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Case Study Comparison of Bubbling Fluidised Bed and Grate-Fired Biomass Combined Heat and Power Plants

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As woody biomass is gaining importance as an energy source for electricity and heat we need to investigate with scientific methodology the main problems that occur with biomass boiler systems. The results of research done on large power plants and lab scale batch boilers are often not applicable in case of small and medium size biomass boilers on which the research has been limited. This study focuses on the smaller-size CHP plants of which there is a rapidly growing number in Europe.
This case study compares two biomass combined heat and power (CHP) plants with 2 MW electrical and 8 MW thermal capacity. One boiler system uses grate firing and the other one bubbling fluidised bed (BFB) technology. The article focuses on comparison of design and actual operating parameters measured during acceptance tests of the two CHP plants.
The tests were carried out to confirm that the built CHP plants achieved the performance guarantees specified in the contract. The tests were carried through by the same company according to the same standards. In these tests, data regarding fuel properties, working parameters, emissions etc. was collected. The distance between the two plants is 127 km, making the operational conditions very similar. The test for the grate-fired plant were carried out in June 2012 and for the BFB plant in March 2016.
This case study is unique in the way that it is based on extensive comparable data on two industrial CHP plants using the same fuel and having exactly the same capacities, but at the same time having very different combustion technologies and supporting equipment.

1. Introduction

Biomass is the key fuel in Europe for CO2 reduction and the number of energy efficient small scale biomass CHP (Combined Heat and Power) and heating plants has been increasing for the past decades (Verma et al., 2009). Grate combustion is a widespread technology in such applications. However during past years also BFB (Bubbling Fluidised Bed) boilers with fuel input below 20 MW thermal are being built. The aim of this case study is to find out based on actual operational data from two same-sized plants if the BFB technology is competitive compared to grate firing in technical perspective in this boiler-size category. Research from that perspective has been limited.
The main driver for combustion technology development is reduction of emissions. In combustion of biomass special attention must be paid on problems associated with energy efficiency and environmental impact (Karafov et al 2014). Boriouchkine et al. (2012) studied combustion dynamics in a conical grate boiler mathematically and a conclusion was drawn that the air flow can be used for a more efficient combustion of high moisture fuels.
Combustion of biomass, especially in small scale heating systems, is the source of particulate matter (PM, < 1 μm) (Verma et al., 2011). Bologa et al. (2010) demonstrated that the Electrostatic Precipitator (ESP) filter efficiency strictly depends on fuel types and flue gas velocity. Li et al (2015) carried through numerical analysis of flow dynamics of cyclone separator for a large 240 t/h CFB boiler. Stoppiello et al (2014) placed catalytic wall flow filters and was successful in the reduction of biomass boilers PM and CO emissions. Migliavacca et al (2014) studied the efficiency of ESPs and found indications that long electrode ESP has better performance and reliability that short electrode ESP.

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Yin, C. et al (2008) made an extensive literature review of the current studies in the field of grate firing and found that there is insufficient monitoring data from industrial boilers for modelling. The main problems are associated with pollutants, deposits and corrosion. According to Yin, further research should involve mechanism study of combustion chemistry, monitoring uneven fuel, air distribution and burning, general model for biomass conversion in fuel bed, advanced CFD (fluid dynamics) modelling, increase efficiency, reliability and decrease emissions. This article will add actual data from industrial boilers and compare them with a focus on the questions of efficiency and emissions.

2. Experiment

Two small-scale CHP plant industrial boilers systems are compared based on design and measured acceptance test data.

The grate-fired CHP plant is a base load unit. This means the plant normally runs continuously on full load of 8 MW thermal in order to produce a maximum of electricity. The produced heat is supplied to the district heating grid of the Latvian town of Valka. The surplus of heat is cooled down via a wet cooling system. The plant started operation in 2012.

The BFB-fired CHP plant operates according to the heat load of the Estonian town of Paide with a thermal capacity between 1.8 MW in the summer and the nominal 8 MW in the winter. There is an additional 8 MW biomass boiler and there are liquid fuel (LFO) boilers to supply the peak and reserve load. The plant started operation in 2013.

Some of the design parameters are presented in Table 1. There is a two times difference in design pressure. Due to the higher steam pressure the electrical efficiency of the grate-fired plant should be higher.

Table 1: Main design parameters for the two CHP plants

Parameter	Unit	Grate-fired CHP plant	BFB-fired CHP plant
Fuel			
Ash melting point	°C	> 1,100	-
Nitrogen content	%	< 1	-
Chlorine content	%	< 0.1	-
Min size	Mm	1	20
Max size	Mm	250	200
Boiler			
Steam pressure	Bar	51	25
Steam temperature	°C	450	450
Ambient air	°C	15	25
Ambient air range	°C	-	-21…+35
Ambient air pressure	mbar(abs)	1,013	1,013

The main equipment used in the two plants is compared in Table 2. As we can see, in addition to the different type of boiler, a crucial difference is the flue gas cleaning system used and minor differences are wet/dry ash removal and the presence of the cooling tower and steam cooling after superheater.

Table 2: Main equipment used in the two CHP plants

	Grate-fired CHP plant	BFB-fired CHP plant
Furnace	Moving grate	Bubbling fluidised bed (BFB)
Turbine	Steam	Steam
Steam cooler	No steam cooler after superheater	Steam cooler after superheater
Flue gas cleaning	Multicyclone	Electrostatic precipitator (ESP)
Ash removal	Wet system	Dry system
Cooling	Wet cooling tower	No cooling tower

Figure 1 shows the difference in the boiler system setup of the two plants. The main difference is that the grate-fired boiler has 3 economiser sections and no air pre-heaters, while the BFB-boiler has only one economiser and 4 air pre-heater sections. A description of both plant's combustion and boiler systems is given in two sub-chapters below.

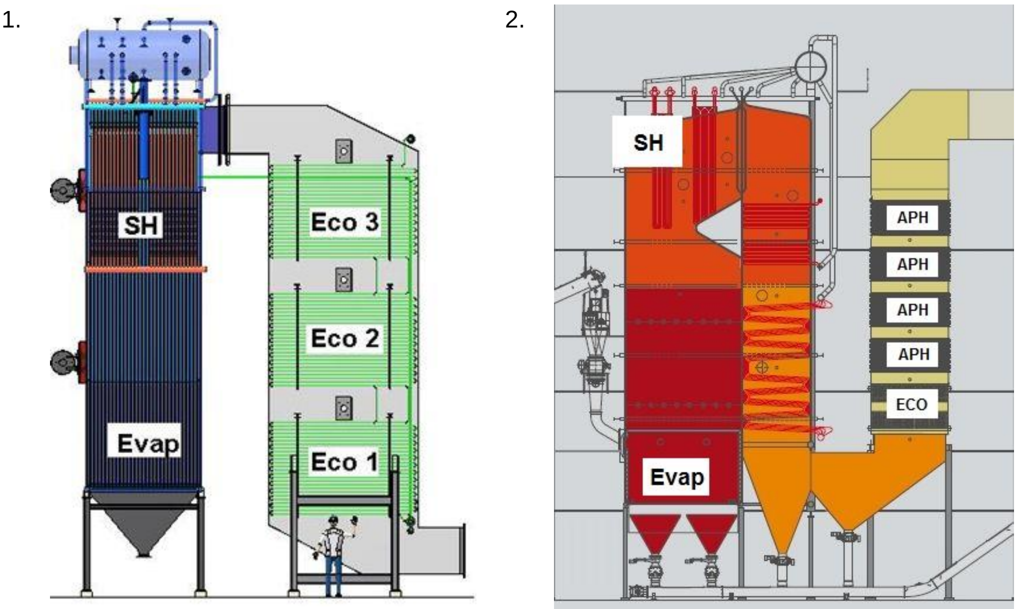

Figure 1: Boiler system diagrams for both plants, 1. – grate-fired, 2. – BFB, Evap – evaporator, SH – superheater, Eco – economiser, APH – air pre-heater

2.1 Grate-fired boiler system

The boiler is a 3-pass boiler with a single steam drum. The boiler is partially separated into two compartments by an inner membrane wall to create the dual draft system. The flue gasses leave the boiler in the upper part of the back wall in the second draft at a temperature of approximately 370 °C. In a separate third economizer pass (economizers 1, 2, 3) the flue gas cools down till 160 °C.

The fuel is fed from the top of the boiler from the fuel chute with 3 separate pushing zones. The grate has an un-cooled combustion chamber with movable step grate system. This is constructed from a sturdy steel jacket, internally lined with refractory brick work and insulated. The movable grate system consists of grate bars with a high content of chromium in the casting.

The temperature in the furnace is controlled between 950 °C and 1,050 °C assisted by recirculation of flue gas after dust filtration.

2.2 Bubbling fluidized bed fired boiler system

The boiler is a natural circulation type 3-pass boiler with a single steam drum. The furnace and 2nd pass are water cooled and walls are made of membrane tube panels. 3rd pass is uncooled and located inside the pass there are flue gas air preheaters and the economizer. Combustion air will be preheated with low pressure steam to 55 °C and further with flue gas. Final air preheat temperature is about 195 °C.

Wood based biomass is the primary fuel and light fuel oil is used as a start-up fuel to heat the fluid bed up to 700 °C. Fuel is fed with two feeding chutes through boiler front wall into the furnace.

Grate is made of heat resisting steel and integrated as a part of the boiler pressure vessel. Temperature in the furnace is sustained near 800 °C. The boiler is designed to operate at 20 % load by adding the possibility to operate with only half of the BFB grate.

2.3 Acceptance tests

The acceptance tests for the grate-fired plant were carried through in June 2012 and for the BFB plant in March 2016. Measurements were made and data from Supervisory Control and Data Acquisition (SCADA) system was used. All the equipment used in the tests was calibrated and had certificates. Certain data collected has been excluded from the scope of this article, in example the plants' noise levels.

During each test, four samples of fuel per hour were collected for a total number of 16 samples per test. Fuel analyses were been carried out at the laboratory of Riga Technical University - Institute of Energy Systems and Environment.

In order to calculate the boiler efficiency by the indirect method, all the losses that occur in the furnace and boiler were established. These losses were calculated to the amount of fuel burnt.

The various losses associated with the operation of the furnace and boiler were calculated based on standard EN12952-15.

The guarantees given by the manufacturer with respect to fuel input and electrical output are valid only if certain boundary conditions are satisfied.
During the course of the Performance Guarantee tests it was impossible to use wood chips with moisture content and temperature as indicated for the Performance guarantee values and design basis. Since any parameters other than that guaranteed has an effect on the fuel parameters and losses, a correction needed to be made. Correction to moisture content and fuel temperature was done according to EN12952-15.
The Boiler Efficiency by the indirect method was then calculated according to EN12952-15 – 8.4-7N and correspond to guarantee conditions.
The tests were carried through according to the following standards: heat balance EN 12952-15, radiation loss EN 12952-15, curve: brown coal, fluidized-bed boilers, flow measurements ISO 5167 VDI/VDE 2040, fuel sampling ISO 1998 and EN 14778, sample preparation CEN/TS 14780, moisture content in fuel EN 14774-3 and EN 14774-2, ash content in fuel EN 14775, calorific value of fuel EN 14918, emission guarantees ISO 9096 and ISO 10849. Steam tables and water density by Magnus Holmgren according to IAPWS IF-97 – the International Association for the Properties of Water and Steam – were used.
Both series of tests were carried through by the same qualified Latvian company SIA Ekodoma. The simplified set-up of the experiment is shown in Figure 2.

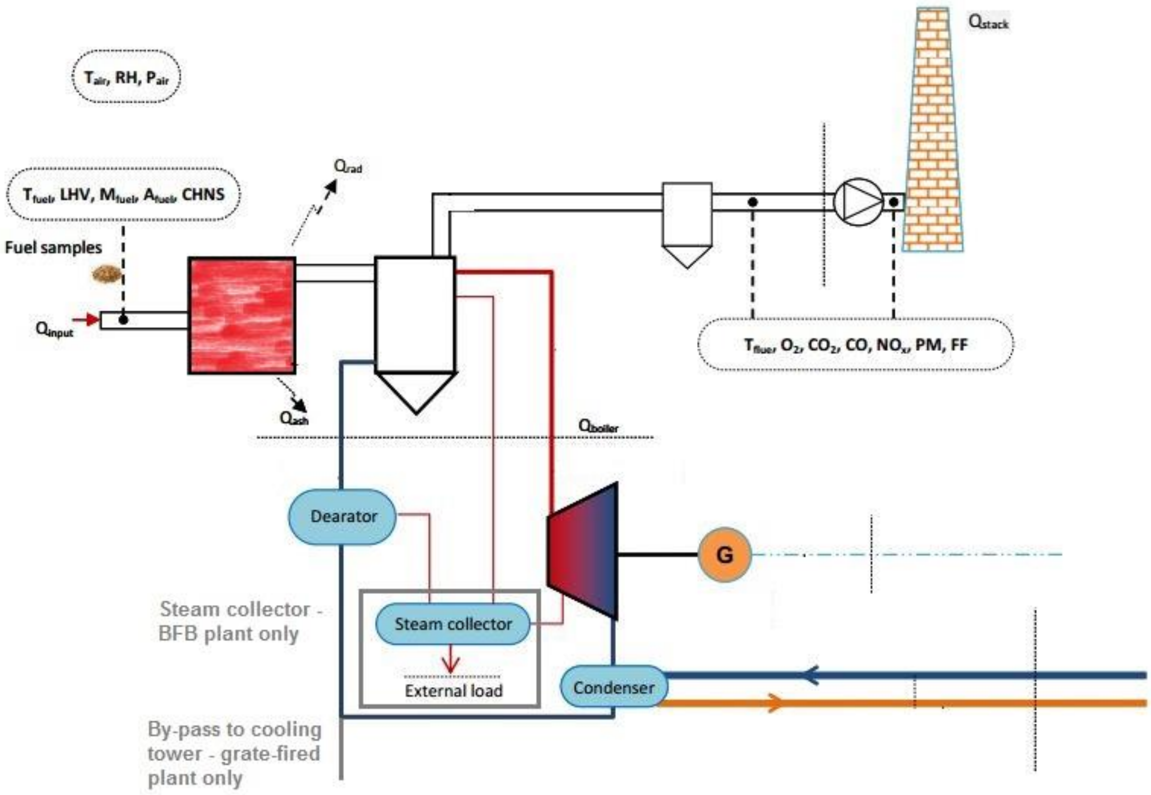

Figure 2. Simplified diagram of measurements made for both plants. Combustion air: T_{air} – temperature, RH – relative humidity, p_{air} – pressure. Fuel: t_{fuel} – temperature, LHV – Lower Heating Value, A_{fuel} – ash content, CHNS – Carbon, Hydrogen, Nitrogen, Sulphur content. Amount of heat: Q_{input} - input, Q_{rad} – radiation, Q_{boiler} – boiler, Q_{stack} – stack. Flue gas: t_{flue} – temperature, contents: O2, CO2, CO, NOx, PM. FF – flue gas volume flow rate.

3. Results and Comparison of Data

Design, acceptance test, SCADA and fuel sample data from the two biomass systems – grate-fired and bubbling fluidized bed, was collected and analysed. The average fuel composition during tests is given in Table 3. The table shows that differences in the chemical content of the fuel are minor.
A comparison of the data from two plants is presented in Table 4. In the table, the calculated fuel input value is corrected according to the principle explained in paragraph 2 while for moisture and district heating temperatures the actual measured values are presented.

Table 3: Comparison of average fuel composition used during the tests

	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen (%)
Grate-fired CHP plant	52.7	6.08	0.1	0.002	41.1
BFB boiler CHP plant	47.8	5.84	0.2	0.01	42.9

The average combustion air temperature, moisture and pressure in Table 4. These conditions are comparable.

Table 4: Comparison of average combustion air temperature, moisture and pressure during the tests

	Primary air temperature (°C)	Secondary air temperature (°C)	Air moisture (%)	Barometric air pressure (mbar)
Grate-fired CHP plant	37.2	47.9	19.1	998
BFB boiler CHP plant	44.9	33.8	16.0	1,016

SOx emission measurements were not carried through during grate-fired CHP plant's acceptance tests as the Sulphur content in the wood chips fuel was very small. The total efficiency was not a guarantee point for the grate-fired plant and thus not measured during the acceptance test.
In the table, only comparable data is presented. There were non-common tests and guarantee points for the two CHP plants as the supply contracts were different. These have been excluded from the scope of this study.

Table 4: Comparison of design and acceptance test parameters of the two CHP plants

Parameter	Unit	Grate-fired CHP plant		BFB boiler CHP plant	
		Design	Actual	Design	Actual
Fuel input	MWth	12.6	11.9	12.6	13.0
Thermal output	MWth	8	-*	8	8.26
Electrical output, gr	MWe	2	2	2	2
Electric output, net	MWe	1.85	1.88	1.73	1.80
Total efficiency**	%	78.2%	-	77.2%	77.4%
Fuel					
LHV	MJ/kg	8.02	Avg. 9.6	7.48	Avg. 7.8
LHV range	MJ/kg	7.2-12.6		6-13	
Moisture	%	50	Avg. 44.4	55	Avg. 50.7
Moisture range	%	35-55		30-60	
Ash content	wt %	<2	0.7	3	2.8
Boiler					
Steam pressure	bar	51	50	25	26.7
Steam temperature	°C	450	-	450	463.1
DH water, supply	°C	90	90.3	100	98.7
DH water, return	°C	55	55	55	54.2
Exiting flue gas temp.	°C	160	152	150 (not guaranteed)	189
Emissions					
Max dust	mg/Nm³	375	117.6	100	98.4
Max SO2	mg/Nm³	200	-	-	0.0
Max NOx	mg/Nm³	400	148.5	375	199.3
Max CO	mg/Nm³	250	78.5	-	211.8

* Thermal output was not measured during the performance test.
** Based on LHV and net electric capacity

We can see from the table that the average LHV of the fuel used in the grate-fired plant is much higher than for the BFB plant. Operational experience has shown that a higher quality fuel has to be used in the grate-fired plant to achieve an efficient mode of operation while the BFB plant is less demanding on the fuel quality.
The lower actual fuel input for the grate-fired plant shows that the plant's gross relative electrical efficiency is higher due to higher steam pressure.
As a result of the tests, both CHP plants achieved the guarantee values in the contract and were accepted by the customer. Both plants are in operation during the writing of this article.

4. Conclusions and Further Research

This case study is significant as it is based on comparable and well documented acceptance tests of two new biomass CHP plants with 2 MW electrical and 8 MW thermal capacity. The plant based on grate-firing and located in Latvia was tested in June 2012 and the plant with a BFB boiler and located in the neighbouring Estonia in March 2016. The tests were carried through to demonstrate that the plants were in accordance with the guarantees in the delivery contracts.

Based on design data and data collected and measured during performance tests, the following conclusions can be made regarding the two CHP plants:

- The net electric output of the grate-fired CHP plant is higher (1.88 MW vs 1.80 MW) although the gross generator capacity is the same (2 MW). This could be due to the fact that the BFB boiler uses fans to keep the bubbling bed in the air and thus consumes more electricity.
- The BFB boiler can burn a wider range of biomass fuel by moisture (30 – 60 % vs 35 – 55 %), LHV (6 – 13 MJ/kg vs 7.2 – 12.6 MJ/kg) and ash content (3 wt % vs 2 wt %), but the fuel particle size is more limited than for the grate-fired boiler (20 – 200 mm vs 1 – 250 mm).
- The BFB boiler has slightly lower actual dust emissions (98.39 mg/Nm³ vs 117.6 mg/Nm³). The main reason for the smaller emission is that in its offer the contractor accidently opposed on himself a very strict limit of 100 mg/Nm³, while the original requirement of the client was 250 mg/Nm³ that equals to 100 mg/MJ. Generally, the dust emissions of a BFB boiler should be higher due to creation of small particles in the process. The use of ESP for the BFB plant helped to achieve the low emission, while the grate-fired plant uses a multicyclone for flue gas cleaning.
- The NOx (199.3 mg/Nm³ vs 148.5 mg/Nm³) and especially CO emissions (211.8 mg/Nm³ vs 78.5 mg/Nm³) of the BFB boiler are higher than for the grate-fired boiler. This could be due to many reasons. The BFB boiler was still being fine-tuned during the testing and these results might be different later.
- Exiting flue gas temperature from the BFB boiler plant was 189 °C and from the grate fired boiler it was 152 °C. This shows that the heat from the combustion was collected more efficiently in this grate-fired boiler. The design flue gas exit temperature for the BFB is lower (150 °C vs 160 °C).

Data over a longer period should be collected to make comprehensive conclusions regarding the efficiency and emissions of the two plants. Further research could include comparison of differences in work regimes, long-term efficiency and problems with mineral matter and corrosion with these two case study CHP plants. Following the standards and principles from this article, additional plants with either combustion technology could be tested and the results compared with the data from this article to make general conclusions regarding the more suitable technology for biomass combustion below 20 MW of fuel input.

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