Formation, Sintering and Removal of Biomass Ash Deposits - DTU Orbit (28/10/2019)

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Over the last century, increasing global average temperatures have necessitated the switch from fossil fuels to renewable sources of energy. Biomass, being a CO₂ neutral fuel, can potentially replace coal for electricity and heat production. The biomass sector contributes 9.1% of the global energy consumption and has been growing by 2.5% every year since 2010, with several countries adopting biomass-firing and cofiring in power plants. However, biomass combustion in boilers may lead to several operational problems. Biomass typically contains a high amount of volatile and chemically aggressive ash species, such as K, Cl, and S, which form troublesome deposits on boiler surfaces, especially on superheater tubes. Ash deposits hinder heat transfer to the steam cycle, thereby reducing boiler efficiency, and may completely block flue gas channels in severe cases, causing unscheduled boiler shutdowns. Moreover, biomass ash deposits may cause severe corrosion of boiler surfaces. Therefore, reducing deposit formation and timely deposit removal are essential for optimal boiler operation.

The formation, sintering and removal of boiler deposits has been investigated in this PhD project, by simulating boiler conditions in laboratory-scale setups. Deposit formation was simulated in an Entrained Flow Reactor, to investigate the effect of operating conditions and ash chemistry on the rate of deposit formation. Experiments were performed 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 model fly ash particles were mixed with air, and injected into the reactor, to form deposits on an air-cooled probe. The influence of flue gas temperature (589 – 668 °C), probe surface temperature (300 – 550 °C), Fe₂O₃, KCl concentration (0.7 – 3.5 m), the model fly ash flux (10000 – 40000 g/m²h), fly ash particle size (3.5 – 90 μm) and probe residence time (up to 60 min) were investigated. The results revealed that increasing flue gas temperature and probe surface temperature increased the sticking probability of the fly ash particles/deposit surface, 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, it was observed that the deposit formation rate increased with time, fly ash flux and fly ash particle size. 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. The deposition formation rate of the investigated species decreased in the following order: KOH > K₂SO₄ > KCl > K₂Si₄O₉ > SiO₂ > CaO, at the applied conditions. Addition of KCl to K₂Si₄O₉, SiO₂, CaO, and K₂SO₄ in the model fly ash mixture resulted in an increased deposit formation rate and induced rapid deposit sintering. Furthermore, addition of KOH to K₂Si₄O₉ in the model fly ash mixture resulted in a large increase in the deposit formation rate. The relative deposition formation rates of the investigated boiler fly ashes were observed to increase in the following order: wood fly ash, followed by straw + wood cofired fly ash and straw fly ash. Inertial impact was the primary mechanism of deposit formation on the upstream side of the steel tube, when the model fly ash was present as solid or semi-molten particles. However, presence of vapor species or submicron ash particles in the flue gas resulted in the formation of deposits on both sides of the steel tube via condensation or thermophoresis.

In order to understand deposit shedding in boilers, the shear adhesion strength of biomass ash deposits was quantified by laboratory experiments. Artificial deposits were prepared using biomass fly ash from full-scale boilers, as well as from mixtures of KCl, K₂SO₄, CaO, CaSO₄, SiO₂, K₂CO₃, Fe₂O₃, K₂Si₄O₉ and KOH. The deposits were prepared on superheater steel tubes and sintered in an oven. Subsequently, the deposits were sheared off by an electrically controlled arm, and the corresponding adhesion strength was measured. The effects of sintering temperature (500 – 1000 °C), sintering time (0 – 24 h), deposit composition, thermal shocks on the deposit, and steel type were investigated. The results revealed that the adhesion strength of ash deposits was dependent on two factors: the ash melt fraction, and corrosion occurring at the deposit–tube interface. Adhesion strength increased with increasing sintering temperature, sharply increasing at the ash deformation temperature. However, sintering time, as well as the type of steel used, did not have a significant effect on the adhesion strength, under the investigated conditions. Addition of compounds which increased the melt fraction of the ash deposit, typically by forming a eutectic system, increased the adhesion strength, whereas addition of inert compounds with a high melting point decreased the adhesion strength. Furthermore, the study indicated that sulfation of ash deposits might lead to an increase in the deposit strength, while cooling down the deposits after sintering decreased the adhesion strength. Finally, it was observed that adhesion strength data displayed a significant degree of scatter, following a log-normal distribution.

Additionally, the tensile adhesion strength of biomass ash deposits was investigated under the influence of a temperature gradient across the deposit. Model biomass ash deposits, containing mixtures of KCl, K₂SO₄, CaO, CaSO₄ and K₂Si₄O₉, 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 effects of 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 of the deposit. The sharp increase was typically observed near the melting temperature (or deformation temperature) of the investigated model deposits. A large temperature gradient across the deposits induced migration of molten/vapor species from the outer layer of the deposit to the deposit–tube interface, causing liquid state sintering, and thereby increasing 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 deposit adhesion strength. The tensile adhesion strength data qualitatively and quantitatively agreed with the shear adhesion strength data.

Finally, heterogeneous sulfation of model biomass ash deposits was simulated in three different experimental setups. The effect of sulfation time (0 – 24 h), SO₂ concentration (0 – 600 ppm) and sintering temperature (500 – 650 °C) on the
shear/tensile adhesion strength of the deposits was investigated. While increasing sulfation time resulted in a gradual increase in the adhesion strength of the deposits, varying SO₂ concentrations and sintering temperature did not significantly influence the deposit adhesion strength at the investigated conditions. A low degree of sulfation was observed in the experiments (<1 wt % S), suggesting that further investigation is required to understand the effect of heterogeneous sulfation on the adhesion strength.

General information
Publication status: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre
Contributors: Laxminarayan, Y.
Number of pages: 172
Publication date: 2018

Publication information
Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark
Original language: English
Electronic versions:
PhD_Thesis_Yashasvi_Laxminarayan_v2_January_2018.pdf
Source: PublicationPreSubmission
Source ID: 147216980