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Optimisation of Combustion Process in Biomass-fuelled Cogeneration Plant

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Among the modern technologies used for decentralized heat and power generation from biomass, ORC (Organic Rankine Cycle) plants are commercially available systems for biomass utilization, which ensure good conversion efficiencies. However, there are still unsolved problems related to the lack of practical experience in the integration of ORC plants in the energy management systems of urban areas. The biomass CHP plant located in Ostfildern/Germany is a practical example for the utilization of the ORC technology for the energy supply of municipal areas. The practical experience that has been gathered since the beginning of the plant operation 2004 was used for the system performance analysis as well as for the optimization of the energetically and ecological parameters of the plant operation.

1. Introduction

In the European Union over 66 % of renewable energy is produced from biomass and wood is the largest contributor to the amount of energy generated from biomass. There is a growing interest in biomass as energy source and modern bioenergy technologies are anticipated to provide a significant contribution to the future primary energy supply (IEA, 2007a).
Today biomass is most efficiently used in decentralized cogeneration plants as they combine high efficiency with reasonable fuel transport distances (Zahoransky, 2009). It is expected that the CHP (combined heat and power) energy generation from biomass will grow, with a comparable increase in heat towards more efficient bioenergy technologies (IEA, 2007b). Among commercial available technologies the ORC (Organic Rankine Cycle) is the only market proven technology for heat and power production in decentralized cogeneration plants. In combination with relatively low emission values the utilization of wood potentials in biomass fuelled ORC plants is the most reasonable alternative for energy generation from wood (Maraver et al., 2009). However, the technology is rather new and practical experience is required to assess the real efficiency and reliability. Problems still occur due to changing fuel quality and ineffective combustion control systems. A major challenge is to obtain stable operating conditions with varying biomass quality.

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2. Integration of Biomass CHP Plant into the Local Energy Supply System

The cogeneration plant Scharnhauser Park located near Stuttgart, Germany is a practical example for the utilization of the ORC technology. The plant was integrated into energy supply system of a newly built urban area with 8,000 inhabitants. The installation has pilot project character and has been used to gather practical experience related to the performance of the combination of ORC module and biomass furnace. The plant works in heat driven mode and covers 80 % of the heat demand and about 50 % of the electricity demand of the urban area. Through the use of biomass as fuel about 4,000 MWh fossil fuel energy can be saved each year, which is equal to a carbon dioxide emission reduction of about 10,000 t/y.

2.1 Energy Supply System Description

Scharnhauser Park is a modern urban settlement located in Stuttgart-Ostfildern, Germany (Figure 1). The 140 ha area consists mainly of residential buildings and has 130000 m^2 of living space and 48,000 m^2 of mixed commercial area. The main portion of the energy supply of the area is provided by a biomass cogeneration plant with 6 MW_{th} nominal capacity. The plant is fired mainly by natural wood scraps and forested wood is burned additionally. Additional two gas boilers (5 and 10 MW) have been installed on the plant to cover the heat demand during peak load periods.

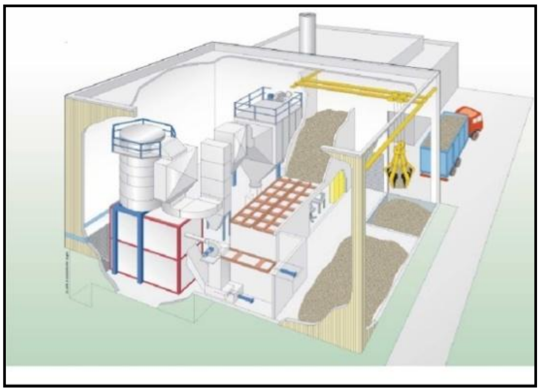

Figure 1: Schematic illustration of the biomass cogeneration plant (SWE 2005)

Cogeneration of electricity and heat takes place in ORC module, where silicone oil is used as the working medium. The use of silicone oil as the working medium has the advantage that electricity can be produced at lower levels of pressure and temperature, which enables considerable reduction of the investment and operating costs. An additional advantage of the ORC technology is the excellent part load behavior (Obernberger, 2002). The ORC module can operate efficiently in the range between 30 and 100 per cent of the full load and can be therefore treated as a suitable solution for a heat driven cogeneration within a heating network. The waste heat from the electricity generation process is transferred to the heating network of the area Scharnhauser Park, which spreads over a length of more than 13 km. The feed temperature of the district heating network is controlled by the ambient temperature, which allows an effective operation through a reduction of the heat losses. The good part load performance of the ORC module enables flexible adaptation of the plant output capacity to the heating needs of inhabitants with an almost constant degree of efficiency.

2.2 Biomass Heat Supply

The plant works in heat driven mode and therefore it is especially important to estimate the expected heat demand and load profiles for the district heating area. The definition of the heat load profiles for the Scharnhauser Park area is based on detailed measurements of the heat production and was established according to the VDI 4655 (Dubielzig et al., 2007) guideline.

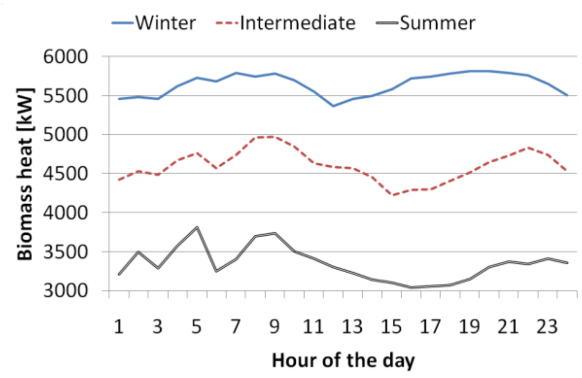

Figure 2: Biomass heat load profiles

The main portion of generated heat is demanded by residential buildings which determine the heat load profiles. The seasonal heat demand profiles presented in Figure 2 have a typical shape for residential buildings with two peaks: in the morning and in the evening. This is most likely due to user behavior when more energy is demanded before the start of the working hours and after coming back home in the evening. During working time the heating demand of residential buildings decreases due to the low activity level and reduced use of heating appliances.

According to the load profiles the daily heat demand value for each season can be estimated. Additionally the expected heat production in each season as well as for the whole calendar year can be calculated (Table 1). The analysis results showed that 39,696 MWh biomass heat can be generated each year, which means that the biomass plant would achieve about 6,600 full load hours per year.

Table 1: Biomass heat generation [MWh]

Heat load [MWh]	Winter	Intermediate	Summer
Daily	135	110	80
Seasonally	17,065	13,469	9161
	TOTAL YEARLY AMOUNT:		39,696

2.3 Environmental Impact

The major concern related to energy generation from biomass is the maintenance of low pollutant emission values. The emission values from biomass CHP plant Scharnhauser Park are measured on a regular basis and can be used for the estimation of the environmental impact of biomass cogeneration. The emission values from the biomass plant can be evaluated on the basis of a comparison with typical specific emission factors presented in the Table 2.

Table 2. Specific emission factors (Hartmann et al., 2007, (FNR 2009)

Energy generation	CO_2 [kg/MWh]	CO [kg/MWh]	Particles [kg/MWh]	NO_X [kg/MWh]	Fuel costs [€/MWh]	El. eff. [%]
Natural gas	228	0.201	0	0.07	49.6	-
Fuel oil	342	0.201	4.7E-04	0.13	60	-
Wood pellets	68	0.566	0.07	0.27	39	-
HKS*	8.8	0.002	0.025	1.00	19	13

*HKS – Biomass cogeneration plant Scharnhauser Park (measured)

The environmental impact of different heating appliances can be compared on the basis of emission factors and by considering the calculated yearly biomass heat generation (Table 3).

Table 3. Calculated yearly emissions

Energy generation	CO_2 [t/y]	CO [t/y]	Particles [t/y]	NO_X [t/y]	Fuel costs [t.€/y]	Electricity [MWh/y]
Natural gas	10282	9.06	-	3.16	2237	-
Fuel oil	15080	8.86	0.21	5.73	2646	-
Wood pellets	2998	24.96	3.09	11.91	1720	-
HKS*	472	0.11	1.34	53.63	867	6971

*HKS – Biomass cogeneration plant Scharnhauser Park

On the basis of the presented results a yearly reduction of about 10,000 t CO_2 emissions can be achieved when heat is generated in biomass cogeneration plant instead of using a natural gas boiler. Due to the installation of a state of the art biomass grate furnace efficient combustion and therefore low carbon monoxide emissions can be achieved. The plant is equipped with a combination of multicyclone and electrofilter for flue gas cleaning which enables significant reduction of particle emissions. The relatively high fuel nitrogen content is probably the reason for increased NO_X emissions. However, the measured NO_X emissions are still lower that the strict emission limit values for medium-scale biomass combustion appliances. The biomass cogeneration plant Scharnhauser Park can also be characterized by the lowest fuel costs. In case of the researched plant additional profits of about 940,000 €/y can be achieved by selling electricity. The generated electricity is a by-product of the heat driven ORC plant and can be sold to the grid for a price of 13.5 €cent/kWh, which is established by the feed in tariff.

3. Biomass Combustion

The core of the plant is a state of the art biomass furnace (Figure 3) with a nominal output capacity of 6 MW. The furnace serves as the thermal energy source for the ORC module where electricity is produced. Therefore, the thermal efficiency of the boiler will substantially influence the overall system efficiency. The biomass boiler has also to be controlled properly in order to prevent problems related to varying fuel properties, which are typical for woody biomass. Different operating conditions and varying fuel properties have a considerable effect on biomass combustion in a grate furnace. In order to analyze the complex combustion process in the grate boiler a mathematical model for the analyzed furnace was established. In order to analyze the process the furnace was divided into zones according to the individual combustion stages.

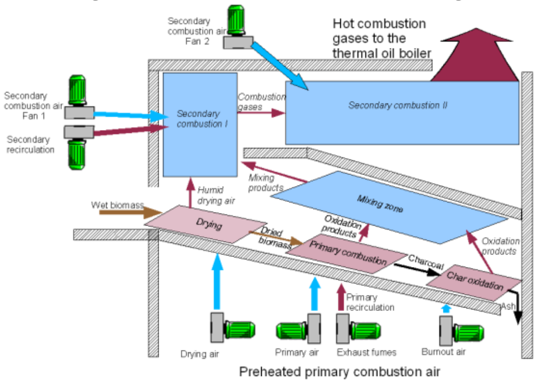

Figure 3: Schematic illustration of the biomass furnace

Each step of the fuel conversion will be analyzed on the basis of energy balance equations which have to be fulfilled at each moment of the process. This approach enables calculations of the most important process parameters which include, among others combustion temperature profiles, staging and stoichiometry of combustion, and thermal efficiency as a function of process parameters and fuel properties. The main objective of the simulation is to develop a thermodynamic model of biomass combustion which could be used for model based optimization of control strategies. In order to optimize the efficiency and reduce temperature fluctuations in the combustion chamber following goals will be realized:

i) Analysis of the combustion process in order to define the main energy flows on the basis of energy balance equations
ii) Parametric studies in order to achieve stable conditions of the thermal decomposition of biomass
iii) Parametric studies in order to define optimal process parameter values (i.e. process requirements vs. material requirements)
iv) The results of those investigations will help designers as well as plant operators to predict the rough burning characteristics of natural wood scraps.

4. Conclusions

The ORC biomass cogeneration plant Scharnhauser Park is a practical example for integration of biomass in energy supply systems of urban areas. Each year about 80 % of the heat demand of an urban settlement with 8,000 inhabitants can be covered with biomass.

Through the use of biomass as a fuel 4,000 MWh fossil fuel energy and about 10,000 tons of carbon dioxide emissions can be saved each year.

The emissions of carbon monoxide and fine particles are relatively low in case of the researched plant. The analyzed plant can also be characterized by lowest fuel costs and additional benefits can be achieved due to the production of electricity.

Biomass is burned in a state of the art grate furnace which serves as the thermal energy source for the cogeneration module, where electricity is produced. A thermodynamical model of the combustion process will be applied in order to define the optimal process parameter values.

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