plant operators need to choose pellets with a finer internal particle size distribution.
Biomass ignition in mills and storages – is it explained by conventional thermal ignition theory?

Self-ignition temperatures determined in the framework of conventional thermal ignition theory do not explain why biomass is much more susceptible to spontaneous ignition in power plant mills or storages. Examining the onset of reactions at low temperatures may provide a better understanding of the process, which can then be incorporated into refined models of self-ignition for biomass and other organic solids. In the present study, the slow, transient heating of several lignocellulosic biomasses and a bituminous coal from ambient temperature to around 300°C were investigated in a lab scale tube oven, with sample sizes between 11–40 g. Tests were carried out under oxidizing (20 % O2) and inert atmospheres. Judged by off-gas measurements of CO and CO₂, a reaction onset could be seen at temperatures below 100°C. Under oxidizing atmosphere, reactions were more intense and set off earlier, suggesting that a heterogeneous oxidation is the dominating mechanism in self-ignition. It could also be shown that both mechanisms compete for reactive material. While oxidation was exothermic, pyrolysis was largely thermally neutral in these experiments. Reaction behavior was seen to depend highly on the material, and the results indicate that higher ash contents may promote reaction onset. However, further work is needed to arrive at a comprehensive model of self-ignition.
CFD simulations on marine burner flames

The marine industry is changing with new demands concerning high energy efficiency, fuel flexibility and lower emissions of NOX and SOX. A collaboration between the company Alfa Laval and Technical University of Denmark has been established to support the development of the next generation of marine burners. The resulting auxiliary boilers shall be compact and able to operate with different fuel types, while reducing NOX emissions.

The specific boiler object of this study uses a swirl stabilized liquid fuel burner, with a pressure swirl spill-return atomizer (Fig.1). The combustion chamber is enclosed in a water jacket used for water heating and evaporation, and a convective heat exchanger at the furnace outlet super-heats the steam.

The purpose of the present study is to gather detailed knowledge about the influence of fuel spray conditions on marine utility boiler flames. The main goal of work presented in this paper was to obtain a spray description to setup a particle injection region in the CFD simulations of the boiler.

Deposit Shedding in Biomass-Fired Boilers: Shear Adhesion Strength Measurements

Ash deposition on boiler surfaces is a major problem encountered in biomass combustion. Timely removal of ash deposits is essential for optimal boiler operation. In order to improve the understanding of deposit shedding in boilers, this study investigates the adhesion strength of biomass ash from full-scale boilers, as well as model fly ash deposits containing KCl, K2SO4, CaO, CaSO4, SiO2, K2CO3, Fe2O3, K2Si4O9, and KOH. Artificial biomass ash deposits were prepared on superheater tubes and sintered in an oven with temperatures ranging from 500 to 1000 °C. Subsequently, the deposits were sheared off by an electrically controlled arm, and the corresponding adhesion strength was measured. The effect of sintering temperature, sintering time, deposit composition, thermal shocks on the deposit, and steel type was investigated.

The results reveal that the adhesion strength of ash deposits is dependent on two factors: ash melt fraction, and corrosion occurring at the deposit–tube interface. Adhesion strength increases with increasing sintering temperature, sharply increasing at the ash deformation temperature. However, sintering time, as well as the type of steel used, does not have a significant effect under the investigated conditions. Addition of compounds which increase the melt fraction of the ash deposit, typically by forming a eutectic system, increases the adhesion strength, whereas addition of inert compounds with a high melting point decreases the adhesion strength. Furthermore, the study indicated that sulfation of ash deposits leads to an increase in adhesion strength, while cooling down the deposits after sintering decreases the adhesion strength.

Finally, it was observed that adhesion strength data follow a log-normal distribution.
The objective of this work was to generate comprehensive data on the formation of residual fly ash during the initial stages of suspension-firing of biomass. Combustion experiments were carried out with pulverized biomass fuels (two straw fuels
and two wood fuels), in an entrained flow reactor at 1200-1400 °C, simulating full-scale suspension-firing of biomass. By
the use of a movable, cooled and quenched gas/particle sampling probe, samples were collected at different positions
along the vertical axis in the reactor, corresponding to gas residence times ranging from 0.25 – 2.0s. The collected
particles were subjected to various analyses, including char burnout level, particle size distribution, elemental composition,
and particle morphology and composition. Furthermore, the transient release, i.e. the vaporization of the flame-volatile
inorganic elements K, Cl and S, from the burning fuel particles to the gas phase, has been quantified by using two different
calculation methods. The ash formation mechanisms were found to be quite similar for straw and wood. The degree of
conversion (char burn-out level) was generally good at residence times ≥ 1s. The size distribution of the residual fly ash
particles evolved with residence time. For all ashes at long residence times a peak of residual ash particles in the range of
20 – 100 µm was observed. The residual ash particles were rich in Si, K and Ca. Further, at long residence times,
submicron particles consisting primarily of KCl (condensed aerosols) became abundant in the ashes from straw
combustion. Release of K to the gas phase was nearly 100 % for the two wood fuels and one of the straw fuels. A straw
sample (Straw 2) with high Si/K molar ratio and a relative shortage of Ca showed a limited release of K in the range of 65
%; this suggests larger retention of K in Si-rich, Ca-lean fuels, due to incorporation of K into silicate structures. All S and Cl
were nearly completely released to the gas phase for all studied samples.

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Full-scale Milling Tests of Wood Pellets for Combustion in a Suspension-Fired Power Plant Boiler

The size reduction of pelletized wood is crucial in suspension-fired power plants, and hence its milling characteristics are of interest to optimize the milling and combustion process. The objective of the study was to compare the size and shape of pellets disintegrated in hot water with that from pellets comminuted at different mill loads. The milling performance of two industrial wood pellet qualities in large-scale coal vertical roller mills at different mill operating conditions was studied. The milling performance was assessed by determining the specific grinding energy consumption (SGEC), and analyzing the comminuted particle shape and particle size distribution (PSD). Large-scale pellet comminution produced finer and wider PSDs than pellet disintegration in hot water, but only slightly altered the particle shape. The mill pressure loss, absorbed mill power, and hence SGEC depended on the pellet quality. Decreasing the mill load produced finer and wider PSDs, and reduced the mill pressure loss and absorbed mill power. However, the SGEC was negatively correlated with the mill load. Adjustments of mill operating conditions had a minor effect on the comminuted particle shape.

H₂CAP - Hydrogen assisted catalytic biomass pyrolysis for green fuels

Fast pyrolysis of biomass produces a high yield of bio-oil through well-established technologies [1]. To utilize this oil as liquid fuel the oxygen content must be reduced from 15-30 wt.% down to <1 wt.%, which increases heating value and stability and decreases acidity [1]. Upgrading bio-oil by catalytic hydrodeoxygenation (HDO) is challenged by severe polymerization and coking upon heating the oil. Alternatively, performing fast pyrolysis in high-pressure hydrogen atmosphere in a fluid bed reactor with a HDO catalyst as bed medium, could immediately stabilize reactive pyrolysis
Fast pyrolysis of biomass produces a high yield of bio-oil through well-established technologies [1]. To utilize this oil as liquid fuel the oxygen content must be reduced from 15-30 wt.% down to <1 wt.%, which increases heating value and stability and decreases acidity [1]. Upgrading bio-oil by catalytic hydrodeoxygenation (HDO) is challenged by severe polymerization and coking upon heating the oil. Alternatively, performing fast pyrolysis in high-pressure hydrogen atmosphere in a fluid bed reactor with a HDO catalyst as bed medium could immediately stabilize reactive pyrolysis vapors [2]. An additional vapor phase HDO reactor ensures removal of oxygen down to <1 wt%, resulting in separate hydrocarbon oil and water phases being recovered. A schematic diagram for such a process is shown in Figure 1. A simplified bench scale setup has been constructed at DTU Chemical Engineering. With a capacity of 100 to 300 g/h solid biomass, the aim is to provide a proof-of-concept for the continuous conversion of solid biomass to low oxygen, fuel-grade bio-oil.
Hydrogen assisted catalytic biomass pyrolysis for green fuels

Fast pyrolysis of biomass is a well-known technology for producing bio-oil, however in order to use the oil as transportation fuel the oxygen content must be decreased from approximately 30 wt.% to below 1 wt.%. This can be achieved by catalytic hydrodeoxygenation (HDO). Unfortunately, deactivation due to coking of the catalyst is an inhibitive problem for this technology. The objective of the present work is to produce oxygen free gasoline and diesel from biomass by hydrogen assisted catalytic fast pyrolysis. Fast pyrolysis of beech wood has been performed in high-pressure hydrogen atmosphere in a fluid bed reactor with a commercial CoMoS/MgAl2O4 catalyst as bed medium followed by an additional vapor phase, fixed bed HDO reactor using a commercial NiMoS/Al2O3 catalyst. The obtained bio-oil is essentially oxygen free. Oxygen specific GC-AED showed only traces of phenols, benzofurans and naphthols (< few ppm) as the remaining oxygenates. The temperature in the fluid bed reactor has been varied between 365 and 470 oC and pressure has been varied between 15 and 35 barg in order to investigate the impact on yields and oil composition. The char yield decreased with increasing temperature and decreasing pressure. Increasing the pressure also increased the water yield and decreased the CO/CO2 yield, indicating that the reaction pathway for the oxygen removal is highly pressure dependent. GCxGC-FID analysis of the condensed oil product showed a chromatic area up to 79 % for aromatics, indicating that the aromatic content in the oil is equilibrium controlled. Elemental analysis showed that the oxygen content in the char decreased with increasing temperature in the fluid bed reactor. Oil yields of up to 21.6 wt.% were obtained, corresponding to an energy recovery of 51 %. An experiment without the HDO reactor showed that most oxygen is removed in the fluid bed reactor.

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Hydrogen assisted catalytic biomass pyrolysis for green fuels

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Imaging of Flames in Cement Kilns To Study the Influence of Different Fuel Types
The cement industry aims to use an increased amount of alternative fuels to reduce production costs and CO2 emissions. In this study three cement plants firing different kinds and percentages of alternative fuel were studied. A specially developed camera setup was used to monitor the flames in the three cement kilns and assess the effect of alternative fuels on the flame. It was found that cofiring with solid recovered fuel (SRF) would delay the ignition point by about 2 m and lower the intensity and temperature of the kiln flame compared to a fossil fuel flame. This is related to a larger particle size and moisture content of the alternative fuels, which lowers the conversion rate compared to fossil fuels. The consequences can be a lower kiln temperature and cement quality. The longer conversion time may also lead to the possibility of localized reducing conditions in the cement kiln, which can have a negative impact on the clinker quality and process stability. The burner design may alleviate some of the issues encountered with SRF cofiring. At one of the test plants the burner was changed from a design with an annular channel for axial air to a jet design. This proved to be beneficial for an early ignition and improved dispersion of the fuel and led to an increase in cement quality and higher use
Impact of KCl impregnation on single particle combustion of wood and torrefied wood

In this work, single particle combustion of raw and torrefied 4 mm wood particles with different potassium content obtained by KCl impregnation and washing was studied experimentally under a condition of 1225 °C, 3.1% O₂ and 26.1% H₂O. The ignition time and devolatilization time depended almost linearly on the fuel particle mass. The char conversion time was influenced by both the char mass and char reactivity. Both KCl impregnation and torrefaction promoted char yield, while washing slightly inhibited char formation. The char reactivity was increased by KCl impregnation, decreased by washing, and unchanged by torrefaction. Compared to the raw wood particle, the char conversion time was increased by torrefaction, decreased by washing, and almost unchanged by KCl impregnation due to its promoting effect on both char yield and reactivity.

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Measurements of NOx precursor concentration profile above the bed at a full scale W-t-E plant and the effect of precursor speciation on the NOx formation

Satisfactory result from CFD modelling of NOx formation during combustion of waste in grate-fired waste-to-energy plants relies heavily on an accurate description of the temperature field in the free-board, this is a consequence of the high dependency of the temperature on the fuel NOx chemistry [1,2]. Modelling of the temperature field in the free-board in a CFD code relies on an accurate determination of the boundary conditions from the bed into the computational domain, e.g., species concentrations, gas temperature and gas velocity. Most CFD models of grate-fired waste-to-energy plants use a stand-alone model of the bed, describing the waste devolatilisation and the partial oxidation of volatiles, which have been coupled with the CFD model. The drying, devolatilisation and volatile oxidation in the bed is strongly coupled with the combustion of gaseous species in the free-board due to the radiation onto the bed as indicated in figure 1. The devolatilisation of the fuel and partial oxidation of the volatiles in the bed, generated during devolatilisation, has been coupled with the combustion of gaseous species in the freeboard and been applied with success in previous studies [3, 4].

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Mechanistic Model for Ash Deposit Formation in Biomass Suspension-Fired Boilers. Part 2: Model Verification by Use of Full Scale Tests

A model for deposit formation in suspension firing of biomass has been developed. The model describes deposit build-up by diffusion and subsequent condensation of vapors, thermoforesis of aerosols, convective diffusion of small particles, impaction of large particles and reaction. The model describes particle sticking or rebound by a combination of the description of (visco)elastic particles impacting a solid surface and particle capture by a viscous surface. The model is used to predict deposit formation rates measured during tests conducted with probes in full-scale suspension-fired biomass boilers. The rates predicted by the model was reasonably able to follow the rates observed in the tests, although with some variation, primarily as overestimations of the deposit formation rates. It is considered that the captive properties of the deposit surface are overestimated. Further examination of some physical parameters related to the description of surface capture are suggested. Based on these examinations of the model ability to describe observed deposit formation rates, the proposed model can be regarded as a promising tool for description of deposit formation in full-scale biomass suspension fired boilers.

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Mechanistic Model for Ash Deposit Formation in Biomass Suspension Firing. Part 1: Model Verification by Use of Entrained Flow Reactor Experiments

Two models for deposit formation in suspension firing of biomass have been developed. Both models describe deposit buildup by diffusion and subsequent condensation of vapors, thermophoresis of aerosols, convective diffusion of small...
particles, impaction of large particles, and reaction. The models differ in the description of the sticking probability of impacted particles: model #1 employs a reference viscosity in the description of the sticking probability, while model #2 combines impaction of viscoelastic particles on a solid surface with particle capture by a viscous surface. Both models were used to describe the deposit formation rates and deposit chemistry observed in a series of entrained flow reactor (EFR) experiments using straw and wood as fuels. It was found that model #1 was not able to describe the observed influence of temperature on the deposit buildup rates, predicting a much stronger influence of this parameter. Model #2 was able to provide a reasonable description of the influence of temperature on the deposit buildup rates observed in the EFR experiments. A parametric study was conducted to examine the influence of some physical parameters, including ash concentration, viscosity of ash and deposits, surface tension, Young’s modulus, and porosity. On the basis of this model evaluation, where a wide range of temperatures (700–1000 °C) and fuels (straw and wood) were applied, model #2 can be regarded as a promising tool for the description of deposit formation from biomass ashes.
Optimizing catalytic deoxygenation of biomass derived fast pyrolysis vapors

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Understanding Biomass Ignition in Power Plant Mills
Converting existing coal fired power plants to biomass is a readily implemented strategy to increase the share of renewable energy. However, changing from one fuel to another is not straightforward: Experience shows that wood pellets ignite more readily than coal in power plant mills or storages. This is not very well explained by applying conventional thermal ignition theory. An experimental study at lab scale, using pinewood as an example fuel, was conducted to examine self-heating and self-ignition. Supplemental experiments were performed with bituminous coal. Instead of characterizing ignition temperature in terms of sample volume, mass-scaling seems more physically correct for the self-ignition of solids. Findings also suggest that the transition between self-heating and self-ignition is controlled both by the availability of reactive material and temperature. Comparison of experiments at 20% oxygen with those under inert atmosphere revealed two distinct pathways, pyrolysis and exothermic heterogeneous oxidation. At low temperatures and sufficient oxygen availability, heterogeneous oxidation of the solid seems to be favored over pyrolysis for wood, but not for coal. Current ignition models do not reflect the existence of these different pathways, which may be the reason behind the discrepancy between theory and observations.

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Adhesion Strength of Biomass Ash Deposits
Ash deposition on boiler surfaces is a major problem encountered during biomass combustion. Ash deposition adversely influences the boiler efficiency, may corrode heat transfer surfaces, and may even completely block flue gas channels in severe cases, causing expensive unscheduled boiler shutdowns. Therefore, timely removal of ash deposits is essential for optimal boiler operation. In order to improve the qualitative and quantitative understanding of deposit shedding in boilers, this study investigates the shear adhesion strength of biomass ash deposits on superheater tubes. Artificial biomass ash deposits were prepared on superheater tubes and sintered in an oven at temperatures up to 1000 °C. Subsequently, the deposits were sheared off by an electrically controlled arm, and the corresponding adhesion strength was measured. The results reveal the effect of temperature, ash/deposit composition, sintering duration, and steel type on the adhesion strength.

Agglomeration and Deposition Behaviour of Solid Recovered Fuel
Waste-derived fuels, such as solid recovered fuel (SRF), are increasingly being used in, e.g., the cement industry as a means to reduce cost. The inhomogeneous nature of SRF makes it difficult to combust, and many problems may arise within, e.g., combustion control, feeding of fuel, deposit formation, or accumulation of impurities. The combustion of polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), wood, and SRF were studied in a rotary drum furnace. The combustion was recorded on a camera (60 frames per second), so that any agglomeration or deposition of fuel or ash could be monitored. PE and PP pose no significant risk of forming deposits in a combustion environment (T > 800 °C) as a result of a rapid devolatilization, while PET may cause deposits as a result of a sticky char residue. The deposition tendency of the investigated SRF is low, and it may be managed by a careful combustion control. The ash from SRF or wood does not pose a significant risk of melting and deposits at temperatures up to 1000 °C, but the presence of glass impurities in some SRF may limit operation temperatures to 900 °C as a result of ash melting.
A review: Fly ash and deposit formation in PF fired biomass boilers

In recent years suspension fired boilers have been increasingly used for biomass based heat and power production in several countries. This has included co-firing of coal and straw, up to 100% firing of wood or straw and the use of additives to remedy problems with biomass firing. In parallel to the commercialization of the suspension biomass firing technology a range of research studies have improved our understanding of the formation of fly ash and the impact on deposit formation and corrosion in such boilers. In this paper a review of the present knowledge with respect to ash and deposit formation in biomass suspension fired boilers is provided. Furthermore the influence of co-firing and use of additives on ash chemistry, deposit properties and boiler operation is discussed.

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Atmospheric Hydrodeoxygenation of Biomass Fast Pyrolysis Vapor by MoO3

MoO3 has been tested as a catalyst in hydrodeoxygenation (HDO) of both model compounds (acetone and guaiacol) and real biomass pyrolysis vapors under atmospheric pressure. The pyrolysis vapor was obtained by fast pyrolysis of wood or lignin in a continuous fast pyrolysis reactor at a fixed temperature of 500 °C, and it subsequently passed through a downstream, close coupled, fixed bed reactor containing the MoO3 catalyst. The influences of the catalyst temperature and the concentration of H2 on the HDO of the pyrolysis vapors were investigated. The level of HDO of the biomass pyrolysis vapors was not significant at temperatures below 400 °C. At 450 °C catalyst temperature and 93 vol % H2 concentration, the wood pyrolysis vapor was more active toward cracking forming gas species instead of performing the desired HDO forming hydrocarbons. The lignin pyrolysis vapor was more resistant to cracking and yielded 16.2 wt %daf organic liquid, while achieving 52% degree of deoxygenation at 450 °C catalyst temperature under 89 vol % H2 concentration. The corresponding energy recovery in the liquid phase was 23.5%. The spent catalyst showed two deactivation routes, coke formation and reduction of MoO3 to MoO2, which is inactive in HDO. The catalyst experienced severe reduction at temperatures higher than 400 °C. The yields of coke relative to the fed biomass were in the range of 3–4 wt %daf for lignin and 5–6 wt %daf for wood. Compared to untreated bio-oil the upgraded lignin organic liquid showed improved compatibility with hydrocarbons and was miscible with a toluene/heptane mixture.

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Behavior of Alkali Metals and Ash in a Low-Temperature Circulating Fluidized Bed (LTCFB) Gasifier

A low-temperature circulating fluidized bed system (LTCFB) gasifier allows for pyrolysis and gasification to occur at low temperatures, thereby improving the retention of alkali and other inorganic elements within the system and minimizing the amount of ash species in the product gas. In addition, the low reactor temperature ensures that high-alkali biomass fuels can be used without risk of bed defluidization. This paper presents the first investigation of the fate of alkali metals and ash in low-temperature gasifiers. Measurements on bed material and product gas dust samples were made on a 100 kW and a 6 MW LTCFB gasifier. Of the total fuel ash entering the system, the largest fraction (40–50%) was retained in the secondary cyclone bottoms, while a lower amount (8–10%) was released as dust in the exit gas. Most of the alkali and alkaline earth metals were retained in the solid ash, along with Si and a minor fraction of Cl. Most Cl and S were released in gaseous form, with chlorine partly as methyl chloride. The tar in the product gas from the LTCFB gasifier contained only negligible amounts of potassium and other inorganic elements. The release of condensed ash species from the system was controlled by the particle size and the cut size of the primary and secondary cyclones. A model accounting for the ash collection by the plant cyclones was shown to predict the product gas ash particle release reasonably well.
Characterization of free radicals by electron spin resonance spectroscopy in biochars from pyrolysis at high heating rates and at high temperatures
The concentration and type of free radicals from the decay (termination stage) of pyrolysis at slow and fast heating rates and at high temperatures (above 1000°C) in biomass char have been studied. A room temperature electron spin resonance spectroscopy study was conducted on original wood, herbaceous biomass, holocelluloses, lignin and their chars, prepared at high temperatures in a wire mesh reactor, an entrained flow reactor, and a tubular reactor. The radical concentrations in the chars from the decay stage range up between $7 \cdot 10^{16}$ and $1.5 \cdot 10^{18}$ spins g$^{-1}$. The results indicated that the biomass major constituents (cellulose, hemicellulose, lignin) had a minor effect on remaining radical concentrations compared to potassium and silica contents. The higher radical concentrations in the wheat straw chars from the decay stage of pyrolysis in the entrained flow reactor compared to the wood chars were related to the decreased mobility of potassium in the char matrix, leading to the less efficient catalytic effects of potassium on the bond-breaking and radical re-attachments. The high Si levels in the rice husk caused an increase in the char radical concentration compared to the wheat straw because the free radicals were trapped in a char consisting of a molten amorphous silica at heating rates of $10^2-10^4$ K s$^{-1}$. The experimental electron spin resonance spectroscopy spectra were analyzed by fitting to simulated data in order to identify radical types, based on g-values and line widths. The results show that at high temperatures, mostly aliphatic radicals (g = 2.0026-2.0028) and PAH radicals (g = 2.0027e-2.0031) were formed.
Comparison of high temperature chars of wheat straw and rice husk with respect to chemistry, morphology and reactivity

Fast pyrolysis of wheat straw and rice husk was carried out in an entrained flow reactor at high temperatures (1000-1500) C. The collected char was analyzed using X-ray diffractometry, N2-adsorption, scanning electron microscopy, particle size analysis with CAMSIZER XT, \(^{29}\)Si and \(^{13}\)C solid-state nuclear magnetic resonance spectroscopy and thermogravimetric analysis to investigate the effect of inorganic matter on the char morphology and oxygen reactivity. The silicon compounds were dispersed throughout the turbostratic structure of rice husk char in an amorphous phase with a low melting temperature (\(\sim 730\)) C, which led to the formation of a glassy char shell, resulting in a preserved particle size and shape of chars. The high alkali content in the wheat straw resulted in higher char reactivity, whereas the lower silicon content caused variations in the char shape from cylindrical to near-spherical char particles. The reactivities of pinewood and rice husk chars were similar with respect to oxidation, indicating less influence of silicon oxides on the char reactivity. © 2016 Elsevier Ltd. All rights reserved.

General information

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Technical University of Munich, University of Copenhagen
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Publication information
Journal: Biomass and Bioenergy
Deactivation of Ni-MoS$_2$ by bio-oil impurities during hydrodeoxygenation of phenol and octanol

The stability of Ni-MoS$_2$/ZrO$_2$ toward water, potassium, and chlorine containing compounds during hydrodeoxygenation (HDO) of a mixture of phenol and 1-octanol was investigated in a high pressure gas and liquid continuous flow fixed bed setup at 280 °C and 100 bar. To maintain the stability of the catalyst, sufficient co-feeding of a sulfur source was necessary to avoid oxidation of the sulfide phase by oxygen replacement of the edge sulfur atoms in the MoS$_2$ structure. However, the addition of sulfur to the feed gas resulted in the formation of sulfur containing compounds, mainly thiols, in the oil product if the residence time was too low. At a weight hourly space velocity (WHSV) of 4.9 h$^{-1}$ the sulfur content in the liquid product was 980 ppm by weight, but this could be decreased to 5 ppm at a WHSV of 1.4 h$^{-1}$. A high co-feed of sulfur was needed when water was present in the feed and the H$_2$O/H$_2$S molar ratio should be below ca. 10 to maintain a decent stability of the catalyst. Chlorine containing compounds caused a reversible deactivation of the catalyst when co-fed to the reactor, where the catalytic activity could be completely regained when removing it from the feed. Commonly, chlorine, H$_2$O, and H$_2$S all inhibited the activity of the catalyst by competing for the active sites, with chlorine being by far the strongest inhibitor and H$_2$S and H$_2$O of roughly the same strength. Dissimilar, potassium was a severe poison and irreversibly deactivated the catalyst to <5% degree of deoxygenation when impregnated on the catalyst in a stoichiometric ratio relative to the active metal. This deactivation was a result of adsorption of potassium on the edge vacancy sites of the MoS$_2$ slabs.
Original language: English
Keywords: Bio-oil, Hydrodeoxygenation, HDO, Stability, Deactivation, Characterization
Electronic versions:
Accepted_version_from_journal.pdf. Embargo ended: 03/06/2018
Defluidization in fluidized bed gasifiers using high-alkali content fuels

Major concern in thermal conversion of biomass encountered in fluidized beds is bed agglomeration, which may result in de-fluidization, leading to unscheduled downtime and additional costs. Biomass fuels, especially herbaceous plants, often contain significant amounts of silicon, potassium and calcium, which may form viscous melts that adhere on the surface of the colliding bed particles and bind them to form agglomerates. In this paper, studies were made to understand the behavior of inorganic elements (mainly K, Si and Ca) on agglomeration and de-fluidization of alkali rich bed-material samples under non-oxidizing conditions in a bench-scale fluidized bed reactor set up. The de-fluidization studies involved measurements with sand and pure potassium salts (KCl and K₂CO₃) as well as with bed material samples obtained from a 6 MW Low Temperature Circulating Fluidized Bed (LTCFB) gasifier using straw as a fuel. It was seen that in sand + KCl agglomerates, the sand particles were bound by KCl melts. Only very limited chemical reaction was observed between KCl and the sand particles and no presence of silicate melts in the agglomerates. For sand + K₂CO₃ mixtures and for LTCFB bed material samples, agglomeration could be attributed to viscous silicate melts formed from reaction of inorganic alkaline and alkali earth species with silica from the bed particles. A mathematical model that addresses the defluidization behavior of alkali-rich samples was developed based on the experiments performed in the bench-scale fluidized bed reactor as well as on results from literature. The model was then used to predict the de-fluidization behavior of alkali-rich bed material in a large-scale LTCFB gasifier.
Deposit Shedding in Biomass-fired Boilers: Shear Adhesion Strength Measurements

Ash deposition on boiler surfaces is a major problem encountered during biomass combustion. Ash deposition adversely influences the boiler efficiency, may corrode heat transfer surfaces, and may even completely block flue gas channels in severe cases, causing expensive unscheduled boiler shutdowns. Therefore, timely removal of ash deposits is essential for optimal boiler operation. In order to improve the understanding of deposit shedding in boilers, this study investigates the shear adhesion strength of biomass ash deposits on superheater tubes. Artificial biomass ash deposits were prepared on superheater tubes and sintered in an oven at temperatures up to 1000 °C. Subsequently, the deposits were sheared off by an electrically controlled arm, and the corresponding adhesion strength was measured. The results reveal the effect of temperature, deposit composition, sintering duration, and steel type on the adhesion strength.

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DOIs: 10.1016/j.biombioe.2016.05.009
Research output: Research - peer-review → Journal article – Annual report year: 2016
Devolatilization kinetics of woody biomass at short residence times and high heating rates and peak temperatures
This work combines experimental and computational fluid dynamics (CFD) results to derive global kinetics for biomass (pine wood) devolatilization during heating rates on the order of $10^2$Ks$^{-1}$, bulk flow peak temperatures between 1405 and 1667 K, and particle residence times below 0.1 s. Experiments were conducted on a laboratory laminar entrained flow reactor (LFR) using solid fuel feed rates on the order of 10-20 mgh$^{-1}$. Employing a simple single step first order (SFQR) mechanism with an Arrhenius type rate expression, the best fit of the pyrolysis kinetics was found to be: $A=18.9\times10^3$ s$^{-1}$, $E_a=21305$ Jmol$^{-1}$. The accuracy of the derived global kinetics was supported by comparing predictions to experimental results from a 15 kW furnace. The work emphasizes the importance of characterizing the temperature history of the biomass particles when deriving pyrolysis kinetics. The present results indicate faster kinetics than found in the literature, leading to predicted residence times required for full conversion one order of magnitude lower than when compared to thermogravimetric analysis (TGA) derived kinetics.

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  Scopus rating (2017): CiteScore 8.44 SJR 3.162 SNIP 2.765
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  Scopus rating (2015): CiteScore 6.4 SJR 2.835 SNIP 2.593
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  Web of Science (2015): Indexed yes
  BFI (2014): BFI-level 2
  Scopus rating (2014): CiteScore 6.93 SJR 3.158 SNIP 3.218
  Web of Science (2014): Impact factor 5.613
  Web of Science (2014): Indexed yes
  BFI (2013): BFI-level 1
  Scopus rating (2013): CiteScore 6.59 SJR 3.06 SNIP 3.346
  Web of Science (2013): Impact factor 5.261
Direct upgrading of fast pyrolysis lignin vapor over the HZSM-5 catalyst

Lignin has been pyrolyzed in a continuous fast pyrolysis reactor and the vapor was subsequently upgraded in situ over a downstream, close coupled HZSM-5 catalyst in a fixed bed reactor. The effect of the catalyst temperature on the HZSM-5 upgrading of lignin derived pyrolysis vapor was investigated. The results show that a high catalyst temperature (600 °C) is required in order to produce oxygen free aromatics. At a catalyst temperature of 600 °C, an organic liquid product, which contains 70 wt% oxygen free aromatics (mainly benzene and toluene), is obtained. However, the yield of the organic liquid is reduced from 27.6 wt%daf without a catalyst to 5.7 wt%daf (600 °C catalyst temperature). The energy recovery in the liquid organics is 8.7% (600 °C catalyst temperature), compared to the 33.0% energy recovery in the organic liquid from the non-catalytic run. Oxygen is removed from the pyrolysis vapor mainly in the form of H₂O and CO when using the HZSM-5 zeolite, which is less optimal compared to if CO₂ was the product. The organic liquid fraction, obtained from the 600 °C catalyst temperature experiment, has a low oxygen content of 4.0 wt%, compared to the 23.4 wt% oxygen content in the untreated organic liquid.
Effect of fast pyrolysis conditions on biomass solid residues at high temperatures

Fast pyrolysis of wood and straw was conducted in a drop tube furnace (DTF) and compared with corresponding data from a wire mesh reactor (WMR) to study the influence of temperature (1000-1400°C), biomass origin (pinewood, beechwood, wheat straw, alfalfa straw), and heating rate (103 °C/s, 104 °C/s) on the char yield and morphology. Scanning electron microscopy (SEM), elemental analysis, and ash compositional analysis were applied to characterize the effect of operational conditions on the solid residues (char, soot) and gaseous products. The char yield from fast pyrolysis in the DTF setup was 3 to 7% (daf) points lower than in the WMR. During fast pyrolysis pinewood underwent drastic morphological transformations, whereas beechwood and straw samples retained the original porous structure of the parental fuel with slight melting on the surface. The particle size of Danish wheat straw char decreased in its half-width with respect to the parental fuel, whereas the alfalfa straw char particle size remained unaltered at higher temperatures. Soot particles in a range from 60 to 300 nm were obtained during fast pyrolysis. The soot yield from herbaceous fuels was lower than from wood samples, possibly due to differences in the content of lignin and resin acids.
Effects of Biomass Feedstock on the Yield and Reactivity of Soot from Fast Pyrolysis at High Temperatures

This study investigated the effect of feedstock on the yield, nanostructure and reactivity of soot. Woody and herbaceous biomass were pyrolyzed at high heating rates and temperatures of 1250 and 1400°C in a drop tube furnace. The collected solid residues were structurally characterized by electron microscopy techniques, X-ray diffraction and N₂-adsorption. The reactivity of soot was investigated by thermogravimetric analysis. The results showed that the reactivity of soot, generated at 1400°C was higher than that at 1250°C for all biomass types. Wood and wheat straw soot demonstrated differences with respect to the alkali content, particle size and nanostructure. Potassium was incorporated in the soot matrix and to a
significant extent influenced the soot reactivity. The particle size distribution of pinewood soot produced at 1250°C was in the range from 27.2 to 263 nm which was broader compared to that of beechwood soot (from 33.2 to 102 nm) and wheat straw soot (from 11.5 to 165.3 nm). In addition, pinewood soot particles contained mainly multi-core structures at 1250°C. The potassium content played a more important role on the soot reactivity than the particle size and nanostructure.

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Event: Poster session presented at SFC program conference, Gothenburg, Sweden.

**Effects of several types of biomass fuels on the yield, nanostructure and reactivity of soot from fast pyrolysis at high temperatures**
This study presents the effect of biomass origin on the yield, nanostructure and reactivity of soot. Soot was produced from wood and herbaceous biomass pyrolysis at high heating rates and at temperatures of 1250 and 1400 °C in a drop tube furnace. The structure of solid residues was characterized by electron microscopy techniques, X-ray diffraction and N2 adsorption. The reactivity of soot was investigated by thermogravimetric analysis. Results showed that soot generated at 1400 °C was more reactive than soot generated at 1250 °C for all biomass types. Pinewood, beechwood and wheat straw soot demonstrated differences in alkali content, particle size and nanostructure. Potassium was incorporated in the soot matrix and significantly influenced soot reactivity. Pinewood soot particles produced at 1250 °C had a broader particle size range (27.2–263 nm) compared to beechwood soot (33.2–102 nm) and wheat straw soot (11.5–165.3 nm), and contained mainly multi-core structures.

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Scopus rating (2016): CiteScore 7.78 SJR 3.011 SNIP 2.61
Web of Science (2016): Impact factor 7.182
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 6.4 SJR 2.835 SNIP 2.593
Web of Science (2015): Impact factor 5.746
Entrained flow gasification of coal/bio-oil slurries

Coal/bio-oil slurry (CBS) is a new partial green fuel for bio-oil utilization. CBS reacts with gasification agents at high temperatures and converts into hydrogen and carbon monoxide. This paper provides a feasibility study for the gasification of CBS in an atmospheric entrained flow reactor for syngas production. Experiments have shown that CBS can be successfully processed and gasified in the entrained flow reactor to produce syngas with almost no tar content and low residual carbon formation. High reactor temperature and steam/carbon ratio is favourable for H2 production. At 1400 °C with steam/carbon ratio of 5, the syngas components are similar with that in equilibrium. A synergistic effect exists
between coal and bio-oil in coal/bio-oil slurry gasification which might be caused by the catalysis effect of alkali metals and alkaline earth metals in bio-oil.

**General information**

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Chinese Academy of Sciences, Karlsruhe Institute of Technology  
Contributors: Feng, P., Lin, W., Jensen, P. A., Song, W., Hao, L., Raffelt, K., Dam-Johansen, K.  
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Web of Science (2018): Indexed yes  
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Web of Science (2017): Indexed yes  
BFI (2016): BFI-level 2  
Scopus rating (2016): CiteScore 5.17 SJR 1.974 SNIP 1.823  
Web of Science (2016): Impact factor 4.52  
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Scopus rating (2014): CiteScore 5.7 SJR 2.575 SNIP 2.602  
Web of Science (2014): Impact factor 4.844  
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BFI (2013): BFI-level 2  
Scopus rating (2013): CiteScore 5.02 SJR 2.458 SNIP 2.556  
Web of Science (2013): Impact factor 4.159  
ISI indexed (2013): ISI indexed yes  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 2  
Scopus rating (2012): CiteScore 4.25 SJR 1.935 SNIP 2.214  
Web of Science (2012): Impact factor 3.651  
ISI indexed (2012): ISI indexed yes  
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 2  
Scopus rating (2011): CiteScore 4 SJR 1.566 SNIP 2.01  
Web of Science (2011): Impact factor 3.487  
ISI indexed (2011): ISI indexed yes  
Web of Science (2011): Indexed yes  
BFI (2010): BFI-level 2  
Scopus rating (2010): SJR 1.712 SNIP 2.46  
Web of Science (2010): Impact factor 3.597  
Web of Science (2010): Indexed yes
Entrained Flow Reactor Study of K-Capture by Solid Additives

A method to simulate the reaction between gaseous K-species and solid additives, at suspension fired conditions has been developed, using an entrained flow reactor (EFR). A water slurry containing solid additives (kaolin or coal fly ash) and KCl, is injected into the EFR and the solid products are collected from the cyclone and filter. The K-capture reaction is evaluated by determining the fraction of water-insoluble K in the products. The results showed that KCl can effectively be captured by kaolin and coal fly ash, forming water-insoluble K-aluminosilicates. The amount of K, captured per gram of additives, rose when increasing the molar ratio of K/(Al+Si) in the reactants. A change of the reaction temperature, from 1100 °C to 1450 °C, did not significantly influence the extent of the reaction, which is in contradiction to the trend observed in previous fixed-bed reactor studies. The method using the EFR, developed in this study, will be applied for further studies on the reaction of different additives and alkali species.

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Research output: Research - peer-review › Article in proceedings – Annual report year: 2016

Entrained Flow Reactor Study of KCl Capture by Solid Additives

An option for abating deposition and corrosion caused by alkali species during biomass combustion, is the introduction of additives into boilers for transforming harmful gaseous alkali compounds (e.g. KCl, KOH) into less corrosive ash species with a higher melting point. Kaolin and coal fly ash have been proved to be very promising additives and have received extensive studies during the past decades. However, most previous studies were carried out in fixed-bed reactors where
the reaction conditions are obviously different from that in suspension fired boilers. Detailed knowledge on the reaction between K-species and solid additives under suspension-fired conditions is still limited. In this study, a water slurry containing K-salt and solid additives was introduced into an entrained flow reactor (EFR) to study K-capture at suspension-fired conditions. A model will be developed based on experimental data and recommendations for optimal use of additives in full scale boilers will be provided.

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Research output: Research - peer-review > Poster – Annual report year: 2016

Extension of apparent devolatilization kinetics from thermally thin to thermally thick particles in zero dimensions for woody biomass
This work aims to provide an accurate and simple model, predicting the time dependent devolatilization of woody biomass at conditions (T_{gas}<2000 K) and particle sizes (<2 mm) relevant to suspension fired boilers. The zero dimensional model is developed from reference calculations with a one-dimensional heat transport model coupled with a drying and a devolatilization model. The model output has been used to generate pyrolysis kinetics corrected for non-isothermal effects, i.e. intraparticle heat transport limitations. Analysis of the modeling results indicate that heat transport corrections of even small particles are necessary. The current work divides a given particle size distribution into suitable size categories based on their internal heat transport properties. The devolatilization is described by size category specific rate constants based on a single first order reaction mechanism. This approach allows for significantly more accurate devolatilization predictions of any particle size distribution to be described by simple kinetic mechanisms and isothermal particle heat balances. Such an approach is easily implemented into most commercial CFD (computational fluid dynamics) codes without adding any additional strain to the computational requirements

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BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 5.17 SJR 1.974 SNIP 1.823
Web of Science (2016): Impact factor 4.52
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Scopus rating (2015): CiteScore 5.03 SJR 2.22 SNIP 2.037
Original language: English

Keywords: Devolatilization kinetics, Pyrolysis, Biomass, Computational fluid dynamics (CFD), Non-isothermal, High heating rate

H2CAP - Hydrogen assisted catalytic biomass pyrolysis for green fuels

General information
**In-Flame Characterization of a 30 MWth Bio-Dust Flame**

This work presents a comprehensive flame characterization campaign on an operating full-scale Danish power plant. AmagerVærket Unit 1 (AMV1, 350 MWth, 12 identical burners on 3 burner levels) is 100% fuelled with wood dust burned in suspension and stabilized by swirling flows in a triple concentric low-NOx configuration. The measurements focus on a single 30 MWth flame and include: Quantification of the gas temperature, the gas phase composition: O2, CO, CO2, H2O, and light hydrocarbons by intrusive probe measurements. It also includes both seeded and unseeded 2D laser doppler anemometry (LDA) velocity measurements, flame shape observations by video imaging, and particle entrainment by high speed infrared (IR) imaging. The flame is characterized along the geometrical centreline as well as in the horizontal and vertical plane of the flame. The results shed light on the flame anatomy of a full-scale burner and provide a comprehensive data set that quantifies key parameters: Gas phase temperature, composition, and flow field required in order to evaluate the performance of CFD simulations of complex combustion systems.

**Influence of Torrefaction on Single Particle Combustion of Wood**

This study focuses on the influence of torrefaction on the char reactivity, char yield, and combustion time of 3-5 mm spherical wood particles in a single particle combustion reactor (SPC) operating at a nominal temperature of 1231 °C. The devolatilization times were reduced and the char burnout times were increased with increasing torrefaction degree. The devolatilization time depended linearly on the particle mass. The torrefaction pretreatment resulted in a marked increase in char yield and char particle density but no intrinsic reactivity change as determined by thermogravimetric analysis. The char yield and char particle density increased from 9 wt % and 123 kg/m3 for raw particles to 14 wt % and 259 kg/m3 for particles pretreated at 290 °C for 4 h. The results of this study demonstrate that the higher char yield and density are the main reasons for the longer combustion time of torrefied wood.
Influence on nickel particle size on the hydrodeoxygenation of phenol over Ni/SiO$_2$

Hydrodeoxygenation (HDO) of phenol over nickel nano-particles of different size (5-22 nm) supported on SiO$_2$ has been investigated in a batch reactor at 275 °C and 100 bar. Deoxygenation was only observed as a consecutive step of initial hydrogenation of phenol at the given conditions. Both the hydrogenation and deoxygenation reaction were found to be Ni-particle size dependent. Rapid hydrogenation of phenol to cyclohexanol was achieved over the catalysts with large particles, while the rate of deoxygenation of cyclohexanol was slow. For the catalysts with small Ni particles, the opposite behavior was observed. Specifically, the turn over frequency (TOF) of hydrogenation was 85 times slower for 5 nm particles than for 22 nm particles. On the contrary, the TOF of cyclohexanol deoxygenation increased by a factor of 20 when decreasing the particle size from 20 nm to 5 nm. A simple kinetic model showed that the rate limiting step for phenol HDO shifted from deoxygenation to hydrogenation when the particle size was below 9-10 nm. Surface site population theory evidenced that the deoxygenation reactions were favored on step/corner sites, giving higher deoxygenation rates at small particles. For hydrogenation, the influence of particle size on the rate could be related to the size of the Ni facets with larger facets thus being better.
A water slurry, consisting of KCl and Al-Si based additives (kaolin and coal fly ash) was fed into an entrained flow reactor (EFR) to study the K-capturing reaction of the additives at suspension-fired conditions. Solid products collected from the reactor were analysed with respect to total and water-soluble K content to quantify the extent of the K-capturing reaction. The results showed that under suspension-fired conditions (1100 °C-1450 °C), kaolin and coal fly ash can effectively capture gaseous KCl. When increasing the mass ratio of KCl to Al-Si additives in the reactants, the conversion of KCl to K-aluminosilicate decreased. When reaction temperature increased from 1100 °C to 1450 °C, the conversion of KCl does not change significantly, which differs from the trend observed in fixed-bed reactor.

**General information**

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**Rotor for a pyrolysis centrifuge reactor**

The present invention relates to a rotor for a pyrolysis centrifuge reactor, said rotor comprising a rotor body having a longitudinal centre axis, and at least one pivotally mounted blade being adapted to pivot around a pivot axis under rotation of the rotor body around the longitudinal centre axis. Moreover, the present invention relates to a pyrolysis centrifuge reactor applying such a rotor.

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Organisations: Technical University of Denmark, Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Jensen, P. A., Trinh, N. T., Lundgaard Christensen, R., Dam-Johansen, K., Bech, N.
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Research output: Research › Patent – Annual report year: 2016

**Activity and stability of Mo₂C/ZrO₂ as catalyst for hydrodeoxygenation of mixtures of phenol and 1-octanol**

Mo₂C/ZrO₂ was investigated as catalyst for hydrodeoxygenation (HDO) of phenol in 1-octanol as a simplified bio-oil model system in a fixed-bed setup at 100bar. Mo₂C/ZrO₂ selectively converted phenol to benzene above 320°C. During long-term testing, limited stability of the catalyst was observed, with the conversion of 1-octanol and phenol decreasing from 70% to 37% and from 37% to 19%, respectively, over 76h of operation. Repeating the experiment but also co-feeding 30% water, the catalyst deactivated completely within 12h of operation. Thermodynamic calculations and in situ XRD analysis showed that Mo₂C is transformed to MoO₂ in the presence of water at the given conditions, and this was probably the source of deactivation in the experiments. Thus, Mo₂C-based catalyst for HDO seems interesting, but requires further stabilization or regeneration of the carbide phase as bio-oil contains high levels of water and water is a by-product during HDO.

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Karlsruhe Institute of Technology
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Adhesion Strength of Biomass Ash Deposits

This study investigates the shear adhesion strength of biomass ash deposits on superheater tubes. Artificial biomass ash deposits were prepared on superheater tubes and sintered in an oven at temperatures up to 1000°C. Subsequently, the deposits were sheared off with the help of an electrically controlled arm. Higher sintering temperatures resulted in greater adhesion strengths, with a sharp increase observed near the melting point of the ash. Repetition of experiments with fixed operation conditions revealed considerable variation in the obtained adhesion strengths, portraying the stochastic nature of the debonding process.

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Adhesion_Strength_of_Biomass_Ash_Deposits_Yashasvi_Laxminarayan.pdf

Agglomeration and Deposition Behaviour of Solid Recovered Fuel

Waste derived fuels such as Solid Recovered Fuel (SRF) are increasingly being used in the cement industry as a means to reduce cost [1]. SRF is produced by separating the combustible fraction from industrial or municipal solid waste (MSW) [2]. The inhomogeneous nature of SRF [3] makes it difficult to combust and many problems may arise concerning e.g. combustion control, feeding of fuel [2,4], deposit formation [5], or accumulation of impurities [3]. Laboratory ash fusion tests typically show that SRF ash starts melting in the range of 1150-1200 °C [6–8], which is somewhat lower than most coal ashes. However, experiments performed in fluidized bed has shown agglomeration taking place as low as 970-990 °C [9,10], and the predictability by ash fusion tests is generally poor [10]. SRF contains significant quantities of common plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). Fluidized bed experiments to examine the pyrolysis of polymers have shown that bed agglomeration can result from melting plastics or sticky char residues in the case of PET [11,12]. The main objective of this study was to characterize the combustion of SRF and especially the deposition propensity of SRF and the main constituents of SRF. This relates both to the low temperature deposits formed during plastic pyrolysis and the high temperature deposits formed by ash. The issues reported in the literature regarding plastic pyrolysis will here be investigated at temperatures above 800 °C that are more common in combustion. It will also be attempted to determine if SRF ash may cause issues below 1000 °C, as indicated by some literature results.

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A Scientific Basis for the Development of the Next Generation of Biomass Burners

The kinetics derived from the classical engineering study are used to simulate the devolatilization and char burn-out phases in the CFD model. Likewise, the study on morphology development will be used to estimate suitable sub-routines, e.g., effective drag coefficients. The full-scale campaign is used to evaluate the results of the generic CFD models. As the qualitative trends can be reproduced, the CFD models can be used to extend the experimental matrix and facilitate process optimization.

Combustion Characterization of Individual Bio-oil Droplets

Single droplet combustion characteristics have been investigated for bio-oil slurries, containing biomass residue, and compared to conventional fuels for pulverized burners, such as fuel oil (start up) and wood chips (solid biomass fuel). The investigated fuels ignition delays and pyrolysis behavior was tested in a single particle reactor at conditions relevant for suspension firing (A: 1200 °C, 5.5 % O2; B: 1200 °C, 2.9 % O2 and C: 990 °C, 5.5 % O2). The slurries were tested to optimize the bio-oil composition for use as an alternative power plant start-up fuel. Pyrolysis times for 5 mg bio-oil samples (app. dp 1 mm) were generally in a similar range (1300 to 2700 ms) as fuel oil, (app 1800 ms) and wood blocks (app 2400 ms), within the 600 ms standard deviation. The 5 different bio-oil slurries samples showed considerable data variability, indicating some extent of sample heterogeneity. With respect to the ignition delay, the bio-oils were in contrast to the fuel oil (125±70 ms), associated with either a longer ignition delay or an ignition phase with sporadic gas phase ignitions (350 to 1050 ms with no stable flame), which could be a cause for concern for a start-up fuel, due to flame lift above the nozzles and thereby decreased flame stability. Most promising were oil or diesel (not palm oil) containing slurries (1 and 5) with heating values in the range of 15 MJ/kg.
**De danske kraftværkers omstilling fra kul til biomasse**

Det er målet at sikre en energi- og kosteffektiv omstilling frem mod fuldstændig udfasning af kul på de danske kraftværkemængder i 2030. For at støtte denne omstilling er der gennemført et ph.d.-projekt, som har fokuseret på modellering af biostøvflammer.

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**Effect of Fast Pyrolysis Conditions on Structural Transformation and Reactivity of Herbaceous Biomasses at High Temperatures**

Fast pyrolysis of wheat straw and rice husks was carried out in an entrained-flow reactor (EFR) and compared with the results from the wire-mesh reactor (WMR) in terms of the char yield at high-temperatures (1000-1500°C) to study the effect of heating rate, final temperature, ash content and particle size on the char yield. X-ray diffraction (XRD), N-adsorption (BET), scanning electron microscopy (SEM), particle size analysis (CAMSIZER XT), nuclear magnetic resonance spectroscopy (29Si NMR; 13C NMR) and electron spinning resonance spectroscopy (ESR) were conducted to investigate the effect of organic and inorganic matter on the char structural transformations. The results indicate no influence of the free radicals on char reactivity and burnout. The formation of free radicals in fast pyrolysis is related to the differences in ash composition, namely presence of K+ ions in the wheat straw and formation of silanol silicons at higher temperatures. The microscopy and 2D imaging analysis show that the differences in ash and extractives of rice husks and wheat straw affect significantly the char particle size and shape. The char yields of rice husks in the EFR, correspond to the WMR results, emphasizing its excellent properties as an ash tracer for the more precise recovery of elemental mass balances in pyrolysis.
Effect of Fast Pyrolysis Conditions on Structural Transformation and Reactivity of Herbaceous Biomasses at High Temperatures

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Effect of Fast Pyrolysis Conditions on the Biomass Solid Residues at High Temperatures (1000-1400°C)

Fast pyrolysis of wood and straw was conducted in a drop tube furnace (DTF) and compared with the experimental work on the wire-mesh reactor (WMR) to study the influence of temperature (1000-1400°C), biomass origin (softwood, hardwood, grass) and heating rate (1000°C/s, 10^4 °C/s) on the char yield and morphology. Scanning electron microscopy (SEM/EDS), elementary analysis, CAMSIZER XT, ash compositional analysis were applied to characterize the effect of operational conditions on the solid and gas products. Char yield from fast pyrolysis in the DTF setup was 2 to 6 % (daf) lower than in the WMR apparatus. During fast pyrolysis pinewood underwent drastic morphological transformations, whereas beechwood and straw samples retained the original porous structure of the parental fuel with the slight melting on the surface. Particle size of Danish wheat straw char decreases in a half-width with respect to the parental fuel, whereas alfalfa straw char particle size remained unaltered with the higher temperatures. In this study, the retained shape of beechwood and herbaceous biomass samples is related to the presence of extractives and formation of silicates. Soot yield from herbaceous fuels occurs lower than from wood samples. During fast pyrolysis, additionally to the soot and char particles, spherical solid residues of particle size (60-300 nm) were obtained. Based on the previous studies, these smooth spherical particles are associated with the formation of condensed tars under fast heating rates and at very high temperatures.

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Effect of Fast Pyrolysis Conditions on the Biomass Solid Residues at High Temperatures (1000-1400°C)

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Entrained Flow Reactor Test of Potassium Capture by Kaolin

In the present study a method to simulate the reaction between gaseous KCl and kaolin at suspension fired condition was developed using a pilot-scale entrained flow reactor (EFR). Kaolin was injected into the EFR for primary test of this method. By adding kaolin, KCl can effectively be captured, forming water-insoluble K-aluminosilicate. The amount of K captured by 1 g kaolin rose when increasing the molar ratio of K/Si in the reactant. Changing of reaction temperature from 1100 °C to 1300 °C did not influence the extent of reaction, which is different from the results observed in previous fixed-bed reactor. The method using the EFR developed in this study will be applied for further systematic investigation of different additives.

H₂CAP - Hydrogen Assisted Catalytic Biomass Pyrolysis for Green Fuels

Influence of fast pyrolysis conditions on yield and structural transformation of biomass chars

Fast pyrolysis of biomass (wood, straw, rice husk) and its major components (cellulose, hemicellulose, lignin) was conducted in a wire mesh reactor. The aim of this study was to understand the influence of temperature (350-1400 °C), heating rate (10-3000 °C/s), particle size (0.05-2 mm) and holding time (1-4 s) on the char morphology and char yield. Scanning electron microscopy (SEM) and elemental analysis were conducted to determine the effect of operating conditions on char softening and melting during pyrolysis. The char yield decreased with heating rate for rates ≤ 600 °C/s; above this value a similar biomass char yield was obtained. The potassium content affected the char yield stronger than other minerals, while the distribution of the three major biomass constituents (cellulose, hemicellulose, lignin) affected the char yield only to a minor degree. Moreover, it was found that the heat treatment temperature had a larger influence on the char yield than the heating rate. Scanning electron microscopy indicated different types of biomass char plasticization.
influenced by the applied temperatures, heating rates, particle sizes and holding times, except for the rice husk char that formed chars with a structure similar to the parental fuel at all conditions. The less severe morphological changes of rice husk char were attributed to a high silica content.

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The behavior of ash species in suspension fired biomass boilers

While fluid bed and grate fired boilers initially was the choice of boilers used for power production from both wood and herbaceous biomass, in recent years suspension fired boilers have been increasingly used for biomass based power production. In Denmark several large pulverized fuel boilers have been converted from coal to biomass combustion in the last 15 years. This have included co-firing of coal and straw, up to 100% firing of wood or straw and the use of coal ash as an additive to remedy problems with wood firing. In parallel to the commercialization of the pulverized biomass firing technology a long range of research studies have been conducted, to improve our understanding of the influence and behavior of biomass ash species in suspension fired boilers. The fuel ash plays a key role with respect to optimal boiler operation and influences phenomena’s as boiler chamber deposit formation, corrosion of steam coils, deactivation of SCR catalysts and utilization of residual products. A broad range of research tools as probe measurements on power plants, entrain flow reactor studies and deposit modelling have been used to gain an improved understanding of ash transformation and ash deposit formation in suspension fired boilers. The presentation provides an overview of the knowledge obtained with respect to ash species behavior in suspension fired biomass boilers. A mechanistic understanding of the fly ash formation process in biomass fired PF boilers isobtained today. A high fraction of alkali salt species are released to the gas phase during the initial fuel combustion process. The salt species are present in gas phase in the boiler chamber and upon cooling in the convective pass aerosols are formed. Recent studies indicates that a large fraction of the residual condensed phase ash fragments to generate ash particles typically in the size range of 50 to 200 μm on biomass suspension fired power plant boilers. A fragmentation rate of fuel particles of 3 have been used to describe both the residual ash formation process in laboratory entrained flow reactors and in full scale boilers. A range of advanced deposit probe measurements have been conducted on biomass powerplants. The measurements have provided insight into the relations between the chemical composition of fuel ash, fly ash and deposits. Furthermore the measurements have provided quantitative data on deposit formation rates as a function of fuel composition, and local surface and flue gas temperature. The processes of deposit removal by both natural shedding and soot blower induced deposit shedding have also been studied by the probe measurements. In most cases deposits are removed by debonding, where the deposits break up near the interface to the steam tube metal surface. Especially an increased tube temperature makes it more demanding to remove the ash deposit. Modelling of the deposit formation process have been developed by combining sub-models of the ash formation process, the condensation of ash species on tube surfaces, ash particle deposition, heat transfer in the deposit and deposit sintering. The model mainly provides information on how changes in fuel ash composition and local conditions influences deposition rate and deposit chemistry. Comparison of the modeling results with laboratory and full scale data shows that further development of both the particle adherence model and the alkali condensation model is wanted. The speciation of potassium from the biomass in the boiler chamber as salts or aluminasilicates and other species with high melting temperatures strongly influence the operation of both the boiler and flue gas cleaning equipment. Different additive types can be used to reduce the alkali salt content in the boiler chamber. The additive often works by reaction with the salts thereby binding the alkali metal to high melting temperature species and release the chlorine to the gas phase as HCl. Presently coal fly ash with a high content of Si and Al is used as an additive on wood fired plants to reduce the problems with alkali salt de-activation of SCR catalysts. While the fundamental chemistry of the additives are well known detailed reaction models of the interaction of salts and additive particles are presently not available.
A Comparative Study of Two Full-Scale Swirl Stabilized Bio-Dust Flames Power Plant Flames

In this study, sieving, 2D imaging analysis (CAMSIZER/CAMSIZER XT) and optical microscopy were applied to the characterization of the size and shape of biomass particles. The 2D imaging technology was found to be the most convenient characterization method, providing information on the shape and external surface area of the particles. Different biomass samples were measured with an optical microscope and the results were compared with those from 2D imaging analysis. The main result of this study is that the data on particle width, measured by these two techniques, is identical. However, for the particle length, measured by 2D imaging analysis, it is proposed to apply a correction factor equal to cos (45°). Based on the analysis of different biomass types, it is recommended to set the particle's thickness to 2/3 of its width. In this study, a way to quantify all three dimensions of biomass particles was established.

For the shape representation of biomass particles in the combustion model, measurements on CAMSIZER/CAMSIZER XT were carried out to estimate geometrical parameters as sphericity, aspect ratio and symmetry of the total particle size distribution. Additionally, a calculation of shape factors was conducted, in which shape factors were determined by relating irregular-shaped biomass particles to regular geometrical bodies such as a cylinder, parallelepiped, sphere and ellipsoid. Based on the calculated shape factors and the main principles of the combustion phenomena, it is recommended to represent a biomass particle in CFD models as an infinite cylinder with the ratio of volume to surface area (V/A) measured with CAMSIZER/CAMSIZER XT technology for the total particle size distribution and multiplied with the estimated correction factor 1.5. Alternatively, the ratio of volume to surface area (V/A) can be implemented by using equations for the volume and surface area of different geometrical forms, correlated to three dimensions, measured either by 2D imaging technology with the main advantage to conduct measurements quickly with the reproducible results by using small amount of samples, or optical microscopy.

Deposit Probe Measurements in Large Biomass-Fired Grate Boilers and Pulverized-Fuel Boilers

A number of full-scale deposit probe measuring campaigns conducted in grate-fired and suspension-fired boilers, fired with biomass, have been reviewed and compared. The influence of operational parameters on the chemistry of ash and deposits, on deposit build-up rates, and on shedding behavior has been examined. The firing technology and the fuel
utilized influence the fly ash and deposit chemical composition. In grate-firing, K, Cl, and S are enriched in the fly ash compared to the fuel ash, while the fly ash in suspension-firing is relatively similar to the fuel ash. The chemical composition of the deposits formed is determined by the fly ash composition and the flue gas temperature; increases in the local flue gas temperature lead to higher contents of Si and Ca and lower contents of Cl in the deposits. The net deposit build-up rates in grate-fired and suspension-fired boilers are at similar levels, 0–100 g/m²·h, while the ash deposit propensity is an order of magnitude larger in grate fired boilers than in suspension-fired boilers. Deposit build-up rates were found to increase at flue gas temperatures close to the melting temperatures of the fly ash. Furthermore, the rate of deposit build-up increased with the K-content of the fuel ash and fly ash for grate-fired boilers. For suspension-fired boilers, deposition rates are comparatively low for wood-firing and increase with increasing fuel straw shares. Shedding of deposits occurs by melting during straw-firing on a grate at high flue gas temperatures (>900 °C). At lower flue gas temperatures, the deposits can be removed by soot blowing. The required soot blower impact pressure is strongly influenced by the surface temperature, such that a high surface temperature makes the deposit more difficult to remove. During straw/wood-firing in suspension-fired boilers, shedding occurred by debonding with incomplete removal at flue gas temperatures of 600–1000 °C and by debonding with complete removal during wood-firing in suspension-fired boilers at high flue gas temperatures (1300 °C). Shedding events were not observed during wood suspension-firing at low flue gas temperatures.
Effect of pyrolysis conditions and composition on the char structure and char yield of biomass chars

The char yield as well as physical and chemical structure of chars generated from different types of biomass divided into five different particle size fractions from 50μm to 1mm were studied to better understand the influences of holding time, final temperatures and heating rates on the pyrolysis characteristics of biomass chars. An additional study of the char phase-organic transformation was conducted on the biomass organic matter.

Char samples were generated in a wire-mesh reactor up to 1400°C, and with the heating rates between 10 K/s and 3000 K/s. The results were compared with the data gained from slow (10 K/min) and fast heating (600 K/min) by thermogravimetric analysis (TGA). Scanning electron microscopy (SEM/EDS), elementary analysis and Fourier transform infrared spectroscopy (FTIR) were conducted to determine the effect of operating conditions and the biomass composition on the char structural changes.

A significantly different char yield was observed between heating rates 10 K/s and 1000 K/s. For heating rates > 600 K/s a similar biomass char yield was obtained. Overall, it was found that the final temperature has more influence on the char yield than the heating rate. The scanning electron microscopy indicated different types of softening and melting of the biomass chars at all applied temperatures, heating rates and holding times, except for rice husks, which formed chars with a structure similar to the parent fuel. The char particles generated at high pyrolysis temperatures had many small pores and showed complete melting, while the biomasses like wheat straw and beech wood showed larger pores and not complete melting with the remaining carbon skeleton of different forms. FTIR analysis was conducted to estimate the remaining organic composition of the char consisting mainly of hemicellulose and lignin.
Electron microscopy study of the deactivation of nickel based catalysts for bio oil hydrodeoxygenation

Hydrodeoxygenation (HDO) is proposed as an efficient way to remove oxygen in bio-oil, improving its quality as a more sustainable alternative to conventional fuels in terms of CO2 neutrality and relative short production cycle [1]. Ni and Ni-MoS2 nanoparticles supported on ZrO2 show potential as high-pressure (100 bar) catalysts for purification of bio-oil by HDO. However, the catalysts deactivate in presence of sulfur, chlorine and potassium species, which are all naturally occurring in real bio-oil.

The deactivation mechanisms of the Ni/ZrO2 have been investigated through scanning transmission electron microscopy (STEM), energy dispersive X-ray spectroscopy (EDX), scanning electron microscopy (SEM) and X-ray diffraction (XRD). Catalytic testing has been performed using guaiacol in 1-octanol acting as a model compound for bio-oil. Addition of sulphur (0.3 vol% octanethiol) in the feed resulted in permanent deactivation of the catalyst by formation of a catalytically inactive Ni-S phase, as suggested by the very similar spatial distribution of nickel and sulphur signals in STEM-EDX elemental maps (Figure 1) and confirmed by XRD and X-ray absorption spectroscopy (XAS) techniques. Deactivation by chlorine (0.3 vol% chlorooctane) co-feeding was found to be reversible, as the catalyst could regain close to its initial deoxygenation activity upon restoration of a clean feed. SEM-EDX investigations excluded the presence of chlorine species; however, XRD analysis revealed sintering of nickel nanoparticles (Figure 2). Impregnating KCl and KNO3 on two different batches of catalysts decreased permanently their deoxygenation activity, suggesting the adsorption of potassium at low coordinated nickel sites [2]. The high mobility of potassium under the electron beam [3] prevented the spatial distribution study of this element through STEM-EDX. Moreover, nickel sintering was observed in the KCl poisoned sample and was ascribed once again to the formation of mobile Ni-Cl species upon reaction of HCl with surface oxides [4].

Furthermore, environmental transmission electron microscopy (ETEM) has been used in order to investigate the oxidation of Ni-MoS2/ZrO2 catalyst active phase as a function of different HDO reaction conditions and using methanol as a model molecule for bio-oil.

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Pyrolysis of biomass produces a high yield of condensable oil at moderate temperature and low pressure. This bio-oil has adverse properties such as high oxygen and water contents, high acidity and immiscibility with fossil hydrocarbons. Catalytic hydrodeoxygenation (HDO) is a promising technology that can be used to upgrade the crude bio-oil to fuel-grade oil. The development of the HDO process is challenged by rapid catalyst deactivation, instability of the pyrolysis oil, poorly investigated reaction conditions and a high complexity and variability of the input oil composition. However, continuous catalytic hydropyrolysis coupled with downstream HDO of the pyrolysis vapors before condensation shows promise.
(Figure 1). A bench scale experimental setup will be constructed for the continuous conversion of solid biomass (100g/h) to low oxygen, fuel-grade bio-oil. The aim is to provide a proof-of-concept for the proposed process (Figure 1), to understand the reaction mechanisms of HDO, to develop highly active and durable catalysts for hydropyrolysis and HDO and to optimize the operating conditions; all in order to develop a sustainable production of green transportation fuels from biomass. To support the process development, the conversion of different bio-oil model compounds over a widerange of catalyst classes (reduced types, oxides, phosphides and sulfides) will be investigated. Special attention will be paid to operating conditions (e.g. temperature, H₂ partial pressure, residence time) and tolerance against water, sulfur, chlorine and potassium which are abundant in bio-oil.

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Local Measurements in Two Full-Scale Swirl Stabilized Bio-Dust Burners: A Parametric Study

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Properties of slurries made of fast pyrolysis oil and char or beech wood

The properties of slurries made of pyrolysis oil mixed with wood, char or ground char were investigated with respect to phase transitions, rheological properties, elemental compositions, and energy density. Also the pumping properties of the slurries were investigated at temperatures of 25, 40 and 60 C and solid loadings from 0 to 20 wt%. The phase transitions of the wood slurry samples were observed at lower solid loadings compared to the char slurry samples. The apparent viscosity of the slurry samples was found to be considerably impacted by solid loading (0e20 wt%) and temperature (25e60 C), especially in the phase transition region. The slurry viscosities with 20 wt% char loading, 20 wt% ground char loading and 15 wt% wood loading (at a shear rate of 100 s⁻¹) are 0.7, 1.0 and 1.7 Pa.s, respectively at 60 C and these values increases 1.2e1.4 times at 40 C and 3e4 times at 25 C. The wood, char and ground char slurry samples with 5e20 wt% solid loading obtain a volumetric energy density of 21e23 GJ/m³. The slurry sample with 20 wt% ground char having a d80 of 118 mm was pumped successfully into a pressurized chamber (0e6 bar) while plugging appeared when the slurry samples with 15 wt% char having a d80 of 276 mm was pumped into the pressurized chamber.

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Release of Chlorine and Sulfur during Biomass Torrefaction and Pyrolysis

The release of chlorine (Cl) and sulfur (S) during biomass torrefaction and pyrolysis has been investigated via experiments in two laboratory-scale reactors: a rotating reactor and a fixed bed reactor. Six biomasses with different chemical compositions covering a wide range of ash content and ash-forming elements were torrefied/pyrolyzed in the temperature range of 150-500 degrees C. The relative release of chlorine and sulfur was calculated based on mass balance and analysis of the biomass before and after torrefaction. In selected cases, measurement of methyl chloride (CH3Cl) in the gas from straw torrefaction has furthermore been conducted. The release of chlorine from straw was first observed at 250 degrees C and peaked with about 60-70% at 350 degrees C. Analysis of the released gas showed that most of the chlorine was released as methyl chloride. Increasing the straw content in the reactor resulted in a lower fractional release of Cl, probably due to more reactive sites in contact with gas phase Cl species leading to secondary binding of Cl to the solid product. Almost complete release of chlorine was observed for woody biomass at 350 degrees C. This result is in agreement with previous studies reporting that biomasses with a lower chlorine content release a higher fraction of chlorine during the pyrolysis process. A significant sulfur release (about 60%) was observed from the six biomasses investigated at 350 degrees C. The initial sulfur content in the biomass did not influence the fraction of sulfur release during torrefaction.

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Residual Ash Formation during Suspension-Firing of Biomass: Effects of Residence Time and Fuel-Type

Through 50+ years, high quality research has been conducted in order to characterize ash and deposit formation in utility boilers fired with coal, biomass and waste fractions. The basic mechanism of fly ash formation in suspension fired coal boilers is well described, documented and may even be modeled relatively precisely. Concerning fly ash formation from
Stability and resistance of nickel catalysts for hydrodeoxygenation: carbon deposition and effects of sulfur, potassium, and chlorine in the feed

The long term stability and resistance toward carbon deposition, sulfur, chlorine, and potassium of Ni/ZrO₂ as a catalyst for the hydrodeoxygenation (HDO) of guaiacol in 1-octanol (as a model compound system for bio-oil) has been investigated at 250 degrees C and 100 bar in a trickle bed reactor setup. Without impurities in the feed good stability of the Ni/ZrO₂ catalyst could be achieved over more than 100 h of operation, particularly for a sample prepared with small Ni particles, which minimized carbon deposition. Exposing the catalyst to 0.05 wt% sulfur in the feed resulted in rapid deactivation with complete loss of activity due to the formation of nickel sulfide. Exposing Ni/ZrO₂ to chlorine-containing compounds (at a concentration of 0.05 wt% Cl) on-stream led to a steady decrease in activity over 40 h of exposure. Removal of the chlorine species from the feed led to the regaining of activity. Analysis of the spent catalyst revealed that the adsorption of chlorine on the catalyst was completely reversible, but chlorine had caused sintering of nickel particles. In two experiments, potassium, as either KCl or KNO₃, was impregnated on the catalyst prior to testing. In both cases the adsorption of chlorine on the catalyst was completely reversible, but chlorine had caused sintering of nickel particles. In two experiments, potassium, as either KCl or KNO₃, was impregnated on the catalyst prior to testing. In both cases the adsorption of chlorine on the catalyst was completely reversible, but chlorine had caused sintering of nickel particles. In two experiments, potassium, as either KCl or KNO₃, was impregnated on the catalyst prior to testing. In both cases the adsorption of chlorine on the catalyst was completely reversible, but chlorine had caused sintering of nickel particles. In two experiments, potassium, as either KCl or KNO₃, was impregnated on the catalyst prior to testing. In both cases the adsorption of chlorine on the catalyst was completely reversible, but chlorine had caused sintering of nickel particles.
In this work the physical and chemical transformations of biomass chars during fast pyrolysis, considered as a 2nd stage of combustion, has been investigated. Seven biomasses containing different amount of ash and organic components were reacted at up to 1673 K with high heating rates in a wire-mesh reactor and the resulting chars were retrieved. In order to obtain information on the structural and compositional transformations of the biomass chars, samples were subjected to elemental analysis, scanning electron microscopy with EDX and Raman spectrometry. The results show that there are significant changes in both the organic and inorganic constituents of the chars. Under high heating rates (> 100 K/s) char particles underwent different types of melting and pores of different size were developed in dependency on the temperature and biomass composition. The Si-rich rice husks char did not show any melting behavior up to 1673K. Samples with high lignin content tended to melt completely and developed micropores, while the samples with the high hemicellulose content softened and transformed into the separated molten carbon skeleton particle with the form similar to
the virgin biomass particle and with inner and outer macropores. From the lab-scale experiments on the wire-mesh reactor, it was observed that the final temperature has more significant effect on the char yield than heating rate. The applied variation of holding time from 1 to 4 sec and a particle size fraction from 50 micron up to 1 mm showed that the char yield depends mainly on the biomass type.

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**Treatment of Lignin and Waste residues by Flash Pyrolysis: Final report**

Lignin, sewage sludge and macroalgae (nonconventional biomasses) fast pyrolysis properties has been studied through experimental investigations on a laboratory Pyrolysis Centrifugal Reactor (PCR) and a model on lignin pyrolysis have been developed. Furthermore the nonconventional biomass pyrolysis properties were compared with the pyrolysis properties of wood and straw. The PCR treatment of sewage sludge provides an oil that can be used for energy purposes and a solid residue rich in organic nutrients that may be used as fertilizer product. By fast pyrolysis of lignin from the IBUS ethanol plant a bio-oil can be produced with oil yields of 36% (daf) and an energy recovery of 45%. This is a relatively low bio-oil yield compared to other feedstock’s, however, it may increase the value of the lignin residual product, such that the lignin char is used for combustion on the ethanol plant, and the bio-oil is sold for use on heavy oil burners. The macroalgae is a promising feedstock with a high bio-oil yield of 54 wt% daf and an energy recovery of 76 % in the liquid oil. Detailed characterization of the pyrolysis products in the form of bio-oil, gas and char has been performed. The properties of slurries made of char and pyrolysis oil that potentially may be used as a feed for pressurized gasifiers has been investigated. It was shown that slurries made of mixtures of wood and bio-oil can be pumped into pressurized systems. A new patented version of the PCR rotor unit, which can be operated at low rotational speed was constructed. The new rotor systems should make it easier to make an up-scaling of the process.

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**A Comparison of Lignin, Macroalgae, Wood and Straw Fast Pyrolysis**

A fast pyrolysis study on lignin and macroalgae (non-conventional biomass) and wood and straw (conventional biomass) were carried out in a pyrolysis centrifugal reactor at pyrolysis temperature of 550 ºC. The product distributions and energy recoveries were measured and compared among these biomasses. The fast pyrolysis of macroalgae showed a promising result with a bio-oil yield of 65 wt% dry ash free basis (daf) and 76 % energy recovery in the bio-oil while the lignin fast pyrolysis provides a bio-oil yield of 47 wt% daf and energy recovery in bio-oil of 45 %. The physiochemical properties of the bio-oils were characterized with respect to higher heating value (HHV), molecular mass distribution, viscosity, pH, density, thermal behaviors, elemental concentrations, phase separation and aging. The lignin and macroalgae oil
properties were different compared to those of the wood and straw oils with respect to carbon and oxygen contents, HHV, thermal behaviors and mean molecular weight. The HHV of wood, straw, lignin and algae oils were 24.0, 23.7, 29.7 and 25.7 MJ/kg db, respectively. The distributions of metals, Cl and S in char and bio-oil were investigated for the biomasses. Almost all the metals (Al, Ca, Fe, K, Mg, Na, P and Si) were contained in the chars at the pyrolysis temperature of 550 °C. The char properties were characterized and their potential applications are discussed.

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Catalytic Conversion of Bio-oil to Fuel for Transportation

The incitement for decreasing the modern society's dependency on fossil based fuel and energy is both environmentally and politically driven. Development of biofuels could be part of the future solution. The combination of ash pyrolysis and catalytic upgrading of the produced bio-oil has been identified as a prospective route to bio-fuels. The upgrading is most favorably done by hydrodeoxygenation (HDO), producing bio-fuels at a quality equivalent to conventional fossil fuels. The topic of this Ph.D. thesis has been the development of active and stable catalysts for this reaction. In the search for new HDO catalyst 23 catalytic systems were screened in a batch reactor at 100 bar H₂ and 275 °C with phenol as bio-oil model compound, comparing different combinations of active phase and support. Among the tested catalysts, reduced metal catalysts displayed the highest activity, with the apparent order of activity for some of the most active catalysts being: Ni/ZrO₂ > Ru/C > Ni/Al₂O₃ > Ni/SiO₂ Pd/C > Pt/C. Catalysts should be effective in both hydrogenation and deoxygenation to effectively convert phenol at the applied conditions. Ni/SiO₂ was further investigated by varying the Ni particle size, showing that deoxygenation was linked to low coordinated sites (e.g. steps and corners), favored at small nickel particles. Hydrogenation was also influenced by particle size, where the reaction was hindered at small particles due to competitive adsorption of alcohols on the nickel sites. However, the support was found to have the largest effect on the hydrogenation rate. A good support should have high availability of Lewis acid sites. Overall Ni/ZrO₂ prepared with small (<10 nm) nickel particles was found as a very prospective catalyst for HDO, displaying both good hydrogenation and deoxygenation activity. With Ni/ZrO₂ identified as a prospective HDO catalyst, the stability and resistance toward bio-oil impurities was investigated in a high pressure gas and liquid continuous flow setup with bio-oil model compounds and compared to the more traditional hydrotreating catalysts Mo₂C/ZrO₂ and Ni-MoS₂/ZrO₂. The investigated bio-oil impurities included water (up to 30 wt% in bio-oil), chlorine, potassium and sulfur. Of the tested catalysts, Ni/ZrO₂ displayed the highest activity, requiring only 250 °C for performing HDO of aromatic compounds, followed by Ni-MoS₂/ZrO₂ (requiring 280 °C), and then Mo₂C/ZrO₂, which required temperatures >320 °C. Ni/ZrO₂ and Ni-MoS₂/ZrO₂ displayed good stability for HDO of pure model compounds over periods of more than 100 h. However, Ni-MoS₂/ZrO₂ required a significant co-feed of sulfur (as dimethyl disulfide or H₂S) to remain stable, as oxidation of the sulde phase took place in the absence of sulfur. Part of the sulfur was incorporated in the liquid product as thios, if the residence time was not sufficiently high. Mo₂C/ZrO₂ displayed poor stability during HDO of a mixture of phenol and 1-octanol at 300 °C, losing roughly 50% activity over 74 h of operation. The loss of activity was found to be due to oxidation of the catalyst by the water formed from the HDO reaction. This was evidenced in a separate experiment co-feeding water, where all activity was lost over only 12 h of operation, and further verified by thermodynamic calculations showing the affinity for oxidation of Mo₂C with water at the given operating conditions. Ni-MoS₂/ZrO₂ was also found to be unstable in the presence of water if not co-fed with sufficient sulfur. The best stability of the catalyst was obtained when co-feeding sulfur in a H₂O/H₂S ratio of 9.4, but in this case still 36% loss of activity occurred over 94 h of operation. This loss of activity was probably linked to the loss of edge sulfur atoms during exposure to water. Potassium was found to severely deactivate both Ni/ZrO₂ and Ni-MoS₂/ZrO₂, as the activity of the catalyst decreased by 88% and 94%, respectively, when impregnated with potassium (in a stoichiometric ratio between active metal and potassium) compared to the un-poisoned cases. Chlorine was inhibiting both catalysts but the activity could be regained when removing it from the feed. Sulfur was found as the overall worst poison for Ni/ZrO₂, as this transformed the nickel to a...
NiSx phase leading to fast and complete loss of activity. This is in contrast to the Ni-MoS2/ZrO2 catalyst where sulfur was a requirement to maintain the activity. Overall, Ni-MoS2/ZrO2 displayed the best resistance, but the somewhat high temperature requirement and heavy dependency of a sulfur source are drawbacks. Ni/ZrO2 was in contrast more easily poisoned by especially sulfur, but is an attractive catalyst as it catalyzes HDO at relative low temperatures. However, in general a lot of work is still needed in catalyst development.

Characterization and quantification of deposits build up and removal in straw suspension fired boilers
This project deals with ash deposit formation in suspension fired biomass power plant boilers. The project has been conducted in a tight collaboration between Vattenfall and the CHEC Research Centre at DTU Department of Chemical Engineering. A large part of the project has been performed by conducting advanced probe measurements at the Amagerværkets Vattenfall owed boilers. It was the objective of the project to provide an improved understanding of ash deposit formation and removal in biomass suspension fired boilers. The project have provided a large amount of knowledge on the following issues: 1) The influence of local boiler conditions on deposit formation in suspension fired boilers using wood or co-firing straw and wood, 2) quantification of deposit removal in biomass suspension firing boilers with regards both to natural shedding and soot blower induced shedding, 3) established relations of the properties of fuel ash, fly ash and deposits, 4) use of coal ash to remedy biomass ash induced boiler deposit problems.

Characterization of Residual Particulates from Biomass Entrained Flow Gasification
Biomass gasification experiments were carried out in a bench scale entrained flow reactor, and the produced solid particles were collected by a cyclone and a metal filter for subsequent characterization. During wood gasification, the major part of the solid material collected in the filter is soot. Scanning electron microscopy (SEM) images coupled with energy dispersive spectroscopy (EDS) show agglomerated nanosize spherical soot particles (<100 nm) that are very rich in carbon. In comparison to wood gasification, the soot content in the filter sample from straw gasification is quite low, while the contents of KCl and K2SO4 in the filter sample are high. SEM images of the straw filter samples show that with steam addition during gasification, where the soot yield is lower, the filter sample becomes richer in KCl and K2SO4 and appears as irregular crystals, and the typical particle size increases from below 100 nm to above 100 nm. During gasification of dried lignin, the filter sample mainly consists of soot and nonvolatilizable inorganic matter. SEM images of the parent wood particles and the derived char samples show that they have similar structure, size, and shape but the derived char particle surface looks smoother indicating some degree of melting. The reactivity of the organic fraction of the samples was determined by thermogravimetry, and it was found that char was more reactive than soot with respect to
both oxidation and CO2 gasification. The activation energy for the soot conversion is higher than for the char conversion. These results support the observation from gasification experiments that char is more easily converted than soot. Surprisingly, the soot produced at a higher temperature is more reactive than the soot produced at a lower temperature.

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Co-firing of Coal with Biomass and Waste in Full-scale Suspension-fired Boilers

The energy policy in Denmark has for many years focused on lowering the net CO2 emission from heat and power production by replacing fossil fuels by renewable resources. This has been done by developing dedicated grate-fired boilers for biomass and waste fuels but also by developing coal-based suspension-fired boilers to accept still higher fractions of biomass or waste material as fuels. This last development has been challenging of many reasons, including pre-treatment of fuels, and solving potential emission and operational problems during the simultaneous development of supercritical steam cycles with steam temperatures close to 600°C, providing power efficiencies close to 50% [Hein, 2008]. For 25 years the CHEC (Combustion and Harmful Emission Control) Research Centre at DTU Chemical Engineering, has attained a leading role in research, supporting power producing industry, plant owners and boiler manufacturers to optimize design and operation and minimize cost and environmental impact using alternative fuels in suspension fired boilers. Our contribution has been made via a combination of full-scale measuring campaigns, pilot-scale studies, lab-scale measurements and modeling tools. The research conducted has addressed many issues important for co-firing, i.e. fuel processing, ash induced boiler deposit formation and corrosion, boiler chamber fuel conversion and emission formation, influence on flue gas cleaning equipment and the utilization of residual products. This paper provides an overview of research activities, aiming at increasing biomass shares during co-firing in suspension, conducted in close collaboration with the Danish power industry. The research has lead to an improved understanding of the alternative fuels interaction with coal in the boiler chamber. Further, the applied research has provided results with implications for operation of milling and burner equipment, appropriate fuel mixing strategies, minimization of ash deposit formation and corrosion, minimization of NO formation, appropriate operation of SCR catalyst equipment and utilization of residual products. © Tsinghua University Press, Beijing and Springer-Verlag Berlin Heidelberg 2012.
Deposit formation in a full-scale pulverized wood-fired power plant with and without coal fly ash addition

Ash transformation and deposition in a pulverized wood-fired power plant boiler of 800 MWth were studied with and without the addition of coal fly ash. The transient ash deposition behavior was investigated by using an advanced deposit probe system at two different boiler locations with flue gas temperatures of ~1300°C and ~800°C, respectively. It was found that during pulverized wood combustion, the deposit formation at the high-temperature location was characterized by a slow and continuous growth of deposits followed by the shedding of a large layer of deposits, while the deposit formation at the low-temperature location showed a slow initial build-up and a stable mass of deposits after approximately 1-5 h. The deposits collected during pulverized wood combustion contained a considerable amount of K₂SO₄, KCl, and KOH/K₂CO₃. With the addition of coal fly ash (~4 times of the mass flow of wood ash) to the boiler, these alkali species were effectively removed both in the fly ash and in the deposits, and a more frequent shedding of the deposits was observed. The results imply that coal fly ash can be an effective additive to reduce ash deposition and corrosion problems in a pulverized wood-fired boiler.

Efficient Fuel Pretreatment: Simultaneous Torrefaction and Grinding of Biomass

Combining torrefaction and grinding of biomass in one reactor may be an attractive fuel pretreatment process. A combined laboratory torrefaction and ball mill reactor has been constructed for studies of the influence of temperature and residence time on the product yields and particle size reductions of Danish wheat straw, spruce chips, and pine chips. On the basis of initial experiments, which evaluated the influence of reactor mass loading, gas flow, and grinding ball size and material, a standard experimental procedure was developed. The particle size reduction capability of the torrefaction process has been evaluated by the relative change in d₅₀, and this method was compared to the Hardgrove grindability index (HGI), showing reasonably similar results. Significant differences in torrefaction behavior have been observed for straw and spruce chips torrefied at 270–330 °C. Torrefaction of straw for 90 min yielded a higher mass loss (27–60 wt %) and relative size reduction (59–95%) compared with spruce (mass loss of 10–56 wt % and size reduction of 20–60%). The two types of biomass investigated differ with respect to hemicellulose type, lignocellulosic composition, particle morphology, and ash composition, where straw has a higher alkali content. This and other studies indicate that the large difference in the alkali contents of the biomasses is the main cause for the observed difference in torrefaction characteristics. Experiments with separate particle heating and grinding showed a swift grinding of the torrefied biomass. This implies that the rate-limiting step in the laboratory reactor is the heat transfer and not the grinding process. Large pine particles (8–16 mm) showed a slightly higher mass loss than 4–8 and <4 mm particles. This could be the consequence of exothermic reactions in the particle core, which locally increase the temperature and conversion.
Experimental investigation of flash pyrolysis oil droplet combustion

The aim of this work is to investigate and compare the combustion behaviour of a single droplet of pyrolysis oil derived from wheat straw and heavy fossil oil in a single droplet combustion chamber. The initial oil droplet diameters were in between 500 μm to 2500 μm. The experiments were performed at a temperature ranging between 1000 and 1400°C with an initial gas velocity of 1.6 m/s and oxygen concentration of 3%. The evolution of combustion of bio-oil droplets was recorded by a digital video camera. It was observed that the combustion behaviour of pyrolysis oil droplet differ from the heavy oil in terms both of ignition, devolatilisation and char oxidation. The pyrolysis oil is more difficult to ignite and has a shorter devolatilisation time and a longer char oxidation time. Copyright © 2013, AIDIC Servizi S.r.l.

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Experimental Study on Effects of Particle Shape and Operating Conditions on Combustion Characteristics of Single Biomass Particles

An experimental study is performed to investigate the ignition, devolatilization, and burnout of single biomass particles of various shapes and sizes under process conditions that are similar to those in an industrial combustor. A charge coupled device (CCD) camera is used to record the whole combustion process. For the particles with similar volume (mass), cylindrical particles are found to lose mass faster than spherical particles and the burnout time is shortened by increasing the particle aspect ratio (surface area). The conversion times of cylindrical particles with almost the same surface area/volume ratio are very close to each other. The ignition, devolatilization, and burnout times of cylindrical particles are also affected by the oxidizer temperature and oxygen concentration, in which the oxygen concentration is found to have a more pronounced effect on the conversion times at lower oxidizer temperatures.

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Fast Pyrolysis of Lignin Using a Pyrolysis Centrifuge Reactor

Fast pyrolysis of lignin from an ethanol plant was investigated on a lab scale pyrolysis centrifuge reactor (PCR) with respect to pyrolysis temperature, reactor gas residence time, and feed rate. A maximal organic oil yield of 34 wt % dry basis (db) (bio-oil yield of 43 wt % db) is obtained at temperatures of 500−550 °C, reactor gas residence time of 0.8 s, and feed rate of 5.6 g/min. Gas chromatography mass spectrometry and size-exclusion chromatography were used to characterize the Chemical properties of the lignin oils. Acetic acid, levoglucosan, guaiacol, syringols, and p-vinylguaiacol are found to be major chemical components in the lignin oil. The maximal yields of 0.62, 0.67, and 0.38 wt % db were obtained for syringol, p-vinylguaiacol, and guaiacol, respectively. The reactor temperature effect was investigated in a range of 450−600 °C and has a considerable effect on the observed chemical components and molecular mass distribution of the lignin oils. The obtained lignin oil has a very different components composition when compared to a beech wood oil.
Impact of coal fly ash addition on ash transformation and deposition in a full-scale wood suspension-firing boiler

Ash transformation and deposition during pulverized wood combustion in a full-scale power plant boiler of 800 MWth were studied with and without the addition of coal fly ash. The transient ash deposition behavior was characterized by using an advanced deposit probe system at two boiler locations with flue gas temperatures of about 1300 C and 800 C, respectively. The mechanisms of ash transformation and deposit formation were elaborated through a detailed characterization of the collected deposits and fly ashes. The results implied that during pulverized wood combustion, the formation of deposits at the location with high flue gas temperatures was characterized by a slow and continuous growth of deposits followed by the shedding of a large layer of deposits, while at the location with low flue gas temperature the deposit formation started with a slow build-up and the amount of deposits became almost constant after a few hours. The formed deposits, especially those at the location with low flue gas temperatures, contained a considerable amount of K2SO4, KCl, and KOH/K2CO3. With the addition of a large amount (about 4 times of the mass flow of wood ash) of coal fly ash to the boiler, these alkali species were effectively removed both in the fly ash and in the deposits. Although the ash deposition rate at the location with high flue gas temperature was increased with coal fly ash addition, the removability of the deposits was significantly improved, resulting in a more frequent shedding of the deposits. Overall, the results from this work suggest that coal fly ash can be an effective additive to minimize the possible ash deposition and corrosion problems during suspension-firing of wood. © 2013 Elsevier Ltd. All rights reserved.

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In-Flame Measurements on Full-Scale Swirl Stabilized Bio-Dust Burners at Different Operational Conditions

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Influence of Biomass Chemical Properties on Torrefaction Characteristics

Different biomass types may differ with respect to torrefaction characteristics, and an improved understanding and ability to predict the torrefaction performance is, therefore, desired. In this study, the influence of the chemical properties (lignocellulose composition and alkali content) on the torrefaction behavior with respect to mass loss and grindability is investigated by simultaneous thermal analysis (STA) and by using a combined torrefaction and grinding reactor. The torrefaction behavior of six raw biomass samples and selected pretreated samples (washed and impregnated with KCl and K2CO3) has been studied. The investigated biomasses have reasonably similar carbohydrate compositions (hemicelluloses 18–25 wt % db; cellulose 38–48 wt % db; lignin 17–29 wt % db) with the exception of spruce bark, which is lower in hemicellulose content (12.9 wt % db) and cellulose content (24 wt % db), and higher in lignin content (36.8 wt % db). An increasing biomass potassium (K) content decreases the temperature of maximal conversion for both raw and alkali-impregnated biomass samples, thus decreasing the solid product yield at 270 and 300 °C. This was especially pronounced when the biomass potassium content increased from 0 to 0.2 wt %. However, the higher lignin content in bark causes a higher solid yield than what would be expected from the alkali content, illustrating that both potassium content and lignocellulose composition affect the solid yield obtained by torrefaction. The grindability of the torrefied products was evaluated by determining the d50 value of the particle size distribution of the biomass before and after torrefaction in the combined torrefaction and mill reactor. A significant decrease in d50 value was observed when the alkali content increased from 0 to 0.2 wt % db, whereas no additional effect is seen for higher potassium contents.

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Influence of the Pyrolysis Temperature on Sewage Sludge Product Distribution, Bio-Oil, and Char Properties

Fast pyrolysis may be used for sewage sludge treatment with the advantages of a significant reduction of solid waste volume and production of a bio-oil that can be used as fuel. A study of the influence of the reaction temperature on sewage sludge pyrolysis has been carried out using a pyrolysis centrifugel reactor (PCR) at 475, 525, 575, and 625 °C. Maxima of both organic oil yield of 41 wt % on a dry ash free feedstock basis (daf) and a sludge oil energy recovery of 50% were obtained at 575 °C. The water-insoluble fraction, molecular-weight distribution, higher heating value (HHV), and thermal behaviors of sludge oils were found to be considerably influenced by the applied pyrolysis temperatures. The sludge oil properties obtained at the optimal temperature of 575 °C were a HHV of 25.5 MJ/kg, a water-insoluble fraction of 18.7 wt %, a viscosity of 43.6 mPa s at 40 °C, a mean molecular weight of 392 g/mol, and metal concentrations lower than 0.14 wt % on a dry basis (db). Less optimal oil properties with respect to industrial applications were observed for oil samples obtained at 475 and 625 °C. Char properties of the 575 °C sample were an ash content of 81 wt % and a HHV of 6.1 MJ/kg db. A total of 95% of the sewage sludge phosphorus content was recovered in the char. The solid waste amount (char compared to sludge) was reduced to 52% on a bulk volume basis at the pyrolysis temperature of 575 °C.

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Liquid Fuel Production by Fast Pyrolysis of Biomass

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
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Mechanistic Insight in Hydrodeoxygenation on Nickel Based Catalysts

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Karlsruher Institut für Technologie
Contributors: Mortensen, P. M., Grunwaldt, J., Jensen, P. A., Jensen, A. D.
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Performance of diesel particulate filter catalysts in the presence of biodiesel ash species

The utilization of bio-fuels, such as biodiesel, is expected to contribute significantly towards the planned 10% of renewable energy within the EU transport sector by 2020. Increased biodiesel blend percentages may change engine exit flue gas ash composition and affect the long-term performance of cleaning technologies, such as oxidation catalysts and diesel particulate filters. In this work the performance of a commercial catalyst has been studied for conversion of diesel particulate matter (SRM 2975) at 10% O2, in the presence of salts simulating ash species derived from engine oil and biodiesel. Simultaneous thermal analysis experiments of the diesel particulate matter showed that it was dominated by soot with approximately 10 wt.% condensed hydrocarbons. The presence of a commercial catalyst (5:1 wt. ratio of catalyst to soot), in tight contact with the diesel particulate matter, decreased the temperature at which the oxidation rate peaked from 662 ± 1 °C to 526 ± 19 °C. The introduction of biodiesel ash species such as Na2CO3, K2CO3 or K3PO4 decreased the peak conversion temperature further (422 ± 12; 404 ± 4 and 423 ± 7 °C), with a limited dependence on ash concentration. A deterioration in catalytic conversion, i.e. increased peak conversion temperatures, was seen for two engine oil ash species and one mixed ash species (from engine oil and biodiesel) – CaSO4 (569 ± 6 °C), Ca(H2PO4)2 (699 ± 13 °C) and K2SO4 (581 ± 16 °C).

Kinetic parameters (A and Ea), obtained from Arrhenius plots of the data, showed a lower activation energy in the presence of the commercial catalyst (Ea = 91 ± 5 kJ/mol) or CeO2 (Ea = 62 ± 8 kJ/mol) compared to pure SRM 2975 (Ea = 220 ± 3 kJ/mol). The obtained kinetic data were able to describe the peak conversion temperature and the associated part of the mass loss curve, but an initial low-temperature gradual increase in conversion was not adequately described.
Screening of Catalysts for Hydrodeoxygenation of Phenol as Model Compound for Bio-oil

Four groups of catalysts have been tested for hydrodeoxygenation (HDO) of phenol as a model compound of bio-oil, including: oxide catalysts, methanol synthesis catalysts, reduced noble metal catalysts, and reduced non-noble metal catalysts. In total 23 different catalysts were tested at 100 bar H2 and 275 °C in a batch reactor. The experiments showed that none of the tested oxides and methanol synthesis catalysts had any significant activity for phenol HDO at the given conditions, which were linked to their inability to hydrogenate the phenol. HDO of phenol over reduced metal catalysts could effectively be described by a kinetic model involving a two-step reaction were phenol initially was hydrogenated to cyclohexanol and then subsequently deoxygenated to cyclohexane. Among reduced noble metal catalysts ruthenium, palladium, and platinum were all found to be active, with decreasing activity in that order. Nickel was the only active non-noble metal catalyst. For nickel, also the effect of support was investigated and ZrO2 was found to perform best. Pt/C, Ni/CoO2, and Ni/CoO2-ZrO2 were the most active catalysts for the initial hydrogenation of phenol to cyclohexanol, but were not very active for the subsequent deoxygenation step. Overall, the order of activity of the best performing HDO catalysts was: Ni/ZrO2 > Ni-V2O5/ZrO2 > Ni-V2O5/SiO2 > Ru/C > Ni/Al2O3 > Ni/SiO2 >> Pd/C > Pt/C. The choice of support influenced the activity significantly. Nickel was found to be practically inactive for HDO of phenol on a carbon support, but more active than the carbon supported noble metal catalysts when supported on ZrO2. This observation indicates that the nickel based catalysts require a metal oxide as carrier on which the activation of the phenol for the hydrogenation can take place through heterolytic dissociation of the O-H bond to facilitate the reaction.
Stability and Resistance of Nickel-Based Catalysts for Hydrodeoxygenation

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**Torrefaction of biomass for power production**

In order to increase the share of biomass for sustainable energy production, it will be an advantage to utilize fuels as straw, wood and waste on large suspension fired boilers. On a European scale, currently large straw resources are available that are not fully utilized for energy production. Straw can be co-fired with coal in suspension fired power plants with a maximum straw share of 10 to 20 wt%. However, 100% straw firing induced several problems that can impede both boiler availability and power efficiency. Straw is highly fibrous and tenacious in nature, therefore a relatively high amount of energy is needed to pulverize the straw to a size where a good burn out can be obtained. Also the large alkali and chlorine content in straw often induce severe chlorine rich deposit formation on super heaters. The chlorine rich deposits are corrosive and to prevent high superheater corrosion rates, relatively low superheater temperatures have to be applied, which in turn lower the power efficiency.

The idea for this Ph.D. project is to develop a biomass pretreatment method that could provide the heating value of the fuel for the boiler, but in a way such that the fuel is easily pulverized and the superheating can be done without an exposure of alkali rich flue gas on superheaters. A potential pretreatment process is to use a ball mill with an integrated torrefaction process. The char produced is very fragile and can be easily pulverized down to a size where a high burn out is obtained. The present Ph.D. thesis focus on the following subjects: 1) the development of experimental procedures for a novel laboratory scale reactor (simultaneous torrefaction and grinding) and a study on the torrefaction properties of Danish wheat straw and spruce chips. A standard experimental procedure was developed based on initial experiments which evaluated the influence of reactor mass loading, gas flow and grinding ball size and material. The particle size reduction capability of the torrefaction process has been evaluated by using the relative change in d50 of the product size distribution, and this method was compared with the Hardgrove Grindability Index (HGI), showing reasonably similar results. Significant differences in torrefaction behavior have been observed for straw and spruce chips torrefied at 270 – 330 °C. Torrefaction of straw for 90 minutes yielded a higher mass loss (27 – 60 wt %) and a larger relative size reduction (59 – 95%) compared to spruce (mass loss of 10 – 56 wt% and a size reduction of 20 – 60%). The two types of biomass investigated differ with respect to hemicellulose type, lignocellulosic composition, particle morphology and ash composition where straw has higher alkali content. Experiments with separate particle heating and grinding showed a swift grinding of the torrefied biomass which implies that the rate limiting step in the laboratory reactor is the heat transfer, and not the grinding process.

Different torrefaction characteristics are observed from straw and wood chips, therefore an improved understanding and ability to predict the torrefaction characteristic of different biomass types are desired. In this study, the influence of biomass chemical properties (carbohydrate composition and alkali content) on the torrefaction behavior with respect to mass loss and grindability is investigated. Six raw biomass samples (Danish wheat straw, miscanthus, spruce, beech, pine, and spruce bark) with different chemical and physical properties were pyrolyzed by Simultaneous Thermal Analysis (STA) and torrefied in the simultaneous torrefaction and grinding reactor. The effect of biomass alkali content on torrefaction characteristics were furthermore investigated by washing or impregnating (KCl and K2CO3) of selected biomass. The solid yields at the investigated torrefaction temperatures (270 and 300 °C) are strongly influenced by the
biomass potassium content as well as to some extent the lignocelluloses composition. High biomass potassium content leads to a relatively low solid yield; however in a single case (spruce bark), a high lignin content leads to a relatively high solid yield even in the presence of relatively high potassium content. In summary both potassium content and lignocelluloses composition affect the solid yield obtained by torrefaction. A significant decrease in d50 value of the torrefied products was observed when the alkali content is increased from 0 to 0.2 wt% db, while no additional effect is seen for higher potassium contents.

The release of chlorine (Cl) and sulfur (S) to gas phase during biomass torrefaction has been investigated via experiments in laboratory-scale reactors by using six biomasses which cover a wide range of ash content and ash-forming elements in the temperature range of 150 – 500 °C. The relative release of chlorine and sulfur was calculated based on mass balance and analysis of the biomass before and after torrefaction. In few cases, measurement of methyl chloride (CH3Cl) in the gas released from straw torrefaction has been conducted. Initial release of chlorine was observed at 250 °C and about sixty percent of chlorine was released from straw at 350 °C. The analysis of methyl chloride from the released gas showed that most of chlorine was released as CH3Cl. By using a large amount of straw (40 g compared to 5 – 20 g), less Cl is released, probably due to more reactive sites available for secondary reactions. The secondary reactions can be reaction with relatively stable basic functionalities on the char surface or reaction with potassium to generate KCl. Almost complete release of chlorine was observed for woody biomass at 350 °C. This result showed an agreement with the previous studies reported that the biomass with a lower chlorine content released a higher fraction of chlorine during the pyrolysis process. Significant sulfur release (about 60%) was observed from the six biomasses investigated at 350 °C. It is seen that the initial sulfur content in biomass did not influence the fraction of sulfur release during torrefaction.

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**Trace elements in co-combustion of solid recovered fuel and coal**
Trace element partitioning in co-combustion of a bituminous coal and a solid recovered fuel (SRF) was studied in an entrained flow reactor. The experiments were carried out at conditions similar to pulverized coal combustion, with SRF shares of 7.9 wt.% (wet basis), 14.8 wt.% and 25.0 wt.%. In addition, the effect of additives such as NaCl, PVC, ammonium sulphate, and kaolinite on trace element partitioning was investigated. The trace elements studied were As, Cd, Cr, Pb, Sb and Zn, since these elements were significantly enriched in SRF as compared to coal. During the experiments, bottom ash was collected in a chamber, large fly ash particles were collected by a cyclone with a cut-off diameter of ~2.5 μm, and the remaining fly ash particles were gathered in a filter. It was found that when coal was co-fired with SRF, the As, Cd, Pb, Sb and Zn content in filter ash/cyclone ash increased almost linearly with their content in fuel ash. This linear tendency was affected when the fuels were mixed with additives. The volatility of trace elements during combustion was assessed by applying a relative enrichment (RE) factor, and TEM–EDS analysis was conducted to provide qualitative interpretations. The results indicated that As, Cd, Pb, Sb and Zn were highly volatile when co-firing coal and SRF, whereas the volatility of Cr was relatively low. Compared with coal combustion, co-firing of coal and SRF slightly enhanced the volatility of Cd, Pb and Zn, but reduced the volatility of Cr and Sb. The Cl-based additives increased the volatility of Cd, Pb and As, whereas addition of ammonium sulphate generally decreased the volatility of trace elements. Addition of kaolinite reduced the volatility of Pb, while the influence on other trace elements was insignificant. The results from the present work imply that trace element emission would be significantly increased when coal is co-fired with SRF, which may greatly enhance the toxicity of the dusts from coal-fired power plant. In order to minimize trace element emission in co-combustion, in addition to lowering the trace element content in SRF, utilizing SRF with low CI content and coal with high S and aluminosilicates content would be desirable.

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Scopus rating (2009): SJR 1.531 SNIP 1.851
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Scopus rating (2005): SJR 0.748 SNIP 1.152
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Scopus rating (2004): SJR 0.807 SNIP 1.239
Scopus rating (2003): SJR 0.907 SNIP 1.151
Scopus rating (2002): SJR 0.689 SNIP 1.106
Ash transformation and deposit build-up during biomass suspension and grate firing: Full-scale experimental studies

An attractive option for reducing the net CO2 emissions is to substitute coal with biomass in large power plant boilers. However, the presence of chlorine (Cl) and alkali metals (K, Na) in biomass may induce large operational problems due to ash deposit formation on the superheater tubes. The aim of this study was to investigate ash transformation and deposition behavior in two biomass-fired boilers, firing wheat straw and/or wood. The influence of straw firing technology (grate and suspension) on the ash transformation, deposit formation rate and deposit characteristics has been investigated. Bulk elemental analysis of fly ashes revealed that fly ash from suspension firing of straw has high contents of Si, K and Ca, while fly ash from straw firing on grate was rich in the volatile elements K, Cl and S. Investigations of deposit formation rates were made in the superheater and convective pass regions of the boilers by use of an advanced online deposit probe. During straw firing on grate, the measured deposit formation rate was close to 38 g/m²/h. Data from straw suspension firing showed a deposit formation rate of 41 g/m²/h. The deposit formation rates during straw suspension firing and straw grate firing were on similar levels. This was observed even though the concentration of fly ash in the flue gas was significantly higher during straw suspension firing. The influence of co-combustion of wood with straw on deposit formation rate, probe heat uptake and deposit characteristics was also investigated during suspension firing conditions. Data from 35% straw suspension firing with wood showed a deposit formation rate of 33 g/m²/h for the first 12 h. The deposit formation rate increased to 41 g/m²/h with 100% straw firing. The probe heat uptake reduction up to 40 h of exposure time was 3.0, 7.3, 8.4 and 16.5 kW/m² during 35, 65, 80 and 100% straw firing, respectively.

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Scopus rating (2016): CiteScore 4.15 SJR 1.397 SNIP 1.729
Web of Science (2016): Impact factor 3.752
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.09 SJR 1.501 SNIP 1.817
Ash transformation and deposition behavior during co-firing biomass with sewage sludge

In the present work, the ash transformation and deposition behavior during wheat straw and wood waste combustion were investigated by combustion experiments in an entrained flow reactor. The influence of sewage sludge addition on ash chemistry and deposition tendency was also studied. During combustion wheat straw, fine fly ash particles smaller than 2.5 μm are mainly formed due to vaporization, nucleation and condensation of K, Cl, S and P species. Large fly ash particles consist of condensed potassium chloride crystals and molten/partial molten spherical particles rich in K-silicates and K-Ca-silicates. The deposits formed on a well-controlled sampling probe are dominated by molten particles rich in K
silicates. Over 70% of K in the fly ash is water soluble. The fine fly ash from wood waste combustion consists of mainly KCl and NaCl.

Both ash clusters and molten spherical particles are found from the ash deposits, which mainly contain K-silicates, K-Al-silicates and K-Ca-silicates. The sewage sludge addition significantly reduced the water soluble K and Na in the fly ash from wheat straw and wood waste combustion. Compared to pure wheat straw and wood waste, the ash deposition rates were increased due to sewage sludge addition. However, the ash deposition propensity decreased significantly. In addition, the content of water soluble K and Cl in the deposits reduced as a result of sewage sludge addition. The results from present work suggest co-firing of sewage sludge could alleviate deposit formation during suspension firing of risky biofuels.

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**Biomass Gasification Behavior in an Entrained Flow Reactor: Gas Product Distribution and Soot Formation**

Biomass gasification and pyrolysis were studied in a laboratory-scale atmospheric pressure entrained flow reactor. Effects of operating parameters and biomass types on the syngas composition were investigated. In general, the carbon conversion during biomass gasification was higher than 90% at the optimal conditions of 1400 °C with steam addition. The biomass carbon that was not converted to gas in the gasification process only appeared as soot particles in the syngas in all of the experiments, except for the two experiments performed at 1000 °C, where a very small amount of char was also left. In comparison to pyrolysis, lower yields of soot, H2, and CO were produced during gasification. The yield of soot could be reduced by a longer residence time, larger feeder air flow, lower oxygen concentration, higher excess air ratio, higher steam/carbon ratio, and higher reactor temperature. Changes in residence time, feeder air flow, and oxygen concentration did not show a noticeable influence on H2 and CO yields. Increasing the excess air ratio decreased both the H2 and CO yields; increasing the steam/carbon ratio increased the H2 yield but decreased the CO yield; and increasing the reactor temperature increased both the H2 and CO yields. Wood, straw, and dried lignin had similar gasification behavior, except with regard to soot formation. The soot yield was lowest during straw gasification possibly because of its high potassium content.

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Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
Catalytic Conversion of Syngas into Higher Alcohols over Carbide Catalysts

This work investigates the use of the bulk carbides Mo2C, WC, and NbC as catalysts for the conversion of syngas into higher alcohols. K2CO3/WC produces mainly CH3OH and CH4 with a low activity. NbC has a very low activity in CO hydrogenation. K2CO3/Mo2C produces mixed alcohols with a reasonable activity and selectivity. In a 94 h test the activity and the specific surface area of the K2CO3/Mo2C catalyst decreased significantly, but X-ray diffraction and transmission
electron microscopy did not indicate a strong sintering of the carbide. A likely cause for the deactivation is the formation of carbonaceous deposits on the catalyst. At the same general activity level Li, K, and Cs provide similar promotional effects for Mo2C, although K at a loading level of alkali metal/Mo = 0.164 mol/mol provides the better behavior at equal conditions. The effect of further additives on the K2CO3/Mo2C system was evaluated, but only Cu yielded an improvement.

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Scopus rating (2017): CiteScore 3.4 SJR 0.978 SNIP 1.203
Web of Science (2017): Impact factor 3.141
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Scopus rating (2016): CiteScore 3.1 SJR 0.95 SNIP 1.155
Web of Science (2016): Impact factor 2.843
Web of Science (2016): Indexed yes
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Scopus rating (2015): CiteScore 2.87 SJR 0.938 SNIP 1.145
Web of Science (2015): Impact factor 2.567
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Scopus rating (2014): CiteScore 2.85 SJR 1.009 SNIP 1.287
Web of Science (2014): Impact factor 2.587
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
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Scopus rating (2012): CiteScore 2.56 SJR 1.054 SNIP 1.32
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Web of Science (2011): Impact factor 2.237
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Danish Experiences with Deposit Probe Measurements in Grate and Pulverized Fuel Biomass Power Boilers

Several measuring campaigns with focus on deposition behavior have been conducted at full-scale power plants firing biomass in Denmark. These campaigns have been reviewed in this work. The focus is the obtained experiences on deposit formation, shedding and chemistry.

When comparing results from grate- and suspension-firing, it is found that the rates of deposit formation are comparable, while the chemical composition of the fly ashes are quite different, even for the same type of fuel. The flue gas temperature is considered to be an important parameter in the deposit behavior. Increasing the flue gas temperature leads to increased deposition rates and deposits with higher contents of Si and Ca and lower contents of K and Cl.

The shedding behavior is influenced by both probe surface temperature, flue gas temperature and deposits chemistry. The influence of temperature on the degree of sintering varies with the fuel type. Possibly, increased contents of Si and Ca leads to increases in the sintering temperature and thus altered shedding behavior.
Deposit Probe Measurements in Danish Grate and Pulverized Fuel Biomass Power Boilers

Several measuring campaigns with focus on deposition behavior have been conducted at full-scale power plants firing biomass in Denmark. These measuring campaigns have been reviewed in this work. The focus of the review is the obtained experiences on deposit formation, chemistry and shedding. Corresponding samples of fuels, ash deposits and fly ash have provided information on the transformation of inorganics in the boiler. Generally, grate fired boilers provide a fly ash containing high contents of K, Cl and S compared to the fuel ash, while suspension fired boilers fly ash has a composition nearly similar to the fuel ash. Inner most biomass deposits are always salt-rich, while thicker deposit layers also contain some Si and Ca. Deposit probe formation rate measurements have been performed in different ways on several boilers. Grate and suspension fired boilers seems to cause similar deposit formation rates. Suspension fired boilers generate more fly ash, while grate boilers form a fly ash with a higher fraction of melt formation (and thereby a higher sticking probability) at similar temperatures. For suspension fired units it is observed that wood with a lower ash content than straw gives rise to lower deposit formation rates. The flue gas temperature is an important parameter in the deposit behavior of biomass-fired boilers. Increases in the flue gas temperature of both grate and suspension fired boilers leads to increased deposition rates and deposits with higher contents of Si and Ca. This can be explained by increased deposition by inertial impaction due to higher melt fractions of ash particles (containing Si and Ca) at increased temperatures. The shedding behavior is influenced by exposure time, probe surface temperature, flue gas temperature and deposits chemistry. The influence of temperature on the degree of sintering varies with the fuel type. Possibly, increased contents of Si and Ca will lead to increases in the sintering temperature and thus to altered shedding behavior. It is recognized that the exposure time of the deposits in the flue gas influences the removability of the deposits.

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Flash pyrolysis properties of algae and lignin residue
A fast pyrolysis study on lignin and macroalgae (non-conventional biomass) and wood and straw (conventional biomass) were carried out in a pyrolysis centrifugal reactor. The product distributions and energy recoveries were measured and compared among these biomasses. The fast pyrolysis of macroalgae showed a promising result with on yield of 54 wt% dry ash free basis (daf) and 78% energy recovery in the bio-oil. The physiochemical properties of the bio-oils were characterized with respect to higher heating value, molecular mass distribution, viscosity, pH, density and elemental compositions. The lignin and macroalgae oil properties were quite different to those of the conventional oils.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, The Danish Polymer Centre, DONG Energy AS
Contributors: Trinh, N. T., Jensen, P. A., Sørensen, H. R., Dam-Johansen, K., Hvilsted, S.
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Electronic versions:
Flash Pyrolysis Properties Of Algae And Lignin Residue
Full-scale ash deposition measurements at Avedøre Power Plant unit 2 during suspension-firing of wood with and without coal ash addition.

The formation of deposits during suspension-firing of wood at Avedøre Power Plant unit 2 (AVV2) was studied by using an advanced deposit probe system. The tests were conducted both with and without coal ash addition, and at two different locations with flue gas temperatures of 1250-1300 °C and 750-800 °C respectively. The deposit formation process was studied quantitatively though the mass uptake data from the load-cell of the probe, while camera pictures were used to qualitatively verify the obtained mass uptake data and to explain the deposit buildup/shedding mechanisms. The collected deposits along with the fly ash and bottom ash from the plant were characterized extensively by SEM-EDS, ICP-OES/IC and XRD. Based on the results from the present work, the deposit formation and shedding mechanisms under different operational conditions were proposed and discussed. The influence of coal ash addition on deposit formation during wood suspension-firing at AVV2 was evaluated. It was revealed that the addition of coal fly ash could significantly influence the ash deposition/shedding behaviors and the deposit properties. The effect was evident at both measurement locations. At the location with a high flue gas temperature of 1250-1300 °C, although the addition of coal fly ash increased the differential deposit formation rate (DDF-rate) and the ash deposition propensity, the deposit removal frequency were considerably increased and the major shedding mechanism was changed from soot-blowing induced shedding to natural shedding. This implied that the deposits at high temperatures were more easily removable when coal ash was added. Besides, the amount of K2SO4 in the high-temperature deposits was considerably reduced when coal ash was added, which was probably favorable in order to minimize corrosion. At the location with a low flue gas temperature of 750-800 °C, the addition of coal fly ash reduced the ash deposition propensity and caused the formed deposits being easily removable. Moreover, the KCl and KOH/K2CO3 found in the low-temperature deposits without coal ash addition disappeared when coal ash was added, which was also favorable from a corrosion point of view.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Wu, H., Shafique Bashir, M., Jensen, P. A.
Number of pages: 95
Publication date: 2012

High-temperature entrained flow gasification of biomass
Biomass (wood and straw) gasification has been studied in a laboratory scale atmospheric pressure entrained flow reactor. Effects of reaction temperature, steam/carbon molar ratio, excess air ratio, and biomass type on the solid, liquid and gas products were investigated. The biomass was completely converted at all investigated operating conditions and the syngas contained nearly no tar but some soot at the highest applied reaction temperature of 1350°C. With a rise of reaction temperature from 1000°C to 1350°C, the yield of producer gas (defined as the sum of H2, CO, CO2 and hydrocarbons up to C3 species) increased dramatically by 72%. The H2/CO molar ratio in syngas was close to 1 at reaction temperature above 1200°C with steam addition. Higher temperature was beneficial to lower the amount of tar while the soot yield showed a peak of 56.7g/kg fuel at 1200°C. With steam addition, the producer gas yield and in particular the H2 yield increased gradually, while the CO yield decreased slowly. The molar ratio of H2/CO was equal to 1 with the largest supplied amount of steam addition (H2O/C=1). Steam addition gave an obvious reduction in the soot yield, but it was not possible to completely avoid soot. Increasing excess air ratio from 0.25 to 0.50 gave no significant change in the producer gas yield, but the yields of H2, CO, and soot decreased, the CO2 yield increased, and the molar ratio of H2/CO decreased. Moreover, wood and straw gasification provided similar product compositions. At 1350°C and with steam addition, the syngas composition is close to equilibrium as verified by calculation.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Qin, K., Lin, W., Jensen, P. A., Jensen, A. D.
Pages: 589-600
Publication date: 2012
Screening of Catalysts for Bio-oil Hydrodeoxygenation

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Mortensen, P. M., Jensen, A. D., Jensen, P. A.
Publication date: 2012
Peer-reviewed: No
Event: Abstract from 15th International Congress on Catalysis, Munich, Germany.
Electronic versions:
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Source: dtu
Source-ID: u::4033
Research output: Research › Conference abstract for conference – Annual report year: 2012

Suspension-Firing of Biomass: Part 1, Full-Scale Measurements of Ash Deposit Build-up
This paper is Part 1 in a series of two describing probe measurements of deposit build-up and removal (shedding) in a 350 MWth suspension boiler, firing straw and wood. The influence of fuel type (straw share in wood), probe exposure time, probe surface temperature (500, 550, and 600 °C), and flue gas temperature (600–1050 °C) on ash deposition rate has been investigated. Investigations of deposit formation rates were made by use of an advanced online deposit probe that allowed nearly continuous measurement of the deposited mass. Two different measures of deposition rates are used in the analysis of the data. The first is the integral deposition rate (IDF-rate) found by dividing the integral mass change over integral time intervals (of order several hours) by the time interval. The IDF-rate is similar to deposition rates based on total deposit mass uptake divided by probe exposure time reported in previous full-scale investigations, but it is a relatively crude measure that includes all deposition events in addition to actual deposition. To remove major shedding events from the determination of deposition rates a second measure, the derivative-based deposition rate (DDF-rate), was devised. This was determined by averaging the deposit mass uptake signals over short time intervals (on the order of minutes), calculating the local values of the time derivative of the mass uptake, and finally smoothing the derivatives to remove excessive noise. The DDF-rate was influenced by flue gas temperature and straw share, while changes in probe surface temperature had no significant influence. The IDF-rate, qualitatively related to the ratio between the time-integrated DDF-rate and the integration time, followed the same trends. Ash transformation was investigated by bulk ash analysis of the fuel, fly, and bottom ash during straw and/or wood suspension firing. Bulk ash analysis of fly ashes showed that the contents of volatile elements (K, Cl, S) were slightly greater than in the fuel ash, while Ca and Si remained either in the same proportion or were slightly reduced. It was also found that, with an increase in fuel ash K/Cl molar ratio, the concentration of the volatile elements, K, Cl, and, to some extent, S, increased in the fly ash. The bottom ash was dominated by Si and Ca, with almost no S and Cl, possibly as a result of the high volatility of S and Cl during combustion at higher temperatures.

General information
State: Published
Suspension-Firing of Biomass: Part 2, Boiler Measurements of Ash Deposit Shedding

This paper is the second of two papers, describing probe measurements of deposit buildup and removal (shedding), conducted in a 350 MWth suspension-fired boiler, firing straw and wood. Investigations of deposit buildup and shedding have been made by use of an advanced online deposit probe and a sootblowing probe. The influences of feedstock (i.e., straw share in wood), flue gas temperature (600−1050 °C), probe surface temperature (500 and 600 °C), and probe exposure time on deposit shedding have been quantified. Quantification of naturally occurring deposit shedding and deposit shedding during plant sootblowing was made via deposit mass uptake signals obtained from the deposit probe. The deposit shedding process was characterized by calculation of the amount of deposit removed at a shedding event (g/m²) and the frequency of the shedding events (h−1). The results showed that the shedding process is stochastic and that the amount of deposit shed varies even at constant local conditions. However, the deposit shedding rates showed an increasing trend with increase in flue gas temperatures and probe deposit mass loads. The deposit shedding rate was in most cases higher at a probe temperature of 500 °C than at a probe temperature of 600 °C. A possible reason for this is partial melting and/or sintering of the innermost deposit layer (rich in K, Cl, and S) at higher probe surface temperature. This could cause the adhesion strength of the deposit to the probe to increase at the higher probe temperature. Quantification of the necessary peak impact pressure (PIP) needed to remove the deposit was also made by use of a sootblowing probe in conjunction with the deposit probe. Results of deposit removal by artificial sootblowing showed that the deposits formed on a 500 °C probe temperature and at exposure times of <91 h can be removed with a PIP of <55 kPa. However, increase in probe exposure time and/or probe surface temperature (600 °C) significantly increases the PIP needed to remove the deposits.

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Vattenfall
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BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
Suspension-firing of wood with coal ash addition: Probe measurements of ash deposit build-up at Avedøre Power Plant (AVV2)

This report is about full-scale probe measurements of deposit build-up and removal conducted at the Avedøreværket Unit 2, a 800 MWth suspension boiler, firing wood and natural gas with the addition of coal ash. Coal ash was used as an additive to capture potassium (K) from wood-firing. Investigations of deposit formation rate were made by use of an advanced online ash deposition/shedding probe. Quantification of ash deposition and shedding was made via deposit mass uptake signals obtained from the deposit probe. The influence of coal ash, flue gas temperature, probe surface temperature and boiler load on ash deposition propensity was investigated. Results of ash deposition propensity showed increasing trend with increasing flue gas temperature. Video monitoring revealed that the deposits formed were not sticky and could be easily removed, and even at very high flue gas temperatures (> 1350 °C), deposit removal through surface melting was not identified. SEM-EDS analysis of the deposits showed significant presence of Ca, Al and Si, indicating that a significant amount of K has been captured by coal ash to form deposits rich in calcium-aluminum-silicates, and possible release of Cl to the gas phase as HCl(g). Effect of boiler operational parameters on gas emissions has also been investigated.

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Publication information
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Source: dtu
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Research output: Research › Report – Annual report year: 2012

Wood Gasification Behaviour in an Entrained Flow Reactor

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Qin, K., Lin, W., Jensen, P. A., Jensen, A. D.
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Publication date: 2012
Peer-reviewed: No
Event: Abstract from General Section Meeting of the Scandinavian-Nordic Section of the Combustion Institute, Trondheim, Norway.
Electronic versions:
scandinav_french_abstract_1_.pdf
Source: dtu
Source-ID: u::4119
Research output: Research › Conference abstract for conference – Annual report year: 2012

Catalytic synthesis of long-chained alcohols from syngas

This work has been an investigation of the catalytic conversion of syngas into mixed alcohols with Mo-based catalysts. The primary focus has been on the use of alkali promoted cobalt-molybdenum sulfide as a catalyst for the alcohol synthesis. The alcohol synthesis is a possibility for the production of gasoline additives/replacements from biomass via a gasification process. It is observed that the sulfide catalyst is able to operate both with and without a sulfur source in the syngas feed, but the presence of a sulfur source like H2S can exert a significant influence on the catalytic properties. The presence of 103 ppmv or more of H2S in the syngas feed stabilizes a large fraction of higher alcohols in the product. With 57 ppmv or less of H2S in the feed the production of higher alcohols is however gradually declining, while the methanol production increases.

The present investigations could suggest that these changes in the product distribution, which occur in sulfur-free or sulfur-poor syngas, are related to changes in the state of cobalt, which is added to the catalyst to promote chain-growth. The distribution of methanol and higher alcohols in the product after 25 hours on stream is largely independent of the cobalt content in the catalyst, although the fraction of higher alcohols initially benefits significantly from an increased
presence of cobalt. In catalysts that have operated in sulfur free syngas, cobalt is incorporated into larger, coagulated structures, and signs of crystalline Co9S8, which is considered to be inactive, can be observed in the spent catalyst. It is hypothesized that the loss of sulfur from the catalyst in the reducing atmosphere is driving the conversion of cobalt from its active form (possibly a mixed cobalt-molybdenum sulfide) into larger, more sulfur-deficient structures and into Co9S8. It must however be added that X-ray absorption spectroscopy investigations have not provided direct evidence for a Co-Mo coordination in neither the fresh nor the spent sulfide catalysts. That the catalyst requires the presence of a sulfur source in the feed to stabilize a large fraction of higher alcohols in the product introduces a dilemma, because the presence of a sulfur sauce like H2S in the gas can lead to an undesirable incorporation of sulfur species into the alcohol product. It is observed that the sulfur content in the condensed alcohol product increases linearly with the H2S level in the syngas feed from 1250 ppmv S with 46 ppmv H2S to 1905 ppmv S with 460 ppmv H2S. Without H2S in the feed sulfur species are also incorporated into the condensed reaction product, but in this case the products sulfur content decreases over time. The primary sulfur species in the alcohol product are the thiols corresponding to the formed alcohols. With the increasingly stringent regulations for sulfur in motor fuels this incorporation of sulfur into the alcohol product is an important issue for the use of the alcohol product as a fuel additive/substitute.

It has been discovered that alcohol coupling reactions, which appear to occur via aldol condensation pathways, contribute to the chain-growth over the sulfide catalyst. Such coupling reactions via aldol condensation pathways can explain the observed presence of branched alcohols (e.g., iso-butanol) in the product. This discovery arose from the observation that ethanol co-fed along with the syngas especially causes an increased production of 1-butanol. Various investigations have been carried out to clarify the effect of the feed composition on the catalytic properties of the sulfide catalyst. In a sulfur free syngas it is observed that the production of higher alcohols is optimal with an equimolar mixture of CO and H2 in the feed, while the methanol production benefits from an increasing hydrogen content in the feed. It has often been argued that the sulfides ability to operate in a sulfur containing atmosphere may enable the user to employ a less thorough and therefore less costly syngas cleaning. To evaluate, to which extent a removal of other components in the raw syngas is necessary, the influence of NH3 and H2O in the feed has also been investigated. Ammonia (741 ppmv) in the feed is observed to cause a general and largely reversible deactivation of the catalyst. Operation with elevated water levels in the syngas feed (4.7-13.4 mol%) is observed to cause a deactivation of the catalyst, and it is especially the chain-growth, which is affected. A permanent, general deactivation is observed once the water is removed from the feed – a deactivation which could be caused by an accelerated sintering in the presence of water.

Since the use of the sulfide catalyst encompasses the risk of the sulfur being incorporated into the alcohol product, carbide catalysts have been investigated as a possible nonsulfided alternative. Various catalysts based upon the bulk carbides Mo2C, WC and NbC have been synthesized and evaluated with respect to the catalytic behavior in high-pressure CO hydrogenation. NbC is largely inactive, and K2CO3/WC produces mainly methanol and methane with a low activity, while K2CO3/Mo2C produces a mixture of methanol and higher alcohols, but also significant amounts of hydrocarbons. The role of the choice of alkali cation in Mo2C promoted by an alkali salt has also been evaluated at a promoter level of Alkali/Mo = 0.164±0.001 mol/mol. At 275 °C-300 °C the behavior of catalysts promoted by Cs2CO3 and K2CO3 is qualitatively similar, although K provides a markedly better activity (31 % at 300 °C, 100 bar, 5000 h-1) and a better selectivity at identical conditions. At 275 °C an Li(CH3COO) promoted catalyst is very active and produces only hydrocarbons. If the effect of the different alkali promoters is compared at the same general activity level, corresponding to the Li-containing catalyst being operated at a lower temperature, the Li-promoted catalyst is however only slightly inferior to the K-promoted catalyst in terms of the alcohol selectivity. Finally different multiply promoted Mo2C catalysts have been evaluated in terms of the CO hydrogenation properties. Addition of Re (1 wt%) or Mn (1 or 5 wt%) to the K2CO3/Mo2C system results in a slight reduction in the catalytic activity. The addition of Cu (0.84 wt%) was on the other hand observed to improve the activity (by 33 % at 275 °C, 100 bar, 5000 h-1) and improve the selectivity of the K2CO3/Mo2C system without altering the distribution of the alcohol product. Mo2C modified with La (5 wt%) and V (3 wt%) produces mainly hydrocarbons.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Christensen, J. M., Jensen, A. D., Jensen, P. A.
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Publication information
Publisher: Technical University of Denmark, Department of Chemical and Biochemical Engineering
Original language: English
Electronic versions:
Catalytic_synthesis_of_long_chained.pdf
Source: dtu
Source-ID: u::11017
Research output: Research › Ph.D. thesis – Annual report year: 2011
A review of catalytic upgrading of bio-oil to engine fuels

As the oil reserves are depleting the need of an alternative fuel source is becoming increasingly apparent. One prospective method for producing fuels in the future is conversion of biomass into bio-oil and then upgrading the bio-oil over a catalyst, this method is the focus of this review article. Bio-oil production can be facilitated through flash pyrolysis, which has been identified as one of the most feasible routes. The bio-oil has a high oxygen content and therefore low stability over time and a low heating value. Upgrading is desirable to remove the oxygen and in this way make it resemble crude oil. Two general routes for bio-oil upgrading have been considered: hydrodeoxygenation (HDO) and zeolite cracking. HDO is a high pressure operation where hydrogen is used to exclude oxygen from the bio-oil, giving a high grade oil product equivalent to crude oil. Catalysts for the reaction are traditional hydrodesulphurization (HDS) catalysts, such as Co–MoS2/Al2O3, or metal catalysts, as for example Pd/C. However, catalyst lifetimes of much more than 200h have not been achieved with any current catalyst due to carbon deposition. Zeolite cracking is an alternative path, where zeolites, e.g. HZSM-5, are used as catalysts for the deoxygenation reaction. In these systems hydrogen is not a requirement, so operation is performed at atmospheric pressure. However, extensive carbon deposition results in very short catalyst lifetimes. Furthermore a general restriction in the hydrogen content of the bio-oil results in a low H/C ratio of the oil product as no additional hydrogen is supplied. Overall, oil from zeolite cracking is of a low grade, with heating values approximately 25% lower than that of crude oil. Of the two mentioned routes, HDO appears to have the best potential, as zeolite cracking cannot produce fuels of acceptable grade for the current infrastructure. HDO is evaluated as being a path to fuels in a grade and at a price equivalent to present fossil fuels, but several tasks still have to be addressed within this process. Catalyst development, understanding of the carbon forming mechanisms, understanding of the kinetics, elucidation of sulphur as a source of deactivation, evaluation of the requirement for high pressure, and sustainable sources for hydrogen are all areas which have to be elucidated before commercialisation of the process.

General information
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Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Haldor Topsoe AS
Contributors: Mortensen, P. M., Grunwaldt, J., Jensen, P. A., Knudsen, K., Jensen, A. D.
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BFI (2019): BFI-level 1
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BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.48 SJR 1.237 SNIP 1.257
Web of Science (2017): Impact factor 4.521
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.26 SJR 1.202 SNIP 1.336
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 4.08 SJR 1.218 SNIP 1.427
Web of Science (2015): Impact factor 4.012
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.04 SJR 1.335 SNIP 1.602
Web of Science (2014): Impact factor 3.942
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.01 SJR 1.448 SNIP 1.554
Web of Science (2013): Impact factor 3.674
ISI indexed (2013): ISI indexed yes
Biomass gasification behavior in an entrained flow reactor

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Qin, K., Lin, W., Jensen, P. A., Jensen, A. D.
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Peer-reviewed: No
Electronic versions: Technologies_1_.pdf
Co-combustion of pulverized coal and solid recovered fuel in an entrained flow reactor: General combustion and ash behavior

Co-combustion of a bituminous coal and a solid recovered fuel (SRF) was carried out in an entrained flow reactor, and the influence of additives such as NaCl, PVC, ammonium sulphate, and kaolinite on co-combustion was investigated. The co-combustion experiments were carried out with SRF shares of 7.9 wt.%, 14.8 wt.% and 25 wt.%, respectively. The effect of additives was evaluated by maintaining the share of secondary fuel (mixture of SRF and additive) at 14.8 wt.%. The experimental results showed that the fuel burnout, NO and SO2 emission in co-combustion of coal and SRF were decreased with increasing share of SRF. The majority of the additives inhibited the burnout, except for NaCl which seemed to have a promoting effect. The impact of additives on NO emission was mostly insignificant, except for ammonium sulphate which greatly reduced the NO emission. For SO2 emission, it was found that all of the additives increased the S-retention in ash. Analysis of the bulk composition of fly ash from different experiments indicated that the majority of S and Cl in the fuels were released to gas phase during combustion, whereas the K and Na in the fuels were mainly retained in ash. When co-firing coal and SRF, approximately 99 wt.% of the K and Na in fly ash was present in water insoluble form such as aluminosilicates or silicates. The addition of NaCl, PVC, and ammonium sulphate generally promoted the vaporization of Na and K, resulting in an increased formation of water soluble alkalis such as alkali chlorides or sulphates. The vaporization degree of Na and K was found to be correlated during the experiments, suggesting an interaction between the vaporization of Na and K during pulverized fuel combustion. By collecting deposits on an air-cooled probe during the experiments, it was found that the ash deposition propensity in co-combustion was decreased with increasing share of SRF. The addition of NaCl and PVC significantly increased the ash deposition propensity, whereas the addition of ammonium sulphate or kaolinite showed a slight reducing effect. The chlorine content in the deposits generally implied a low corrosion potential during co-combustion of coal and SRF, except for the experiments with NaCl or PVC addition.

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Journal: Fuel
Volume: 90
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BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 5.4 SJR 1.891 SNIP 2.127
Web of Science (2017): Impact factor 4.908
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.9 SJR 1.736 SNIP 2.207
Web of Science (2016): Impact factor 4.601
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.46 SJR 1.781 SNIP 2.123
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.14 SJR 1.634 SNIP 2.294
Web of Science (2014): Impact factor 3.52
Dust-Firing of Straw and Additives: Ash Chemistry and Deposition Behavior

In the present work, the ash chemistry and deposition behavior during straw dust-firing were studied by performing experiments in an entrained flow reactor. The effect of using spent bleaching earth (SBE) as an additive in straw combustion was also investigated by comparing with kaolinite. During dust-firing of straw, the large (>∼2.5 μm) fly ash particles generated were primarily molten or partially molten spherical particles rich in K, Si, and Ca, supplemented by Si-rich flake-shaped particles. The smaller fly ash particles (
Effects of Feed Composition and Feed Impurities in the Catalytic Conversion of Syngas to Higher Alcohols over Alkali-Promoted Cobalt–Molybdenum Sulfide

Alkali-promoted cobalt–molybdenum sulfide is a potential catalyst for the conversion of syngas into higher alcohols. This work is an investigation of how the feed composition influences the behavior of the sulfide catalyst. In a sulfur-free syngas the production of higher alcohols is observed to be optimal with an equimolar mixture of CO and H2 in the feed, while the methanol production benefits from an increasing hydrogen content in the feed. The influence of NH3 and H2O in the syngas feed has also been investigated. Ammonia (741 ppmv) in the feed is observed to cause a general and largely reversible deactivation of the catalyst. Operation with elevated water levels in the syngas feed (4.7–13.4 mol %) is observed to cause a deactivation of the catalyst, and it is especially the chain growth that is affected.
Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil

Production of bio-oil, gas and biochar from pyrolysis of biomass is considered a promising technology for combined production of bioenergy and recalcitrant carbon (C) suitable for sequestration in soil. Using a fast pyrolysis centrifuge reactor (PCR) the present study investigated the relation between fast pyrolysis of wheat straw at different reactor temperatures and the short-term degradability of biochar in soil. After 115 days incubation 3–12% of the added biochar-C had been emitted as CO2. On average, 90% of the total biochar-C loss occurred within the first 20 days of the experiment, emphasizing the importance of knowing the biochar labile fraction when evaluating a specific biochars C sequestration potential. The pyrolysis temperature influenced the outputs of biochar, bio-oil and syngas significantly, as well as the stability of the biochar produced. Contrary to slow pyrolysis a fast pyrolysis process may result in incomplete conversion of biomass due to limitations to heat transfer and kinetics. In our case chemical analysis of the biochars revealed unconverted cellulosic and hemicellulosic fractions, which in turn were found to be proportional with the short-term biochar degradation in soil. As these labile carbohydrates are rapidly mineralized, their presence lowers the biochar-C sequestration potential. By raising the pyrolysis temperature, biochar with none or low contents of these fractions can be produced, but this will be on the expense of the biochar quantity. The yield of CO2 neutral bio-oil is the other factor to optimize when adjusting the pyrolysis temperature settings to give the overall greatest climate change mitigation effect.

General information
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Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4 SJR 1.235 SNIP 1.436
Web of Science (2017): Impact factor 3.358
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.71 SJR 1.198 SNIP 1.385
Web of Science (2016): Impact factor 3.219
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.03 SJR 1.51 SNIP 1.596
Web of Science (2015): Impact factor 3.249
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.36 SJR 1.865 SNIP 1.964
Web of Science (2014): Impact factor 3.394
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 4.42 SJR 1.666 SNIP 1.811
Web of Science (2013): Impact factor 3.411
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
Katalytisk omdannelse af syntesegas til højere alkoholer: 3. Kan et karbid klare katalysen?

**General information**

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Contributors: Christensen, J. M., Jensen, P. A., Jensen, A. D.
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Leaching from waste incineration bottom ashes treated in a rotary kiln

Leaching from municipal solid waste incineration bottom ash treated in a rotary kiln was quantified using a combination of lab-scale leaching experiments and geochemical modelling. Thermal treatment in the rotary kiln had no significant effect on the leaching of Al, Ba, Ca, Mg, Si, Sr, Zn, sulfate and inorganic carbon. Leaching of these elements from the treated residues remained unchanged and was, in general, controlled by solubility of the same minerals as in the untreated residues. Leaching of Cd, Co, Ni, Ti, Be, Bi, and Sn from both untreated and treated residues was found to be close to or below their detection limits; no effects of the thermal treatment on leachability of these metals were observed. The leaching of Cl, dissolved organic carbon (DOC), Cu and Pb decreased by at least one order of magnitude after the thermal treatment. This could be explained by evaporation (Cl) and by a better burnout of organic matter which then limited metal–DOC complexation and mobility. At the same time, leaching of Mo and Cr appeared to increase by a factor of 4 and more than two orders of magnitude, respectively. The large changes in Cr leaching may be explained by decreases in Al reduction capacity after the thermal treatment. Overall, rotary kiln thermal treatment of bottom ashes can be recommended to reduce the leaching of Cu, Pb, Cl and DOC; however, increased leaching of Cr and Mo should be expected.

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Modeling char conversion under suspension fired conditions in O2/N2 and O2/CO2 atmospheres

The aim of this investigation has been to model combustion under suspension fired conditions in O2/N2 and O2/CO2 mixtures. Experiments used for model validation have been carried out in an electrically heated Entrained Flow Reactor (EFR) at temperatures between 1173 K and 1673 K with inlet O2 concentrations between 5 and 28 vol.%. The COal COmbustion MOdel, COCOMO, includes the three char morphologies: cenospheric char, network char and dense char
each divided between six discrete particle sizes. Both combustion and gasification with CO2 are accounted for and reaction rates include thermal char deactivation, which was found to be important for combustion at high reactor temperatures and high O2 concentrations. COCOMO show in general good agreement with experimental char conversion profiles at conditions covering zone I–III. From the experimental profiles no effect of CO2 gasification on char conversion has been found. COCOMO does however suggest that CO2 gasification in oxy-fuel combustion at low O2 concentrations can account for as much as 70% of the overall char consumption rate during combustion in zone III.

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Oxy-Fuel Combustion of Coal

This Ph.D. thesis describes an experimental and modeling investigation of the thermal conversion of coal and an experimental investigation of the emission of NO from char combustion in O2/N2 and O2/CO2 atmospheres. The motivation for the work has been the prospective use of the technology “Oxy-Fuel Combustion” as a mean of CO2 abatement in large scale energy conversion.

Entrained Flow Reactor (EFR) experiments have been conducted in O2/N2 and O2/CO2 mixtures in the temperature interval 1173 K – 1673 K using inlet O2 concentrations between 5 – 28 vol. %. Bituminous coal has been used as fuel in all the experiments. Devolatilization experiments showed that the volatile weight loss was not affected by the change from N2 to CO2. Analysis by Scanning Electron Microscopy (SEM) and Brunauer-Emmett-Teller (BET) surface area of sampled char did not reveal differences between the two atmospheres either. Char conversion profiles, obtained from sampled char, did not show differences in conversion rate between O2/N2 and O2/CO2 atmospheres across the span of O2 concentrations in the interval of reactor temperatures 1173 K – 1373 K. At the reactor temperatures 1573 K and 1673 K and an inlet O2 concentration of 5 vol. % it was found that char conversion rate was lowered in O2/CO2 compared to O2/N2. This is caused by the lower diffusion coefficient of O2 in CO2 (~ 22 %) that limits the reaction rate in zone III compared to combustion in O2/N2. Using char sampled in the EFR experiments ThermoGravimetric Analyzer (TGA) reactivity profiles for combustion and CO2 gasification has been found at 5 vol. % O2 or 80 vol. % CO2 and a heating rate of 5 K/min to a peak temperature of 1273 K or 1373 K. These experiments did not reveal differences in reactivity between EFR-chars formed in O2/N2 and O2/CO2. Reactivity profiles for TGA combustion of partly converted EFR-char, sampled at 1173 K and 28 vol. % O2, showed the presence of two phases of distinctly different reactivity. The least reactive of these phases are believed to be formed from interactions between mineral matter and secondary volatiles evolved during the fierce heating upon particle ignition at the high O2 concentrations. From TGA reactivity profiles of EFR-chars devolatilized at 1173 K – 1673 K intrinsic kinetic parameters has been found for combustion. The rate constant includes both a deactivation and an activation term.

Intrinsic kinetics was also found for CO2 gasification though using only EFR-char devolatilized at 1273 K, 1473 K and 1573 K due to a lack of samples. Interestingly, it was found that devolatilization temperature did not affect the gasification rate constant. A detailed COal Combustion MOdel (COCOMO) encompassing among others the three char morphologies; cenospheres, network- and dense chars, each distributed between six discrete particle sizes has been developed. The model showed a reasonable ability to predict the conversion profiles obtained in the EFR experiments using the intrinsic TGA kinetics for combustion and gasification. At the reactor temperature 1173 K COCOMO over predicts char conversion at O2 inlet concentrations of 5 and 28 vol. %. At the reactor temperature 1273 K COCOMO also over predicts char
conversion at an inlet O2 concentration of 5 vol. %. Over prediction at the high O2 concentration is caused by the formation of char with a low reactivity as discussed above. Simulation under these conditions show that particle excess temperatures of 500 – 600 K is reached upon ignition at heating rates as high as 20000 K/s, which can indeed cause a significant release of secondary volatiles. At the low O2 concentration deviation between model and experiments is caused by an experimental delay in ignition that is not captured by the model. Though this causes a deviation in total conversion COCOMO still predicts conversion rates accurately after ignition. A laboratory scale Fixed Bed Reactor (FBR), operated isothermally at 1073 K, has been used for combustion of millimeter-sized lignite- and bituminous char particles in 5 – 80 vol. % O2 in N2 or CO2 atmospheres. Particle temperatures have been recorded by a Charged Coupled Device (CCD) camera and experiments have been carried out with single and multiple particles of different sizes. NO emission from lignite char were not affected by the change of N2 with CO2. Emissions from bituminous char were lower in O2/CO2. Emissions for both char types decreased as the O2 concentration or the particle size increased. An intermediate particle size was found where emissions peaked for the bituminous char. The CCD camera measured in situ temperatures accurately during experiments and the ability of film recording proved a valuable tool for data interpretation. The results suggest that transport phenomena and kinetics alone can not account for changes in NO emissions between O2/N2 and O2/CO2. The effect of mineral catalysis and the presence of other N-containing species, such as HCN and NH3, may also play a role.

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OxyFuel combustion of Coal and Biomass
The power and heat producing sector is facing a continuously increasing demand to reduce its emissions of CO2. Oxyfuel combustion combined with CO2 storage is suggested as one of the possible, promising technologies which will enable the continuous use of the existing fleet of suspension-fired power plants burning coal or other fuels during the period of transition to renewable energy sources. The oxyfuel combustion process introduces several changes to the power plant configuration. Most important, the main part of the flue gas is recirculated to the boiler and mixed with pure oxygen. The oxidant thus contains little or no nitrogen and a near-pure CO2 stream can be produced by cooling the flue gas to remove water. The change to the oxidant composition compared to combustion in air will induce significant changes to the combustion process. This Ph.D. thesis presents experimental investigations on the combustion of coal, biomass (straw), and blends of coal and straw in air and O2/CO2 mixtures. The experiments have been performed in semi-technical scale in a once-through 30 kWth swirl-stabilized flame. The work has focused on improving the fundamental knowledge on oxyfuel combustion of coal and straw at conditions relevant to suspension-fired boilers by clarifying the effect of the change in combustion atmosphere on fuel burnout, flame temperatures, emissions of polluting species (NO, SO2, and CO), fly ash quality, and deposit formation. This work is one of the first to investigate the important aspects of ash and deposit formation during co-firing of coal and biomass and combustion of pure biomass in oxyfuel atmospheres in semi-technical scale. The presented work has lead to the identification of reference operating conditions which enables a direct comparison of combustion in air and oxyfuel atmospheres. Apart from slightly improved burnout and reduced emissions of NO during oxyfuel combustion these operating conditions yield similar combustion characteristics in both environments. Co-firing coal and biomass or combustion of pure biomass in an oxyfuel power plant could yield a significant, additional CO2 reduction, or even lead to below-zero emissions of CO2 from power production. This work has shown that no significant changes occur to the fundamental combustion characteristics for straw when burned in the O2/CO2 atmosphere. Additionally, the combustion of a coal/straw blend with a straw share of 50 wt% has added valuable understanding to the trends in ash and deposits chemistry for coal/straw co-firing. Recirculation of untreated flue gas in oxyfuel plants will increase the in-boiler levels of NO and SO2 significantly. Experiments with simulated recirculation of NO and SO2 have provided insight into the mechanisms of the significant reduction in NO emission rates from the boiler and the increased uptake of sulphur in fly ash and deposits which were observed. The single-largest penalty to the electrical efficiency and operating expenses of an oxyfuel power plant is the production of near-pure oxygen by cryogenic distillation. This thesis presents a possible strategy for reducing the oxygen demand and hence the penalty to the process. The strategy exploits the fact that the oxygen excess level during oxyfuel combustion is not directly linked to the flow of oxidant but can be adjusted independently. By increasing the concentration of oxygen in the oxidant, i.e. by reducing the flue gas recirculation ratio, it is possible to achieve similar burnout at lower oxygen excess levels. Further work on implications of this strategy are necessary in order to fully clarify its potential for improving the process economics of oxyfuel combustion. Generally, no characteristics of the oxyfuel combustion process have been identified in this work
which would be detrimental to its implementation as a carbon capture technology in full-scale power plants.

Probe Measurements of Ash Deposit Formation Rate and Shedding in a Biomass Suspension-Fired boiler
The aim of this study was to investigate ash deposit formation rate, heat uptake reduction and deposit removal by using advanced online ash deposition and sootblowing probes in a 350 MWth suspension-fired boiler, utilizing wood and straw pellets as fuel. The influence of fuel type (straw share in wood), probe exposure time, probe surface temperature (500, 550 and 600 °C) and flue gas temperature (600 - 1050 °C) on ash deposit formation rate, heat uptake by the probe, the fly ash and deposit characteristics, and deposit removal have been investigated. The results indicated that increase in flue gas temperature increased the ash deposit formation rate. It was also found that probe heat uptake reduction was not strongly sensitive to the deposit mass load on the probe. This indicated that the heat transfer from the flue gas to the probe was dominated by the rear side, where little material was accumulated on the probe if the deposit mass load was very high on the flue gas facing side of the probe. Results of deposit removal by using sootblowing probe indicated that probe exposure time and surface temperature significantly influence the Peak Impact Pressure (PIP) needed to remove the deposits. The video recordings of all deposit probe experiments revealed that deposit shedding was primarily through debonding from the surface of the tubes in the superheater region. Chemical analysis of fly ashes indicated that during suspension-firing of straw and wood, the fly ashes were rich in Si, K, Ca and Cl, but the relative percentage of volatile elements (K, Cl and S) was much less compared to grate-firing conditions. The chemical analysis of the deposits showed that the inner most layer was dominated by contents of K, Cl and S compared to the upper layers rich in K, Si and Ca.

Production of methanol/DME from biomass: EFP06
In this project the production of DME/methanol from biomass has been investigated. Production of DME/methanol from biomass requires the use of a gasifier to transform the solid fuel to a synthesis gas (syngas) - this syngas can then be catalytically converted to DME/methanol. Two different gasifier types have been investigated in this project: • The Two-Stage Gasifier (Viking Gasifier), designed to produce a very clean gas to be used in a gas engine, has been connected to a lab-scale methanol plant, to prove that the gas from the gasifier could be used for methanol production with a minimum of gas cleaning. This was proved by experiments. Thermodynamic computer models of DME and methanol plants based on using the Two-Stage Gasification concept were created to show the potential of such plants. The models showed that the potential biomass to DME/methanol + net electricity energy efficiency was 51-58% (LHV). By using waste heat from the plants for district heating, the total energy efficiencies could reach 87-88% (LHV). • A lab-scale electrically heated entrained flow gasifier has been used to gasify wood and straw. Entrained flow gasifiers are today the preferred gasifier type for commercial coal gasification, but little information exists on using these types of gasifiers for biomass gasification. The experiments performed provided quantitative data on product and gas composition as a function of operation conditions. Biomass can be gasified with less oxygen consumption compared to coal. The organic fraction of the biomass that is not converted to gas appears as soot. Thermodynamic computer models of DME and methanol plants based on using entrained flow gasification were created to show the potential of such plants. These models showed that the
potential torrefied biomass to DME/methanol + net electricity energy efficiency was 65-71% (LHV). Different routes to produce liquid transport fuels from biomass are possible. They include production of RME (rapeseed oil methyl ester), ethanol from fermentation or gasification based synthesis of DME, methanol, Fisher Tropsch fuels etc. A comparison of these different methods to provide biomass based transport fuels has shown that the gasification based route is an attractive and efficient technology.

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Organisations: Biomass Gasification, Biosystems Division, Rise National Laboratory for Sustainable Energy, Thermal Energy, Department of Mechanical Engineering, CHEC Research Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark
Contributors: Ahrenfeldt, J., Henriksen, U. B., Münster-Swendsen, J., Fink, A., Clausen, L. R., Christensen, J. M., Qin, K., Lin, W., Jensen, P. A., Jensen, A. D.
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PSO 7171 - Oxyfuel Combustion for below zero CO2 emissions
The reduction of CO2 emissions is of highest concern in relation to limiting the anthropogenic impacts on the environment. Primary focus has gathered on the large point sources of CO2 emissions constituted by large heat and power stations and other heavy, energy-consuming industry. Solutions are sought which will enable a significant reduction of the anthropogenic CO2 emissions during the transformation period from the use of fossil fuels to renewable sources of energy. Carbon capture and storage (CCS) has the potential to significantly reduce CO2 emissions from power stations while allowing for the continuous utilisation of the existing energy producing system in the transformation period. Oxyfuel combustion is one of the possible CCS technologies which show promising perspectives for implementation in industrial scale within a relatively short period of time. Oxyfuel combustion deviates from conventional combustion in air by using a mixture of pure oxygen and recirculated flue gas as the combustion medium thereby creating a flue gas highly concentrated in CO2 making the capture process economically more feasible compared to technologies with capture from more dilute CO2 streams. This project has investigated a number of the fundamental and practical issues of the oxyfuel combustion process by experimental, theoretical, and modelling investigations in order to improve the knowledge of the technology. The subjects investigated cover: general combustion characteristics of coal and biomass (straw) and mixtures thereof, formation and emission of pollutants, ash characteristics, flue gas cleaning for SO2 by wet scrubbing with limestone and for NOx by selective catalytic reduction (SCR), corrosion of boiler heat transfer surfaces, operation and control of large suspension-fired boilers, and the perspectives for the implementation of oxyfuel combustion as a CO2 sequestration solution in the Danish power production system. Regarding the fundamental combustion characteristics (combustion, emissions, and ash), the project has not identified any disqualifying characteristics. On the contrary, oxyfuel has the potential to improve fuel burnout and significantly reduce NOx emissions compared to conventional combustion in air. However, the significantly increased levels of CO2, H2O, CO (and SO2) within the boiler will have a negative effect on the risk of corrosion through a number of mechanisms such as carbureisation (CO2 and H2O), water wall corrosion due to reducing conditions (CO), and both high- and low-temperature sulphur-induced corrosion (SO2/SO3). Both the wet flue gas desulphurisation and the selective catalytic reduction process for NOx removal have shown satisfying performance in oxyfuel atmospheres. At the same time, process calculations have shown that it is possible to retrofit an existing boiler to oxyfuel combustion. Different configurations; cold and hot recirculation of flue gas; are possible each with differences in the associated uncertainty, necessary level of process re-design, and reductions in the plant efficiency. It was generally seen that the configuration with the highest level of re-design, i.e. hot recirculation of flue gas, provided the possibility of the highest electrical efficiency but also the largest number of technical challenges. Generally, it has been concluded that it would be beneficial to mainly apply the oxyfuel technology to new-build plants rather than as a retrofit solution. In that respect, it is unlikely that oxyfuel power plants are commissioned in Denmark before 2020. However, in order to meet the very strict demands for the reduction of CO2 emissions within EU by 2050 application of oxyfuel combustion capture at power stations burning CO2 neutral fuels (biomass) could be an advantageous solution due to the associated, negative CO2 emissions.

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Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Materials and Surface Engineering, Department of Mechanical Engineering, DONG Energy AS
Co-combustion of refuse derived fuels (RDF) with coal in pulverized coal-fired power plants can potentially increase the electrical efficiency of utilizing RDF and reduce the formation of some harmful pollutants such as dioxins. The objective of this project was to provide a general assessment of the technical issues related to co-combustion of coal and RDF, and to improve the fundamental understandings of this subject. The project was carried out in collaboration between the CHEC Research Centre at DTU Chemical Engineering and DONG Energy Power A/S, and was financially supported by Energinet.dk. The project work mainly involved conducting pilot-scale experiments in the CHEC entrained flow reactor, carrying out full-scale aerosol measurements at the Esbjergværket (ESV), doing global equilibrium calculations, and performing thermogravimetric experiments. Through performing co-combustion experiments in the CHEC entrained flow reactor, the burnout, NO and SO2 emissions, the transformation of ash forming species, the formation of deposits, and the partitioning of trace elements during co-combustion of coal and solid recovered fuel (SRF) were studied systematically. The effect of different coal properties, SRF properties, and mass share of SRF on co-combustion was investigated.

Besides, global equilibrium calculations were conducted to interpret the results of the entrained flow experiments. The formation of fine particles during co-combustion of coal and SRF was also investigated, through performing full-scale aerosol measurements at the Esbjergværket (ESV). The influence of co-combustion on the concentration and composition of the fine particles was evaluated, and the impact on the dust emissions was discussed. In addition, a fundamental study on the interactions of coal and different waste materials during pyrolysis was conducted through thermogravimetric experiments. In general, the results obtained from this project have significantly improved the understandings of fuel conversion, ash transformation, ash deposition, and pollutant formation during co-combustion of coal and refuse derived fuels. These results have also provided essential knowledge regarding the fuel selection and process optimization of co-firing refuse derived fuels and coal under suspension-firing conditions.
Quantification of Ash Deposit Build-up and Removal in a Straw and Wood Suspension-Fired Boiler

The aim of this study was to investigate ash deposit formation rate, heat uptake reduction and deposit removal by using advanced online ash deposition and sootblowing probes in a 350 MWth suspension-fired boiler, utilizing wood and straw pellets as fuel. The influence of fuel type (straw share in wood), probe exposure time, probe surface temperature (500, 550 and 600 oC) and flue gas temperature (600 -1050 oC) on ash deposit formation rate, heat uptake by the probe, the fly ash and deposit characteristics, and deposit removal have been investigated. A systematic mathematical procedure was used to determine derivative deposit formation (DDF) rate. The overall derivative deposit formation (DDF) rates were measured to be between 0 to 3200 g/m²h. Large differences in the DDF rates are observed without the causes presently known. However, the results indicated that an increase in flue gas temperature increases the ash deposit formation rate. It was also found that probe heat uptake reduction was not strongly sensitive to the deposit mass load on the probe. This indicated that the heat transfer from the flue gas to the probe was dominated by the rear side, where little ash material was accumulated while the deposit mass load was very high on the flue gas facing side of the probe. Results of deposit removal by using sootblowing probe indicated that probe exposure time and surface temperature significantly influence the Peak Impact Pressure (PIP) needed to remove the deposits. The video recordings of all deposit probe experiments revealed that deposit shedding was primarily through debonding from the surface of the tubes in the superheater region. Chemical analysis of fly ashes indicated that during suspension-firing of straw and wood, the fly ashes were rich in Si, K, Ca and Cl, but the relative percentage of volatile elements (K, Cl and S) was much less compared to grate-firing conditions. The chemical analysis of the deposits showed that the inner most layers was dominated by contents of K, Cl and S compared to the upper layers rich in K and Si.

REBECa WP IV - Formation and transformation of particles and other pollutants from engines using biofuel: WP IV final report (DTU project no. 50502)

This project expands present knowledge regarding diesel engine emissions and diesel particulate filter (DPF) performance and regeneration during biodiesel usage. This is done through a literature survey, a pilot-scale experimental study of DPF performance and thermo gravimetric studies of PM/catalyst/ash interactions. A pilot-scale experimental study of DPF performance and NO2 influence indicated a lower engine out particulate concentration while using Rapeseed methyl ester (RME, 26 mg/m3) compared to ultra low sulphur diesel (ULSD, 58 mg/m3). Filter regeneration with a 50 % diluted exhaust also showed an improved performance with RME (regeneration at 475 oC and 120 mbar filter pressure loss) compared to ULSD (500 oC and 125 mbar filter pressure loss). The improved filter performance was most likely due to the lower particulate concentration when using RME (lower deposition flux to overcome), because no significant differences in particulate reactivity or engine out NOx concentration were seen. The introduction of 400 ppm NO2 to the RME exhaust (normal NOx concentration ~ 250 ppm (can be oxidized to NO2 by an oxidation catalyst)) caused an improved filter regeneration performance (regeneration at 435 oC and 80 mbar filter pressure loss), which illustrates the importance of NO2 for particle oxidation and thereby the importance NO to NO2 conversion either in a separate oxidation catalyst or as part of the DPF’s catalytic performance. Thermo gravimetric (TG) studies of PM/catalyst/ash interactions in N2 with 10 %
O2 showed that diesel PM conversion (5:1 wt. ratio with commercial catalyst) benefits from the presence of biodiesel salts such as Na2CO3, K2CO3 or K3PO4 – TG peak conversion temperature decreased from 526 ± 19°C to ~ 400-420 °C, with a limited dependence on salt concentration. Other lube oil derived salts (CaSO4 and Ca(H2PO4) or combinations of lube oil and fuel (K2SO4) can have a detrimental effect on catalytic PM conversion. However, utilization of high biodiesel fractions over a prolonged period of time will likely be necessary before any of these effects can be seen, because of the stringent fuel specifications (EN 14214: ≤ 5 mg Na + K/kg; ≤ 5 mg Ca + Mg/kg; ≤ 4 mg P/kg).

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Research output: Research - peer-review ; Report – Annual report year: 2011

**Release and Transformation of Inorganic Elements in Combustion of a High-Phosphorus Fuel**

The release and transformation of inorganic elements during grate-firing of bran was studied via experiments in a laboratory-scale reactor, analysis of fly ash from a grate-fired plant, and equilibrium modeling. It was found that K, P, S, and to a lesser extent Cl and Na were released to the gas phase during bran combustion. Laboratory-scale experiments showed that S was almost fully vaporized during pyrolysis below 700 °C. Sixty to seventy percent of the K and P in bran was released during combustion, in the temperature range 900–1100 °C. The release of K and P was presumably attributed to the vaporization of KPO3 generated from thermal decomposition of inositol phosphates, which were considered to be a major source of P and K in bran. The influence of additives such as CaCO3, Ca(OH)2, and kaolinite on the release was also investigated. Ca-based additives generally increased the molar ratio of the released K/P, whereas kaolinite showed an opposite effect. Thermodynamic modeling indicated that the fly ash chemistry was sensitive to the molar ratio of the released K/P. When the molar ratio of the released K/P was below 1, KPO3 and P4O10(g) were the main stable K and P species at temperatures higher than 500 °C. Below 500 °C, the KPO3 and P4O10 (g) may be converted to H3PO4(l), which may cause severe deposit build-up in the economizers of a grate-fired boiler. By increasing the molar ratio of the released K/P to above 2, the equilibrium distribution of the K and P species was significantly changed and the formation of H3PO4(l) was not predicted by thermodynamic modeling.

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Alternative fuel combustion in cement rotary kilns

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Ash behavior in the combustion of phosphorus rich biofuels - literature survey and experimental studies
Utilization of biofuels such as grain, bran and rapeseed meal in energy production is considered to have ecological and economical benefits. These seed-originated biofuels usually contain significantly higher phosphorus contents than other biofuels, which may induce some ash related operation problems. In this report, the behaviors of inorganic species during the combustion of phosphorus rich biofuels are studied through literature review and experiments. It is found that the majority of P, Mg and K in these biofuels would be present as phytic acid/phytate or other inositol phosphate. During the combustion of phosphorus rich biofuels, the K, P, and S are the main inorganic species released to the gas phase. The release of K and P occurs in a temperature range of 900-1100 °C, and the primarily reason is attributed to the vaporization of phosphate compounds. The addition of Kaolin and Ca-based additives shows some retention effects on the K or P release. By performing thermodynamic calculations, the interactions among the released K, P, and S in the flue gas are investigated, showing that the ash chemistry would be significantly affected by the molar ratio of the released K/P. The results from the thermodynamic calculations are supported by some experimental findings, and are used to explain some practical problems observed in the combustion of bran in a grate-fired power plant. Other operational problems related with the combustion of phosphorus rich biofuels are also discussed and the possible countermeasures are suggested.

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Ash Deposit Formation and Removal in a Straw and Wood Suspension-Fired Boiler
Utilization of biomass on large suspension-fired boilers is a potentially efficient method to reduce net CO2 emissions and reduce the consumption of fossil fuels. However, ash deposit formation on heat transfer surfaces may cause operational problems and in severe cases lead to boiler stop and manual cleaning. Most studies on ash deposition and removal has been done on biomass grate boilers, while only limited data is available from biomass suspension-firing. The aim of this study was to investigate deposit mass uptake, heat uptake reduction, deposit characteristics, and deposit removal by using an advanced online deposit probe in a full scale suspension-fired boiler using wood and straw pellets as fuel (Amageværket Unit 2, AMV2). The 250 MWth boiler has maximum capacity of 60t/h biomass, owned by Vattenfall, and located in Copenhagen, Denmark. The maximum operation period of boiler was limited to two weeks when 100% straw was fired due to ash deposition in the superheater region that has tube spacing specified for coal-firing (113mm). A series of 3-5 days deposit probe experiments were conducted utilizing 35 to 100% straw with wood on mass basis. The applied deposit probe was water and air cooled, and it was possible to register deposit mass uptake, heat uptake, and flue gas temperature. The surface temperature of the probe was kept at 500 °C, and in some of the experiments, a CCD camera registered the deposit formation and removal process on the probe. The probe was placed in the superheater region (1st draught, flue gas temperature, 820-865 °C) and in the tube bank region (2nd draught, flue gas temperature, 580-605 °C). The percentage of ash in the applied straw and wood was 5.9 % and 3.3 %, while the K contents were 0.81% and 0.09% respectively. During 35% straw share, the initial two hours deposit mass uptake rate was 52.8 (g/m²/h), while it was 353.8 (g/m²/h) during 100% straw-firing. All tests in the superheater region for all applied straw shares indicated that with increase in straw share, final deposit mass uptake increased. The comparison of current and previous full scale experimental studies conducted by CHEC indicated that there was not a big difference regarding final deposit mass uptake during straw suspension-firing and combustion on grate. The shedding (deposit removal) events were investigated.
when the nearby plant sootblower was shutdown. It was identified that the mass uptake signal increased linearly and then suddenly dropped when a complete layer of deposits was removed. The shedding events were confirmed through imaging data collected through a CCD camera and a complete layer of deposits removed can be clearly identified (shedding through debonding). The shedding investigation was also made when the nearby plant sootblower (4m below) was working. It was identified that the mass uptake signal remained stable and the deposits in small pieces were continuously removed during 35% and 65% straw-firing. Previous findings of Vattenfall indicated that a mixture of 50% straw with wood gave up to more than one month of continuous boiler operation, because plant sootblowers made the boiler operation stable. During 80% and 100% straw-firing, deposits were removed in small pieces but overall deposit weight uptake signal increased. The probe heat uptake reduction, in the superheater region, was reasonably similar for all applied straw shares. Even with a significant deposit build up on the windward probe direction, heat uptake remained approximately constant. This indicated that the heat transfer from the flue gas to the probe was dominated along the rear side, where little material was accumulated. Elemental analysis of the fuel ash, fly ash and deposit samples was made using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) to determine elemental percentage of Al, Ca, Fe, K, Mg, Na, P, Si, S and Cl. Elemental composition of fly ash samples during straw suspension-firing indicated significant amounts of Si and Ca, compared to grate-firing fly ashes that has a higher content of K and Cl. Elemental analysis of the probe front side deposits indicated that the amount of K and Cl increased by increasing straw share, while Ca contents decreased. It was found that increased deposit surface temperature (> 550 °C) caused reduction of the Cl contents in the front layer of deposits. Based on the current findings, recommendations for the optimal operation strategy of straw and wood suspension-fired boilers with respect to minimization of deposit related problems could be provided.
Catalytic conversion of synthesis gas into higher alcohols

Characterization and Quantification of Deposits Buildup and Removal in Biomass Suspension-Fired Boilers

Utilization of biomass as wood or straw in large suspension-fired boilers is an efficient method to reduce the use of fossil fuels consumption and to reduce the net CO2 formation. However, the presence of chlorine and alkali metals in biomass (straw) generate ash with a low melting point and induce large problems of ash deposit formation on the superheater tubes. Full scale studies on biomass ash deposition and removal had been done on biomass grate boilers, while only limited data is available from biomass suspension-firing. The aim of this study was to investigate deposit mass uptake, heat uptake reduction, fly ash and deposit characteristics, and deposit removal by using an advanced online deposit probe in a suspension-fired boiler using wood and straw pellets as fuel. The influence of fuel type and probe exposure time on the ash deposition rate, the heat uptake, the fly ash and deposit characteristics, and deposit removal have been investigated. The final deposit mass signal after a residence time of 3 to 5 days region was 1041, 1475, 1520 and 1670 g/m² for 35, 65, 80 and 100% straw share respectively in the superheater region (flue gas temperature, 800-900 °C), while the mass uptake was very small in the tube bank region (flue gas temperature, 550-605 °C) during pure wood-firing. It was found that during suspension-firing of pure straw at low boiler load, the overall weight uptake is comparable with grate-firing, even though the amount of fly ash generated was significantly higher during suspension-firing. Deposit removal through debonding was the main mechanism of deposit shedding when no plant sootblower was in operation. Elemental analysis of fly ashes and deposit samples was made in order to determine concentrations of the major elements Al, Ca, Fe, K, Mg, Na, P, Si, S and Cl. It was identified that the straw suspension-firing fly ashes contain high contents of Si and Ca, while grate-firing fly ashes contain higher contents of volatile elements K, Cl and S.

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Coal devolatilization and char conversion under suspension fired conditions in O2/N2 and O2/CO2 atmospheres

The aim of the present investigation is to examine differences between O2/N2 and O2/CO2 atmospheres during devolatilization and char conversion of a bituminous coal at conditions covering temperatures between 1173 K and 1673 K and inlet oxygen concentrations between 5 and 28 vol.%. The experiments have been carried out in an electrically heated entrained flow reactor that is designed to simulate the conditions in a suspension fired boiler. Coal devolatilized in N2 and
CO2 atmospheres provided similar results regarding char morphology, char N2-BET surface area and volatile yield. This strongly indicates that a shift from air to oxy-fuel combustion does not influence the devolutilization process significantly. Char combustion experiments yielded similar char conversion profiles when N2 was replaced with CO2 under conditions where combustion was primarily controlled by chemical kinetics. When char was burned at 1573 K and 1673 K a faster conversion was found in N2 suggesting that the lower molecular diffusion coefficient of O2 in CO2 lowers the char conversion rate when external mass transfer influences combustion. The reaction of char with CO2 was not observed to have an influence on char conversion rates at the applied experimental conditions.

**General information**

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Web of Science (2016): Impact factor 4.601  
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Scopus rating (2015): CiteScore 4.46 SJR 1.781 SNIP 2.123  
Web of Science (2015): Indexed yes  
BFI (2014): BFI-level 2  
Scopus rating (2014): CiteScore 4.14 SJR 1.634 SNIP 2.294  
Web of Science (2014): Impact factor 3.52  
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BFI (2013): BFI-level 2  
Scopus rating (2013): CiteScore 4.31 SJR 1.762 SNIP 2.544  
ISI indexed (2013): ISI indexed yes  
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Co-combustion of solid recovered fuel with coal in an entrained flow reactor and the effect of additives: The 35th International Technical Conference on Clean Coal & Fuel Systems

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Source-ID: 271965
Research output: Research - peer-review › Article in proceedings – Annual report year: 2010

**Coupling of Alcohols over Alkali-Promoted Cobalt-Molybdenum Sulfide**
Double or nothing: Higher alcohols are produced by the hydrogenation of CO with a K-promoted Co-MoS2/C catalyst. Ethanol, which is passed over the sulfide catalyst along with CO and H2, is mainly converted into 1-butanol, which indicates that alcohol condensation contributes to the build-up of higher alcohols over the sulfide catalyst. In a nitrogen atmosphere, ethanol is also in part converted into 1-butanol, although ethyl acetate is the major product.

**General information**
Effect and Modeling of Glucose Inhibition and In Situ Glucose Removal During Enzymatic Hydrolysis of Pretreated Wheat Straw

The enzymatic hydrolysis of lignocellulosic biomass is known to be product-inhibited by glucose. In this study, the effects on cellulolytic glucose yields of glucose inhibition and in situ glucose removal were examined and modeled during extended treatment of heat-pretreated wheat straw with the cellulolytic enzyme system, Cellic (R) 1.5 L, from Trichoderma reesei, supplemented with a beta-glucosidase, Novozym (R) 188, from Aspergillus niger. Addition of glucose (0-40 g/L) significantly decreased the enzyme-catalyzed glucose formation rates and final glucose yields, in a dose-dependent manner, during 96 h of reaction. When glucose was removed by dialysis during the enzymatic hydrolysis, the cellulose conversion rates and glucose yields increased. In fact, with dialytic in situ glucose removal, the rate of enzyme-catalyzed glucose release during 48-72 h of reaction recovered from 20-40% to become approximate to 70% of the rate recorded during 6-24 h of reaction. Although Michaelis-Menten kinetics do not suffice to model the kinetics of the complex multi-enzymatic degradation of cellulose, the data for the glucose inhibition were surprisingly well described by simple Michaelis-Menten inhibition models without great significance of the inhibition mechanism. Moreover, the experimental in situ removal of glucose could be simulated by a Michaelis-Menten inhibition model. The data provide an important base for design of novel reactors and operating regimes which include continuous product removal during enzymatic hydrolysis of lignocellulose.

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Web of Science (2017): Impact factor 1.797
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
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Web of Science (2016): Impact factor 1.751
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.67 SJR 0.575 SNIP 0.736
Web of Science (2015): Impact factor 1.606
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 1.92 SJR 0.644 SNIP 0.94
Web of Science (2014): Impact factor 1.735
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Scopus rating (2013): CiteScore 2.18 SJR 0.747 SNIP 1.027
Web of Science (2013): Impact factor 1.687
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Improved electrical efficiency and bottom ash quality on waste combustion plants

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Contributors: Jensen, P. A., Dam-Johansen, K., Frandsen, F., Bejer, M., Kløft, H., Nesterov, I., Hyks, J., Astrup, T., Lundtorp, K., Madsen, O. H.
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**Oxy-fuel combustion of solid fuels**

Oxy-fuel combustion is suggested as one of the possible, promising technologies for capturing CO2 from power plants. The concept of oxy-fuel combustion is removal of nitrogen from the oxidizer to carry out the combustion process in oxygen and, in most concepts, recycled flue gas to lower the flame temperature. The flue gas produced thus consists primarily of carbon dioxide and water. Much research on the different aspects of an oxy-fuel power plant has been performed during the last decade. Focus has mainly been on retrofits of existing pulverized-coal-fired power plant units. Green-field plants which provide additional options for improvement of process economics are however likewise investigated. Of particular interest is the change of the combustion process induced by the exchange of carbon dioxide and water vapor for nitrogen as diluent. This paper reviews the published knowledge on the oxy-fuel process and focuses particularly on the combustion fundamentals, i.e. flame temperatures and heat transfer, ignition and burnout, emissions, and fly ash characteristics. Knowledge is currently available regarding both an entire oxy-fuel power plant and the combustion fundamentals. However, several questions remain unanswered and more research and pilot plant testing of heat transfer profiles, emission levels, the optimum oxygen excess and inlet oxygen concentration levels, high and low-temperature fireside corrosion, ash quality, plant operability, and models to predict NOx and SO3 formation is required.

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Scopus rating (2016): CiteScore 19.82 SJR 5.443 SNIP 9.119  
Web of Science (2016): Impact factor 17.382  
BFI (2015): BFI-level 2  
Scopus rating (2015): CiteScore 21.6 SJR 8.077 SNIP 10.2  
BFI (2014): BFI-level 2  
Scopus rating (2014): CiteScore 21.55 SJR 7.426 SNIP 11.879  
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Scopus rating (2013): CiteScore 22.43 SJR 8.259 SNIP 12.951  
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ISI indexed (2013): ISI indexed yes  
BFI (2012): BFI-level 2  
Scopus rating (2012): CiteScore 17.82 SJR 5.859 SNIP 12.194  
Web of Science (2012): Impact factor 15.089  
ISI indexed (2012): ISI indexed yes  
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BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 18.43 SJR 7.61 SNIP 11.61
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ISI indexed (2011): ISI indexed yes
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Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 4.706 SNIP 8.327
Web of Science (2008): Indexed yes
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Web of Science (2006): Indexed yes
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Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 2.038 SNIP 5.195
Scopus rating (2003): SJR 1.977 SNIP 6.026
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Scopus rating (2001): SJR 2.131 SNIP 5.259
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Pyrolyse og forbrænding af kul i N2/O2 og CO2/O2 atmosfærer

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Reactor design for minimizing product inhibition during enzymatic lignocellulose hydrolysis II. Quantification of inhibition and suitability of membrane reactors

Product inhibition of cellulolytic enzymes affects the efficiency of the biocatalytic conversion of lignocellulosic biomass to ethanol and other valuable products. New strategies that focus on reactor designs encompassing product removal, notably glucose removal, during enzymatic cellulose conversion are required for alleviation of glucose product inhibition. Supported by numerous calculations this review assesses the quantitative aspects of glucose product inhibition on enzyme-catalyzed cellulose degradation rates. The significance of glucose product inhibition on dimensioning of different ideal reactor types, i.e. batch, continuous stirred, and plug-flow, is illustrated quantitatively by modeling different extents of cellulose conversion at different reaction conditions. The main operational challenges of membrane reactors for lignocellulose conversion are highlighted. Key membrane reactor features, including system set-up, dilution rate, glucose
output profile, and the problem of cellobiose are examined to illustrate the quantitative significance of the glucose product inhibition and the total glucose concentration on the cellulolytic conversion rate. Comprehensive overviews of the available literature data for glucose removal by membranes and for cellulose enzyme stability in membrane reactors are given. The treatise clearly shows that membrane reactors allowing continuous, complete, glucose removal during enzymatic cellulose hydrolysis, can provide for both higher cellulose hydrolysis rates and higher enzyme usage efficiency (kg(product)/kg(enzyme)). Current membrane reactor designs are however not feasible for large scale operations. The report emphasizes that the industrial realization of cellulosic ethanol requires more focus on the operational feasibility within the different hydrolysis reactor designs, notably for membrane reactors, to achieve efficient enzyme-catalyzed cellulose degradation. (C) 2010 Elsevier Inc. All rights reserved.
Achievement of efficient enzymatic degradation of cellulose to glucose is one of the main prerequisites and one of the main challenges in the biological conversion of lignocellulosic biomass to liquid fuels and other valuable products. The specific inhibitory interferences by cellobiose and glucose on enzyme-catalyzed cellulose hydrolysis reactions impose significant limitations on the efficiency of lignocellulose conversion especially at high-biomass dry matter conditions. To provide the base for selecting the optimal reactor conditions, this paper reviews the reaction kinetics, mechanisms, and significance of this product inhibition, notably the cellobiose and glucose inhibition, on enzymatic cellulose hydrolysis. Particular emphasis is put on the distinct complexity of cellulose as a substrate, the multi-enzymatic nature of the cellulolytic degradation, and the particular features of cellulase inhibition mechanisms and kinetics. The data show that new strategies that place the bioreactor design at the center stage are required to alleviate the product inhibition and in turn to enhance the efficiency of enzymatic cellulose hydrolysis. Accomplishment of the enzymatic hydrolysis at medium substrate concentration in separate hydrolysis reactors that allow continuous glucose removal is proposed to be the way forward for obtaining feasible enzymatic degradation in lignocellulose processing. (C) 2010 Elsevier Inc. All rights reserved.

**Reactor design for minimizing product inhibition during enzymatic lignocellulose hydrolysis: I. Significance and mechanism of cellobiose and glucose inhibition on cellulolytic enzymes**

Achievement of efficient enzymatic degradation of cellulose to glucose is one of the main prerequisites and one of the main challenges in the biological conversion of lignocellulosic biomass to liquid fuels and other valuable products. The specific inhibitory interferences by cellobiose and glucose on enzyme-catalyzed cellulose hydrolysis reactions impose significant limitations on the efficiency of lignocellulose conversion especially at high-biomass dry matter conditions. To provide the base for selecting the optimal reactor conditions, this paper reviews the reaction kinetics, mechanisms, and significance of this product inhibition, notably the cellobiose and glucose inhibition, on enzymatic cellulose hydrolysis. Particular emphasis is put on the distinct complexity of cellulose as a substrate, the multi-enzymatic nature of the cellulolytic degradation, and the particular features of cellulase inhibition mechanisms and kinetics. The data show that new strategies that place the bioreactor design at the center stage are required to alleviate the product inhibition and in turn to enhance the efficiency of enzymatic cellulose hydrolysis. Accomplishment of the enzymatic hydrolysis at medium substrate concentration in separate hydrolysis reactors that allow continuous glucose removal is proposed to be the way forward for obtaining feasible enzymatic degradation in lignocellulose processing. (C) 2010 Elsevier Inc. All rights reserved.
Release of Corrosive Species above the Grate in a Waste Boiler and the Implication for Improved Electrical Efficiency

A relatively low electrical efficiency of 20−25% is obtained in typical west European waste boilers. Ash species released from the grate combustion zone form boiler deposits with high concentrations of Cl, Na, K, Zn, Pb, and S that cause corrosion of superheater tubes at high temperature. The superheater steam temperature has to be limited to around 425 °C, and thereby, the electrical efficiency remains low compared to wood or coal-fired boilers. If a separate part of the flue gas from the grate has a low content of corrosive species, it may be used to superheat steam to a higher temperature, and thereby, the electrical efficiency of the plant can be increased. In this study, the local temperature, the gas concentrations of CO, CO2, and O2, and the release of the volatile elements Cl, S, Na, K, Pb, Zn, Cu, and Sn were measured above the grate in a waste boiler to investigate if a selected fraction of the flue gas could be applied for increased steam superheating. On a 26 ton/h grate-fired waste boiler, Vestforbrænding unit 5 in Denmark, local probe measurements were performed in five ports along the grate and in the top of the boiler chamber. New extraction probe equipment were designed and used to extract a flue gas with high contents of tar. Gas concentration measurements of O2, CO, and CO2 showed that the waste experienced pyrolysis and combustion on grate sections 1 and 2, some char combustion takes place on section 3, and the slag was cooled on sections 4 and 5. The measurements showed that the waste grate combustion process can provide a flue gas with a high energy content and a relatively low concentration of corrosive species. This opens up for the possibility of using an additional superheater section to increase the steam temperature and, thereby, increase electrical efficiency.
Ash Properties of Alternative Biomass

The ash behavior during suspension firing of 12 alternative solid biofuels, such as pectin waste, mash from a beer brewery, or waste from cigarette production have been studied and compared to wood and straw ash behavior. Laboratory suspension firing tests were performed on an entrained flow reactor and a swirl burner test rig, with special emphasis on the formation of fly ash and ash deposit. Thermodynamic equilibrium calculations were performed to support the interpretation of the experiments. To generalize the results of the combustion tests, the fuels are classified according to their ash content of silica, alkali metal, and calcium and magnesium. To further detail the biomass classification, the relative molar ratio of Cl, S, and P to alkali were included. The study has led to knowledge on biomass fuel ash composition influence on ash transformation, ash deposit flux, and deposit chlorine content when biomass fuels are applied for suspension combustion.
Ash transformation in suspension fired boilers co-firing coal and straw: Final report, PSO-Eltra 4766
To study the influence of local conditions on the reaction between gaseous KCl and kaolin or coal fly ash experiments were done on CHECs electrically heated entrained flow reactor, which can simulate the local conditions in suspension fired boilers. The experimental results were compared with model calculations to support the interpretation. The extent of the reaction between KCl vapor and coal minerals was evaluated by the amount of formed water insoluble potassium in the product. The effects of reaction temperature, residence time and potassium load on the potassium capture by coal minerals were studied. Due to not completely well controlled conditions during the experiments only preliminary conclusions can be provided. For experiments done at 1100°C with a molar ratio of K/Si=0.3 and a residence time of 1.07s approximately 80% of potassium from KCl reacted with kaolin. A changed temperature (1100-1300 °C) or a changed amount of KCl (K/Si = 0.1 – 0.34) did only change the KCl conversion slightly. Si and Al rich coal ash seems to be less efficient to react with KCl compared to kaolin. However the applied coal ash had a larger particle size (d50 = 22μm) compared to the kaolin (d50 = 10μm).

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Appendix_D_Potassium_capture_by_kaolin_and_fly_ash_powder_in_an_entained_flow_reactor[1].pdf
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Source-ID: 313205
Research output: Research - peer-review › Report – Annual report year: 2008

Ash transformation in suspension fired boilers co-firing coal and straw: Final report, PSO-Eltra 4766
The properties of the ash from co-firing of coal and straw have a large influence on boiler operation, flue gas cleaning equipment and appropriate utilization of the fly ash. A study on the fuel composition and local conditions influence on fly ash properties has been done by making entrained flow reactor experiments with co-firing of coal and straw, making mineral and alkali vapor laboratory reactor experiments and by developing a model of KCl reaction with kaolin. The results include correlations that can be used to estimate the speciation of potassium in the fly ash when co-firing straw and bituminous coal. The laboratory experiments indicated which mineral types and local conditions that provide the most efficient binding of potassium to species with a high melting point, and where a simultaneous release of chlorine as gaseous HCl takes place.

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Biochar soil application to mitigate climate change

Production of energy carriers (oil, gas) and biochar from pyrolysis of biomass is by many considered a promising technology for combined production of bioenergy and recalcitrant C suitable for sequestration in soil. The mechanism behind biochar-C sequestration is straightforward: Due to its recalcitrant characteristics the microbial decomposition of biochar is much slower in comparison to the mineralization of the original feedstock. Conversion of organic residues like household waste or cereal straw to biochar is hence proposed a way to withdraw CO2 from the atmosphere and sequester it on a long term basis in the soil. The experiments presented here illustrate the C sequestration potentials of biochar originating from fast pyrolysis of wheat straw. It is documented that after 47 days in soil 95 % of the added biochar-C is still present in the soil as compared to only 56 % if straw is applied untreated to the soil. The type and settings of pyrolysis influence the chemical quality of the biochar produced significantly. Biochar chemical analysis revealed that the degradation of biochar in soil appears to be proportional with the biochar cellulosic and hemicellulosic fraction.

Furthermore, the pyrolyzer temperature settings strongly influence the proportion of cellulose and hemicellulose remaining in the biochar. As these biochar fractions relatively rapidly are mineralized to CO2 by microbial respiration they are – in climate mitigation perspective - unwanted. At the upcoming Climate Conference in Copenhagen (COP15) December 2009, the use of biochar as a mitigation tool will be on the agenda and for the time being (July 2009) 20 countries and Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have made submissions to the UNFCCC seeking the inclusion of biochar as a climate mitigation and adaptation tool.

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Source: orbit
Source-ID: 250309
Research output: Research › Article in proceedings – Annual report year: 2009

Biomass Suspension Combustion: Effect of Two-Stage Combustion on NOx Emissions in a Laboratory-Scale Swirl Burner

A systematic study was performed in a suspension fired 20 kW laboratory-scale swirl burner test rig for combustion of biomass and co-combustion of natural gas and biomass. The main focus is put on the effect of two-stage combustion on the NO emission, as well as its effect on the incomplete combustion. When two-stage combustion was applied, the NO emission level can be significantly reduced. The experimental results show that an optimal first-stage combustion stoichiometry (λ1) exists, at which a minimum NO emission can be achieved. An optimal stoichiometry of around 0.8 in the fuel-rich zone exists with respect to minimizing NO emissions. When using wood and straw as co-firing fuels, 15–25% of the fuel-N is converted to NO. Straw appears to give the lowest conversion of fuel-N to NO. The results indicate that the optimal stoichiometry in the fuel-rich (λ1) zone for gaining the lowest NO may result from the homogeneous reaction, by comparing the NO emissions when firing natural gas with NH3 addition and co-firing natural gas and biomass. The experimental results also show no significant increase of incomplete combustion of gas and char by applying optimized two-stage combustion.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Co-combustion of coal and SRF in an entrained flow reactor: a preliminary study

Investigations on co-firing of SRF with two kinds of bituminous coal were carried out in an entrained flow reactor. The experimental results showed that co-combustion of coal and SRF increased the unburnt carbon in fly ashes. The emissions of NO and SO2 were reduced with an increasing share of SRF both due to the low nitrogen and sulphur contents in the SRF and the synergy effects of the fuels. Influences of co-combustion on the deposit formation rate on an air-cooled probe were rather different for the two coals. For COPRIB coal and SRF co-combustion, the deposit formation rate decreased slightly with an increasing share of SRF. For SAKLEI coal and SRF co-combustion, the deposit formation rate showed an increasing trend up to 10 mass percent of SRF, and started to decrease at a higher SRF share. By analyzing the ash samples, it has been found that the concentrations of some trace elements such as Cd, Cu, Pb and Zn were highly enriched in the fly ashes from coal and SRF co-combustion. The effect may due to there are more organically associated trace elements in SRF than coals, and the high Cl content in SRF may enhance the enrichment of trace elements in fly ashes.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, DONG Energy AS
Number of pages: 6
Publication date: 2009

Combustion of Char Particles Under Oxy-Fuel Conditions: Formation of NO and Particle Temperature

General Information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Brix, J., Jensen, A. D., Jensen, P. A.
Publication date: 2009
Peer-reviewed: No
Event: Paper presented at Joint Meeting of the Scandinavian-Nordic and French Section of the Combustion Institute, Snekkersten, Denmark.
Source: orbit
Source-ID: 258273
Research output: Research › Paper – Annual report year: 2009

Determining the elemental composition of fuels by bomb calorimetry and the inverse correlation of HHV with elemental composition

This article presents a method to obtain a simplified elemental analysis of an organic sample in which oxygen, nitrogen, and sulphur are lumped. The method uses a bomb calorimeter, water, and ash measurements combined with a numerical procedure based on a generalised equation for predicting higher heating value. By analysing pure organic substances, literature data, and fuels it is demonstrated that the method can provide hydrogen estimates within +/- 0.7% daf.
carbon and sum of oxygen, nitrogen, and sulphur estimates within +/- 2% daf. for fuels containing less than 90% ash db., 2% nitrogen daf., and 1% daf. sulphur.

**General information**

State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 534-537
Publication date: 2009
Peer-reviewed: Yes

**Publication information**

Journal: Biomass & Bioenergy
Volume: 33
Issue number: 3
ISSN (Print): 0961-9534
Ratings:

- BFI (2019): BFI-level 2
- Web of Science (2019): Indexed yes
- BFI (2018): BFI-level 2
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 2
- Scopus rating (2017): CiteScore 4 SJR 1.235 SNIP 1.436
- Web of Science (2017): Impact factor 3.358
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Scopus rating (2016): CiteScore 3.71 SJR 1.198 SNIP 1.385
- Web of Science (2016): Impact factor 3.219
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 2
- Scopus rating (2015): CiteScore 4.03 SJR 1.51 SNIP 1.596
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 2
- Scopus rating (2014): CiteScore 4.36 SJR 1.865 SNIP 1.964
- Web of Science (2014): Impact factor 3.394
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 2
- Scopus rating (2013): CiteScore 4.42 SJR 1.666 SNIP 1.811
- Web of Science (2013): Impact factor 3.411
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 2
- Scopus rating (2012): CiteScore 3.66 SJR 1.516 SNIP 1.754
- Web of Science (2012): Impact factor 2.975
- ISI indexed (2012): ISI indexed yes
- Web of Science (2012): Indexed yes
- BFI (2011): BFI-level 2
- Scopus rating (2011): CiteScore 4.74 SJR 1.759 SNIP 2.296
- Web of Science (2011): Impact factor 3.646
- ISI indexed (2011): ISI indexed yes
- Web of Science (2011): Indexed yes
- BFI (2010): BFI-level 2
- Scopus rating (2010): SJR 1.914 SNIP 2.251
- Web of Science (2010): Impact factor 3.84
- Web of Science (2010): Indexed yes
Effect of experimental conditions on biomass gasification in an entrained-flow reactor

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Qin, K., Jensen, P. A., Lin, W., Jensen, A. D.
Publication date: 2009
Peer-reviewed: No
Event: Paper presented at 1st Joint Meeting of the Scandinavian-Nordic and French Sections of the Combustion Institute, Snekkersten, Denmark.
Source: orbit
Source-ID: 258227
Research output: Research › Paper – Annual report year: 2009

Effects of H2S and process conditions in the synthesis of mixed alcohols from syngas over alkali promoted cobalt-molybdenum sulfide

The present work is an investigation of how the process conditions influence the synthesis of mixed alcohols from syngas over a K2CO3/CoMoS2/C catalyst. The emphasis in the investigations is upon the effects of H2S in the syngas feed. However the effects of the temperature and of the partial pressures of H2 and CO are also investigated. With or without H2S in the feed the pre-sulfided catalyst requires an initiation period to reach a stabilized behavior, but the duration of this period depends upon the H2S level. Operation with a feed containing more than 103 ppmv H2S leads to a fairly rapid stabilization of the product distribution and ensures that higher alcohols are the dominant reaction products. With less than 57 ppmv H2S in the feed the stabilization of the product distribution is much slower, and methanol is the dominant product. An investigation of the reaction kinetics indicates a high CO coverage and low hydrogen coverage. Hydrogen sulfide in the syngas feed generally promotes chain growth for both alcohols and hydrocarbons, but lowers the alcohol selectivity by enhancing the hydrocarbon formation. The highest alcohol productivity reached in these investigations was 0.276 g/g cat./h, and this was achieved at 350 °C, 100 bar, GHSV = 5244 h−1, Feed: 49.9 vol% H2, 50.1 vol% CO. Finally it is found that sulfur fed to the reactor as H2S is incorporated into the condensed alcohol product, and the incorporation of sulfur species into the product continues for some time after H2S has been removed from the feed. When the catalyst is operated with an S-free syngas feed, the amount of sulfur in the condensed liquid product decreases over time, but after 35 h of operation with an S-free syngas the alcohol product still contains 340 ppmw of sulfur. Thiols appear to be the
dominant sulfur compounds in the product.

**General information**
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Christensen, J. M., Mortensen, P. M., Trane, R., Jensen, P. A., Jensen, A. D.
Pages: 29-43
Publication date: 2009
Peer-reviewed: Yes

**Publication information**
Journal: Applied Catalysis A: General
Volume: 366
Issue number: 1
ISSN (Print): 0926-860X
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.48 SJR 1.237 SNIP 1.257
Web of Science (2017): Impact factor 4.521
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.26 SJR 1.202 SNIP 1.336
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 4.08 SJR 1.218 SNIP 1.427
Web of Science (2015): Impact factor 4.012
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.04 SJR 1.335 SNIP 1.602
Web of Science (2014): Impact factor 3.942
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.01 SJR 1.448 SNIP 1.554
Web of Science (2013): Impact factor 3.674
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 3.89 SJR 1.573 SNIP 1.641
Web of Science (2012): Impact factor 3.41
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 4.15 SJR 1.727 SNIP 1.752
Web of Science (2011): Impact factor 3.903
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.786 SNIP 1.641
Web of Science (2010): Impact factor 3.384
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Experimental and numerical investigation of gas phase freeboard combustion: Part II: Fuel-NO formation
In part 1 of the present work (10.1021/ef900752a), experimental data and computational fluid dynamics (CFD) modeling predictions for velocity field, temperatures, and major species were compared for a 50 kW axisymmetric, non-swirling natural gas-fired combustion setup, constructed to simulate the conditions in the freeboard of a grate-fired boiler. Here, in part 2, the ability of CFD to predict volatile N oxidation to NO and N(2) is evaluated. Trace amounts of ammonia were added to the natural gas, and local measurements of NH(3) and NO in the reactor were compared to modeling predictions. Different modeling approaches, including global schemes and analytically reduced mechanisms, were tested in the CFD calculations. In addition, the simplified schemes were compared to reference calculations with a detailed mechanism under isothermal plug flow reactor conditions. While none of the global ammonia schemes was able to provide satisfactory predictions over a wider range of conditions, an analytically reduced nitrogen scheme generally provided a satisfactory agreement with the detailed mechanism. Application of the selected schemes in a CFD analysis showed that both the standard Fluent postprocessing approach with the De Soete global scheme and the combination of a skeletal combustion mechanism with the analytically reduced N scheme provided reasonable agreement with the experimental data. Most of the tested ammonia oxidation schemes were able to qualitatively predict the trends in NO formation going from one operational case to the other, but the main combustion solution on which the ammonia oxidation was based proved to have a large impact on the quantitative NO prediction.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Andersen, J., Jensen, P. A., Hvid, S., Glarborg, P.
Pages: 5783-5791
Publication date: 2009
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 23
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
Experimental and numerical investigation of gas phase freeboard combustion: Part I: Main combustion process
Experimental data for velocity field, temperatures, and gas composition have been obtained from a 50 kW axisymmetric non-swirling natural gas fired combustion setup under two different settings. The reactor was constructed to simulate the conditions in the freeboard of a grate-fired boiler but under well-defined conditions. The experimental results are compared to computational fluid dynamics (CFD) modeling predictions, using the eddy dissipation model (EDM) as well as the eddy dissipation concept (EDC). The use of EDC allows for implementation of more advanced combustion schemes; we have tested the four-step global mechanism by Jones and Lindstedt (Combust. Flame 1988, 73, 233-249), and the 16 species and 41 reaction skeletal mechanism by Yang and Pope (Combust. Flame 1998, 112 16-32). The CFD model captured the main features of the combustion process and flow patterns. The application of more advanced chemical mechanisms did not improve the prediction of the overall combustion process but did provide additional information about species (especially H(2) and radicals), which is desirable for postprocessing pollutant formation.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Andersen, J., Jensen, P. A., Meyer, K., Hvid, S., Glarborg, P.
Pages: 5773-5782
Publication date: 2009
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 23
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
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BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.3
Web of Science (2014): Impact factor 2.79
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.52
Web of Science (2013): Impact factor 2.733
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.25
Web of Science (2012): Impact factor 2.853
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Influence of operating conditions on gas composition, soot and tar in entrained flow gasification

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Qin, K., Jensen, P. A., Lin, W., Jensen, A. D.
Publication date: 2009
Peer-reviewed: No
Event: Paper presented at International Conference on Polygeneration strategies, 
Source: orbit
Source-ID: 258225
Research output: Research › Paper – Annual report year: 2009

Influence of operating conditions on gas composition, soot and tar in entrained flow gasification of biomass

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Biomass Gasification, Biosystems Division, Risø National Laboratory for Sustainable Energy
Contributors: Qin, K., Lin, W., Jensen, P. A., Jensen, A. D., Egsgaard, H.
Publication date: 2009

Host publication information
Title of host publication: International Conference on Polygeneration Strategies 09
Keywords: Bio energy, Biomass gasification
Source: orbit
Source-ID: 256251
Research output: Research - peer-review › Article in proceedings – Annual report year: 2009

Modelling solid-convective flash pyrolysis of straw and wood in the Pyrolysis Centrifuge Reactor

Less than a handful of solid-convective pyrolysis reactors for the production of liquid fuel from biomass have been presented and for only a single reactor a detailed mathematical model has been presented. In this article we present a predictive mathematical model of the pyrolysis process in the Pyrolysis Centrifuge Reactor, a novel solid-convective flash pyrolysis reactor. The model relies on the original concept for ablative pyrolysis of particles being pyrolysed through the
formation of an intermediate liquid compound which is further degraded to form liquid organics, char, and gas. To describe the kinetics of the pyrolysis reactions the Broido-Shafizadeh scheme is employed with cellulose parameters for wood and modified parameters for straw to include the catalytic effect of its alkali-containing ash content. The model describes the presented experimental results adequately for engineering purposes for both wood and straw feedstock even though conditions for ablative pyrolysis from a reaction engineering point of view are not satisfied. Accordingly, even though the concept of an ablatively melting particle may constitute a limiting case, it can still be used to model flash pyrolysis provided that the reacting particle continuously shed the formed char layer.

**General information**

**State:** Published  
**Organisations:** CHEC Research Centre, Department of Chemical and Biochemical Engineering  
**Contributors:** Bech, N., Larsen, M. B., Jensen, P. A., Dam-Johansen, K.  
**Pages:** 999-1011  
**Publication date:** 2009  
**Peer-reviewed:** Yes

**Publication information**

**Journal:** Biomass & Bioenergy  
**Volume:** 33  
**Issue number:** 6-7  
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**Ratings:**  
BFI (2019): BFI-level 2  
Web of Science (2019): Indexed yes  
BFI (2018): BFI-level 2  
Web of Science (2018): Indexed yes  
BFI (2017): BFI-level 2  
Web of Science (2017): Impact factor 3.358  
Web of Science (2017): Indexed yes  
BFI (2016): BFI-level 2  
Scopus rating (2016): CiteScore 3.71 SJR 1.198 SNIP 1.385  
Web of Science (2016): Impact factor 3.219  
Web of Science (2016): Indexed yes  
BFI (2015): BFI-level 2  
Scopus rating (2015): CiteScore 4.03 SJR 1.51 SNIP 1.596  
Web of Science (2015): Impact factor 3.249  
Web of Science (2015): Indexed yes  
BFI (2014): BFI-level 2  
Scopus rating (2014): CiteScore 4.36 SJR 1.865 SNIP 1.964  
Web of Science (2014): Impact factor 3.394  
Web of Science (2014): Indexed yes  
BFI (2013): BFI-level 2  
Scopus rating (2013): CiteScore 4.42 SJR 1.666 SNIP 1.811  
Web of Science (2013): Impact factor 3.411  
ISI indexed (2013): ISI indexed yes  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 2  
Scopus rating (2012): CiteScore 3.66 SJR 1.516 SNIP 1.754  
Web of Science (2012): Impact factor 2.975  
ISI indexed (2012): ISI indexed yes  
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 2  
Scopus rating (2011): CiteScore 4.74 SJR 1.759 SNIP 2.296  
Web of Science (2011): Impact factor 3.646  
ISI indexed (2011): ISI indexed yes  
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.914 SNIP 2.251
Web of Science (2010): Impact factor 3.84
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.728 SNIP 2.183
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.614 SNIP 2.137
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.361 SNIP 1.825
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.268 SNIP 1.991
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.214 SNIP 1.401
Scopus rating (2004): SJR 1.027 SNIP 1.665
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.659 SNIP 1.378
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 0.396 SNIP 0.775
Scopus rating (2001): SJR 0.455 SNIP 1.048
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 0.447 SNIP 0.958
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.429 SNIP 1.064

Original language: English
Keywords: Pyrolysis centrifuge reactor, Ablative, Solid convective, Flash pyrolysis, Biocrude, Bio-oil, Wheat straw, Pine wood, Modelling
DOIs:
10.1016/j.biombioe.2009.03.009
Source: orbit
Source-ID: 249167
Research output: Research - peer-review › Journal article – Annual report year: 2009

Oxy-fuel forbrænding af fossile brændsler

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 14-15
Publication date: 2009
Peer-reviewed: Yes

Publication information
Journal: Dansk Kemi
Volume: 90
ISSN (Print): 0011-6335
Ratings:
ISI indexed (2013): ISI indexed no
ISI indexed (2012): ISI indexed no
ISI indexed (2011): ISI indexed no
Web of Science (2007): Indexed yes
Web of Science (2004): Indexed yes
Original language: Danish
Source: orbit
Source-ID: 258244
Research output: Research - peer-review › Journal article – Annual report year: 2009
Release of Potassium from the Systems K-Ca-Si and K-Ca-P

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark
Pages: 3423-3428
Publication date: 2009
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 23
Issue number: 7
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.3
Web of Science (2014): Impact factor 2.79
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.52
Web of Science (2013): Impact factor 2.733
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.25
Web of Science (2012): Impact factor 2.853
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.05
Web of Science (2011): Impact factor 2.721
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Web of Science (2010): Impact factor 2.444
Web of Science (2010): Indexed yes
Shedding of ash deposits
Ash deposits formed during fuel thermal conversion and located on furnace walls and on convective pass tubes, may seriously inhibit the transfer of heat to the working fluid and hence reduce the overall process efficiency. Combustion of biomass causes formation of large quantities of troublesome ash deposits which contain significant concentrations of alkali, and earth-alkali metals. The specific composition of biomass deposits give different characteristics as compared to coal ash deposits, i.e. different physical significance of the deposition mechanisms, lower melting temperatures, etc. Low melting temperatures make straw ashes especially troublesome, since their stickiness is higher at lower temperatures, compared to coal ashes. Increased stickiness will eventually lead to a higher collection efficiency of incoming ash particles, meaning that the deposit may grow even faster. Deposit shedding can be defined as the process of deposit removal from the heat transfer surfaces. Mechanical and thermal shock devices for deposit removal can be implemented within into the boiler, which can be then referred to as artificial shedding. Sootblowing is one such process, where a pressurized fluid is used to cause a mechanical and/or thermal shock that would cause a failure or fissure in the deposit. On the other hand, shedding can be caused without any operational or mechanical influence by erosion, gravity shedding, or simply by a thermal shock. The mechanism that will be dominant depends on the ash characteristics and the boiler operation. Different deposit characteristics will govern the ash deposit behaviour, and thus the mechanism of deposit shedding. The deposit strength will influence the erosion and gravity shedding mechanisms. The ash viscosity and the melting behaviour will govern the gravity shedding mechanism, while the thermal expansion coefficient will influence the thermal shock behaviour of the deposit.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Zbogar, A., Frandsen, F., Jensen, P. A., Glarborg, P.
Pages: 31-56
Publication date: 2009
Peer-reviewed: Yes

Publication information
Journal: Progress in Energy and Combustion Science
Volume: 35
Issue number: 1
ISSN (Print): 0360-1285
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 24.19 SJR 6.751 SNIP 9.626
Web of Science (2017): Impact factor 25.242
Web of Science (2017): Indexed yes
A kinetic study of gaseous potassium capture by coal minerals in a high temperature fixed-bed reactor

The reactions between gaseous potassium chloride and coal minerals were investigated in a lab-scale high temperature fixed-bed reactor using single sorbent pellets. The applied coal minerals included kaolin, mullite, silica, alumina, bituminous coal ash, and lignite coal ash that were formed into long cylindrical pellets. Kaolin and bituminous coal ash that both have significant amounts of Si and Al show superior potassium capture characteristics. Experimental results show that capture of potassium by kaolin is independent of the gas oxygen content. Kaolin releases water and forms metakaolin when heated at temperatures above 450°C. The amounts of potassium captured by metakaolin pellet decreases with increasing reaction temperature in the range of 900-1300°C and increases again with further increasing the temperature up to 1500°C. There is no reaction of pre-made mullite with KCl at temperatures below 1300°C. However, the weight gain by mullite is only slightly smaller than that by kaolin in the temperature range of 1300-1500°C. A simple model was developed for the gas-solid reaction between potassium vapor and metakaolin pellet at 900°C.
Alkali/chloride release during refuse incineration on a grate: Full-scale experimental findings

Waste to energy (WtE) plants are utilised for the production of heat and electricity. However, due to corrosion at super heater surfaces a relatively low 25% of the waste lower heating value can with the present technology be converted to electricity. High contents of Cl, Na, K, Zn, Pb and S in waste cause relatively high super heater corrosion rates. The Cl-content in waste is one of the key-factors for volatilisation of alkali and heavy metals in WtE plants. Little is known about the release of Cl, Na, K, Zn, Pb, and S along grate of waste incineration plants. The 26 t h(-1) WtE plant Vestforbraending unit S in Denmark was used for measurements of temperature, gas-concentration (O₂/CO/CO₂), and sampling of gas phase Cl, Na, K, Pb, Zn, and S along grate of waste incineration plants. The experiments showed the majority of Cl, Na, and K to be volatilised during the early stages of combustion. The maximum release of Cl, Na, and K was measured in port 2 as 177 ppm(nu), 71 ppm(nu) and 44 ppm(nu) respectively. The maximum average gas temperature of 1140 was measured in port 3 compared to the temperatures at ports 2 and 4 of 816 and 551 respectively. It has been suggested to use flue gas from the area of the grate near port 3 with a high temperature, that contains relatively low amounts of corrosive elements, and lead to a separate high temperature super heater and thus increase the electrical efficiency.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Department of Mechanical Engineering
Contributors: Bøjer, M., Jensen, P. A., Frandsen, F., Dam-Johansen, K., Madsen, O. H., Lundtorp, K.
Pages: 528-539
Release of Potentially Corrosive Constituents from the Grate of a Waste-to-energy Boiler – A detailed investigation

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Bøjer, M., Jensen, P. A., Dam-Johansen, K., Madsen, O. H., Lundtorp, K.
Publication date: 2008

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Title of host publication: Impacts of Fuel Quality on Power Production and the Environment
Place of publication: Banff, Canada
Source: orbit
Source-ID: 232079
Research output: Research - peer-review › Article in proceedings – Annual report year: 2008

Combustion of wood for heat and power production may cause problems such as ash deposition, corrosion, and harmful emissions of gases and particulate matter. These problems are all directly related to the release of inorganic elements (in particular Cl, S, K, Na, Zn, and Pb) from the fuel to the gas phase. The aims of this study are to obtain quantitative data on the release of inorganic elements during wood combustion and to investigate the influence of fuel composition.
Quantitative release data were obtained by pyrolyzing and subsequently combusting small samples of wood (~30 g) at various temperatures in the range of 500–1150 °C in a laboratory-scale tube reactor and by performing mass balance calculations based on the weight measurements and chemical analyses of the wood fuels and the residual ash samples. Four wood fuels with different ash contents and inorganic compositions were investigated, including wood chips from spruce and beech, bark, and fiber board. The results showed a high release of Cl (~85–100%) and S (~50–70%) already at 500 °C, so that only small variations in the release trends of Cl and S were seen between the different fuels in the range of 500–1150 °C. The release of the alkali metals K and Na was, however, strongly dependent on both the temperature and the fuel composition under the investigated conditions. The release of the heavy metals Zn and Pb started around 500 °C and increased sharply to more than 85% at 850 °C in the case of spruce, beech, and bark, and was therefore mainly dependent on the temperature. By comparing the data to literature data, and by using tools such as scanning electron microscopy, chemical fractionation analysis, and equilibrium calculations, a better understanding of the release mechanisms was obtained. Mechanisms for the release of Cl, S, K, Na, Zn, and Pb during wood combustion are proposed.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: van Lith, S. C., Jensen, P. A., Frandsen, F., Glarborg, P.
Pages: 1598-1609
Publication date: 2008
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 22
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
Suspension Combustion of Wood: Influence of Pyrolysis Conditions on Char Yield, Morphology, and Reactivity

Chars from pine and beech wood were produced by fast pyrolysis in an entrained flow reactor and by slow pyrolysis in a thermogravimetric analyzer. The influence of pyrolysis temperature, heating rate and particle size on char yield and morphology was investigated. The applied pyrolysis temperature varied in the range 673−1673 K for slow pyrolysis and between 873 and 1573 K for fast pyrolysis. The chars were oxidized in a thermogravimetric analyzer and the mass loss data were used to determine char oxidation reactivity. Char yield from fast pyrolysis (104−105 K/s) was as low as 1 to 6% on a dry ash free basis, whereas it was about 15−17% for slow pyrolysis (10−20 K/min); char yield decreased as pyrolysis temperature increased.
temperature increased. During fast pyrolysis wood particles underwent melting, yet to different extents for the two investigated fuels: pine wood produced chars of porous spherical particles, whereas beech sawdust chars showed a somewhat less drastic change of morphology with respect to the parent fuel. Char produced by low heating rate pyrolysis fully retained the original fibrous structure of wood. Fast pyrolysis chars were significantly more reactive than slow pyrolysis chars; moreover, char oxidation reactivity decreased as pyrolysis temperature increased. The amount and composition of the ash forming matter of the wood fuels seems to play an important role in determining the differences in char yield, morphology and reactivity.
Ablative Flash Pyrolysis of Straw and Wood: Bench-scale Results

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Publication date: 2007

Host publication Information
Title of host publication: Proceedings
Source: orbit
Source-ID: 211010
Research output: Research - peer-review › Article in proceedings – Annual report year: 2007

Aerosol Formation during the Combustion of Straw with Addition of Sorbents
The influence of six sorbents on aerosol formation during the combustion of straw in a 100 MW boiler on a Danish power plant has been studied in full-scale. The following sorbents were studied: ammonium sulfate, monocalcium phosphate, Bentonite, ICA5000, clay, and chalk. Bentonite and ICA5000 are mixtures of clay minerals and consist mainly of the oxides from Fe, Al, and Si. The straw used was Danish wheat and seed grass. Measurements were also made with increased flow of primary air. The experiments showed between 46% and 70% reduction in particle mass concentrations when adding ammonium sulfate, calcium phosphate, Bentonite, ICA5000, and clay. The addition of chalk increased the aerosol mass concentration by 24%. Experiments in a laminar flow aerosol condenser with the six sorbents were carried out in the laboratory using a synthetic flue gas to avoid fluctuations in the alkali feeding. These experiments showed similar reductions to the ones found in full-scale. When feeding ammonium sulfate, the aerosol mass concentration increased as a result of the feeding method. The chemical compositions of the fine particles suggest that there is chemical equilibrium in the gas for the sulfation reaction at temperatures above 812 degrees C.

General information
State: Published
Organisations: Department of Chemistry, CHEC Research Centre, Department of Chemical and Biochemical Engineering, DONG Energy AS
Pages: 699-709
Publication date: 2007
Peer-reviewed: Yes

Publication Information
Journal: Energy & Fuels
Volume: 21
<table>
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A kinetic study of gaseous potassium capture by coal minerals in a high temperature fixed bed reactor

Ash Deposits Removal in Biomass Power Plant Boilers

Ash transformation during co-firing coal and straw
Deposit probe measurements in the Avedøre and Ensted straw fired grate boilers

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Hansen, J., Jensen, P. A., Glarborg, P.
Number of pages: 17
Publication date: 2007

Publication information
Publisher: Technical University of Denmark, Department of Chemical Engineering
Original language: English
Source: orbit
Source-ID: 195860
Research output: Research - peer-review › Journal article – Annual report year: 2007

Dynamic mechanistic model of superheater deposit growth and shedding in a biomass fired grate boiler

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Zhou, H., Jensen, P. A., Frandsen, F.
Pages: 1519-1533
Publication date: 2007
Peer-reviewed: Yes

Publication information
Journal: Fuel
Volume: 86
ISSN (Print): 0016-2361
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 5.4 SJR 1.891 SNIP 2.127
Web of Science (2017): Impact factor 4.908
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.9 SJR 1.736 SNIP 2.207
Web of Science (2016): Impact factor 4.601
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.46 SJR 1.781 SNIP 2.123
Harvesting Straw Bio-Oil on the Field

General information
How to deal with one of the main obstacles for an increased use of CO2 neutral biomass in power plant boilers - Optimal ash deposits removal in straw fired boilers

Product inhibition of cellulases during enzymatic hydrolysis of the pre-treated ligno-cellulose

Quantification of glucose inhibition of enzymatic cellulose degradation in pre-treated wheat straw

Release of K from the system: K-Ca(-Si)-P - The Effects of the a/Si- and Ca/P-ratios
Release of Potentially Corrosive Constituents from the Grate of a Waste-to-Energy Boiler

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Babcock & Wilcox Vølund A/S
Contributors: Bøjer, M., Jensen, P. A., Frandsen, F., Dam-Johansen, K., Madsen, O. H., Lundtorp, K.
Pages: 1-17
Publication date: 2007

Wood in Pulverized Fuel Power Plants: Char Characterization and Char Combustion

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Dall'Ora, M., Jensen, P. A., Jensen, A. D.
Publication date: 2007

Ash transformation in suspension fired boilers co-firing coal and straw: Final report, PSO-Eltra 4786
In this literature report is provided a status for the present knowledge level on ash properties when co-firing coal and biomass. The fly ash formed in boilers using co-firing of coal and straw do have a large influence on ash deposit formation, boiler corrosion, fly ash utilization and operation of flue gas cleaning equipment. This survey includes discussions on the inorganic constituents transformation during straw and coal combustion, alkali-ash and alkali sulfur reactions, a survey of power plant and test rig co-firing experiments, a discussion of equilibrium calculations, a discussion of alkali getter experiments and a discussion of modeling of alkali reaction with kaolin. Presently there is still a need for a better understanding of especially the reaction of potassium with coal ash, thereby making better predictions of co-firing ash properties.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Number of pages: 94
Publication date: 2006

Publication information
Publisher: Technical University of Denmark, Department of Chemical Engineering
Volume: Appendix A: Literature review of ash transformation during co-firing coal and straw
Original language: English
(CHEC; No. R0803).
Electronic versions:
prod21321877166933.R0803_-_Main_report_Ash_transformation_inSuspensionFiredBoilerscoFiringCoalAndStraw[1].pdf
Source: orbit
Source-ID: 313200
Research output: Research - peer-review › Report – Annual report year: 2006
Final report – Ash deposit formation and removal in biomass fired boilers. Fundamental data provided with deposit probes

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark
Publication date: 2006

Publication information
Publisher: CHEC Research Centre
Original language: English
Electronic versions:
PART 1
PART 2
PART 3
Source: orbit
Source-ID: 188665
Research output: Research - peer-review › Journal article – Annual report year: 2006

During wood combustion, inorganic elements such as alkali metals, sulfide, chlorine, and some heavy metals are partly released to the gas phase, which may cause problems in combustion facilities because of deposition formation and corrosion. Furthermore, it may cause harmful emissions of gases and particulate matter. The aim of this study is to obtain quantitative data on the release of inorganic elements during wood combustion, which will serve as input data for models aiming to address ash-related problems. Three quantification methods were developed. In all three methods, the release of inorganic elements was quantified by a mass balance based on the weights and inorganic compositions of the fuel and the ash residues obtained by high-temperature (500-1150 C) treatment in a laboratory-scale tube reactor. However, method A involved the pyrolysis and combustion of a small fuel sample (~30 g) in this reactor, whereas methods B and C involved initial pyrolysis and combustion, respectively, of a large fuel sample (~5 kg) in a bench-scale fixed-bed reactor at 500 C. The methods were evaluated by comparing the data on the release of Cl, S, K, Na, Zn, and Pb from fiber board obtained by the three methods. The release data were interpreted by use of literature information, equilibrium calculations, and scanning electron microscopy analysis of the ash samples. Large differences in the release trends (especially for S, Na, and Zn) were observed for the three methods because of the differences in sample size, oxidizing/reducing conditions, and the ash formation process. The combined results of the three methods provide a good understanding of the ash transformations and release of inorganic elements during wood combustion on a grate. Method A gives information on the local (or primary) release, whereas methods B and C provide insight into the influence of secondary reactions taking place in larger fuel beds.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark
Release of Inorganic Elements during Wood-firing on a Grate

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: van Lith, S. C., Jensen, P. A., Frandsen, F., Glarborg, P.
Publication date: 2006

Host publication information
Source: orbit
Source-ID: 195626
Research output: Research - peer-review › Article in proceedings – Annual report year: 2006

Retrol vision: Preliminary Techno-Economical Analysis

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Andric, P., Dam-Johansen, K., Jensen, P. A., Rosgaard, L.
Publication date: 2006
Peer-reviewed: No
Source: orbit
Source-ID: 195811
Research output: Research › Poster – Annual report year: 2006

Retrol vision: Preliminary Techno-Economical Analysis

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center
Contributors: Andric, P., Dam-Johansen, K., Gani, R., Jensen, P. A.
Publication date: 2006

Host publication information
Title of host publication: Sustainable Power Systems
Source: orbit
Source-ID: 195810
Research output: Research - peer-review › Article in proceedings – Annual report year: 2006

Shedding of Ash Deposits in a Straw-fired Boiler

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark
The Effects of Ca-based Sorbents on Sulfur Retention in Bottom Ash from Grate-fired Annual Biomass

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Lang, T., Jensen, P. A., Knudsen, J.
Pages: 796-806
Publication date: 2006
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 20
ISSN (Print): 0887-0624
Ratings:
- BFI (2019): BFI-level 2
- Web of Science (2019): Indexed yes
- BFI (2018): BFI-level 2
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 2
- Scopus rating (2017): CiteScore 3.55
- Web of Science (2017): Impact factor 3.024
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Scopus rating (2016): CiteScore 3.49
- Web of Science (2016): Impact factor 3.091
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 2
- Scopus rating (2015): CiteScore 3.34
- Web of Science (2015): Impact factor 2.835
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 2
- Scopus rating (2014): CiteScore 3.3
- Web of Science (2014): Impact factor 2.79
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 2
- Scopus rating (2013): CiteScore 3.52
- Web of Science (2013): Impact factor 2.733
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 2
- Scopus rating (2012): CiteScore 3.25
- Web of Science (2012): Impact factor 2.853
- ISI indexed (2012): ISI indexed yes
- Web of Science (2012): Indexed yes
- BFI (2011): BFI-level 2
- Scopus rating (2011): CiteScore 3.05
- Web of Science (2011): Impact factor 2.721
Transformation of K, Cl and S during Co-firing of Coal and Straw

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, DONG Energy AS
Publication date: 2006

Host publication information
Title of host publication: Impact of Fuel Quality on Power Production
Source: orbit
Source-ID: 195622
Research output: Research - peer-review › Article in proceedings – Annual report year: 2006

Combustion experiments with biomass fuels and additives in a suspension fired entrained flow reactor – Test of Ca and P rich additives used to minimize deposition and corrosion

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Jensen, P. A., Sørensen, L. H., Hu, G., Holm, J. K., Frandsen, F., Henriksen, U. B.
Publication date: 2005

Publication information
Original language: English
Source: orbit
Source-ID: 181915
Research output: Research › Report – Annual report year: 2005

Databook entry of deposit measurements in bio boiler Avedøre 2 using additives performed by CHEC, DTU, November 2004

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Contributors: Hansen, J., Jensen, P. A.
Number of pages: 13
Publication date: 2005
Heat transfer in ash deposits: A modelling tool-box

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Zbogar, A., Frandsen, F., Jensen, P. A., Glarborg, P.
Pages: 371-421
Publication date: 2005
Peer-reviewed: Yes

Publication information
Journal: Progress in Energy and Combustion Science
Volume: 31
Issue number: 5-6
ISSN (Print): 0360-1285
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 24.19 SJR 6.751 SNIP 9.626
Web of Science (2017): Impact factor 25.242
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 19.82 SJR 5.443 SNIP 9.119
Web of Science (2016): Impact factor 17.382
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 21.6 SJR 8.077 SNIP 10.2
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 21.55 SJR 7.426 SNIP 11.879
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 22.43 SJR 8.259 SNIP 12.951
Web of Science (2013): Impact factor 16.909
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 17.82 SJR 5.859 SNIP 12.194
Web of Science (2012): Impact factor 15.089
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 18.43 SJR 7.61 SNIP 11.61
Web of Science (2011): Impact factor 14.22
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 5.154 SNIP 9.996
Web of Science (2010): Indexed yes
Numerical modeling of straw combustion in a fixed bed

Straw is being used as main renewable energy source in grate boilers in Denmark. For optimizing operating conditions and design parameters, a one-dimensional unsteady heterogeneous mathematical model has been developed and experiments have been carried out for straw combustion in a fixed bed. The straw combustion processes include moisture evaporation, straw pyrolysis, gas combustion, and char combustion. The model provides detailed information of the structure of the ignition flame front. Simulated gas species concentrations at the bed surface, ignition flame front rate, and bed temperature are in good agreement with measurements at different operating conditions such as primary air-flow rate, pre-heating of the primary air, oxygen concentration, moisture content in straw, and bulk density of the straw in the fixed bed. A parametric study indicates that the effective heat conductivity, straw packing condition, and heat capacity of the straw have considerable effects on the model predictions of straw combustion in the fixed bed.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 389-403
Publication date: 2005
Peer-reviewed: Yes

Publication information
Journal: Fuel
Volume: 84
Issue number: 4
ISSN (Print): 0016-2361
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 5.4 SJR 1.891 SNIP 2.127
Web of Science (2017): Impact factor 4.908
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.9 SJR 1.736 SNIP 2.207
Web of Science (2016): Impact factor 4.601
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.46 SJR 1.781 SNIP 2.123
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.14 SJR 1.634 SNIP 2.294
Web of Science (2014): Impact factor 3.52
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 4.31 SJR 1.762 SNIP 2.544
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.99 SJR 1.813 SNIP 2.425
Web of Science (2012): Impact factor 3.357
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 4.1 SJR 2.041 SNIP 2.423
Web of Science (2011): Impact factor 3.248
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.957 SNIP 2.298
Web of Science (2010): Impact factor 3.604
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.985 SNIP 2.27
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.613 SNIP 2.156
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.364 SNIP 1.86
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.229 SNIP 1.64
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.596 SNIP 1.73
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 1.203 SNIP 1.864
Scopus rating (2003): SJR 1.068 SNIP 1.446
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 1.065 SNIP 1.284
Scopus rating (2001): SJR 1.062 SNIP 1.269
Scopus rating (2000): SJR 1.161 SNIP 1.295
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 1.086 SNIP 1.141
Original language: English
Retention of Organic Elements during Solid Fuel Pyrolysis with Emphasis on the Peculiar Behavior of Nitrogen

General information
State: Published
Organisations: Center for Phase Equilibria and Separation Processes, Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Lang, T., Jensen, A., Jensen, P. A.
Pages: 1631-1643
Publication date: 2005
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 19
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.3
Web of Science (2014): Impact factor 2.79
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.52
Web of Science (2013): Impact factor 2.733
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.25
Web of Science (2012): Impact factor 2.853
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.05
Web of Science (2011): Impact factor 2.721
ISI indexed (2011): ISI indexed yes
Secondary Capture of Chlorine and Sulfur during Thermal Conversion of Biomass

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Contributors: Knudsen, J. N., Jensen, P. A., Lin, W., Dam-Johansen, K.
Pages: 606-617
Publication date: 2005
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 19
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.3
Web of Science (2014): Impact factor 2.79
Web of Science (2014): Indexed yes
Measurements on sootblowing of ash deposits in a convective pass of a straw fired boiler (AVV2)

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Zhou, H., Hansen, J., Jensen, P. A.
Publication date: 2004

Publication information
Place of publication: DTU, Kgs. Lyngby
Original language: English
Source: orbit
Source-ID: 116857
Research output: Research - peer-review › Report – Report year: 2004

Quantification of the release of Cl, K and S to the gas phase from combustion of annual biomass.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Knudson, J., Jensen, P. A., Dam-Johansen, K.
Pages: U1075-U1075
Publication date: 2004
Peer-reviewed: Yes

Publication information
Journal: Abstracts of Papers of the American Chemical Society
Volume: 227
ISSN (Print): 0065-7727
Ratings:
Web of Science (2019): Indexed yes
Web of Science (2018): Indexed yes
Web of Science (2017): Indexed yes
Scopus rating (2014): SJR 0.101 SNIP 0.013
Web of Science (2014): Indexed yes
Scopus rating (2013): SJR 0.101 SNIP 0.003
Web of Science (2013): Indexed yes
Scopus rating (2012): SJR 0.1 SNIP 0
Scopus rating (2011): SJR 0.101 SNIP 0
Web of Science (2011): Indexed yes
Scopus rating (2010): SJR 0.102 SNIP 0
Scopus rating (2009): SJR 0.102 SNIP 0
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.102 SNIP 0
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.102 SNIP 0
Scopus rating (2006): SJR 0.102
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.104
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.104 SNIP 0.028
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.123 SNIP 0.013
Scopus rating (2002): SJR 0.141 SNIP 0.096
Web of Science (2002): Indexed yes
Quantification of the Release of Cl, K and S to the Gas Phase from Combustion of Annual Biomass

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Publication date: 2004

Host publication information
Title of host publication: Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, 10-14 May, Rome, Italy
Publisher: Energy Research Centre of the Netherlands (ECN)
Source: orbit
Source-ID: 41498
Research output: Research › Conference abstract in proceedings – Annual report year: 2004

Release of inorganic elements during wood combustion.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: van Lith, S. C., Jensen, P. A., Frandsen, F., Glarborg, P.
Pages: U1075-U1075
Publication date: 2004
Peer-reviewed: Yes

Publication information
Journal: Abstract of Papers of the American Chemical Society
Volume: 227
ISSN (Print): 0065-7727
Ratings:
Web of Science (2019): Indexed yes
Web of Science (2018): Indexed yes
Web of Science (2017): Indexed yes
Scopus rating (2014): SJR 0.101 SNIP 0.013
Web of Science (2014): Indexed yes
Scopus rating (2013): SJR 0.101 SNIP 0.003
Web of Science (2013): Indexed yes
Scopus rating (2012): SJR 0.1 SNIP 0
Scopus rating (2011): SJR 0.101 SNIP 0
Web of Science (2011): Indexed yes
Scopus rating (2010): SJR 0.102 SNIP 0
Scopus rating (2009): SJR 0.102 SNIP 0
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.102 SNIP 0
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.102 SNIP 0
Scopus rating (2006): SJR 0.102
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.104
Web of Science (2005): Indexed yes
SEM Investigation of Superheater Deposits from Biomass-Fired Boilers

Straw is used as fuel in relatively small-scale combined heat and power producing (CHP) grate boilers in Denmark. The large content of potassium and chlorine in straw greatly increases the deposit formation and corrosion of the superheater coils, compared to boilers firing coal. In this study, mature superheater deposit samples were extracted from two straw-fired boilers, Masnedø and Ensted, with fuel inputs of 33 MWth and 100 MWth, respectively. SEM (scanning electron microscopy) images and EDX (energy dispersive X-ray) analyses were performed on the deposit samples. Different strategies are adopted to minimize deposit problems at the two boilers. At Masnedø the final superheater steam temperature is 520 °C, no soot blowing of the superheaters is applied and a relatively large superheater area is used. At Ensted, an external wood-fired superheater is used in order to obtain a final steam temperature of 542 °C, while the steam exit temperature of the straw-fired boiler is 470 °C. The mature Masnedø deposit had a thickness of 2 to 15 centimeters and consisted of three distinct main layers. The thick intermediate layer was depleted in chlorine but rich in Si, K, and Ca. This Masnedø intermediate layer was probably generated by in-situ reaction between KCl and Si-rich ash particles, which leads to release of chlorine-containing gases. The innermost layer contained many sublayers of mainly iron oxide, KCl, and K2SO4. The Ensted deposit had a maximum thickness of a few centimeters. The intermediate Ensted layer consisted of melted KCl with inclusions of Ca- and Si-rich particles, and the innermost layer was an iron oxide next to a potassium sulfate layer. Compared to deposits formed on a probe during short-time experiments, the mature superheater deposits contained larger dense inner sublayers of pure KCl and K2SO4. The present study indicates that the innermost layer of the superheater deposits expands by condensation of KCl, even when the deposit has a thickness of several centimeters.

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Elsam A/S, Energi E2 A/S
Contributors: Jensen, P. A., Frandsen, F., Hansen, J., Dam-Johansen, K., Henriksen, N., Herlyck, S.
Pages: 378-384
Publication date: 2004
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 18
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Simultaneous Thermal Analysis (STA) on Ash from High-Alkali Biomass

**General information**

State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Arvelakis, S., Jensen, P. A., Dam-Johansen, K.
Pages: 1066-1076
Publication date: 2004
Peer-reviewed: Yes

**Publication information**

Journal: Energy & Fuels
Volume: 18
Sulfur Transformations during Thermal Conversion of Herbaceous Biomass

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Knudsen, J. N., Jensen, P. A., Lin, W., Frandsen, F., Dam-Johansen, K.
Pages: 810-819
Publication date: 2004
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 18
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.3
Web of Science (2014): Impact factor 2.79
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.52
Web of Science (2013): Impact factor 2.733
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.25
Web of Science (2012): Impact factor 2.853
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.05
Web of Science (2011): Impact factor 2.721
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Web of Science (2010): Impact factor 2.444
Web of Science (2010): Indexed yes
The Joint Project – Straw Combustion on a Grate, Physical, Chemical and Reaction Kinetic Data for Grate Modeling

**General information**
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Department of Mechanical Engineering
Number of pages: 150
Publication date: 2004

**Publication information**
Original language: English
Source: orbit
Source-ID: 129962
Research output: Research - peer-review › Journal article – Annual report year: 2004

Transformation and Release to the Gas Phase of Cl, K, and S during Combustion of Annual Biomass

**General information**
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 1385-1399
Publication date: 2004
Peer-reviewed: Yes

**Publication Information**
Journal: Energy & Fuels
Volume: 18
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Ash and Deposit Formation in the Biomass Co-Fired Masnedø Combined Heat and Power Production Plant

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Pages: 1-17
Publication date: 2003
Peer-reviewed: Yes

Publication information
Heat Transfer in a Fixed Bed of Straw Char

A model for the thermal conductivity of a straw char bed has been developed. The model extends the work of Yagi and Kunii to describe heat transfer in a bed of cylinders, using a relationship between the interparticle distance and the external porosity. To verify the model, thermal conductivity experiments were performed on shredded and un-shredded straw char samples, varying particle size, bed packing (loose or dense), and temperature. Predictions with the model, using the measured external porosity and particle diameter as input parameters, are in agreement with measurements within the experimental uncertainty over the range of conditions investigated. The heat transfer model was used in a parametric study to evaluate the effect of gas flow rate, particle diameter, porosity, and temperature on the thermal conductivity in a straw char bed.

General information
State: Published
Organisations: Department of Mechanical Engineering, CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 1251-1258
Publication date: 2003
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 17
Issue number: 5
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
Deposit Formation and Corrosion in the Air Pre-heater of a Straw-fired Combined Heat and Power Production Boiler

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 1-23
Publication date: 2002
Peer-reviewed: Yes
Experimental study of char thermal deactivation

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 1065-1075
Publication date: 2002
Peer-reviewed: Yes

HCI and SO2 Emissions from Full-Scale Biomass Fired Boilers

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Jensen, P. A., Frandsen, F., Dam-Johansen, K.
Publication date: 2001

Host publication information
Title of host publication: Proceedings
Source: orbit
Source-ID: 63970
Research output: Research › Article in proceedings – Annual report year: 2001

Investigation of Superheater Deposits From Two Straw Fired Boilers, Effects of Coal Quality on Power Plant Management: Ash Problems, Management and Solutions

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Contributors: Jensen, P. A., Frandsen, F., Hansen, J., Skriver, A., Henriksen, N., Hörlyck, S., Dam-Johansen, K.
Publication date: 2001

Host publication information
Title of host publication: Proceedings
Source: orbit
Source-ID: 63984
Research output: Research › Article in proceedings – Annual report year: 2001

Laboratory Investigation of the Release to Gas Phase of Potassium, Sulphur and Chlorine at Grate Combustion Conditions

General information
Low-Temperature Ash Deposit Formation and corrosion in Biomass-Fired Combined Heat and Power Production Boilers

Abstract

Pretreatment of straw for power production by pyrolysis and char wash

Removal of K and Cl by leaching of straw char
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4 SJR 1.235 SNIP 1.436
Web of Science (2017): Impact factor 3.358
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.71 SJR 1.198 SNIP 1.385
Web of Science (2016): Impact factor 3.219
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.03 SJR 1.51 SNIP 1.596
Web of Science (2015): Impact factor 3.249
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.36 SJR 1.865 SNIP 1.964
Web of Science (2014): Impact factor 3.394
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 4.42 SJR 1.666 SNIP 1.811
Web of Science (2013): Impact factor 3.411
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.66 SJR 1.516 SNIP 1.754
Web of Science (2012): Impact factor 2.975
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 4.74 SJR 1.759 SNIP 2.296
Web of Science (2011): Impact factor 3.646
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.914 SNIP 2.251
Web of Science (2010): Impact factor 3.84
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.728 SNIP 2.183
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.614 SNIP 2.137
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.361 SNIP 1.825
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.268 SNIP 1.991
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.214 SNIP 1.401
Scopus rating (2004): SJR 1.027 SNIP 1.665
Web of Science (2004): Indexed yes
The Influence of Inorganic Materials on the Thermal Deactivation of Fuel Chars

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering
Pages: 1110-1122
Publication date: 2001
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 15
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.34
Web of Science (2015): Impact factor 2.835
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.3
Web of Science (2014): Impact factor 2.79
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.52
Web of Science (2013): Impact factor 2.733
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.25
Web of Science (2012): Impact factor 2.853
Experimental Investigation of the Transformation and Release to Gas Phase of Potassium and Chlorine during Straw Pyrolysis

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Contributors: Jensen, P. A., Frandsen, F., Dam-Johansen, K., Sander, B.
Pages: 1280-1285
Publication date: 2000
Peer-reviewed: Yes

Publication information
Journal: Energy & Fuels
Volume: 14
ISSN (Print): 0887-0624
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.55
Web of Science (2017): Impact factor 3.024
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.49
Web of Science (2016): Impact factor 3.091
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Grate Firing of Straw: Activities in the CHEC Research Centre

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Publication date: 2000

Host publication information
Title of host publication: Grate Firing of Straw: Activities in the CHEC Research Centre
Source: orbit
Source-ID: 176862
Research output: Research - peer-review › Article in proceedings – Annual report year: 2000
Release of Potassium and Chlorine during Straw Pyrolysis

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Contributors: Jensen, P. A., Dam-Johansen, K.
Publication date: 1999

Possibilities and evaluation of straw pretreatment.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Nordjyllandværket A/S, Elsam A/S
Pages: 224-228
Publication date: 1998

Pretreatment of Biofuels for Power Production.: 2nd annual progress report (1997)

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Elsam A/S
Contributors: Jensen, P. A., Sander, B., Dam-Johansen, K.
Number of pages: 10
Publication date: 1998

Deposition investigation in straw-fired boilers

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Jensen, P., Stenholm, M., Hald, P.
Pages: 1048-1055
Publication date: 1997
Peer-reviewed: No

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Elsam A/S, Hempel A/S
Publication date: 1997

Publication information
Original language: English
Source: orbit
Source-ID: 296370
Research output: Research › Journal article – Annual report year: 1997

Pretreatment of straw by pyrolysis and char wash

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Hempel A/S, Elsam A/S
Publication date: 1997

Host publication information
Title of host publication: Pretreatment of straw by pyrolysis and char wash
Source: orbit
Source-ID: 174952
Research output: Research › Report – Annual report year: 1997

Biomasses brændsels- og fyringskarakteristika. Analysearbejde

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Stenholm, M., Westborg, S., Jensen, P. A.
Number of pages: 42
Publication date: 1996

Publication information
Place of publication: dk-Teknik, Søborg
Publisher: Forskningscenter Risø
Original language: Danish
(Energiministeriets Forskningsudvalg for produktion og fordeling af el og varme. Brændsler og forbrændingsteknik).
Source: orbit
Source-ID: 295096
Research output: Research › Book – Annual report year: 1996

Biomasses brændsels- og fyringskarakteristika. Fyringsforsøg

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Stenholm, M., Jensen, P. A., Hald, P.
Publication date: 1996

Publication information
Deposition investigation in straw fired boilers

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Jensen, P., Stenholm, M., Christensen, K.
Publication date: 1995
Host publication information
Title of host publication: 210th ACS national meeting
Place of publication: Washington, DC
Publisher: American Chemical Society. Division of Fuel Chemistry
(American Chemical Society preprints of papers, vol. 40, no. 3).
Source-ID: 293708
Research output: Research › Article in proceedings – Annual report year: 1995

Deposition investigation on straw fired boilers

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Jensen, P., Stenholm, M., Hald, P.
Investigation of burn out and deposition at straw fired boiler plants

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Jensen, P.
Publication date: 1995
Peer-reviewed: No
Event: Abstract from Nordic seminar on thermochemical conversion of solid fuels. NTH, Trondheim (NO), 13-14 Dec., .
Source: orbit
Source-ID: 293230
Research output: Research › Conference abstract for conference – Annual report year: 1995

Modelling of swirl stabilised pulverised-coal flames in an axi-symmetric 1.3 MW furnace

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Bech, N. M., Jensen, P. A.
Number of pages: 25
Publication date: 1995
Publication information
ISBN (Print): 87-550-2045-3
Original language: English
(Denmark. Forskningscenter Risoe. Risoe-R; No. 792(EN)).
Keywords: Risø-R-792, Risø-R-792(EN)
Source: orbit
Source-ID: 293525
Research output: Research › Report – Annual report year: 1995

Interview og litteraturundersøgelse af halms udbrændings- og belægningsegenskaber

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Jensen, P. A., Stenholm, M., Haahr Jørgensen, K.
Number of pages: 39
Publication date: 1994
Publication information
ISBN (Print): 87-550-2038-0
Original language: Danish
(Denmark. Forskningscenter Risoe. Risoe-R; No. 786(DA)).
Keywords: Risø-R-786, Risø-R-786(DA)
Source: orbit
Source-ID: 291748
Research output: Research › Report – Annual report year: 1994

Afprøvning og verifikation af laserbaserede metoder i kulstøvfyret kedel

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Clausen, S., Jensen, P. A., Rathmann, O.
Projects:

**Optimization of geo-polymer cement production technology**
Segura, I. P., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, P. A., Main Supervisor
Dame, A. J., Supervisor
01/04/2019 → 31/03/2022
Project: PhD

**Ash transformation in waste boilers and optimization of novel steam superheater**
Dotti, M., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, P. A., Main Supervisor
Clausen, S., Supervisor
01/04/2019 → 31/03/2022
Project: PhD

**Optimized high temperature cyclones used for stone wool production by CFD modelling**
Jønck, K. M., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, P. A., Main Supervisor
Glarborg, P., Supervisor
Hansen, L. E., Supervisor
Zhou, H., Supervisor
Industrial PhD
15/04/2018 → 06/06/2021
Award relations: Optimized high temperature cyclones used for stone wool production by CFD modelling
Project: PhD

**Use of Zeolites for Tar De-Oxygenation**
Eschenbacher, A., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Ahrenfeldt, J., Supervisor
Henriksen, U. B., Supervisor
Jensen, P. A., Supervisor
Samfinansieret - Andet
01/02/2017 → 31/01/2020
Award relations: Use of Zeolites for Tar De-Oxygenation
Project: PhD

**Alternative liquid fuels in burners optimized for low NOx emissions and high burn out**
Cafaggi, G., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, P. A., Main Supervisor
Dam-Johansen, K., Supervisor
Glarborg, P., Supervisor
Fonde
01/01/2017 → 31/12/2019
Award relations: Alternative liquid fuels in burners optimized for low NOx emissions and high burn out
Project: PhD
Design af fremtidens energianlæg
Clausen, L. R., PhD Student, Department of Mechanical Engineering
Elmegaard, B., Main Supervisor
Houbak, N., Supervisor
Jensen, P. A., Examiner
Nielsen, P. E. H., Examiner
Larson, E. D., Examiner
DTU-lønnet stipendie
15/05/2007 → 28/09/2011
Award relations: Design af fremtidens energianlæg
Project: PhD

Oxy-fuel forbrænding af kul og biomasse
Toftegaard, M. B., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Glarborg, P., Supervisor
Jensen, P. A., Supervisor
Sander, B., Supervisor
Jappe Frandsen, F., Examiner
Hupa, M. M., Examiner
Jensen, L. S., Examiner
ErhvervsPhD-ordningen VTU
01/04/2007 → 24/08/2011
Award relations: Oxy-fuel forbrænding af kul og biomasse
Project: PhD

Brændselsfleksible brændere til cement- og mineralindustri
Nørskov, L. K., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Glarborg, P., Supervisor
Jensen, P. A., Supervisor
Larsen, M. B., Supervisor
Jappe Frandsen, F., Examiner
Brink, A. S., Examiner
Emberger, B., Examiner
ErhvervsPhD-ordningen VTU
01/01/2009 → 17/12/2012
Award relations: Brændselsfleksible brændere til cement- og mineralindustri
Project: PhD

Katalytisk syntese af langkædedede alkoholer fra syntesegas fremstillet ved forgasning af kul og biomasse
Christensen, J. M., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Jensen, P. A., Supervisor
Hinrichsen, K., Examiner
Knudsen, K., Examiner
Dahl, S., Examiner
DTU-lønnet stipendie
15/09/2007 → 13/04/2011
Award relations: Katalytisk syntese af langkædedede alkoholer fra syntesegas fremstillet ved forgasning af kul og biomasse
Project: PhD

Emmissioner fra forbrænding af biomasse
Knudsen, J. N., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Jensen, P. A., Supervisor
Lin, W., Supervisor
Livbjerg, H., Examiner
Hupa, M. M., Examiner
Pedersen, L. S., Examiner
Nordisk finansiering
01/04/2001 → 10/01/2005
Award relations: Emissioner fra forbrænding af biomasse  
Project: PhD

Optimized recycling in an integrated melting furnace for production of stone wool melt
Schultz-Falk, V., PhD Student, Department of Chemical and Biochemical Engineering  
Jensen, P. A., Main Supervisor  
Dam-Johansen, K., Supervisor  
Hansen, L. E., Supervisor  
Solvang, M., Supervisor  
Industrial PhD  
01/08/2016 → 13/02/2020  
Award relations: Optimized recycling in an integrated melting furnace for production of stone wool melt  
Project: PhD

Computational Fluid Dynamics (CFD) Study of Bio-Dust Combustion
Leth-Espensen, A., PhD Student, Department of Chemical and Biochemical Engineering  
Glarborg, P., Main Supervisor  
Dam-Johansen, K., Supervisor  
Jensen, P. A., Supervisor  
Technical University of Denmark  
01/05/2016 → 30/04/2019  
Award relations: Computational Fluid Dynamics (CFD) Study of Bio-Dust Combustion  
Project: PhD

Biomass Particle ignition in mill equipment
Schwarzer, L., PhD Student, Department of Chemical and Biochemical Engineering  
Jensen, P. A., Main Supervisor  
Dam-Johansen, K., Supervisor  
Glarborg, P., Supervisor  
Holm, J. K., Supervisor  
Technical University of Denmark  
15/12/2015 → 14/06/2019  
Award relations: Biomass Particle ignition in mill equipment  
Project: PhD

Biomass Particle Morphology and Combustion Properties
Masche, M., PhD Student, Department of Chemical and Biochemical Engineering  
Ahrenfeldt, J., Main Supervisor  
Puig Arnavat, M., Supervisor  
Clausen, S., Supervisor  
Henriksen, U. B., Supervisor  
Holm, J. K., Supervisor  
Jensen, P. A., Supervisor  
Stelte, W., Examiner  
Shang, L., Examiner  
Dahl, J., Examiner  
Samfinansierede - Virksomhed  
01/01/2016 → 31/01/2019  
Award relations: Biomass Particle Morphology and Combustion Properties  
Project: PhD

Hydrogen assisted catalytic biomass pyrolysis for green fuels
Stummann, M. Z., PhD Student, Department of Chemical and Biochemical Engineering  
Jensen, A. D., Main Supervisor  
Hej, M., Supervisor  
Jensen, P. A., Supervisor  
Sundet, J. K., Supervisor  
Hansen, B. B., Examiner  
Knudsen, K., Examiner  
Prins, W., Examiner  
Samfinansieret - Andet  
01/10/2015 → 30/11/2018
Award relations: Hydrogen assisted catalytic biomass pyrolysis for green fuels
Project: PhD

**HCI emission from cement plants**
Pachitsas, S., PhD Student, Department of Chemical and Biochemical Engineering
Wedel, S., Main Supervisor
Dam-Johansen, K., Supervisor
Jensen, L. S., Supervisor
Jensen, P. A., Examiner
Pederssen, K. H., Examiner
Yrjas, P. K., Examiner
Samfinansierede - Virksomhed
15/05/2015 → 04/03/2019
Award relations: HCI emission from cement plants
Project: PhD

**Burners for Cement Kilns**
Pedersen, M. N., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Clausen, S., Supervisor
Jensen, P. A., Supervisor
Jensen, L. S., Supervisor
Christensen, J. M., Examiner
Hansen, L. E., Examiner
Tokheim, L., Examiner
Samfinansierede - Virksomhed
01/03/2015 → 17/09/2018
Award relations: Burners for Cement Kilns
Project: PhD

**NOx reduction in grate-firing solid waste power plants**
Jepsen, M. S., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Jensen, P. A., Supervisor
Norman, T., Supervisor
Jappe Frandsen, F., Examiner
Hvid, S. L., Examiner
Løvås, T., Examiner
Industrial PhD
15/12/2014 → 16/08/2018
Award relations: NOx reduction in grate-firing solid waste power plants
Project: PhD

**Prediction of Deposit Formation in Biomass Fired Suspension Boilers - Gaining fundamental Data neede for Mechanistic Deposit Modelling**
Laxminarayanan, Y., PhD Student, Department of Chemical and Biochemical Engineering
Jappe Frandsen, F., Main Supervisor
Glarborg, P., Supervisor
Sander, B., Supervisor
Wedel, S., Examiner
Hupa, M. M., Examiner
Norman, T., Examiner
Samfinansierede - Virksomhed
15/10/2014 → 22/05/2018
Award relations: Prediction of Deposit Formation in Biomass Fired Suspension Boilers - Gaining fundamental Data neede for Mechanistic Deposit Modelling
Project: PhD

**Using Coal Ash and other Additives in Suspension Fired Biomass Power Plant Boilers using Coal Ash and other Additives in Supension Fired Biomass Power plant Boilers**
Wang, G., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, P. A., Main Supervisor
Jappe Frandsen, F., Supervisor
Glarborg, P., Supervisor
Lin, W., Examiner
Pettersson, A., Examiner
Sander, B., Supervisor
Wadenbäck, J., Examiner
Eksternt finansieret virksomhed
01/10/2014 → 22/05/2018
Award relations: Using Coal Ash and other Additives in Suspension Fired Biomass Power Plant Boilers using Coal Ash and other Additives in Supension Fired Biomass Power plant Boilers
Project: PhD

Flashpyrolyse af Halm in Situ
Bech, N., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Jensen, P. A., Supervisor
Wedel, S., Examiner
Hustad, J. E., Examiner
Madsen, O. H., Examiner
InnovationsPhD
01/09/2004 → 29/08/2008
Award relations: Flashpyrolyse af Halm in Situ
Project: PhD

Reactivity and Burnout of Wood Fuels
Dall'Ora, M., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Jensen, P. A., Supervisor
Glarborg, P., Examiner
Jensen, J. P., Examiner
Skreiberg, Ø., Examiner
Eksternt finansieret virksomhed
01/12/2004 → 14/12/2011
Award relations: Reactivity and Burnout of Wood Fuels
Project: PhD

Gas-phase Sulfur, Chlorine and Alkali Metal Chemistry in Biomass Combustion
Løj, L. H., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Jappe Frandsen, F., Supervisor
Livbjerg, H., Supervisor
Jensen, P. A., Examiner
Hupa, M. M., Examiner
Kristensen, P. G., Examiner
Eksternt finansieret virksomhed
01/09/2003 → 03/09/2007
Award relations: Gas-phase Sulfur, Chlorine and Alkali Metal Chemistry in Biomass Combustion
Project: PhD

Release of inorganic metal species, sulfur and chlorie during biomass combustion on a grate
van Lith, S. C., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Jappe Frandsen, F., Supervisor
Jensen, P. A., Supervisor
Skrifvars, B., Examiner
Pedersen, L. S., Examiner
Unterberger, S., Examiner
Forskningsrådsfinansiering
01/01/2002 → 24/01/2006
Award relations: Release of inorganic metal species, sulfur and chlorie during biomass combustion on a grate
Project: PhD
Flash Pyrolysis of Energy Crops
Ibrahim, N., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Jensen, P. A., Supervisor
Dama, A. J., Examiner
Lundtorp, K., Examiner
Stipendie fra udlanget
01/07/2007 → 21/11/2012
Award relations: Flash Pyrolysis of Energy Crops
Project: PhD

NO Formation and destruction in the freeboard of Grate Boilers: CFD Model Development and Verification by Bench Scale Measurements
Andersen, J., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Hvid, S. L., Supervisor
Jensen, P. A., Supervisor
Hassager, O., Examiner
Eriksson, J. G., Examiner
Levås, T., Examiner
DTU-lønnet stipendie
01/04/2006 → 01/09/2010
Award relations: NO Formation and destruction in the freeboard of Grate Boilers: CFD Model Development and Verification by Bench Scale Measurements
Project: PhD

Pre-Treatment (and Enzymatic Hydrolysis) of Ligno-Cellulose
Andric, P., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Jensen, P. A., Supervisor
Meyer, A. S., Supervisor
Viladsen, J., Examiner
Liden, G., Examiner
Olsen, H. S., Examiner
DTU-lønnet stipendie
01/10/2005 → 21/12/2010
Award relations: Pre-Treatment (and Enzymatic Hydrolysis) of Ligno-Cellulose
Project: PhD

Lignocellulose Pretreatment for Lignin Removal and Maximal Enzymatic (Ligno) Cellulose Degradation
Pedersen, M., PhD Student, Department of Chemical and Biochemical Engineering
Meyer, A. S., Main Supervisor
Johansen, K. S., Supervisor
Pedersen, S., Supervisor
Jensen, P. A., Examiner
Zacchi, G. N., Examiner
Larsen, J., Examiner
DTU, Samfinansiering
01/04/2007 → 01/09/2010
Award relations: Lignocellulose Pretreatment for Lignin Removal and Maximal Enzymatic (Ligno) Cellulose Degradation
Project: PhD

Model for deposition build-up in biomass boilers
Hansen, S. B., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Jappe Frandsen, F., Supervisor
Jensen, P. A., Supervisor
Dama, A. J., Examiner
Jensen, J. P., Examiner
Gupta, R., Examiner
1/3 DTU-stip, 2/3 FUR/andet
Clinker Burning Kinetics and Mechanisms
Telschow, S., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Jappe Frandsen, F., Supervisor
Wedel, S., Supervisor
Jensen, P. A., Examiner
Hupa, M. M., Examiner
Jensen, L. S., Examiner
DTU-lønnet stipendie
01/03/2008 → 24/05/2012
Award relations: Clinker Burning Kinetics and Mechanisms
Project: PhD

Production, Refining and Utilization of Biomass for Energy Services
Saleh, S. B., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Hansen, B. B., Supervisor
Jensen, P. A., Supervisor
Ahrenfeldt, J., Examiner
Holm, J. K., Examiner
Brink, A. S., Examiner
Stipendie fra udlandet
01/01/2010 → 26/02/2014
Award relations: Production, Refining and Utilization of Biomass for Energy Services
Project: PhD

Upgrading Fuel Properties of Biomass Fuel and Waste by Torrefaction
Shang, L., PhD Student, Department of Chemical and Biochemical Engineering
Ahrenfeldt, J., Main Supervisor
Henriksen, U. B., Supervisor
Holm, J. K., Supervisor
Jensen, P. A., Examiner
Nordin, A., Examiner
Teislev, B. I. B., Examiner
Programbevilling
01/01/2010 → 24/06/2013
Award relations: Upgrading Fuel Properties of Biomass Fuel and Waste by Torrefaction
Project: PhD

Biomass and Coal Gasification in entrained-flow reactor
Qin, K., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Jensen, P. A., Supervisor
Lin, W., Supervisor
Henriksen, U. B., Examiner
Engvall, K., Examiner
Jensen, J. P., Examiner
Forskningsrådskendsel
01/01/2009 → 01/03/2013
Award relations: Biomass and Coal Gasification in entrained-flow reactor
Project: PhD

Characterization and quantification of deposits build up and removal in straw suspension fired boilers
Shafique Bashir, M., PhD Student, Department of Chemical and Biochemical Engineering
Dam-Johansen, K., Main Supervisor
Jappe Frandsen, F., Supervisor
Jensen, P. A., Supervisor
Wedel, S., Supervisor
**Glarborg, P., Examiner**  
**Jensen, J. P., Examiner**  
**Tran, H., Examiner**  
**Offentlig finansiering**  
*01/09/2008 → 30/09/2012*  
**Award relations:** Characterization and quantification of deposits build up and removal in straw suspension fired boilers  
**Project:** PhD

**Treatment of Lignin and Waste Residues by Flash Pyrolysis**  
**Trinh, N. T., PhD Student, Department of Chemical and Biochemical Engineering**  
**Dam-Johansen, K., Main Supervisor**  
**Jensen, P. A., Supervisor**  
**Jappe Frandsen, F., Examiner**  
**Jensen, L. S., Examiner**  
**Spliethoff, H., Examiner**  
*1/3 DTU-stip, 2/3 FUR/andet*  
*01/01/2010 → 30/09/2013*  
**Award relations:** Treatment of Lignin and Waste Residues by Flash Pyrolysis  
**Project:** PhD

**Modeling and Experimental Investigation of Entrained-Flow Gasification of Biomass and Fossil Fuels**  
**Brix, J., PhD Student, Department of Chemical and Biochemical Engineering**  
**Jensen, A. D., Main Supervisor**  
**Jensen, P. A., Supervisor**  
**Wedel, S., Examiner**  
**Leckner, B., Examiner**  
**Pedersen, L. S., Examiner**  
**Anden EU-finansiering**  
*01/10/2007 → 11/05/2011*  
**Award relations:** Modeling and Experimental Investigation of Entrained-Flow Gasification of Biomass and Fossil Fuels  
**Project:** PhD

**Gas-Solid reactions and reactor systems**  
**Azizaddini, S., PhD Student, Department of Chemical and Biochemical Engineering**  
**Dam-Johansen, K., Main Supervisor**  
**Jensen, P. A., Supervisor**  
**Lin, W., Supervisor**  
**Henriksen, U. B., Examiner**  
**Li, S., Examiner**  
**Enk Weinell, C., Examiner**  
*1/3 DTU-stip, 2/3 FUR/andet*  
*01/12/2012 → 26/05/2016*  
**Award relations:** Gas-Solid reactions and reactor systems  
**Project:** PhD

**New Catalytic materials for combined particulate and NOx removal**  
**Linde, K., PhD Student, Department of Chemical and Biochemical Engineering**  
**Jensen, A. D., Main Supervisor**  
**Gabrielsonn, P., Supervisor**  
**Hansen, B. B., Supervisor**  
**Jensen, P. A., Supervisor**  
**Ansat eksternt**  
*01/07/2013 → 30/06/2019*  
**Award relations:** New Catalytic materials for combined particulate and NOx removal  
**Project:** PhD

**selective and efficient synthesis of ethanol from dimethyl ether and syngas**  
**Rasmussen, D. B., PhD Student, Department of Chemical and Biochemical Engineering**  
**Jensen, A. D., Main Supervisor**  
**Christensen, J. M., Supervisor**  
**Moses, P. G., Supervisor**  
**Riisager, A., Supervisor**  
*01/09/2011 → 30/09/2012*  
**Award relations:** selective and efficient synthesis of ethanol from dimethyl ether and syngas  
**Project:** PhD
Rossmeisl, J., Supervisor
Studt, F., Supervisor
Jensen, P. A., Examiner
Temel, B., Supervisor
Sehested, J., Examiner
Swang, O., Examiner
1/3 FUU, 1/3 inst 1/3 Andet
15/12/2011 → 30/09/2015
Award relations: selective and efficient synthesis of ethanol from dimethyl ether and syngas
Project: PhD

Single Biomass Particle Combustion and Fuel Characterization
Trubetskaya, A., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Jensen, P. A., Supervisor
Jensen, A. D., Supervisor
Shapiro, A., Supervisor
Ahrenfeldt, J., Examiner
Thunman, H., Examiner
Wadenbäck, J., Examiner
Forskningsrådetsfinansiering
01/04/2012 → 18/08/2016
Award relations: Single Biomass Particle Combustion and Fuel Characterization
Project: PhD

Ash Chemistry in Circulating Fluidized Bed
Narayan, V., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Henriksen, U. B., Supervisor
Jensen, P. A., Supervisor
Illerup, J. B., Examiner
Gebel, B., Examiner
Wang, L., Examiner
Institut, samfinansiering
01/07/2011 → 24/06/2016
Award relations: Ash Chemistry in Circulating Fluidized Bed
Project: PhD

Catalytic Steam reforming of Bio-Oil to Hydrogen Rich Gas
Trane-Restrup, R., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Dahl, S., Supervisor
Jensen, P. A., Examiner
Grunwaldt, J., Examiner
Østergaard, M., Examiner
Technical University of Denmark
15/08/2010 → 18/12/2013
Award relations: Catalytic Steam reforming of Bio-Oil to Hydrogen Rich Gas
Project: PhD

Power plant burners for biodust combustion
Johansen, J. M., PhD Student, Department of Chemical and Biochemical Engineering
Glarborg, P., Main Supervisor
Jensen, P. A., Supervisor
Henriksen, U. B., Examiner
Norman, T., Examiner
Obernberger, I., Examiner
Institut, samfinansiering
01/09/2011 → 20/04/2016
Award relations: Power plant burners for biodust combustion
Project: PhD
Catalytic Conversion of Bio-oil to Fuel for Transportation
Mortensen, P. M., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Grunwaldt, J., Supervisor
Jensen, P. A., Supervisor
Riisager, A., Examiner
Gabrielsen, J., Examiner
Murzin, D., Examiner
1/3 FUU, 1/3 inst 1/3 Andet
15/08/2010 → 23/04/2014
Award relations: Catalytic Conversion of Bio-oil to Fuel for Transportation
Project: PhD

Simultaneous fast pyrolysis and in situ hydrogenation of lignin to obtain a marine diesel fuel
Zhou, G., PhD Student, Department of Chemical and Biochemical Engineering
Jensen, A. D., Main Supervisor
Jensen, P. A., Supervisor
Knudsen, N. O., Supervisor
Hansen, B. B., Examiner
Seshan, K., Examiner
Taarning, E., Examiner
1/3 FUU, 1/3 inst 1/3 Andet
01/10/2012 → 14/03/2016
Award relations: Simultaneous fast pyrolysis and in situ hydrogenation of lignin to obtain a marine diesel fuel
Project: PhD

Enzymatic Upgrading of Plant Biomass
Tsai, C. T., PhD Student, Department of Chemical and Biochemical Engineering
Meyer, A. S., Main Supervisor
Johansen, K. S., Supervisor
Jensen, P. A., Examiner
Liden, G., Examiner
Olsen, H. S., Examiner
DTU, Samfinansiering
01/05/2008 → 30/09/2013
Award relations: Enzymatic Upgrading of Plant Biomass
Project: PhD

CHEC
CHEC is an acronym for the fundamental and applied research programme on Combustion and Harmful Emission Control. CHEC’s main areas of expertise are industrial high-temperature processes, formation and removal of pollutants, particulate solids (characterisation, reactivity and dynamics). Within these areas the objectives are to educate scientists and engineers, to gain new fundamental information on the subjects, to assist industry and public authorities in the selection, development, design and operation of processes in order to improve efficiencies and in order to avoid or minimise harmful emissions, to catalyse international cooperation between Danish companies and Danish and foreign research organisations.

Dam-Johansen, K., Project Manager, Department of Chemical and Biochemical Engineering
Ambrosius, M., Project Participant, Department of Chemical and Biochemical Engineering
Bank, L. H., Project Participant, Department of Chemical and Biochemical Engineering
Becerra, S. V., Project Participant, Department of Chemical and Biochemical Engineering
Cenni, R., Project Participant, Department of Chemical and Biochemical Engineering
Jappe Frandsen, F., Project Participant, Department of Chemical and Biochemical Engineering
Frandsen, J., Project Participant, Department of Chemical and Biochemical Engineering
Glarborg, P., Project Participant, Department of Chemical and Biochemical Engineering
Hansen, E. M. T. H., Project Participant, Department of Chemical and Biochemical Engineering
Hansen, J., Project Participant, Department of Chemical and Biochemical Engineering
Henriksen, A., Project Participant, Department of Chemical and Biochemical Engineering
Jensen, A. D., Project Participant, Department of Chemical and Biochemical Engineering
Jensen, L. S., Project Participant, Department of Chemical and Biochemical Engineering
Jensen, P. A., Project Participant, Department of Chemical and Biochemical Engineering
Jørgensen, T. L., Project Participant, Department of Chemical and Biochemical Engineering
Lans, R. P. V. D., Project Participant, Department of Chemical and Biochemical Engineering
Lin, W., Project Participant, Department of Chemical and Biochemical Engineering
Stenseng, M., Project Participant, Department of Chemical and Biochemical Engineering
Wolfe, T., Project Participant, Department of Chemical and Biochemical Engineering
Zolin, A., Project Participant, Department of Chemical and Biochemical Engineering
Degn, L., Project Participant, Department of Chemical and Biochemical Engineering
Kill, S., Project Participant, Department of Chemical and Biochemical Engineering
Kristensen, K. A., Project Participant, Department of Chemical and Biochemical Engineering
Michelsen, H. P., Project Participant, Department of Chemical and Biochemical Engineering
Olsen, S. M., Project Participant, Department of Chemical and Biochemical Engineering
Skjøth-Rasmussen, M. S., Project Participant, Department of Chemical and Biochemical Engineering
Rejel, H., Project Participant, Department of Chemical and Biochemical Engineering
Schmidt, L. M., Project Participant, Department of Chemical and Biochemical Engineering
Frey, M., Project Participant, Department of Chemical and Biochemical Engineering
Kristensen, L., Project Participant, Department of Chemical and Biochemical Engineering
Nygaard, H. G., Project Participant, Department of Chemical and Biochemical Engineering
Leth-Miller, R., Project Participant, Department of Chemical and Biochemical Engineering
Sullivan, N. P., Project Participant, Department of Chemical and Biochemical Engineering
Bendtsen, A. B., Project Participant, Department of Chemical and Biochemical Engineering
Johnsson, J. E., Project Participant, Department of Applied Chemistry

Ukendt: DKK12,000,000.00
10/01/1986 → …


Award relations: CHEC
Project: Research

Efficient and Clean Use of Biomass for Power and Heat Production. Phase I.

Pretreatment of biomass fuels for power production. Fluid bed combustion of biomass. Ash formation and emission of trace compounds. Formation and sinting of deposits.

Dam-Johansen, K., Project Manager, Department of Chemical and Biochemical Engineering
Andersen, K. H., Project Participant, Department of Chemical and Biochemical Engineering
Jappe Frandsen, F., Project Participant, Department of Chemical and Biochemical Engineering
Hansen, E. M. T. H., Project Participant, Department of Chemical and Biochemical Engineering
Hansen, J., Project Participant, Department of Chemical and Biochemical Engineering
Bank, L. H., Project Participant, Department of Chemical and Biochemical Engineering
Hansen, L. A., Project Participant, Department of Chemical and Biochemical Engineering
Jensen, P. A., Project Participant, Department of Chemical and Biochemical Engineering
Lin, W., Project Participant, Department of Chemical and Biochemical Engineering
Michelsen, H. P., Project Participant, Department of Chemical and Biochemical Engineering
Wolfe, T., Project Participant, Department of Chemical and Biochemical Engineering
Jørgensen, T. L., Project Participant, Department of Chemical and Biochemical Engineering
Johnsson, J. E., Project Participant, Department of Applied Chemistry

Ukendt: DKK5,500,000.00, Ukendt: DKK4,100,000.00
01/01/1996 → 31/12/1998

Award relations: Efficient and Clean Use of Biomass for Power and Heat Production. Phase I., Efficient and Clean Use of Biomass for Power and Heat Production. Phase I.
Project: Research

Activities:

Modelling Thermal Runaway of Pulverized Biomass

Period: 7 Sep 2018
Lars Schwarzer (Speaker)
Peter Arendt Jensen (Other)
Peter Glarborg (Other)
Jens Kai Holm (Other)
Kim Dam-Johansen (Other)

Department of Chemical and Biochemical Engineering
Parameters important for char yield prediction for biomass devolatilized under high heating rates determined by chemometrics
Period: 7 Sep 2018
Anna Leth-Espensen (Speaker)
Peter Glarborg (Other)
Peter Arendt Jensen (Other)
Department of Chemical and Biochemical Engineering
CHEC Research Centre
The Hempel Foundation Coatings Science and Technology Centre (CoaST)

Reaction kinetics for biomass self-ignition at 150–230°C
Period: 29 Jul 2018 → 3 Aug 2018
Lars Schwarzer (Other)
Peter Arendt Jensen (Other)
Peter Glarborg (Other)
Jens Kai Holm (Other)
Kim Dam-Johansen (Other)
Department of Chemical and Biochemical Engineering
CHEC Research Centre
The Hempel Foundation Coatings Science and Technology Centre (CoaST)

37th International Symposium on Combustion
29/07/2018 → 03/08/2018
Camera Measurements in Cement Kilns – Impact of Alternative Fuels on Kiln Flames
Period: 10 Oct 2017 → 11 Oct 2017
Morten Nedergaard Pedersen (Guest lecturer)
Mads Nielsen (Guest lecturer)
Sønnik Clausen (Guest lecturer)
Peter Arendt Jensen (Guest lecturer)
Lars Skaarup Jensen (Guest lecturer)
Kim Dam-Johansen (Guest lecturer)
Department of Chemical and Biochemical Engineering
CHEC Research Centre
The Hempel Foundation Coatings Science and Technology Centre (CoaST)

Description
Presentation and extended abstract given at Nordic Flame Days 2017
Documents:
Extended Abstract Nordic Flame Days 2017 - Morten Pedersen - v2

Related event
Nordic Flame Days
10/10/2017 → 11/10/2017
Stockholm, Sweden
Activity: Talks and presentations › Conference presentations