Experimental and computational evaluation of a gas-solid suspension density distribution under circulating fluidized bed conditions

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Abstract. The paper presents the results of operational measurements of the suspension density distribution in the 966 MWth supercritical Circulating Fluidized Bed boiler. The tests were carried out for four different unit thermal loads, i.e. 40, 60, 80, and 100% MCR. The conducted operational measurements showed that the suspension density distribution of the particulate material in the combustion chamber of the CFB boiler has the form of an exponential curve with maximum values occurring in the bottom part of the furnace. On the basis of the operational data, an attempt was made to reflect the suspension density distribution in the combustion chamber of the boiler using the ANSYS CFD software. The calculations were carried out using the Eulerian multiphase model in an unsteady state condition. As revealed by the simulations, the Eulerian multiphase model allows for a quantitative representation of the suspension density distribution of the granular material only for the maximum boiler load. For other thermal loads, quantitative representation of experimental distributions of suspension density using the Eulerian method is possible except for the dense region.

1. Introduction

The Circulating Fluidized Bed (CFB) combustion technology has been developed continuously for over five decades. Its popularity results from numerous advantages, which can be considered from two points of view: process and environmental. The main environmental advantage of the CFB technology is its ability to combust a diverse range of difficult low-grade fuels of varying quality with low emissions of NOx, low-cost sulfur capture during combustion in the furnace itself, as well as low CO and CxHy emissions due to turbulent conditions and good mixing [1,2]. From the process point of view the advantages of CFB technology can be summarized as follows:

- possibility of multi-fuel combustion,
- stable operation conditions and the good turn-down ratio [3],
- no need for fuel preparation (e.g. pulverizing) [3],
- support firing is not needed except during start-up periods [3],
- increased capacity possible within the same footprint as old boilers [3],
- high bed-to-surface heat transfer coefficients, 100-400 W/m²K [3].

A CFB boiler is a device designed to generate steam by burning or co-burning a diverse range of fuels under special hydrodynamic conditions. Under CFB conditions, fine solids (Geldart group A or B) are transported through a furnace at velocities exceeding the terminal velocity of average particles, yet there
is a degree of refluxing of solids adequate to ensure uniformity of temperature in the furnace [4]. In fact, three distinct phenomenological sub-processes influencing each other take place in a CFB boiler, i.e. hydrodynamic gas-solid contact, heat and mass transfer, and chemical reactions [5]. From a process point of view, the most important is the hydrodynamic gas-solid contact, which can be described by nine parameters: $U_\infty$, $g$, $\rho_p$, $\rho_g$, $d_p$ (or PSD), $\phi$, $\mu$, and $G$ [4,6]. These parameters play a decisive role in the gas-solid suspension density distribution, which is the most important factor influencing the bed-to-wall heat transfer and which can be described by the following equation

$$\rho_{\text{sus}} = \rho_p (1 - \varepsilon) + \rho_p \varepsilon$$

(1)

The knowledge of this parameter is important, especially in large-scale boilers, as it allows determining the temperature profile and heat exchange conditions inside a furnace [7]. The most commonly used method of determining the inert suspended solids density is the measurement of pressure gradients in the combustion chamber. Thus, the time-averaged gas-solid suspension density distribution can be estimated using the following relationship

$$\rho_{\text{av}} = \frac{1}{A_c} \int \rho_{\text{sus}} dA_c = -\frac{1}{g \frac{dp}{dh}}$$

(2)

As follows from experimental studies conducted by many researchers, the wall-to-suspension heat transfer coefficient increases strongly along with $\rho_{\text{sus}}$, primarily because of the particle convection term [8-12].

The complex nature of gas-solids flow in the combustion chamber of a CFB boiler and new challenges for greater operational flexibility of power units and the quality of delivered fuels, force boiler designers to solve new problems with the help of laboratory tests and mathematical modeling. In the latter, an essential role is played by empirical correlations, semi-empirical modeling, and methods of Computational Fluid Dynamics (CFD). The empirical correlations derived based on experimental experience gained over many years of CFB technology development are very often used to provide a simplified description of the parameters required to determine, inter alia, a gas composition or a heat balance. In the semi-empirical approach, which is also called macroscopic modeling, the fluidized bed combustion process is described by the expressions that combine theoretical and empirical contents. Owing to that, some parts of the CFB boiler are modeled with the 3- and others with the 1.5- and 0-dimensional description. The main advantage of semi-empirical modeling is that an entire fluidized bed boiler can be described by one comprehensive model [13]. Unfortunately, the limited confidence in empirical correlations does not allow the free use of semi-empirical modeling, especially in scale-up. In the classic CFD approach, one can choose between Direct Numerical Simulations (DNS), Euler-Lagrange, or two-fluid Euler-Euler models. In the DNS approach, which can be considered as Lagrangian modeling, the solids are treated in a discrete manner. Thus, the main challenge is modeling particle collision and the computational time increases along with Reynolds number. In the case of Euler-Lagrange (E-L) type models, the fluid phase is treated as a continuum while the dispersed phase is the sum of discrete elements (particles). The main advantage of the L-E modeling is that it allows a relatively direct formulation of a fluidized bed system composed of a polydisperse mixture of solids. Moreover, it gives a possibility of predicting particle size distributions of several solid fractions occurring in a boiler. In practice, due to the relatively high computational cost, a number of simplifications are used. The first one, known as ‘two-way coupling’, assumes neglecting the particle-particle collisions. However, if the influence of the particles on the gas flow can also be neglected, the other simplification known as ‘one-way coupling’ is applied [14]. The Euler-Euler (E-E) approach, also called two-fluid modeling assumes that both the gas and solid phases can be treated as interpenetrating continua. In this type of modeling, the main challenge is to find proper closure equations for the particle pressure and the solids phase stress tensor. However, the E-E approach has the advantage of relatively
low computation time, and the ability to obtain a qualitative picture of the gas-solid structure with a careful formulation of the boundary conditions [15].

This paper presents the results of operational measurements of the suspension density distribution in the 966 MWth supercritical fluidized bed boiler operated in Tauron Wytwarzanie S.A. Lagisza Power Plant. On the basis of the operational data, an attempt was made to reflect the boiler operating condition using the ANSYS CFD package. The calculations were carried out using the Eulerian multiphase model in an unsteady state condition.

2. Reference facility
Experimental studies were carried out on the CFB-1300 466 MW$_c$ supercritical CFB boiler operating at the company TAURON Wytwarzanie SA - The Lagisza Power Plant, Poland (Figure 1).

![Schematic diagram and basic parameters of the CFB-1300 466MW$_c$ supercritical CFB boiler.](image)

Figure 1. Schematic diagram and basic parameters of the CFB-1300 466MW$_c$ supercritical CFB boiler.

The total height of the combustion chamber is 48 m. The size of the combustion chamber at the grid level is 27.6 m long and 5.3 m wide. The depth of the combustion chamber is growing with increasing distance from the grid. At the height of 8.95 m, the combustion chamber width is 10.6 m and does not change with a further increase of the distance from the grid. The parameters of the primary and secondary air are presented in Table 1.

Figure 2 presents the particle size distributions (PSD) of the inert material circulating in the Lagisza 966 MW$_{th}$ CFB boiler. For static pressure measurements, the data acquisition system consisted of ADAM-6000 A/C converters, APR-2000ALW smart pressure sensors, and DasyLab10.0 software was employed. The operational tests were carried out for steady boiler operation conditions at 100%, 80%, 60%, and 40% MCR. The static pressures in the boiler combustion chamber were measured at: 42.4, 31, 24, 8.3, 5, 2.5, 2, 1, 0.6, 0.4, and 0.2 m.
Table 1. Parameters of the primary and secondary air used in numerical calculations of Lagisza CFB boiler for different boiler loadings.

| Boiler loading, %MCR | 100  | 80   | 60   | 40   |
|----------------------|------|------|------|------|
| PA kg/s              | 0.3250 | 0.2881 | 0.2323 | 0.2193 |
| SA-level1 kg/s       | 0.0750 | 0.0529 | 0.0332 | 0.0179 |
| SA-level2 kg/s       | 0.0500 | 0.0353 | 0.0221 | 0.0119 |
| SA-level3 kg/s       | 0.0500 | 0.0353 | 0.0221 | 0.0119 |
| PA/SA                | 65/35 | 70/30 | 75/25 | 84/16 |
| U₀ m/s               | 1.14  | 0.93  | 0.70  | 0.59  |

Figure 2. PSD of inert material circulating in the Lagisza 966 MWth CFB boiler.

3. Numerical calculation

The objective of the numerical analysis of the flow in the Lagisza CFB boiler was to:

- determine the static pressure distribution at the wall, where the pressure measurements are taken under different boiler loading conditions,
- determine the suspension density distribution inside the combustion chamber of the boiler, and
- compare results with those obtained during operational tests.

Figure 3 shows the geometry (Figure 3a) and the grid (Figure 3b) of the Lagisza CFB boiler. Since the boiler has a symmetrical design, only half of the combustion chamber volume was used in the calculations. The size of the grid has been chosen as a compromise between the computational time and the accuracy of the numerical calculations. Numerical calculations were carried out using the Eulerian multiphase model in an unsteady state condition and the standard k-ε viscous model available in the Ansys CFD software (ver. 13.0). The general conservation equations for phase q for mass and momentum, respectively, can be written as follows:
\[
\frac{\partial (\varepsilon_q \rho_q)}{\partial t} + \nabla \cdot (\varepsilon_q \rho_q \mathbf{u}_q) = 0
\] (3)

\[
\frac{\partial (\varepsilon_q \rho_q \mathbf{u}_q)}{\partial t} + \nabla \cdot (\varepsilon_q \rho_q \mathbf{u}_q \mathbf{u}_q) = -\varepsilon_q \nabla p + \nabla \cdot \tau_q + \varepsilon_q \rho_q \mathbf{g} + \sum_{p=1}^{n} [K_{pq} (\mathbf{u}_p - \mathbf{u}_q)] + S
\] (4)

**Figure 3.** Geometry (a) and the grid (b) of the Lagisza 966 MWth CFB boiler used in CFD calculations.

Since the contribution of six granular phases was analyzed during the calculations, as many as seven pairs of equations (3) and (4) had to be solved in the calculation process. It should be noted that the analysis was conducted for the cold state only. Thus, the conservation of energy equation did not need to be solved. The boundary conditions and models used in numerical calculations of the Lagisza CFB boiler are presented in table 2.

**Table 2.** Boundary conditions and models used for numerical calculations.

| Model                  | Setting                      |
|------------------------|------------------------------|
| Space                  | 3D                           |
| Time                   | Unsteady                     |
| Viscous                | Standard k-\(\varepsilon\)    |
| Near-wall treatment    | Standard Wall Functions      |
| Multiphase k-\(\varepsilon\) model | Dispersed approach         |
| Eulerian phases:       | Phase 1 - Air \(\bullet T = 293K; U_0 - \) according to table 1 |
|                        | Phase 2 - Granular \(\bullet d_{10} = 25\mu m; \rho_p = 2500 \text{ kg/m}^3\) |
|                        | Phase 3 - Granular \(\bullet d_{30} = 47\mu m; \rho_p = 2500 \text{ kg/m}^3\) |
|                        | Phase 4 - Granular \(\bullet d_{50} = 71 \mu m; \rho_p = 2500 \text{ kg/m}^3\) |
|                        | Phase 5 - Granular \(\bullet d_{70} = 114\mu m; \rho_p = 2500 \text{ kg/m}^3\) |
|                        | Phase 6 - Granular \(\bullet d_{90} = 220\mu m; \rho_p = 2500 \text{ kg/m}^3\) |
| Phase interaction:     | Drag coefficient: Syamlal-O’Brien |
The computational mesh was generated in ANSYS Meshing software using tetrahedral and hexahedral elements. The total number of grid cells is 1,376,389, with a smallest grid element volume of 3.03e-09 m³. At the locations of expected increased pressure gradients, the density of the computational grid was increased. In order to evaluate the influence of the mesh density on the accuracy of the results obtained, several meshes with an increasing number of grids were analyzed by observing the pressure distribution in the combustion chamber. During the simulation calculations, the static pressure values determined in the area where the operational measurements were made, were recorded every 25 iterations. This allowed the results for each boiler load case analyzed to be averaged over more than 1100 data records.

4. Results and discussion
Figure 4a shows a comparison of the distributions of the suspension density of a loose material measured in the combustion chamber and determined by calculation for the maximum thermal load of the boiler. In order to allow direct comparison of the obtained distributions, the results are presented in dimensionless form. As it can be seen from the presented measurement results, the suspension density distribution along the height of the combustion chamber has the form of an exponential curve. It reveals that in most parts of the combustion chamber, the concentration of inert material is low, reaching the maximum in the bottom part of the boiler. Moreover, as shown in Figure 4a, for 100% MCR, the Eulerian multiphase model reflects the static pressure distribution in the boiler combustion chamber both qualitatively and quantitatively. This is of particular importance in the dense region of the furnace, where the most intense interparticle interactions occur, accompanied by rapid mixing processes, and where the recorded changes in pressure variation are greatest. This is confirmed by the distribution of the standard deviation of the suspension density shown in Figure 4b. It indicates that the fluctuations of the suspension density change proportionally along with the height of the combustion chamber, reaching maximum values in the primary air supply area. Qualitatively similar results of suspended solids density distributions can be determined from the Adamczyk's simulation results [16]. However, this does not mean that the distribution of suspension density in the combustion chamber is qualitatively similar for each CFB boiler. Some examples are the results obtained by other researchers [17-20].

![Figure 4a](image1.png)  ![Figure 4b](image2.png)

**Figure 4.** Comparison of suspension density measured in Lagisza 966 MWth CFB boiler and calculated numerically (a) and distribution of standard deviation of suspension density of granular material computationally determined at 100%MCR (b).

Figure 5a shows a comparison of the suspension density distributions measured in the boiler and computationally determined for 80% MCR. As it is revealed from the comparison with the full load results, decreasing the boiler load has the effect of shifting the suspension density L-shape curve towards smaller values. For this boiler load, the simulation calculations reflect very well the results of operational measurements obtained only at heights from 1.0 to 42.4 m. In the vicinity of the grid, the differences
from the measured values are very large, reaching more than 80%. Taking into account the distribution of standard deviation as shown in Figure 5b, it can be stated that the largest fluctuations of suspension density are observed in the exit zone of the combustion chamber, and not, as it should be expected, in the dense area of the bed. Considering the very long averaging time of the simulation results, it is difficult to unequivocally identify the cause of such fluctuations.

Figure 6a shows a comparison of the suspension density distributions measured in the boiler and calculated for 60% MCR. The obtained results show that the level of fitting of the curve calculated as a result of simulation computations is very high, practically in the whole range of measured pressures. The exception are the results achieved in the lower part of the combustion chamber, where the differences between the maximum measured and calculated values are more than 50%.

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**Figure 5.** Comparison of suspension density measured in Lagisza 966 MWth CFB boiler and calculated numerically (a) and distribution of standard deviation of suspension density of granular material computationally determined at 80%MCR (b).

**Figure 6.** Comparison of suspension density measured in Lagisza 966 MWth CFB boiler and calculated numerically (a) and distribution of standard deviation of suspension density of granular material computationally determined at 60%MCR (b).
While analyzing the results of the standard deviation distribution presented in Figure 6b, one can notice a decreasing scatter of the suspension density values of the loose material with increasing distance from the grid. This is a normal tendency, resulting from the disappearance of the cluster structure of particles, accompanied by a gradual equalization of static pressure.

Figure 7a depicts a comparison of the suspension density distributions measured in the boiler and calculated for 40% MCR. As it can be seen from the obtained results, the Eulerian multiphase model allows achieving a very good agreement with the experimental curve also in this case. The exception is the lower part of the combustion chamber, where the observed differences are very high and reach up to 90%. As it can be seen from the analysis of the distribution of standard deviation of suspension density presented in Figure 7a, similarly as in the previous cases, the deviation from the mean value is greater the closer to the grate of the combustion chamber. This is a trend typical for all CFB boilers.

To sum up, it should be stated that the use of the Eulerian multiphase model for the analysis of the suspension density distribution in the combustion chamber of the CFB boiler allows achieving good results only for the maximum load of the boiler, in which the maximum expansion of the loose material occurs. In other cases of boiler load, the reflection of the experimental curves is unsatisfactory only in the bottom part of the boiler, where the highest intensity of the inert material mixing occurs. In this area, mass transfer processes should be analyzed using the hybrid Euler-Lagrange models, known as the multiphase particle-in-cell (MP-PIC) model or the dense discrete phase model (DDPM).

5. Concluding remarks
The conducted operational measurements and computational simulations allow the formulation of the following conclusions:
1. The suspension density distribution of the particulate material in the combustion chamber of the CFB boiler has the form of an exponential curve with maximum values occurring in the bottom part of the furnace.
2. The use of the Eulerian multiphase model with five granular phases allows for a quantitative representation of the suspension density distribution of the granular material only for the maximum boiler load.
3. For thermal loads equal to 80%, 60%, and 40% MCR, quantitative representation of experimental distributions of suspension density by using the Eulerian method is possible except for the dense region. Simulation of the processes occurring in this area should be carried out using more advanced models in which the particle-particle collisions are taken into account.
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Nomenclature

\( A_c \) cross-section of the furnace, m\(^2\)

\( d_p \) particle diameter, m

\( d_{50} \) mass mean particle diameter, m

\( g \) acceleration of gravity, m/s\(^2\)

\( h \) height, m

\( H \) combustion chamber height, m

\( K \) interphase momentum exchange coefficient between phases with subscript \( q \) standing for the \( q \)-th solid phase of a total number \( n \), kg/(m\(^3\)s)

\( MCR \) Maximum Continuous Rating, %

\( n \) number of phases, -

\( U_0 \) superficial gas velocity, m/s

\( u \) velocity vector, m/s

\( p \) pressure or pressure shared by all phases, Pa

\( PSD \) particle size distribution

\( PA/SA \) primary/secondary air ratio, -

\( S \) source term, which can represents an external body force, a lift force or a virtual mass force.

\( T \) temperature, K

\( t \) time, s

\( z \) coordinate of the combustion chamber height, m

Greek symbols

\( \rho \) density, kg/m\(^3\)

\( \rho_{av} \) time-averaged gas-solid suspension density, kg/m\(^3\)

\( \rho_{sus} \) solids suspension density, kg/m\(^3\)

\( \rho_p \) particle density, kg/m\(^3\)

\( \tau \) stress-strain tensor, N/m\(^2\)

\( \varepsilon \) volumetric fraction, -

Subscripts

\( q \) \( q \)-th phase