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The experimental study of full-scale biomass-fired bubbling fluidized bed boiler

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Abstract

This paper presents experimental data concerning combustion characteristics of full-scale biomass-fired bubbling fluidized bed (BFB) steam boiler with a thermal output of 31 MW. The purpose of the experimental measurements is to show how the values of selected combustion parameters vary in reality depending on measurement position. Experimentation involves specifically a determination of combustion gas temperature and concentration of gas species i.e. O_2, CO_2, CO and NO_X at different positions in the furnace and the flue gas trains. Character of results from the furnace indicates the intermediate stage of thermochemical reactions. Increased levels of CO close to the wall have been found, this may be indicating reducing atmosphere and thereby increased corrosion risk. Results from flue gas trains demonstrate that behavior there is related to the fluid dynamics and heat transfer, the temperature is too low for further combustion reactions. Results show great variations among measured values of all measurands depending on a distance along the line from the wall to the center of the boiler. The measurements from permanently installed fixed sensors are not giving value representing average conditions, but overall profiles can be correlated to online measurements from fixed sensors.

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Keywords: Biomass combustion; steam boiler; fluidized bed; temperature measurements; flue gas concentration measurements.

1. Introduction

Fluidized bed combustion is considered as one of the most promising techniques because of its flexibility, high combustion efficiency and low environmental impact [1]. It has been developed and tested over many decades as presented by Koornneef et al. [2]. Nevertheless there are still some issues to be studied in relation to the combustion of biomass as it is a fuel with certain specific properties that affect

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combustion process and equipment. The combustion diagnostics in industrial applications is uncertain since the fixed sensors permanently installed in the boiler are placed in very few positions (Fig. 1.). Therefore, it is necessary to carry out an experimental work in order to get more detailed insight of the combustion process. Examination of the literature shows remarkable studies concerning full-scale steam boilers (e.g. [3-5]), however the availability of the data from biomass fired boilers is very scarce. In relation to the limited access to the data the research project was designed at Malardalen University in order to obtain comprehensive experimental diagnostic data from different full-scale biomass-fired steam boilers. The study presented here is a facet of comprehensive research project and the aim is to provide data from bubbling fluidized bed (BFB) steam boiler with a thermal output of 31 MW. Experimentation involves specifically a determination of combustion flue gas temperature and concentration of gas species i.e. O_2, CO_2, CO, NO_X at different positions in the furnace and flue gas trains. This data will be further used for formation, development and verification of analytical and numerical mathematical models and for controlling and optimization purposes.

2. Material and methods

2.1. Experimentation

The measurement procedure was designed so that the flue gases are extracted from the different points lying on the line at certain positions in the furnace (Fig. 1. Ports SHE1, SHE2), and flue gas trains (Fig 1. Ports SHE3, SHE4, SHE5). The distribution of individual measurement points on the line was proposed in accordance with the assumption that there would be steeper gradients in positions near the wall. Flue gases are drawn through the water-cooled suction pyrometer where the temperature is measured by precalibrated type K thermocouple. After passing suction pyrometer, the flue gases are further dried and purified and then pumped to the calibrated gas analyzers where the gas concentration is measured. Analyzers used are Fuji Electric ZRJ Infrared GA for O_2, CO_2 and CO concentration analysis and Eco Physics CLD 700 EL ht for NO_x concentration analysis (both on dry gas stream). The signal from the measuring instruments is processed in the PC logger and a recorded by PC at 10 second intervals. There are approx. 90 values read for each measurand at each point.

Nominal operating parameters:	
Thermal capacity (without FGC)	30.8 MW_t
Electrical output	10 MW_e
Flue gas condenser (FGC) output	7–8 MW_t
Nominal steam parameters:	
Flow rate of main steam	11.9 $kg{\cdot}s^{-1}$
Temperature of main steam	480 °C
Pressure of main steam	80 bar
Operating parameters during experimentation:	
Total thermal output	25.8 MW_t (± 5%)
Electrical output	7.7 MW_e (± 5%)
FGC output	0 MW_t
Flow rate of main steam	10.1 $kg{\cdot}s^{-1}$ (± 5%)
Fuel properties during experimentation:	
Net calorific value	8400 $kJ{\cdot}kg^{-1}$
Moisture content (as received)	54 wt%
Ash content (dry matter)	1.4 wt%
Composition: Forest residue chips (73 wt%), Stem wood chips (12 wt%), Sawdust (15 wt%)	

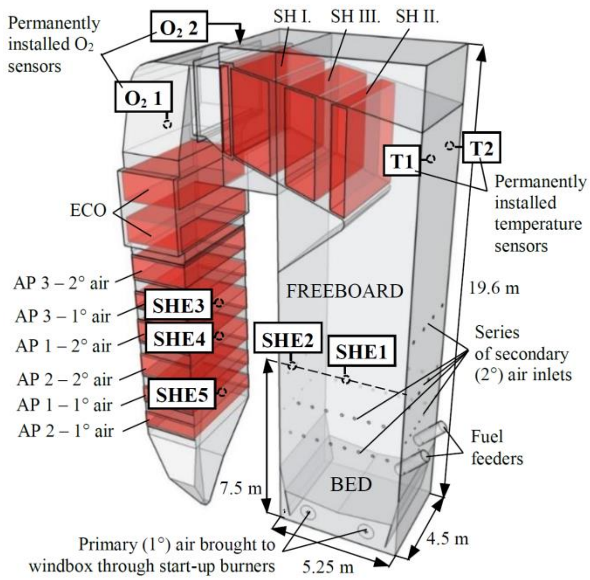

Fig. 1. Bubbling fluidized bed boiler 30.8 MW

2.2. Boiler design and operating parameters

The BFB boiler (Fig. 1.) is used for combined heat and power production and it was constructed by Foster Wheeler AG. The furnace has evaporator membrane water walls on all four sides. The bottom membrane panel and is covered with protective refractory lining, so that bubble caps protrude and lining exceeds and covers membrane walls to a height of approx. 2.5 m from the furnace bottom. Primary air is brought to the furnace through the bottom bubble caps. Secondary air is staged and brought in at several levels along the furnace freeboard. The boiler consist of convective vertical pendant superheaters (SH I., SH II. and SH III.), economizer (ECO) and air preheaters (AP). The boiler is equipped with flue gas recirculation and a flue gas condenser (FGC). Furthermore, there are sensors permanently installed for temperature measurements (Fig. 1. T1 and T2) and O_2 concentration measurements (Fig. 1. O_2 1 and O_2 2). These sensors are placed approx. 0.3 m from the boiler wall and are used for online process monitoring.

During experiments, the boiler was operated with an emphasis on steady operating conditions. However some fluctuations were observed due to operational constrains such as variable fuel properties and fluctuating demand in district heating (for details see, Fig. 1.) Fuel fired during experiments was a mixture of solid biomass-based materials from broadleaves, conifers and shrubs (for details, see Fig. 1.).

3. Results and discussion

Note that average values are used when discussing results and the positive and negative error bars in graphs represent the sample standard deviation both calculated from repeated measurements (approx. 90 values).

Character of the results from the points in the furnace (Ports SHE1, SHE2) indicates the intermediate stage of thermochemical reactions. Results shows that temperature near port SHE1 increases uniformly along the line (Fig. 2.). Temperature profile is correlates negatively with O_2 concentration (Fig. 3.). Whilst CO concentration is low near the wall and then abruptly rises and reaches the limit of the instrument at the distance of 2.0 m (Fig. 4.). Moreover, CO concentration is characterized by a high variation between the repetitions. NO_X concentration rises evenly from point at 0.1 m to 2.0 m, and then slightly decreases at 3.0 m from the wall (Fig. 5.). Thermochemical reactions near SHE1 take place most intensively in the middle of the furnace, where the highest temperature occurs with relatively low level of excess air. Combustion intensity decreases towards the wall. Abrupt change of CO concentration at 1.0 m from the wall (Fig. 4.) suggests that secondary air flows along the boiler wall and does not fully participate on combustion in the center of the furnace and thus creates the oxidizing atmosphere near the wall.

Temperature in the vicinity of port SHE2 is lower than that near SHE1; it rapidly increases from 0.1 m to 0.3 m and then rises moderately (Fig. 2.). O_2 concentration is relatively high at 0.1 m then drops at 0.3 m, considerable peak is noticeable at 2.0 m from the boiler wall; at 3.0 m O_2 concentration decreases (Fig. 3.). Unlike the measurements near SHE1, no significant correlation with temperature is observed. CO concentration reaches higher values at the positions of 0.1 m and 0.3 m with a subsequent decline at 1.0 m and at 2.0 m followed by an increase at 3.0 m from the boiler wall (Fig. 4.). High concentration of CO close to the wall result in increased risk of corrosion and material deterioration of boiler walls, this may reduce lifetime of equipment significantly [1]. Concentration of NO_X follows “a parabolic profile” and reaches the maximum at 3.0 m from the boiler wall (Fig. 5.). As near port SHE1, the most thermochemical reactions take place in the center of the furnace and combustion intensity decrease towards the wall. It is evident that a significant reduction in temperature at 0.1 m is accompanied by a high concentration of O_2 and CO. This indicates poor combustion efficiency, where the O_2 is not fully utilized and the carbon from the fuel is not completely converted into CO_2. With increased CO we can also expect a higher content of pyrolysis products especially on particle surfaces.

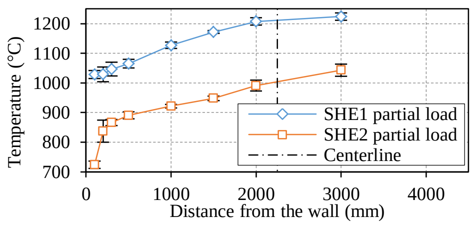

Fig. 2. Temperature profile – side walls of the furnace

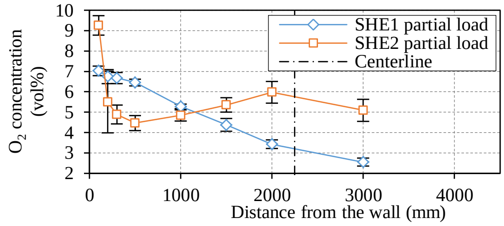

Fig. 3. O_2 concentration profile – side walls of the furnace

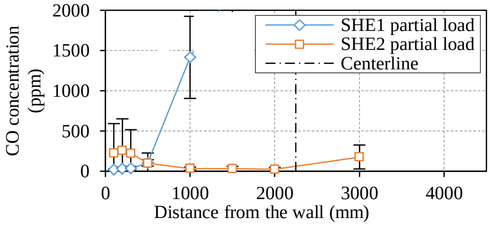

Fig. 4. CO concentration profile – side walls of the furnace

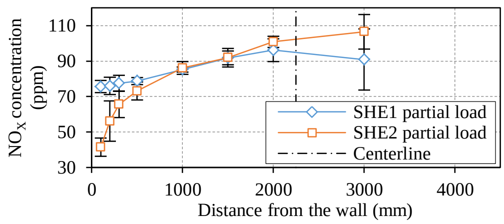

Fig. 5. NO_X concentration profile – side walls of the furnace

Results show that behavior in flue gas trains is related to the fluid dynamics and heat transfer, the temperature is too low for further combustion reactions [6]. The results of measurements in ports SHE3, SHE4 and SHE5 show that the flue gas temperature is distributed unevenly over the line (Fig. 6.). The highest temperature is reached at the distance of 0.1 m (SHE3, SHE4) and 0.35 m (SHE5). The cause of uneven temperature distribution over the line (approximately 50 °C along the line) is asymmetrical air supply due to the AP design. Profile measured next to the port SHE3 shows an abrupt increase of the concentration of O_2 at the distance of 0.35 m from the wall (Fig. 7.). It can be largely explained by the leakage in the air preheater 3 for primary air. This hypothesis is also supported by diluted concentration of CO and NO_X in comparison with concentrations near SHE4 and SHE5. Great variations of presented values near the port SHE3 are caused by changes in operating conditions in relation to the shutdown of the turbine.

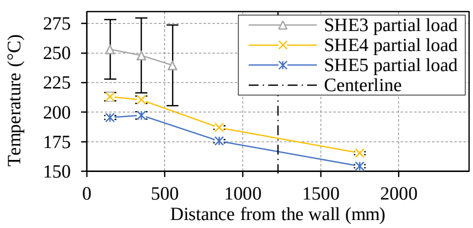

Fig. 6. Temperature profile – air preheaters

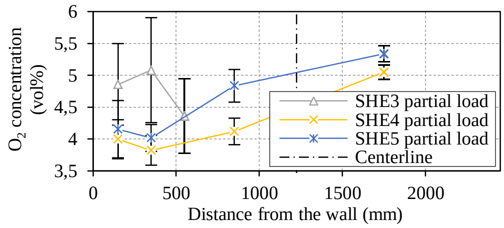

Fig. 7. O_2 concentration profile – air preheaters

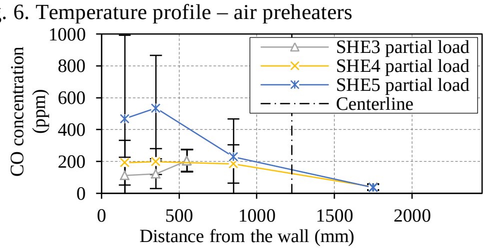

Fig. 8. CO concentration profile – air preheaters

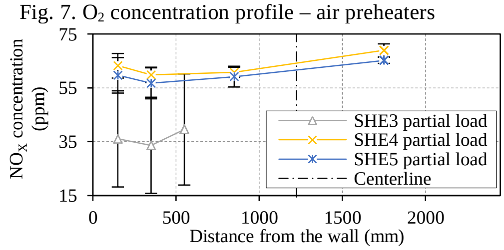

Fig. 9. NO_X concentration profile – air preheaters

In summary, results from the performed experimental measurements vary greatly along the line from the wall to the center, therefore the results from fixed sensors permanently installed can't be considered as entirely representative (e.g. temperature at SHE1 is significantly higher at 3.0 m compare to the values at 0.3 m from the wall). If we assume that our experimental results show correct absolute values, profiles such as these can be correlated with measurements from fixed sensors permanently installed in the boiler to improve control in comparison to only using the data from fixed sensors.

4. Conclusions

Experimental measurements (i.e. combustion flue gas temperature and concentration of O_2, CO_2, CO, and NO_X) were carried out at different points in the full-scale biomass-fired bubbling fluidized bed boiler. Results of the constructed profiles from the furnace indicates the intermediate stage of thermochemical reactions and show that the thermochemical reactions peak at the center of the furnace and combustion intensity decrease towards the wall. Furthermore, increased levels of CO concentration close to the wall has been found in the vicinity of port SHE2. This maybe indicating reducing atmosphere and thereby increased corrosion risk. Results of the constructed profiles from flue gas trains shows that behavior there relates mainly to fluid dynamics and heat transfer. The temperature is too low for further combustion reactions. Asymmetrical cooling of flue gases in flue gas duct was found and a leakage has been identified in the air preheater 3. Moreover, it is evident that there are great variations among measured values of all measurands depending on a distance along the line from the wall to the center of the boiler. This indicates that the measurements from fixed sensors are not giving value representing the average conditions, however overall profiles can be correlated to online measurements from fixed sensors.

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Biography

Jan Skvaril is a PhD student at Mälardalen University, Sweden. He holds a master's degree in Mechanical Engineering and master's degree in Economics and Management, both from Brno University of Technology. Currently he is studying fluid dynamics with emphasis on how temperatures are distributed in different types of furnaces.