Published in: Proceedings of the 16th European Biomass Conference, Valencia, Spain, 2-6 June 2008

OPERATIONAL EXPERIENCES AND OPTIMISATION OF AN ORC BIOMASS COGENERATION PLANT

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ABSTRACT: In the paper, an ORC plant located in Ostfildern/Germany with 1 MW electrical and 5.3 MW thermal power has been analysed during the first four year of operation. After the start of the plant operation in 2004 the performance of the system was not optimal in respect to the expected output performance. Through unfavourable parameters of combusted wood chips such as varying humidity or very fine particle contents and ash melting optimal conditions for the energy generation process could not be achieved. The practical experience in relation to the plant operation and the results of the process parameter evaluation has been used for the analysis of the energy production process. On the basis of research results the renewably generated energy could be improved each year. In conclusion, the practical experience and investigation results that have been collected in the project can serve as a basis for the optimisation of similar installations.
Keywords: combined heat and power generation (CHP), operating experience, ash fouling

1 INTRODUCTION

Modern biomass technologies are anticipated to provide a significant contribution to the global energy supply. Numerous technologies can be used to convert biomass to more convenient energy carriers. The overall global demand for heat and electricity is expected to grow. Biomass offers a good potential to meet this growing energy demand since it is the only carbon based renewable fuel that can directly replace fossil fuels. Although biomass can offer a practical alternative to fossil fuels, it has received relatively low attention. The global potential to increase the use of bioenergy for renewable heating and power generation in CHP plants is therefore large. It is expected that the CHP (combined heat and power) electricity generation will grow, with a comparable increase in available heat towards more efficient bioenergy technologies [1].

Well designed and good quality biomass plants should be installed in order to realise the potential of this energy carrier efficiently. The highest efficiency for the substitution of fossil fuels can be achieved with the energy generation from wood in combined heat and power plants [2]. Decentralised bioenergy plants built reasonably close to the demand load, will reduce transmission losses and improve the energy security by producing additional and alternative resources. Innovative technologies such as the ORC (Organic Rankine Cycle) process represent an economically interesting solution for biomass-fired combined heat and power plants. The paper mainly focuses on the aspects of integration of a CHP plant based on an ORC process into the heat supply system of the area Scharnhauser Park.

The principle of the energy generation by means of an ORC process is similar to the conventional Rankine process with the difference that instead of water an organic working medium is used. The ORC process is connected with a biomass furnace via a thermal oil cycle. Biomass combustion is a fully mature technology and offers an economic option for the production of heat from biomass. Improvements of biomass furnaces with respect to efficiency enhancement and emission reduction have alleviated some of the combustion related problems. However, there is still a potential for further optimisation. Problems occur in relation to changing fuel quality and ineffective combustion control systems.

2 ENERGY SUPPLY SYSTEM SCHARNHAUSER PARK

Scharnhauser Park is a community in Stuttgart-Ostfildern. The 140 ha area mainly consists of new built terraced houses and apartment buildings, but also has individual commercial areas as well as public buildings. The energy demand of Scharnhauser Park and its daily distribution are determined primarily by the residential area.

A wood-fired cogeneration plant was built in order to ensure an environmentally-friendly heat supply for the area. The main goal of the project was the achievement of CO_2 neutral production of heat for the whole district with a rate of 80%. The plant is mainly fired by natural wood scraps and forested wood is burned additionally. The wood chips are stored in a silo with a holding capacity of 1000 m^3. The fuel is automatically transported in a daily storage, which is equipped with a hydraulic floor. The wood chips are then transported hydraulically to the burning chamber.

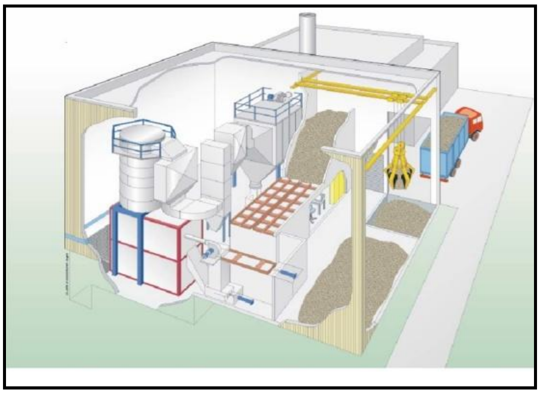

Figure 1: Scheme of the CHP plant

By a heat exchanger the heating emission is transferred to a heat carrier (thermo oil) which acts as a heat transport agent between the burner and the ORC module, where the electricity is produced. Use of thermo oil has the advantage that no steam boiler must be used to produce electricity. This makes the operation of the plant easier and above all more economical. The burner is equipped with an exhaust heat recovery system. After the hot exhaust has transferred its heat to the thermo oil, even more heat is drawn out of it. This takes place in a fume economizer, in which the exhaust fumes first release their heat to the thermo oil and then heat the water of the district heating network. The exhaust heat recovery allows fuel consumption degrees of over 80%.

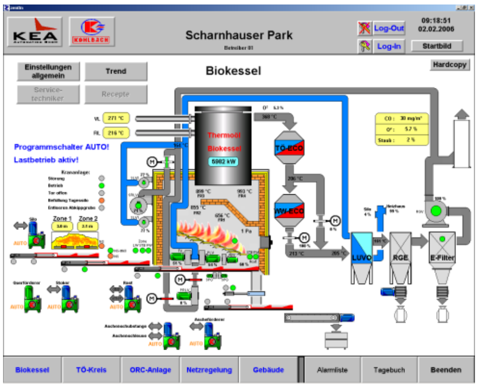

Figure 2: Combustion control system

Cogeneration of electrical and thermal power takes place in an ORC (Organic Rankine Cycle) module. The ORC system is similar to the water-steam process for producing electricity. The main innovation is the use of an organic fluid as the working medium instead of water. In the ORC module at the "Scharnhauser Park" cogeneration plant silicon oil was used as the working medium. The use of silicon oil allows the production of electricity at much lower pressure and temperatures and therefore the ORC module can be installed and operated with relatively low operating and personnel costs. ORC units in general are characterized by a good partial load performance, a fact that is particularly important when the plant is operating within a heating network.

The local heating network of the Scharnhauser Park area has been substantially modernized and extended. The network spreads over a length of more than 13 km and enables all the inhabitants of the area to use environmentally-friendly energy. The local heating network is fed with waste heat from the electricity generation process in the ORC module. The heat energy is transferred to the heating network in its condenser. The main demand for heat in the area is covered by biomass. Additional gas boilers were installed at the plant to cover the peak demands of Scharnhauser Park. Each year 80% of the heating energy and approximately 50% of the electrical power are produced CO_2 neutral in the cogeneration power plant.

Table I: Energy production

Year	Demand [MWh]	Biomass heat [MWh]	Biomass share [%]	El. ORC [MWh]
2004	19899	10802	54.3	1103
2005	23306	17220	73.9	1212
2006	24255	19716	81.3	278
2007	23544	19441	82.6	3308

The core of the plant is the 6 MW_{th} biomass furnace. This modern feed grate firing is equipped with a fully automated control system, which makes a clean and complete combustion possible.

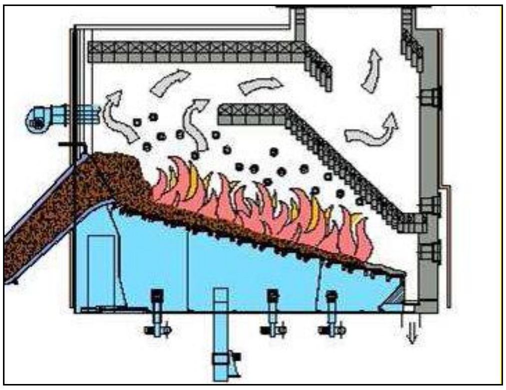

Figure 3: Biomass furnace

The combustion chamber is separated into two different zones (primary and secondary) in order to optimize the process of thermal utilization of wood. In the primary combustion zone, the wood chips are gasified under sub-stoichiometrical ($\lambda<1$) conditions. The main steps in the thermal decomposition of wood in the primary combustion zone are drying, devolatilization, gasification and char combustion. The gasification products from the primary combustion zone are transferred to the secondary zone where they are burned under over-stoichiometrical ($\lambda>1$) conditions.

Automatic biomass furnaces are operated continuously and all steps of the thermal decomposition of wood occur simultaneously in different sections of the combustion chamber. Every step of the combustion process takes place in a separate zone of the furnace and every zone is equipped with a separate combustion air fan. This advanced combustion air management achieves low emissions of unburned components as well as high energy conversion efficiencies. The complex control system enables a plant operation with a variable performance depending on the requirements of the district heating network.

The installation of complex filter equipment at the plant contributes to a significant reduction in combustion-related emissions. After the exhaust fumes have released their heat to the thermo oil and the heating network, they are ducted to the cyclone and electro filter where dust is removed. Additionally a permanent emission monitoring system was installed at the plant in order to control the emissions of pollutants from the combustion process.

Due to the fact that in summertime there is only a demand for hot water, the amount of produced heat decreases significantly. A high efficiency of the biomass utilisation can be achieved only if the energy is demanded the whole year round and at a high capacity. A possible solution is the production of cold through absorption cooling driven by heat from district heating network. The possibility to combine heat power production with the supply of cooling energy will be realised in the course of planning for a new office building. The cold production system is planned to be a pilot installation implementing thermal cooling for air condition of offices and IT structure. The cooling process is realised by lithium bromine based absorption chillier with a cooling power of 105 kW which will be installed in the basement of the building. The supply with cooling energy seems to be a good alternative to reach a sufficient workload and the yearly operation hours with biomass can be higher.

3. PRACTICAL EXPERIENCE

The information availability for decentralised CHP plants based on biomass combustion is generally limited due to the relatively low practical experience of this innovative technology. Many problems that usually arise when building a plant can be avoided when building a second plant. Understanding of technical, economical and environmental plant behaviour will have a positive impact on deployment of modern bioenergy technologies. The analysis of measurement results, information on project circumstances should help to install good quality, well designed bioenergy plants. Information publishing aims to enhance the awareness of bioenergy technologies could also convince the consumers of the benefits that the bioenergy applications might have.

While ORC-modules have been used for producing electricity via geothermal energy for a long time, it can be seen as a new technology in connection with biomass combustion. Therefore missing operational experiences can be considered as one major disadvantage [3]. The publication of information on project circumstances, project success (or otherwise) could help to build professional support for the development of new bioenergy projects. In this context the practical experiences from Scharnhauser Park can serve as a basis for the analysis of the reliability of decentralised CHP plants based on biomass combustion and can provide useful knowledge and information for the development of modern energy supply systems.

3.1 Environmental impact

The main task of the biomass furnace is to generate heat by a complete oxidation of the combusted substance to H_2O and CO_2. The flue gases generated as a result of combustion of biomass also contains undesirable pollutants. If a modern biomass furnace is operated competently, a clear reduction of the emission values can be achieved. The emission values of a biomass furnace should serve as an essential factor for the analysis of the environmental impact of energy supply concepts based on biomass combustion.

Table II: Energy production

Parameter	Emissions in mg/Nm^3	
	Limit values	Measured values
CO	150	8.1
C_{tot}	10	0.15
NO_X	250	199
Particles	20	6.1

3.2 NO_X emissions

The application of two-stage combustion with primary air injection in the fuel bed and secondary air injection in the combustion chamber enabled a significant reduction of NO_X emissions. Besides staged combustion, partial recirculation of exhaust gases was used in the researched furnace for an additional reduction of NO_X emissions. Formed NO_X can be decomposed if the exhaust gases are returned back to the hot combustion chamber.

The measured NO_X emissions are relatively high. The higher NO_X values can be explained by high amount of undesirable fuel contents like grass, which can be found in the combustible at CHP Scharnhauser Park. The combustion of herbaceous biomass, which has higher contents of N, causes higher emissions of NO_X. The typical emission values of NO_X measured for combustion of herbaceous biomass like grass are in a range of (478 mg/Nm^3 [4]) in comparison.

3.3 CO emissions

The achievement of a complete combustion is one of the most important conditions for low emissions in biomass furnaces. The CO emissions can serve as an indicator for the evaluation of thoroughness and quality of the combustion.

The CO emissions measured are very low in comparison to the limit values for biomass combustion. The optimized injection of secondary air in modern furnaces enables good mixing of combustion air with combustible gases in the combustion chamber. If a good mixing is achieved, the concentrations of unburnt pollutants can be reduced to levels close to zero [5].

3.4 Particulate emissions

The reduction of the emissions of particles has a high priority for the limitation of the environmental impact of biomass combustion. The priority must be put on the reduction of particles smaller than 10 µm (PM10) which can be inhaled and cause severe health problems. The emission limit values for PM10 particles have been frequently exceeded in the region of Stuttgart.

The particulate emissions are low in comparison with the emission limit values for particles. The removal of particles in a multicyclone followed by an electro filter leads to a significant reduction in particulate emissions at Scharnhauser Park CHP.

4. EFFECT OF FUEL PROPERTIES

The properties of biomass relevant for the combustion process can vary in a wide range. Unsuitable parameters of solid biofuels can lead to operational problems during combustion. The burning process of woody biomass is mostly influenced by the particle size, moisture and caloric value. The nominal values of process parameters cannot be achieved if the fuel properties do not match the process requirements.

Grate furnaces are manufactured in two basic configurations depending on the fuel moisture: co-current and counter-current. The biomass furnace at the CHP plant Scharnhauser Park was constructed as a counter-current combustion unit. This type of furnace is suitable for burning of freshly harvested biomass with a moisture content of up to 65%. However, depending on the biomass source and storage time the moisture of the delivered wood chips can vary widely. Dryer fuel has a higher burning rate and therefore makes the combustion more intense and hence the temperatures in the combustion zone would increase. Higher temperatures in the grate zone lead to melting of ash which can cause slag and deposit formation in the furnace and boiler. Therefore the temperatures in the grate zone should not exceed the value of 850°C.

An additional humidifier was installed within the fuel supply system in order to achieve suitable moisture of the wood scraps according to the requirements of the combustion unit. Higher moisture of the fuel ensures that the temperatures in the grate zone do not exceed the critical values and therefore prevent the sintering of ash during combustion.

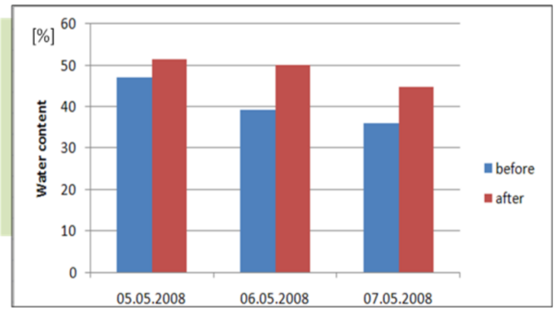

Figure 4: Humidifying of the combustible

The burning rate is mostly influenced by fuel size and smaller fuel particles results in a higher combustion rate. Generally, larger-size particles result in a higher air-to-fuel stoichiometric ratio or less fuel rich combustion [6]. Due to the lower combustion rate of larger particles the required output performance of the furnace cannot always be achieved, which leads to several operational problems. In order to ensure efficient operation of the CHP plant a compromise must be found between the requirements of the district heating network and optimal process parameters which are necessary for clean and complete combustion. The practical experience helps the plant operator to predict the burning characteristics of a new fuel. Nevertheless additional studies on the effect of fuel particle sizes on biomass combustion will carried out in Scharnhauser Park to make the utilisation of biomass more effective and environmental friendly.

The combustion behaviour of biomass is also influenced by the fuel caloric value, which can range from 15 to 22 MJ/kg. The energy density of biomass has an impact on the burning rate and the adiabate temperature of combustion. The lower net caloric value of fuel results in a higher amount of fuel which has to be fed into the burner. Consequently the net caloric value of biomass must be taken into consideration in order to adjust the control system of the furnace properly and to ensure optimal performance and complete combustion.

5. FLY ASH

Higher ash contents and high quantity of ash-forming elements in the fuel can cause the forming of hard agglomerates in the grate zone. The fuel also contains herbaceous biomass which leads to a decreasing ash melting point. Agglomeration, slagging and fouling can occur if herbaceous biomass is burned with wood scraps. Problems still unsolved, that need comprehensive research and development, are reactions taking place in the hot flue gas, causing corrosion and fouling in furnaces and boilers (especially when K-, S- and CL-rich biomass such as straw, cereals and grass are used). Research on possibilities to prevent them (by material selection or appropriate technologies) is of great importance [7].

A number of problems that occurred during the plant operation in Scharnhauser Park are related to ash depositions and fouling. Practical experience gained during the CHP plant operation can be used as a basis for understanding and solving of these ash fouling related problems.

Ash fouling on the surface of heat exchangers affects the heat exchange rate in a negative way. An increase of the thickness of the ash depositions makes the heat transfer between the flue gases and heat carrier inefficient and hence the exhaust gases temperature after the furnace would increase. The thermal oil boiler was equipped with an automatic cleaning system based on pressurised air in order to prevent ash fouling on the heat exchanger surface. This system allows the reduction of the ash depositions related problems. However, the functionality of the nozzles for pressured air has to be controlled systematically. If the system does not work correctly the heat exchanger tubes can be damaged, which leads to a high thermal oil fire danger. Additional manual cleaning of boiler tubes is necessary every six months when the flue gas temperature at the boiler outlet increases significantly. The heat exchanger pipes are then cleaned with dry ice blowing in order to reduce the heat losses.

Ash depositions can cumulate in the exhaust heat recovery system and clog the pipes of the heat exchangers. Flue gas condensate in the blocked channels of water economiser and air pre-heater and can cause corrosion on the heat exchanger tubes. After several operational problems caused by ash depositions in the exhaust heat recovery systems the plant operator decided to upgrade the water economiser and air pre-heater by the installation of an additional automatic pressured air cleaning system. Although the problems were solved, the water economiser was damaged and had to be put out of operation. Due to the fact that the water economiser is now bypassed the whole potential of the combustion unit cannot be used.

Figure 5: Additional boiler cleaning based on pressurised air.

During thermal decomposition of biomass in the primary combustion zone a fraction of ash is related to the gas phase. Solid phase sub-micron particles together with volatilised ash forming compounds from the fuel form fly ash particles. These particles get entrained with flue gases and cause depositions at the bottom of the secondary combustion chamber. The ash depositions have to be systematically removed, usually once per week to ensure regular operation of the furnace. This fact has to be considered concerning the necessary maintenance effort of modern biomass furnaces which strongly depends on fuel properties.

The development of a reliable fuel supply chain has proved to be difficult in Scharnhauser Park. It was found that the fuel properties change depending on the time of the year. The wood chips produced in spring and autumn contain a high amount of waste due to the seasonal cleanup works. The general trend observed during the plant operation shows that higher waste fractions in the combustible negatively influence the plant operation. The amount of produced heat and electricity decrease seasonally, which can be related to the worsening of fuel quality. The construction of additional large fuel storage is currently under consideration. This additional fuel silo should secure reliable biomass supply all-year-round. The seasonable fluctuations of fuel properties have to be considered by plant operators in order to develop their own fuel supply chain specific to local conditions.

5. CONCLUSIONS

The analysis of the practical experience and results gathered during the first four years of operation of the Scharnhauser Park CHP made the evaluation of the efficiency of the utilized energy management concept possible. The results showed a high efficiency of the part load operation of the plant. The efficient adaptation of thermal output performance to the instantaneous value of heat demand of the residential area enabled the achievement of a relatively high fuel consumption degree of over 82%. The implementation of a complex combustion control system in combination with an effective flue gas cleaning system made significant reduction of emission values possible. Energy generation from biomass in plants like Scharnhauser Park CHP is promising, as it combines high efficiency with low emissions. Although biomass combustion is a mature technology problems still occur due to the changing fuel quality and ineffective combustion control systems. The combined arrangements of the combustion air and flue gas fans have to be efficiently coordinated to provide optimial process conditions.

The properties of the biomass fuel are of great importance for a reliable plant operation. Combustible parameters including particle size, moisture and caloric value have a strong effect on the burning characteristics. Larger fuel particles have a lower burning rate, which can lead to problems to achieve the nominal output performance of the furnace. Moisture content of the combustible influences the adiabate burning temperature. Due to the design parameters of the CHP plant the wood chips in Scharnhauser Park have to be humidified before combustion in order to avoid ash melting in the grate zone. The caloric value of the fuel should also be considered as a relevant process parameter, which affects the amount of fuel transported to the burning chamber.

Ash depositions and fouling caused several problems during the plant operation. Ash fouling on the heat exchanger surfaces affects the heat exchange rate in a negative way. Therefore regular manual cleaning of the tube surfaces is necessary. Additional automatic cleaning systems have been installed on the heat exchangers of the exhaust heat recovery system. Ash depositions have to be removed from the bottom of the secondary combustion chamber systematically to ensure stable operation of the furnace.

The practical experience described in the paper can provide information on how to successfully deploy biomass in ORC plants. The paper should enable understanding of the difficulties that have to be overcome when operating an ORC plant based on biomass combustion. Through a description of the issues involved in operating a CHP plant, a guideline for the successful development of similar bioenergy projects should be created.

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