MUNICIPAL SOLID WASTE GASIFICATION PLANT INTEGRATED WITH SOFC AND GAS TURBINE

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ABSTRACT
An interesting source of producing energy with low pollutants emission and reduced environmental impact are the biomasses; particularly using Municipal Solid Waste (MSW) as fuel, can be a competitive solution not only to produce energy with negligible costs but also to decrease the storage in landfills. A Municipal Solid Waste Gasification Plant Integrated with Solid Oxide Fuel Cell (SOFC) and Gas Turbine (GT) has been studied and the plant is called IGSG (Integrated Gasification SOFC and GT). Gasification plant is fed by MSW to produce syngas by which the anode side of a SOFC is fed wherein it reacts with air and produces electricity. The exhausted gases out of the SOFC enter a burner for further fuel combusting and finally the off-gases are sent to a gas turbine to produce additional electricity. Different plant configurations have been studied and the best one found to be a regenerative gas turbine. Under optimized condition, the thermodynamic efficiency of 52% is achieved. Variations of the most critical parameters have been studied and analyzed to evaluate plant features and find out an optimized configuration.

Keywords: Biomass, Municipal Solid Waste, Gasification, SOFC

1 INTRODUCTION
Municipal Solid Waste can be considered a valid biomass to use in a power plant. Some advantages can be obtained; the principal is the reduction of pollutants and greenhouse gases emissions. Another advantage is that by their use it is possible to reduce the storage in landfills and devote these spaces to other human activities.

It is also important to point out that this kind of renewable energy suffers significantly less availability which characterizes other type of renewable energy sources such as in wind and solar energy.

Other important issues to mention are the indirect pollutants due to transport, transformation and manufacture treatments. In addition, controlling the accuracy of separation processes, avoiding using dangerous substances that could damage people’s health could also be noted.

In a gasification process, waste is subject to chemical treatments through air or steam utilization; the result is a synthesis gas, called “Syngas” which is principally composed of hydrogen and carbon monoxide. Traces of hydrogen sulphide could also be present which can easily be separated in a desulphurisation reactor.

The gasification process is usually based on an atmospheric-pressure circulating fluidized bed gasifier coupled to a tar-cracking vessel; the gas produced is then cooled and cleaned.

Syngas can be used as fuel in different kind of power plant such as gas turbine cycle, steam cycle, combined cycle, internal and external combustion engine and Solid Oxide Fuel Cell (SOFC).

SOFC based power plants are known as efficient power generators not only as stands alone (more than 50% thermal efficiency) but also in hybrid cycles, where SOFC is integrated with another plants, such as Gas Turbine or Rankine Cycle (more than 60% thermal efficiency). SOFC plants are also flexible in using different kind of fuels after minor fuel pre-treatment such as desulfurization.

Compared with modern waste incinerators with heat recovery, the gasification process permits an increase in electricity output up of 50%, see e.g. Morris et al. [1], thus solid waste gasification process can compete with incineration technology. In fact waste incinerators require the installation of sophisticated exhaust gas cleaning equipment that can be large and expensive.

2 PLANT MODEL AND CONFIGURATIONS
The plant studied in this investigation is represented through the following block scheme:
The principal components of the plant are the Gasification plant, the SOFC plant and the gas turbine. Through the Gasification plant, Municipal Solid Waste is converted into syngas; a mixture of H₂, N₂, CO, CO₂, H₂O, CH₄ and Ar. The produced syngas is previously cleaned to remove tracks of H₂S that could poison the SOFC.

The cleaned syngas is then sent to the SOFC plant to produce electricity. The SOFC stacks cannot consume all the fuels and therefore the remaining fuel is then sent to the burner to complete the combustion. The combusted gases after the burner are then expanded in a gas turbine (acts as a bottoming cycle) for further electricity production. The heat released through the exhausted gases can be used for other applications (i.e. district heating or district cooling). In fact, from the second principle of the thermodynamic all the heat coming from the combustion process cannot be converted into electric energy and a part of it will be lost. From the block scheme one can also identify two other sources of losses: ashes and tar from the gasification plant.

Apart from the fuel, the other inputs of the plant are air feeding the gasifier and air feeding the cathode side of the SOFC stacks. To introduce these, it is necessary auxiliary energy for a compressor; another use of auxiliary energy is that of blowing the Syngas out from the Gasification Plant to the SOFC.

The efficiency of the plant can be expressed as the ratio between the net produced electric power and the fuel power, where “net power” means the difference between the produced power and the power used in the auxiliary components (compressors, blowers, control systems, etc.).

\[ \eta = \frac{P_{\text{NET}}}{m_{\text{FUEL LHV FUEL}}} = \frac{P_{\text{TOT}} - P_{\text{AUX}}}{m_{\text{FUEL LHV FUEL}}} \]  

(1)

Two different configurations have been studied; the second one includes a regenerative Gas Turbine, as shown in Fig. 2.

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Figure 1: Block scheme of the plant.

Figure 2: Plant scheme, (a) without hybrid recuperator, (b) with hybrid recuperator.
2.1 Input parameters

It could be interesting to study a power plant running on solid waste and to reveal some interesting features such efficiency and power generated. For such plants having high efficiency is important but this is not the main feature; since municipal waste is used as fuel the environmental impact would be the most important advantage. Power production is another important issue to show how much of the power needed in the community can be produced environmental friendly. A good compromise between the amount of waste production in the community, the mass flow of fuel produced in the gasification plant and the efficiency of the entire power plant, seems to be the best way to establish the size of such plants. Therefore, in this study such couplings have been investigated as first step. Further, different plant configurations have been studied to find out the most optimized plant configuration with respect to its efficiency. Thus the placement of the heat exchangers plays an important role for the optimized configuration. It is better to have a realistic values of pressure drops in the heat exchangers rather than too low to be manufactured. The real pressure drops of the heat exchangers remain unknown until separate study is carried out to estimate their pressure drops at each side. This can be done after initial study of the complete plant configuration. Therefore, the initial values for the heat exchangers have firstly been studied depending on their mass flow estimation from a configuration and afterwards it was found that the pressure drops vary between 0,005 bar and 0,04 bar depending on fluids type and mass flow. The lower value corresponds to the fuel side and the higher value corresponds to the gas side of the heat exchangers.

2.2 Simulations results

Simulations, calculations and analysis have been carried out using DNA (Dynamic Network Analysis), an in-house component-based code for energy systems analysis developed at the DTU Thermal Energy Systems department. The solution is provided solving a system of nonlinear equations through the Newton-Raphson modified algorithm, see e.g. Rokni [2].

The gasification model used in this study is based on the “Viking Gasifier”, see e.g Bang-Møller and Rokni [3]. Ahrenfeldt et al. [4] report that the “Viking gasifier” offers some interesting features such as low tar content in produced syngas (<5 [mg/Nm3]), stable unmanned operation, high cold gas efficiency (>95 %), low environmental impact (clean condensate, high carbon conversion ratio), and gasification at ambient pressure. Higher process rates are achieved when a mixture of air and steam is used as gasification agent to lower the operating temperature and increase the hydrogen content. This makes the produced syngas composition suitable for feeding a SOFC plant. It was tested experimentally without any remark.

The SOFC model used in this study was described in detail by Rokni [2] which permits to define the number of cell per stack and the number of stacks. The model was developed based on the experimental results from the cell developed by Risø-TOFC.

The resulted output data are shown in Table 1 wherein case A refers to the configuration without hybrid recuperator and case B refers to the configuration including a hybrid recuperator, as was shown in Fig. 2.

<table>
<thead>
<tr>
<th>Table 1. Simulations Data Output</th>
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<tr>
<td>Data Output</td>
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<tr>
<td>Plant</td>
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<tr>
<td>$P_{tot}$  [MW]</td>
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<tr>
<td>$P_{cons}$ [MW]</td>
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<tr>
<td>$P_{net}$ [MW]</td>
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<td>$C_{fuel}$ [MW]</td>
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<td>$\eta$ [%]</td>
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<td>SOFC</td>
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<td>$P$ [MW]</td>
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<td>$\eta$ [%]</td>
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<tr>
<td>GT</td>
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<td>$P$ [MW]</td>
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As can be seen, plant performances enhance significantly by introduction of the hybrid recuperator that allows preheating the air in additional step before entering the cathode pre-heater. The principle consequences of such hybrid recuperator are:
- higher available heat for the bottoming cycle (gas turbine here);
- higher temperature of flue gas entering the burner;
- higher thermodynamic mean temperature;
- recovering more energy of the smoke gases and consequently higher plant efficiency;
- better integration of heat flows inside the plant.
- lower losses caused by the temperature level of smoke outlet from turbine.

3 SENSITIVITY ANALYSIS

A sensitivity analysis is conducted by varying some crucial parameters while all other values are kept constant. The analyzed parameters in this study are identified as fuel moisture content, gasification temperature and SOFC operating temperature. The results are provided in the following subsections.

3.1 Fuel Moisture Content

Fuel moisture is an important parameter to be studied since its variation influences the fuel properties through the LHV (Lower Heating Value) as discussed by Cocco et al. [5]:

$$LHV_w = LHV - MOI (LHV + r)$$

where $LHV_w$ is the lower heating value on wet basis, $LHV$ is the corresponding value for dry basis fuel, $MOI$ is the moisture content in the fuel and $r$ is the vaporization heat of water (2500 kJ/kg).

By reviewing a large amount of articles in the literature one can conclude that the values of moisture content in MSW ranges between 8% and 20% as shown e.g. in Ladislav et al. [6] and Hernandez et al. [7]; the lower the moisture is, the better the fuel would be. In fact MSW composition could change day by day and it could be beneficial to control this parameter before introducing the fuel into the gasifier.

Fig. 4 shows the LHV of MSW as function of moisture content. Power production and efficiency are influenced significantly with fuel moisture content.

Power production by SOFC and GT decreases with increasing moisture content. This is also true for auxiliary components in which power consumption decreases; particularly the syngas blower and the compressor which are due to reduction of syngas mass flow and consequently the required air. However, the decrements of the auxiliary consumptions are lower than the reduction of total power production which explains why the net power decreases.

Variations of plant efficiency are negligible which can be explained by the fact that the reduction of net power corresponds to the reduction of fuel inlet power and the ratio between these two values remains practically unchanged. SOFC plant efficiency is not affected significantly by moisture variation while the GT efficiency decreases which is due to circumstances that the reduction of...
power production is higher than the reduction of inlet fuel power. The most peculiar result is that the gasification plant efficiency increases slightly when moisture content is increased. Of course, syngas output energy decreases but its reduction is slower than the fuel input energy. In any case it is better to have low moisture content, approximately 10%, mainly because the output net power production will be reduced otherwise.

### 3.2 Gasification Temperature

Gasification temperature is another important parameter to be studied because it affects the fuel composition which will be fed to SOFC. Increasing gasification temperature results in a higher air mass flow required for oxidation (more nitrogen is diluted in the syngas) and hence the produced amount of syngas will be increased. However, the heat value of the fuel is lowered because of chemical equilibrium leading to higher amount of CO and lower amounts of CO2, CH4 and H2 content. Such fuel composition influence the power production by SOFC plant negatively which in turn influences the produced electric power and efficiency as shown in Fig. 5. SOFC produced power decreases due to a decrement of syngas LHV during the gasification process which is because of higher air mass flow is required for oxidation and for this reason auxiliary consumption in the air compressor increases. However, the generated electric power in the GT increases as a consequent to reduction of elaborated mass flow. For this reason total net power production remains more or less unchanged. Generated electric power for each plant affects the corresponding plant efficiency, meaning that all efficiency values decrease as result; except for the GT plant efficiency which is increased which is explained above.

![Figure 5](image)

*Figure 5: Electric power as function of Gasification temperature (a) and plant efficiency as function of Gasification temperature (b).*

### 3.3 SOFC Operating Temperature

SOFC operating temperature has been changed from 780°C to 950°C while anode and cathode inlet temperatures are adjusted accordingly and maintaining a constant temperature difference over the cells of the SOFC stacks (130°C) as discussed in Rokni [2].

![Figure 6](image)

*Figure 6: Electric power as function of SOFC operating temperature (a) and plant efficiency as function of SOFC operating temperature (b).*
SOFC power production and SOFC efficiency decrease when operating temperature increases which are due to reduction of fuel cell equilibrium potential [8] and a thermal expansion among materials [9]. However, auxiliary consumption increases consequently and the plant efficiency decreases. Gas turbine power production and efficiency increase due to a higher energy input through the used fuel coming from SOFC. Thermoeconomic analysis has also been conducted (similar as in [10]) in this study, but due to limited space the details are not presented. The analysis has been developed according to the theory of exergetic cost (TEC) formulated by Lozano and Valero [11]. In this study the municipal waste unitary cost has been assumed to be 0,0022 €/kWh which is negligible in comparison with traditional fuels. Electricity price of 0,098 €/kWh has thus been obtained which is rather low due to low cost of municipal waste. It is notable that the low fuel price has compensated with high price of SOFC stacks. Thus gasification of MSW to feed SOFC may help the entrance of SOFC technology into the energy market. Of course, the investment cost of SOFC influences the price of the produced electricity but future scenarios for SOFC stack price suggest that it will be feasible to increase the plant size with competitive capital investment and price of electricity.

4 CONCLUSIONS

Gasification technology allows using biomass energy with high efficiency; in particular through Municipal Solid Waste gasification in which energy is obtained from a “low-cost” fuel instead of incinerating and/or throwing it in the landfills. Integration of such gasification plant with a hybrid SOFC – GT plant permits to achieve an efficiency of 52% in an optimized configuration which is very high plant efficiency without presence of any dangerous pollutants in the off-gases.

The best performance is obtained with a regenerative gas turbine in which the plant efficiency increases to about 11% due to the recovery of the energy content in the exhausted off-gases.

As discussed the most suitable plant size is of approximately 25 MWe, according to the actual SOFC market which in turn permits to obtain high plant efficiency with a fixed input fuel mass flow. However with such size it is still possible to remove quantities of MSW comparable with the mean production of some small cities which concludes that in the immediate future the analyzed system is going to be feasible and the advantage of integrating such hybrid system with a MSW Gasifier provides a synthesis gas which will be fed to a competitive energy system from a fuel with negligible costs and high plant efficiency.

REFERENCES