EXPERIMENTAL INVESTIGATION OF SPATIAL TEMPERATURE DISTRIBUTION IN A LARGE-SCALE CFB BOILER

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Abstract: The current investigation has been carried out since there are not many publications where ‘at plant’ investigation and experimental verification of temperature distribution in large-scale (>300MW$_{th}$) CFB combustors has been dealt with. The investigation described in the present paper was primarily focused on the determination and assessment of the effect of fuel type on fluidized bed hydrodynamics, pressure and temperature profile in the CFB loop, and flue gas temperature in the upper part of the furnace as well as in the boiler section between cyclone vortex finder and the steam superheater in the convective pass. The research was carried out in a commercial CFB combustor fired with hard coal and two mixtures of hard coal and biomass. The test results indicated that in some boiler zones the actual bed and/or flue gas temperatures were up to 150^{0}C higher than the values reported by the boiler control system to the operation staff. The presence of such zones might be quite problematic for the operator since it may worsen the working conditions of boiler heat exchangers and may become the source of higher emission of pollutants (NO_x, SO_2) from the CFB combustor.

INTRODUCTION

Due to its numerous advantages, mainly associated with the possibility to cofire effectively various fuels (coal, biomass, agromass, waste, etc.), low emission of nitrogen oxides (due to moderate combustion temperature) and relatively easy and cheap desulfurization by in-furnace injection of limestone the technology of circulating fluidized bed combustion (CFBC) has been developed significantly in recent decades. So far, numerous publications have been published where the operation of circulating fluidized bed (CFB) boilers fired with waste, low-quality fuels, such as e.g. high-ash coals, coal slurries, lignite, petcoke, and hard coal has been reported as it can be found in the publication of Bis (2010). However, despite ‘fuel flexibility’ of the CFBC technology numerous industrial experiences have indicated that the design of boiler furnace, particularly with respect to bed hydrodynamics and the location of heat transfer surfaces must take into consideration fuel properties otherwise one may often ascertain unacceptable loss of unburned carbon (Kobyłecki 2011a; Kobyłecki 2011b), erosion or corrosion (Karlsson et al., 2015), or intensive fouling (Opydo, et al., 2016). An important positive feature of the CFBCs is also moderate temperature in the CFB loop and thus quite low emission of nitrogen oxides, NO_x. Industrial data indicate that increase of temperature in the CFB furnace may affect directly the bed hydrodynamics (agglomeration) as well as emission of pollutants and ‘catalyze’ some other unwanted phenomena such as surface corrosion, and damage of heat transfer elements. Some papers, however, do not report links between temperature and emission or agglomeration and the problems seem to occur despite ‘low’ temperature (Gungor, 2009; Saikaew et al., 2012; Nikolopoulos et al., 2014). One of the explanation might by associated with the locations of temperatures which may not determine the real temperature due to wrong location (Lai et al., 2001; Saikaew et al., 2012; Park et al., 2013). The authors point out that the temperature indicated by thermocouple may not correspond with reality, particularly that there are still not many publications where comprehensive investigation of temperature distribution in large-scale combustors, or e.g. the effect of biomass cofiring on temperature distribution in the CFB loop are reported temperature (e.g. Gungor, 2009; Saikaew et al., 2012; Nikolopoulos et al., 2014).

Therefore, the main intention of the present paper is to provide some industrial data on the real values and distribution of temperature in some chosen section of the furnace, as well as in the horizontal flue gas duct between CFB cyclone vortex finder and inlet to the convective section just before the final steam superheater. Authors’ attempts were particularly focused on the determination of differences between real bed and flue gas temperatures and the temperatures measured by boiler control system, as well as the investigation of fuel type (coal, biomass) on the flue gas temperature and operation of steam superheater in order to find out possible causes of superheater deformation.

METHODOLOGY

CFB COMBUSTOR

The investigations were carried out at a commercial large-scale CFB boiler at one of Polish power stations. The CFB loop design is classical, consisting of a roughly 30m high furnace, two water cooled cyclones, two downcomers and two loop seals with two diplegs each. In order to protect the loop walls from erosion the lower part of the furnace, as well as the inner parts of the recirculation system (cyclones, downcomers, and loop seals) were covered with ceramic refractory. The gas and solids carried out from boiler furnace were separated by the cyclones and then recirculated into the combustion chamber via two loop seals with diplegs. The flue gas with some fine solids that were not separated in the cyclones passed through the convective section and then through the electrostatic precipitator (ESP) to the stack. The layout of the whole CFB system is shown in Fig. 1.

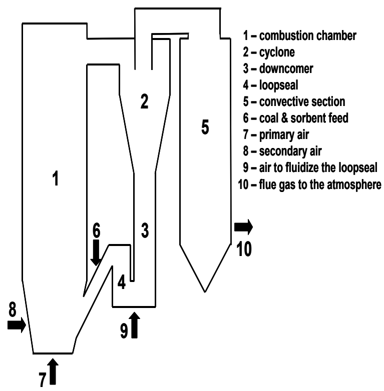


Fig. 1. Schematics of the commercial CFB boiler system.

The boiler was designed to be fired with bituminous coal of particle size less than 6 mm, ash content 8-20%, sulfur content of 0.6-1% and average LHV of 18-24 MJ/kg. In order to meet the sulfur dioxide emission standards fine limestone sorbent with particle <0.7mm was fed into the diplegs of the solids recirculation system. The boiler efficiency exceeds 92%, designed bed temperature in the furnace is roughly 850°C, and the emission of SO_2, NO_x and particulates are maintained below 200 mg/Nm^3, 200 mg/Nm^3 and 50 mg/Nm^3, respectively.

FUEL

The measurement campaign described in the current paper consisted of three tests carried out for full (100%) boiler load. During the tests the boiler was fired with three fuel types i.e. a mixture of hard coal and 20wt% of woodchips (test A), mixture of hardcoal and 30wt% of sunflower husk pellet (test B), and hard coal only (reference test – test C). Main parameters of the fuels are summarized in Table 1.

Table 1. The parameters of fuel mixtures

Fuel type	M_T [%]	$M_I^{air\text{-}dry}$ [%]	$Ash^{air\text{-}dry}$ [%]	$VM^{air\text{-}dry}$ [%]	$FC^{air\text{-}dry}$ [%]	$S^{air\text{-}dry}$ [%]	$HHV^{air\text{-}dry}$ [MJ/kg]
hard coal + woodchips (test A)	14.4	4.3	13.8	36.0	45.9	0.4	24.6
hard coal + sunflower pellet (test B)	7.7	3.2	25.2	33.4	38.3	0.6	21.5
hard coal only (test C)	8.6	3.2	18.1	30.7	48.0	0.6	26.5

M_T=transient moisture, M_I=internal moisture, VM=volatile matter, FC=fixed carbon, S=sulfur, HHV=high heating value

MEASUREMENT SETUP

Special 60m long 3mm i.d. thermocouples were used for the investigation of temperature distribution along the height of the furnace and across the horizontal flue gas duct between the cyclone vortex finder and the inlet to the CFB convective section. During the measurements the thermocouples were introduced vertically through specially-designed ceilings down into the furnace. The ceilings were located at the distance of 1m from the front and rear membrane walls (cf. the ports 01-24 in Fig. 2). The location of measurement ports across the horizontal flue gas duct between the cyclones and the inlet to the convective pass are shown in Fig. 3 (cf. the ports P1-P7).

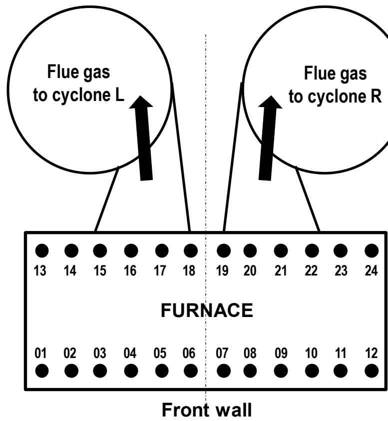


Fig. 2. Top view of the location of measurement ports across the boiler combustion chamber.

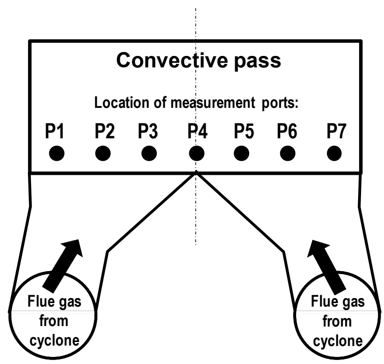
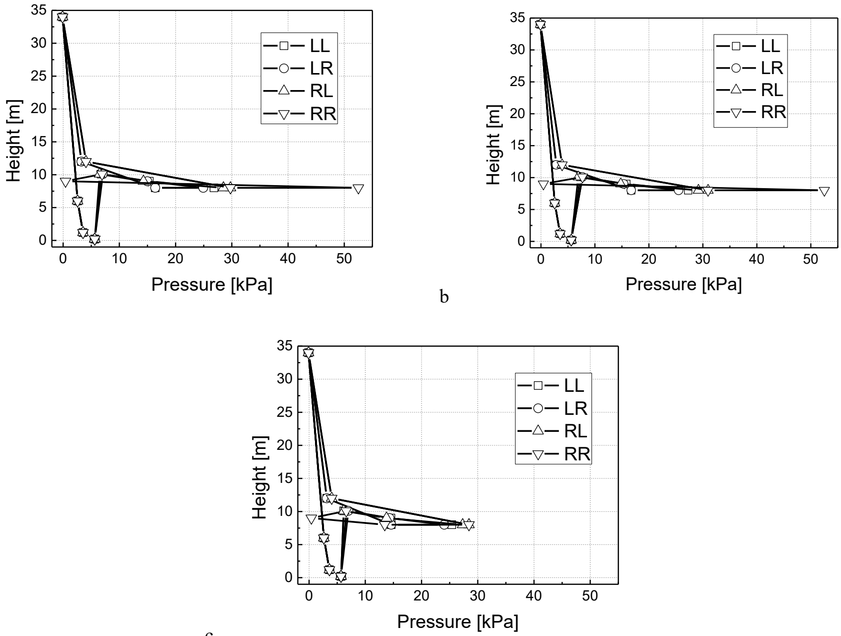


Fig. 3. The location of measurement ports across the horizontal flue gas duct.

RESULTS AND DISCUSSION

PRESSURE AND TEMPERATURE PROFILES

The average pressure profiles in boiler CFB loop during tests No. 1-3 are shown in Fig. 4. The first letters in the legend of Fig. 4 refer to the cyclone (left or right), while the others correspond to the loop seal dipleg: L=left, R=right. The results indicate that the profiles in the furnace are quite similar and the fluidization is maintained so that the boiler is operated without difficulties regardless of fuel type. Some minor differences between the pressure values in the loopseals during the tests were probably brought about by periodic disturbances or random blockage of the measurement system and did not affect boiler operation.



a b c

Fig. 4. Some chosen bed pressure profiles in the CFB loop during tests A-C; boiler load: 100%.

The average bed temperature profiles during the tests No. 1-3 are presented in Fig. 5. Similar to the data in Fig. 4 the first letters in the legend of Fig. 5 refer to the cyclone (left or right), while the others correspond to the loop seal dipleg: L=left, R=right. Analysis of the data confirm fuel flexibility of the CFB boiler – regardless of the fuel type the temperatures in the loop are very similar.

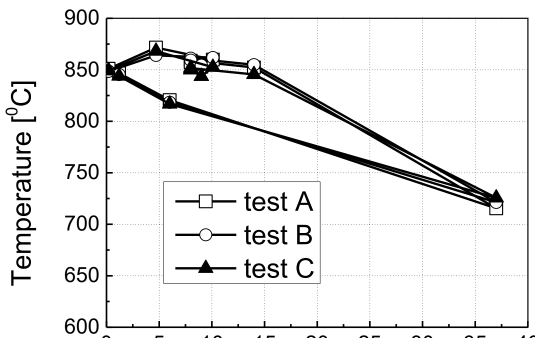


Fig. 5. Average bed temperature profiles in the CFB loop during tests A-C; boiler load: 100%.

TEMPERATURE PROFILE ALONG THE FURNACE

Due to the requirements for the maximum paper length only temperature profiles along the combustion chamber in the upper section of the furnace (i.e. above the upper edge of steam reheater Ω-tube bank) for some chosen measurement ports are shown in Fig. 6 for the tests A-C. The black dots refer to the temperature values determined by boiler control system. The data indicate that although the temperature distribution is quite uniform the profile is slightly affected by the fuel type. The values determined for test B (coal+sunflower husk pellets) are slightly higher than those measured e.g. during test C when only coal was fired. Interesting information can also be drawn up from the comparison of black dots referring to bed temperature values determined by boiler supervision and control system and the values measured by the authors of this paper. The results indicate the presence of significant temperature differences probably brought about by the location of boiler system thermocouple at furnace wall and thus limiting its affection with gas-solids flow. As can be seen from Fig. 6 the temperature reported to the operator by the boiler system may be even 150^0C lower than the 'real' values determined by the authors during the tests A-C. The presence of such 'unexpected' high temperature zones inside of the furnace may be responsible for some unexpected 'malfunctioning' of the boiler and may result in e.g. higher emission of NO_x or local overheating of the steam superheater tubes.

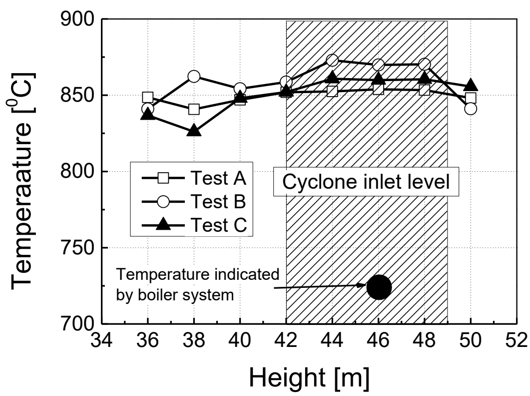


Fig. 6. Temperature profile along the combustion chamber in the upper section of the furnace for the tests A-C for a chosen measurement port. The black dots refer to the temperature values determined by boiler control system.

TEMPERATURE IN THE FLUE GAS DUCT

Figure 7 shows some chosen vertical temperature profiles across the horizontal flue gas duct between the cyclones and the convective pass for the tests A-C. Analysis of the results indicates significant temperature differences depending on the location of the measurement port. Those differences are brought about by the geometry of the duct and thus the structure of the flue gas flow between the cyclones and the convective section. The presence of a 'low temperature' zone in the central part of the duct is clearly visible since regardless of fuel type the temperatures in that zone are roughly 100^0C lower than the maximum ones determined for ports No. P2 and P6 (cf. Fig. 7 and Fig. 3). Due to the change of the direction of the flue gas flow (vertical one in the cyclone vortex finder and a horizontal one at the inlet to the convective section) and the gas convection the measurement data shown in Fig. 7 also indicate non-uniform vertical temperature distribution in the duct – the flue gas temperatures in the upper section of the duct are several tens of degrees higher than in the lower one. Maximum temperatures were determined at roughly 1-2 m from the channel roof.

The experimental results and the temperature differences determined during the measurement clearly indicate that the location of system temperature measurement ports and thermocouples in the CFBC must be chosen very carefully – otherwise the actual temperature values may be burden with significant error and be thus misleading for the operator. As a result, higher emission of pollutants or unwanted damages of boiler elements may occur, both leading then even to boiler emergency shutdown.

The results summarized in Figs 6-7 also indicate that in the case of firing the boiler exclusively with coal (test C) the exhaust flue gas temperatures measured were approximately 15-20^0C lower than in the case of the co-combustion tests A and B.

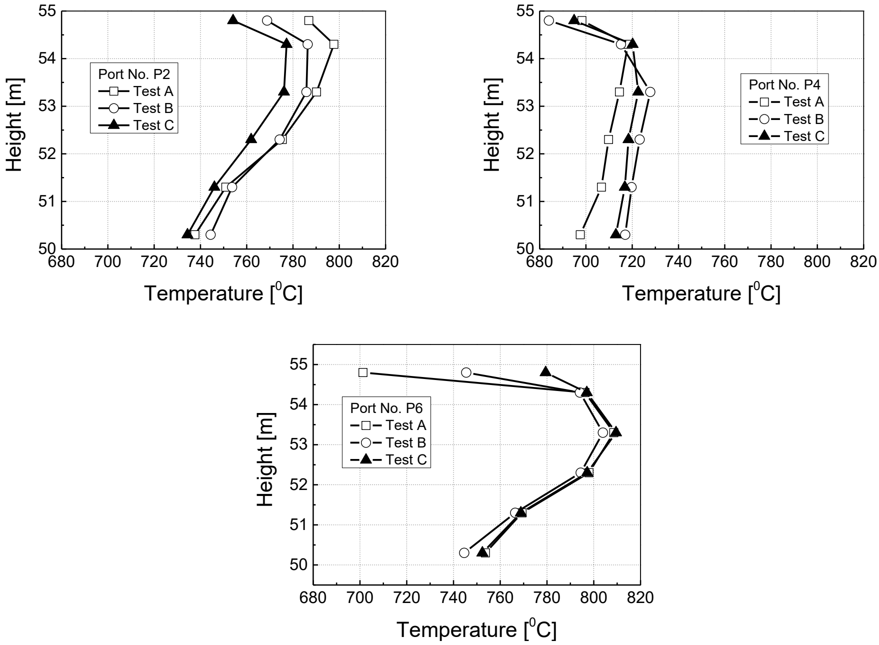


Fig. 7. Temperature profiles along the height of the inlet to the convective pass during the tests A-C for some chosen measurement ports. Boiler load: 100%.

The average flue gas temperature profiles along the convective section of the boiler are shown in Fig. 8. The values are very similar thus confirming good heat transfer between the flue gas and the heat exchangers located in the second pass and also the well-known fuel flexibility of the CFB combustors.

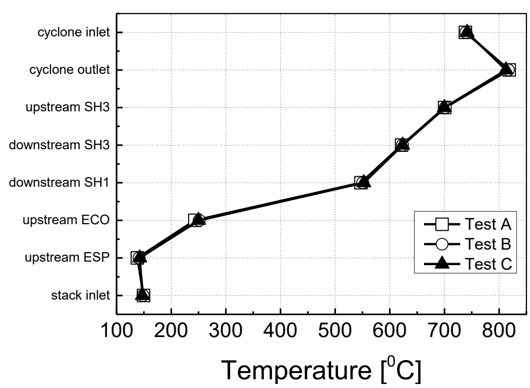


Fig. 8. Average flue gas temperature profiles during the tests A-C for some chosen locations along the convective pass.

SUMMARY

The results of experimental investigations carried out at a commercial large-scale CFB boiler and briefly described in the present paper may be summarized as follows:

1. The industrial tests confirmed successful operation of the CFBC regardless of the fuel type (hard coal or coal/biomass mixture).

2. The measurement of temperature distribution along the upper section of the furnace and across the horizontal flue gas duct between the cyclone vortex finders and the convective pass indicated that in some zones the actual bed and/or flue gas temperatures differed by almost 150^0C. The real temperatures were higher than those determined by boiler control system; such situation occurred particularly in the horizontal flue gas duct between the cyclones and the boiler convective section.
3. The temperature profiles across the horizontal flue gas duct indicated the presence of some ‘lower temperature’ zones in the central part of the duct where the actual temperatures might be even 100^0C lower than in the surrounding areas (cf. Fig. 7). The differences were brought about by the geometry of that boiler section affecting the formation of the flue gas flow in that area.
4. Analysis of temperature profiles in the horizontal flue gas duct at the inlet to the convective section indicated the effect of fuel type on flue gas temperature profile. In the case of coal only (test C) the measured flue gas temperatures were roughly $15\text{-}20^0$C lower than those determined during the co-combustion tests A and B. It may be thus pointed out that the increase of temperature brought about by the cocombustion may in some cases worsen the operating conditions of the steam superheater and thus accelerate the damage of the heat transfer surfaces particularly in the case when significant differences between the real flue gas temperatures and the values determined by boiler system thermocouples will occur.

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