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Distribution of solids concentration and temperature in the combustion chamber of the SC-OTU CFB boiler☆

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Abstract

One of the main parameters influencing heat transfer in a circulating fluidized bed boiler is the distribution of the bed's solids concentration within the contour of the boiler's combustion chamber. This paper contains an analysis of the impact of the solids concentration in a fluidized bed on the vertical temperature profile in the combustion chamber of a SC-OTU CFB boiler. Investigations were conducted at different loads of nominal generator power: 100%, 80%, 60% and 40%. Solids concentration was determined through pressure sensor measurements. Pressure measurements were taken at 11 measuring ports situated on the front wall of the combustion chamber. The vertical temperature profile was produced on the basis of temperature measurements from various furnace elevations. The combustion process was carried out at various primary to secondary air ratios with a constant excess air coefficient.

Keywords: temperature distribution, solids concentration, CFB boiler, bed pressure, unit loads

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1. Introduction

Solids concentration in the contour of the combustion chamber has a significant impact on the work of the whole CFB unit. The solids concentration is affected by the particle size diameter of materials fed to the boiler: limestone, bed material – make-up sand, fuel supply, re-circulated fly ash/bottom ash and internal material recirculation depending on the efficiency of the separator. The particle size distribution of the materials supplied to the combustion chamber affects the course of the combustion process, but is negligible from both the hydrodynamic point of view and the economics side [1].

The wide range of particle size distribution affects the segregation of solids, which is seen in the situation when light particles, i.e. recirculated fly ash, are elutriated by the fluidization gas even in small fluidization velocities and coarse particles sink to form a dense phase in CFB boilers. Also the relative amount of very light materials supplied (having a very small d_{50}) can lead to a situation where even in mid-range fluidization velocities, bigger particles are transported to the higher levels of the combustion chamber by clusters of fine particles. Hence, the proportion of

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Email addresses: ablaszczuk@is.pcz.czest.pl (Artur Błaszczuk*), mkomorowski@fluid.is.pcz.pl (Maciej Komorowski), wnowak@is.pcz.czest.pl (Wojciech Nowak) coarse material to fine particles has to be optimized to obtain good gas-solid, solid-solid mixing, and to avoid the problems associated with the outflow of coarser materials, for example coal particles, which in such case could be combusted in the cyclone instead of the combustion chamber.

Reflecting the vertical distribution of solids particles, the combustion chamber is divided into broad zones such as: bottom bed zone, splash zone and transport area. Research [2] delivered the information that the bottom bed zone is similar to the bubbling bed, with constant concentration and exploding bubbles, and above it is the splash zone. Johnsson et al. [3] found that average bulk density of the bottom bed is about 800 to 1200 kg/m^3 and these values correspond to bed porosity of 0.54 to 0.70. The part of the bed which is characterized by the constant pressure drop is the bottom bed height. Bottom bed density is determined by the pressure drop, with negligible influence from gravitational acceleration [4]. The splash zone can be characterized by the exponential decay of the solid particles concentration in the vertical direction and with strong solid backmixing throughout the cross-section. Data presented by Zhang et al. [5] showed that the core – wall layer structure which is present in the transport zone in large capacity units is similar to the core – annulus structure which is present in a circular cross-sectional combustion chamber with small capacity. From [5] investigations [5], the biggest backmixing is in the wall region and flow is low in the core area downward. In this area, particles which attained the furnace exit form the externally recirculated flow while particles from the wall-layer form the internally recirculated flow. According to [6] the particle concentration in the wall-layer is about three times as high as the cross-section average density.

Each material supplied to the boiler undergoes processes in the combustion chamber such as: solid mixing, fragmentation, attrition and combustion. Polydisperse solids materials which are mixtures of heterogeneous (in diameter and density) loose materials, raised up by fluidization gas, move with different velocities. The variety of particle velocities leads to collisions, causing erosion, attrition and destruction of particles.

According to [3] for solid mixing, the axial profile can be described by the expression:

$$\begin{aligned}\varepsilon(h) = {} & [\varepsilon_d - \varepsilon_\infty exp(-a(H - H_d))] \\ & \cdot exp(-a_{splash}(h - H_d)) \\ & + \varepsilon_\infty exp(a(H - h))\end{aligned} \tag{1}$$

The fragmentation process can be divided into two components – primary and secondary fragmentation [1]. Primary fragmentation starts after fuel is injected into the combustion chamber, leading to losses of mass material (moisture and volatiles) in the combustion chamber due to heating, drying and devolatilization. The coal combustion process leads to secondary fragmentation due to weakening and breaking up. This process occurs in the whole combustion chamber and is very important due to the simple fact that in the bottom region the particles are much coarser than in the upper zone of the combustion chamber.

Particles of much smaller particle size diameter are created from the original, bigger particles due to surface abrasion in the fluidized bed boilers and this whole process is termed ‘particle attrition’. Various studies state that the presence of smaller particles increases the attrition of bigger particles, but not vice versa [1].

The combustion process starts after fuel is injected into the combustion chamber, firstly from moisture loss and devolatilization, then char combustion. The place in the combustion chamber where these processes take place is a very important feature with regard to the forming of the primary combustion products. According to [6] fuel feeding in each point of the combustion chamber effects the axial gradients of the fuel concentration due to solids mixing. In a very large combustion chamber although the solid mixing is very quick, quite high axial gradients of the fuel concentration can occur [7].

Sekret’s research [6] shows that there is significant particle segregation in the combustion chamber, not only in the contour of the furnace (coarser particles falling to the dense zone and light particles transported to the dilute zone), but also axial segregation in the dilute zone (between the core and wall layer). Sekret's investigations show that the low part of the CFB combustion chamber is the place where the predominant mass of fuel particles is burnt. The author in the work [6] shows that in the wall layer of the dense zone the rate of fuel particles is 55%, which means that this is an area of intensive devolitilization. In the core region of the dense area, the reduction rate of fuel particles was higher: 77% This is a zone of intensive fragmentation processes, both mechanical and thermal. This leads to the conclusion that in the axial direction, the dense region is an area of intensive solids mixing. In the dilute area, the rate of fuel particles reduction is much lower: in agreement with results from paper [6] it is 10% and 3% respectively for the core and wall layer. The biggest mass losses in the core regard small particles (due to the combustion process), and in the wall layer regard coarse particles (due to fragmentation, which is intensified by the backflow of gas near the wall and the constant particle mass transfer between the core and hydrodynamic wall layer). In a large scale unit like the Lagisza SC OTU CFB boiler, the higher velocities of falling particles in the hydrodynamic wall layer and the kick-out of the walls in the bed part of the furnace improve internal particle circulation in the bed zone. In large scale boilers, which have a lower H_K/D_e ratio, the mixing process is more intensified, because of the particles falling in the hydrodynamic wall layer.

Fuel preparation and feeding – vital to maintaining the combustion process [8] at the desired operating conditions – are very important in both emission and efficiency control. Fuel injected should have suitable parameters for the boiler, such as: low heating value, ash content, corrosion potential of combustion by-products (chlorine content). The fuel should also be prepared. Fuel feeding is important for keeping the combustion process at steady state conditions: overly large particles can block fuel preparation and fuel feeders, resulting in non-homogenous fuel feeding. Very coarse bed material can lead to problems with combustion and heat transfer, because it has a deleterious effect on the fluidization process. Sintering and slagging cause defluidization and are caused by the chemical composition of fuel fed to the furnace (especially alkali content).

One very important issue is the link between the monitoring of temperature inside the combustion chamber and the control measures for gas emissions. As regards large combustion plants the permissible level of gas emissions in the European Union is regulated by the Large Combustion Plant Directive (2001/80/EC LCP). The main flue gas components are as follows: SO_2, NO_x, CO and solid particles. The temperature within the combustion chamber depends on the following parameters: particle size distribution of boiler materials (i.e. fuel, sorbent, make-up sand), solid hold-up within the combustion chamber, primary-to-secondary air ratio, the height of the bed in the lower part of the combustion chamber, excess of supplied air, circulation of bed material between the combustion chamber and return leg, fuel moisture content and low heating value. Typical work temperatures of the boiler lie in the range 750–900°C. This temperature range is the most suitable range for sulphur oxide bonds and low level NO_x emissions. The degree of the desulphurization process depends on the following factors: quantity of limestone (i.e. reactivity index), combustion temperature, bed height, fluidization velocity, primary-to-secondary air ratio, fly ash recirculation and the qualities of the coal and ash. Combustion temperatures of below 750°C lead to lower NO_x emissions but higher emissions of CO and hydrocarbons. The higher combustion temperature is due to the fact that the efficiency of the sulphur bond is lower in higher temperatures – in many cases the efficiency of desulphurization is much lower above 850°C and the emission level of NO_x is much higher as the combustion temperature increases.

An important factor for the correct and stable fluidization process especially in the grid zone of the boiler is the need to avoid agglomeration phenomena. Agglomeration has multiple causes: the chemical composition of fuel and ashes, overly high furnace temperature. Internal and external material circulation within the furnace volume and between the combustion chamber and recir-

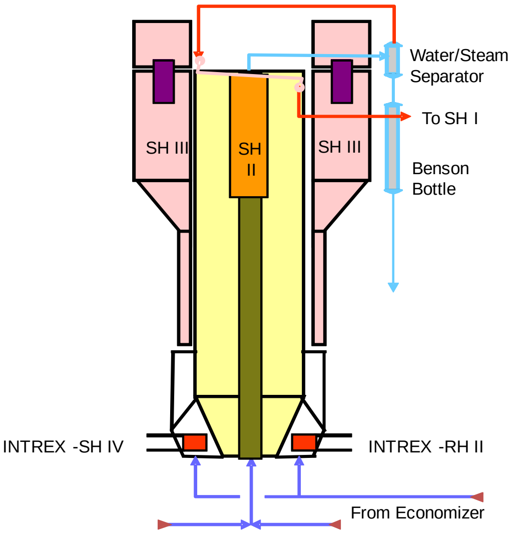

Figure 1: Schematic diagram of the 460 MW_e OUT-SC CFB boiler at Lagisza Power Plant [9].

Table 1: Design parameters of 460MW_e OTU-SC CFB boiler at Lagisza Power Plant [10].

Parameter	Unit	Data
Capacity	MW_e	460
Net electrical efficiency	-	44
Boiler type	-	OTU-SC
Main steam flow	kg/s	360
Main steam pressure	MPa	27.5
Main steam temperature	°C	560
Reheat steam flow	kg/s	307
Reheat steam pressure	MPa	5.5
Reheat steam temperature	°C	580
Feed water temperature	°C	289.7

culation system has a significant influence on heat transfer and is responsible for creating the temperature profile in the contour of the combustion chamber. This statement holds true for such basic assumptions as: layout of the heat exchange area, fuel and sorbent feed points, physical-chemical properties of the fuel and sorbent being stable during boiler work. Changes in the heat transfer coefficient within the combustion chamber through monitoring the mass flux and temperature of the recirculated material from the external heat exchangers is also a control measure and can affect the furnace temperature profile.

2. Experimental setup

Investigation were carried out at the world's largest fluidized bed combustion boiler, which is the second generation of once-through supercritical circulating fluidized bed (CFB OUT-SC) with capacity of 460 MW_e, which is installed in the Lagisza Power Plant of Poludniowy Koncern Energetyczny S.A. in Poland. A schematic diagram of the 460 MW_e OUT-SC CFB boiler is shown in Fig. 1, while basic constructional parameters are shown in Table 1.
Lagisza's boiler is designed to burn bituminous coal as its main fuel. The fuel properties for the boiler are shown in Table 2. There is an option to burn additional fuel, in particular coal slurry. Coal slurry can be combusted in a maximum 30% share by fuel heat input [10]. Light oil is used as a start-up fuel.

Unlike typical CFB boilers, this boiler is equipped with Benson vertical-tubes which are a new supercritical steam technology. At the height of 8.95 m from the grid, the combustion chamber cross section area has a diameter of 27.6 m×10.6 m (width×depth). The total height of the combustion chamber is 48 m. On the bottom of the combustion chamber there is a fluidization grid with primary air nozzles. Secondary air nozzles are located at three elevations above the grid (SA right wall and SA left wall).

The boiler is equipped with 8 solid separators: 4 on both sidewalls. The separators are made of membrane walls, which are cased with a thin layer of erosion-resistant refractory. A similar construction is used for the solid particles' return leg to the $INTREX^{TM}$ chamber, which is integrated with the boiler's sidewalls. In the INTREX chambers the heat is transferred with circulating material to the final superheater and reheater stages. In the combustion chamber there are: points of solid particle returns from the $INTREX^{TM}$ chamber, points of fuel and sorbent (limestone) feed, make-up sand and points of recirculation ash feeding.

Table 2: Fuel properties for 460 MW_e Lagisza OUT-SC CFB boiler [9].

Component	Unit	Overall range
Bituminous coal		
Lower Heating value (LHV)	MJ/kg	18–23
Total moisture	%	6–23
Surface moisture	%	max. 10
Ash content	%	10–25
Carbon content	%	52–60
Hydrogen content	%	3.3–4.2
Oxygen content	%	6.1–8.9
Nitrogen content	%	1.3–1.7
Sulphur content	%	0.7–1.7

3. Results and discussion

All tests were carried out for four different generator loads (i.e. 100%MCR, 80%MCR, 60%MCR and 40%MCR). During each test, bed pressure was at high values of about 6 to 7 kPa.

Temperature measurements in the combustion chamber were carried out on the boiler's front wall at various unit loads and combustion chamber height (42.4 m; 31 m; 24 m; 8.3 m; 5 m; 2 m; 1 m and 0.25 m). During investigations, the temperature distribution within the boiler's combustion chamber was in the range 741°C to 888°C. Recorded temperatures were in the range of typical temperatures for CFB boilers of 750–900°C, which is optimal in the thermal-flow conditions for the reduction of gaseous emissions. Vertical profiles of temperature in the combustion chamber are shown in Fig. 2. In the graph (Fig. 2) furnace temperature differences for all the unit loads can be seen on the X-axis. The relative temperature differences in the range of all unit loads (i.e. 100%MCR, 80%MCR, 60%MCR and 40%MCR) varied between 13°C and 148°C. On the basis of the data shown in Fig. 2, the second generation Lagisza boiler features lower relative temperature within the combustion chamber. Temperature distribution in combustion chamber is nonlinear in character. The result of secondary air influence on the temperature distribution can be seen in Ľ of the combustion chamber height above the dense region. There are significant gradients of temperature at the height of 10 m in the combustion chamber. In particular, this situation could be seen in the area of the dilute circulating bed, where the weak mixing process of the solid phase with gaseous phase took place. This is also a confirmation of the low volumetric concentration of the circulating bed.

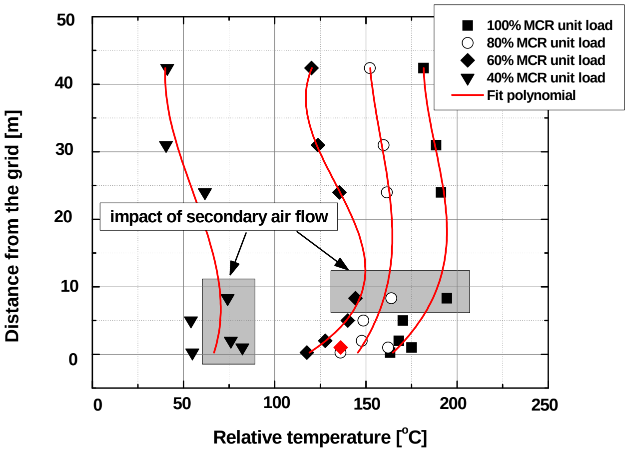

Figure 2: Temperature distribution in the combustion chamber for Lagisza OUT-SC CFB boiler.

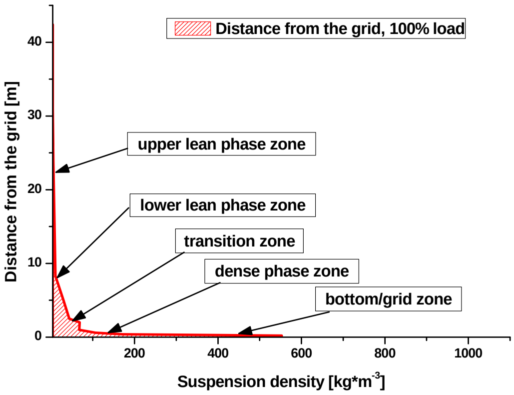

Figure 3: Distribution of solids concentration in the combustion chamber at 100% unit load.

Figures 3 to 6 present the distribution of solids concentration along the height of the combustion chamber. Solids concentration was determined through pressure measurements in the combustion chamber using Aplisens sensors. Pressure

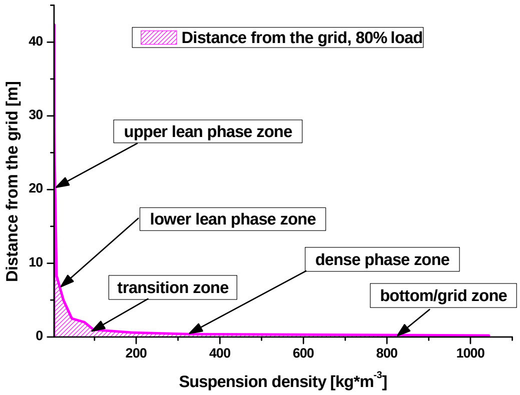

Figure 4: Distribution of solids concentration in the combustion chamber at 80% unit load.

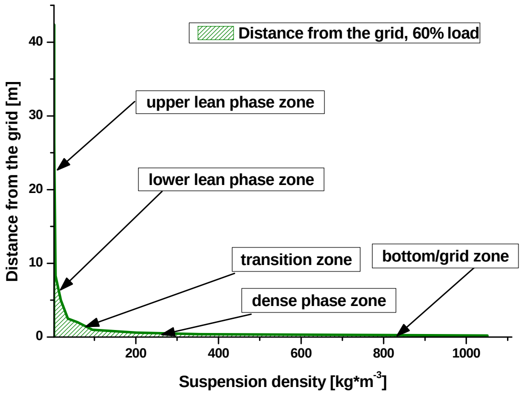

Figure 5: Distribution of solids concentration in the combustion chamber at 60% unit load.

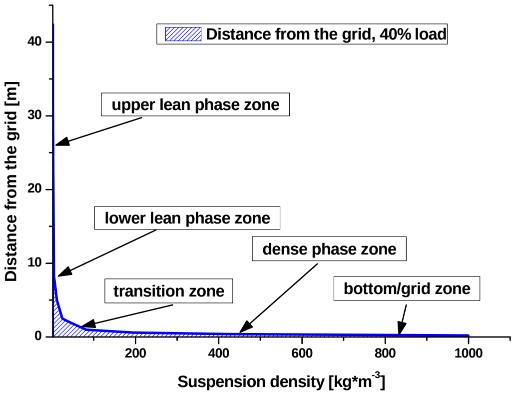

Figure 6: Distribution of solids concentration in the combustion chamber at 40% unit load.

measurements were carried out in 11 measuring ports situated on the front wall of the combustion chamber. Due to the anticipated high vertical pressure gradient of the bed material in the bottom part of the combustion chamber, the measurement ports were thickly spaced in this area. Five main zones along the combustion chamber's height can be readily identified, i.e. from the grid respectively: bottom/grid zone, developed dense phase zone, transition zone, lower lean phase zone (which contains fewer fine and more coarse particles) and upper lean phase zone. From the data, a significant difference in solids concentration can be observed between the grid zone and the upper part of the furnace. This difference is at its lowest for the 100%MCR load and its greatest for 40%MCR, being ca. 140 times and ca. 730 times respectively. These data lead to the conclusion that if the load is nearer to the nominal load, the difference in solids concentration in the contour of the combustion chamber height is significantly smaller than in the case of the lowest unit loads.

4. Conclusions

The circulating fluidized bed boiler at the PKE Lagisza Power Plant operates smoothly under the investigated conditions. The range of changes in relative temperature was not significant and varied between 13°C and 148°C. During the investigation, temperatures in the combustion chamber were in the range of typical temperatures for CFB boilers, i.e. 750–900°C. Increased temperatures are seen at and especially above the level of the secondary air feed to the combustion chamber. The solids concentration in the contour of the furnace was determined from the registered pressure values. A significant difference in solids concentration between the grid and the upper zone of the combustion chamber was observed. This difference increased as the unit load fell, being ca. 140 times and ca. 730 times respectively for 100%MCR and 40%MCR load.

The results lead to the conclusion that units such as the Lagisza Power Plant work flexibly across the whole range of unit loads.

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Nomenclature

$\varepsilon(h)$	voidage along the bed height
ε_d, ε_∞	particle volume fraction in the bottom zone and in the upper zone
a_{splash}, a	decay exponents respectively for the splash zone and transport zone, both in the function of the particle diameter
H	the total height of the combustion chamber
h	the height above the air distributor
H_d	the bottom zone height