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THE INFLUENCE OF SAMPLING POINT ON SOLIDS SUSPENSION DENSITY APPLIED IN SCALING OF THE HYDRODYNAMICS OF A SUPERCRITICAL CFB BOILER

Paweł Mirek*, Jolanta Ziaja

Częstochowa University of Technology, Faculty of Environmental Protection and Engineering, Institute of Advanced Energy Technologies, ul. Dąbrowskiego 69, 42-200 Częstochowa, Poland

The article presents the results of laboratory tests carried out on a scaling model of the 966MW$_{th}$ fluidised-bed boiler operating in the Lagisza Power Plant, made on a scale of 1:20 while preserving the geometrical similarity. The tests were carried out for scaled-down material taken from different locations on the circulation contour in the state of full boiler loading. To reflect the hydrodynamic conditions prevailing in the combustion chamber, solids with properly selected density and particle size distribution were used. The obtained results have made it possible to determine the location for taking the most representative granular material sample.

Keywords: circulating fluidised bed, hydrodynamics, scaling

1. INTRODUCTION

In spite of several dozen years of enthusiastic studies on the hydrodynamics of the circulating fluidised bed (CFB), no sufficiently accurate and unique theoretical description of phenomena occurring within this structure has been successfully formulated to date (Horio, 1997). Model studies carried out on a laboratory and technical scales show that four characteristic regions, differing from one another in suspension density of inert material, can be distinguished in the combustion chamber space of an atmospheric CFB boiler:

- a bottom zone, which is made up by the bottom bubbling bed and the splash zone,
- a dense region,
- a diluted region, and
- an exit region (Fig. 1).

The nature of phenomena observed in each of the regions does not allow a universal functional relationship to be formulated, which would accurately enough relate the flow parameters with the inert material characteristics. In this situation, one of the methods used for the laboratory testing of the CFB hydrodynamics is the dynamic similarity method, whose basic problem is a proper selection of density and particle size distribution of the material circulating within the system.

While selecting the particle density, dynamic criteria known in literature can be used (Glicksman et al., 1997; Knowlton et al., 2005). To determine particle size composition of a material intended for laboratory tests the knowledge of the particle size distribution of the material circulating in the boiler will be needed. As can be seen from Fig. 1, the particle size distribution of the inert material depends largely on the location on the boiler's circulation contour. Therefore, the question is how to prepare a

*Corresponding author, e-mail: pmirek@neo.pl

representative sample of the material circulating in the boiler, the use of which would enable the state of the boiler's hydrodynamics to be reflected on the scaling model. One of the approaches to solving this problem is by making the balance of boiler inter material population, which means very difficult measurements of the solids circulation flux of material circulating within the boiler must be performed. The alternative approach employed in this study is to determine the particle size distributions of material taken from different locations on the circulation contour and to perform a number of verifying tests in order to determine the most representative sample.

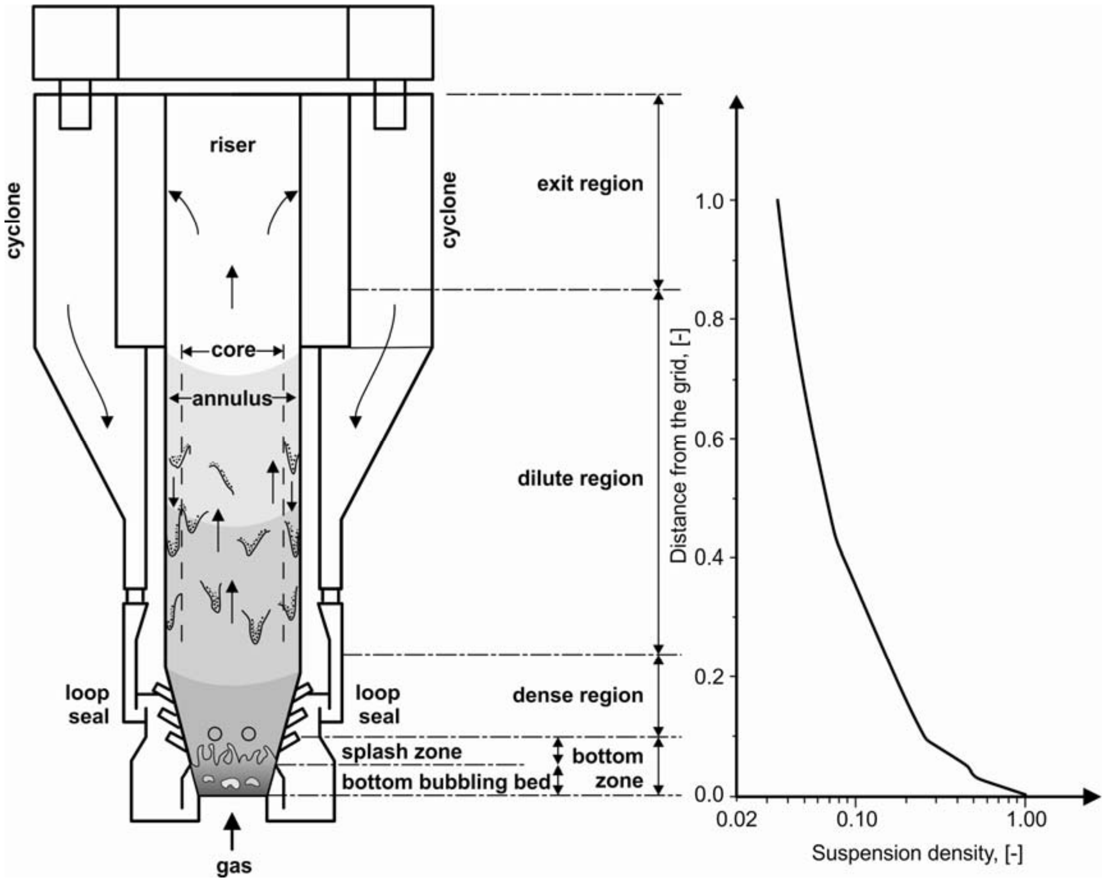

Fig. 1. Typical flow structure in a circulating fluidised bed

2. OPERATIONAL TESTS ON THE LAGISZA 966MW$_{TH}$ CFB BOILER

Industrial tests were carried out on a 966MW$_{th}$ CFB boiler operating in the Lagisza Power Plant. The boiler is equipped with eight cyclones arranged symmetrically on the two opposite walls of the combustion chamber, whose dimensions at the air distributor are 27.6m×10.6m. The overall height of the combustion chamber is 48m. The fuel for the boiler is low-grade hard coal. The basic operational parameters are given in Table 1.

The operational tests were carried out for steady boiler operation conditions under the rated load and with a primary air (PA) to secondary air (SA) ratio of 1.86. During the tests, inert material samples were taken from indicated locations on the boiler's circulation contour, as presented in the schematic diagram shown in Fig. 2.

At the same time, a measurement of static pressure along the combustion chamber height was taken. For this purpose, a measurement system was employed, which consisted of ADAM-6000 A/C converters, APR-2000ALW smart pressure sensors and DasyLab10.0, a measurement data acquisition program.

Table 1. Data design and operating CFB boiler supercritical parameters with a capacity of 966MW$_{th}$, operating at the Lagisza Power Plant

Specification	Unit	Value
Electric power	MW	460
SH flow RH flow	kg/s	361/305.7
SH pressure /RH pressure	MPa	27.5/5.48
SH temperature/RH temperature	K	833/853
Height of the combustion chamber	m	48
Cross-section combustion chamber above funnel	m^2	27.6 x 10.6
Fuel		bituminous coal wet fine coal
Emission limits (0_2=6%)		
NO_x	mg/m_n^3	200
SO_x	mg/m_n^3	200
CO	mg/m_n^3	200
Dust	mg/m_n^3	30

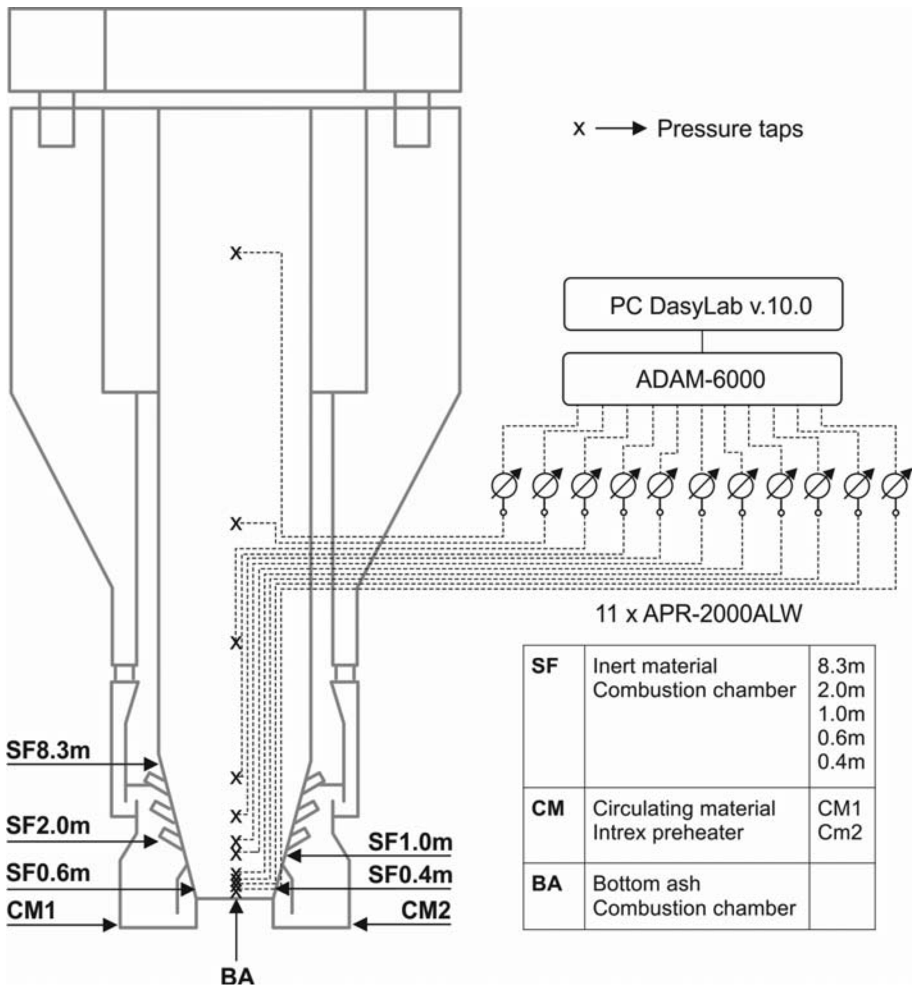

Fig. 2. Distribution of static pressure ports and inert material sampling points in the Lagisza–supercritical CFB boiler

2.1. Inert material suspension density distribution in the boiler

The obtained pressure drop values were converted into suspension density values using the relationship:

$$\rho_{sus} = \frac{\partial p}{\partial h} \frac{1}{(1-\varepsilon)g} + \rho_f \tag{1}$$

where the suspension density values were adjusted to the values resulting from the density difference between air and flue gas. Figure 3 shows the granular material suspension density distribution for the full boiler load with the ratio of PA/SA=1.86. In order to compare the results obtained by different authors and due to the confidentiality agreement between Czestochowa University of Technology and Foster Wheeler OY, the suspension density values shown in Fig. 3 are expressed in a dimensionless form.

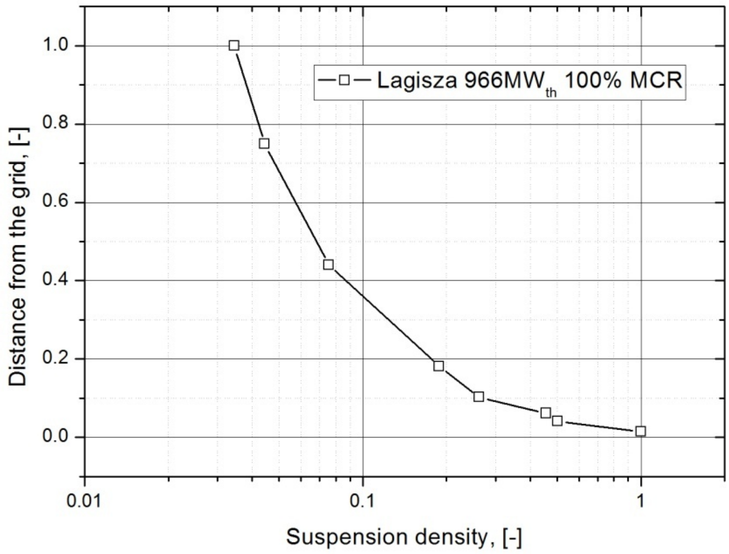

Fig. 3. Suspension density of inert material in boiler for 100%MCR

As can be seen from Fig. 3, the suspension density distribution has an exponential behaviour with a slight deflection in the secondary air feed location. In the lower boiler region (i.e. bottom and dense zone), very large pressure gradients occur, while in the diluted and exit regions the pressure gradients have similar values.

2.2. Particle size distribution of inert materials on the Lagisza 966MWth CFB boiler

Due to the fact that the diameters of particles of the granular material present in the CFB 966MW_{th} boiler vary in a wide range, the particle size distribution in material samples taken from the boiler were determined by two methods:

- by laser diffraction for particle sizes in the range of 0÷1000μm, using a Mastersizer 2000E analyser, and
- by sieve analysis for particle diameters greater than 1000μm.

Figure 4 presents the particle size distributions of inert material taken from the boiler's combustion chamber at a height of 0m, 0.4m, 0.6m, 1.0m, 2.0m and 8.3m, and from the Intrex superheaters chambers for a full load of the boiler. The particle diameter values are expressed in Fig. 4 as relative values, related to the maximum particle diameter. As can be seen from Fig. 4, the coarse fraction share decreases with an increasing distance from the boiler's combustion chamber grid. Accordingly, the particle size distributions of granular material taken from the selected locations on the boiler's circulation contour are contained between the two curves:

- CM, for the finest fractions, and
- BA, for the coarsest fractions of bottom ash.

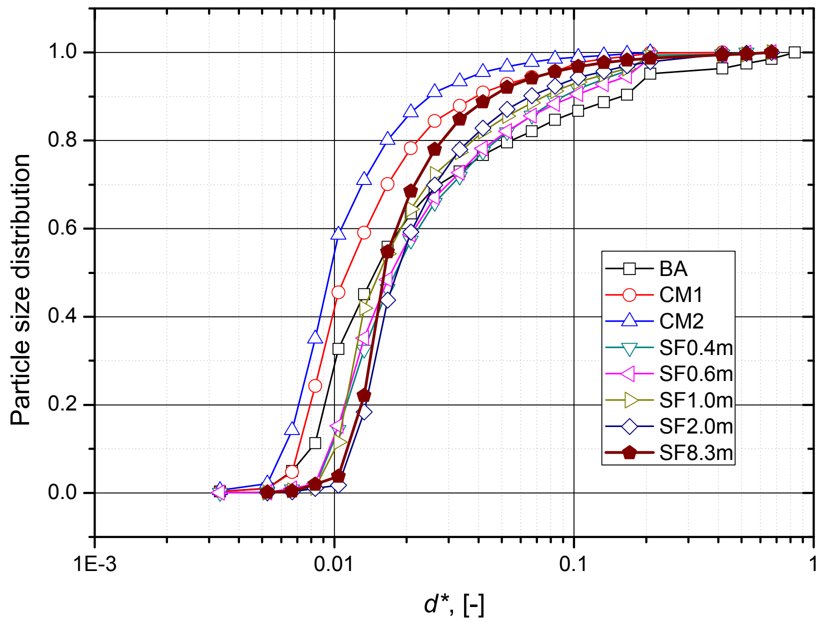

Fig. 4. Cumulative particle size distribution of inert materials for 100% MCR

The curve characterising the material of the highest representativeness should cover both fine and coarse particle fractions by its range. The analysis of the particle size distributions shown in Fig. 4 indicates that materials of the broadest particle diameters spectrum are BA, CM1 and SF8.3m, whose particle size distribution appropriately scaled down was used for model studies.

3. DESCRIPTION OF THE SCALING MODEL

The hydrodynamic parameters of the Lagisza 966MW$_{th}$ CFB boiler has been calculated based on the following scaling relations

$$\frac{U_0^2}{gD}, \frac{U_0}{v_t}, \frac{G_s}{\rho_s U_0} \tag{2}$$

As the measurement of the external solids circulation flux G_s in a real boiler is very difficult to make, it is alternatively assumed that the scaling relations (2) can be substituted with equations of the following form

$$\frac{U_0 d\rho_f}{\mu}, \frac{U_0}{v_t}, \frac{d^3\rho_f(\rho_s-\rho_f)g}{\mu^2} \tag{3}$$

As can be easily noticed, in the scaling relations (2) the Froude number and the ratio $G_s/\rho_s U_0$ have been substituted in the scaling relations (3) with the particle Reynolds number. By introducing the Archimedes number we can directly determine particle size on the scaling model and, as a consequence, determine the superficial velocity U_0 from the condition if equality of particle Reynolds numbers.

Using empirical relationships, the scaling relations (3) can be reduced to two dimensionless numbers, while renouncing the condition U_0/v_t. Then, the terminal velocity of particles in the boiler and on the scaling model can be calculated from the balance of forces acting on a particle in the gas stream. This involves the calculation of the minimum fluidisation velocity which can be determined from the equation below

$$U_{mf} = \frac{Ar\mu\varepsilon^3\phi_s^2}{150d\rho_f(1-\varepsilon)} \tag{4}$$

the dimensionless terminal velocity of particles in the boiler, as defined by the equation

$$U^* = \sqrt{\frac{4}{3}\frac{d^*}{C_d}} \tag{5}$$

where the drag coefficient C_d is defined by Nian-Sheng Cheng's equation (Nian-Sheng Cheng, 2009)

$$C_d = \frac{432}{d^{*3}}\left(1+0.022d^{*3}\right)^{0.54} + 0.47\left(1-e^{-0.15d^{*0.45}}\right) \tag{6}$$

and finally, the terminal velocity of particles in the boilers, which is defined by the following relationship

$$v_t = U^*\left[\frac{\mu\left(\rho_s-\rho_f\right)g}{\rho_f^2}\right]^{\frac{1}{3}} \tag{7}$$

The use of relationship (3) enables to determine the basic parameters of operation of the test stand, as shown in Table 2. Values d_{50} and d_{32} are determined in Table 2 for inert material SF8.3m.

Table 2. Parameters of the Lagisza Supercritical CFB boiler and small-scale equivalents according to equations (3) used in experiments for ϕ_s=1, ε=0.4

	U_o [m/s]	d_{32} [μm]	d_{50} [μm]	ρ_s [kg/m³]	ρ_f [kg/m³]	μ [Pa s]	t [⁰C]	D [m]	v_t [m/s]	Re_d [-]	Ar [-]	U_{mf} [m/s]
Lagisza CFB 966MW$_{th}$	5.10 4.17 3.14 2.62	122.99	234.57	2700	0.3095	$4.456\cdot10^{-5}$	850	11.99	0.479	4.357 3.562 2.682 2.238	7.68	0.00639
Scaling model	1.48 1.21 0.91 0.76	44.05	84.01	2500	1.204	$1.813\cdot10^{-5}$	20	0.6	0.139	4.357 3.562 2.682 2.238	7.68	0.00186

As the Lagisza CFB boiler operates within the viscous flow limits, where $Re_d \leq 15$ (Ishii et al., 1989), the use of scaling relations (3) allows the following to be maintained between the boiler and the scaling model:

- the fluidisation regime,
- the riser solids hold-up by volume, and
- the macroscopic movements of solids (Van der Meer, 1999).

4. EXPERIMENTAL TESTS

Experimental tests have been carried out on a scaling model of the boiler which was made of plexiglass in a scale of 1/20, while preserving the geometrical similarity (Fig. 5). Because of the symmetrical construction of the boiler, the boiler's model comprises half the depth of a 0.69×0.53m^2 cross-section combustion chamber equipped with four cyclone separators (one on each side).

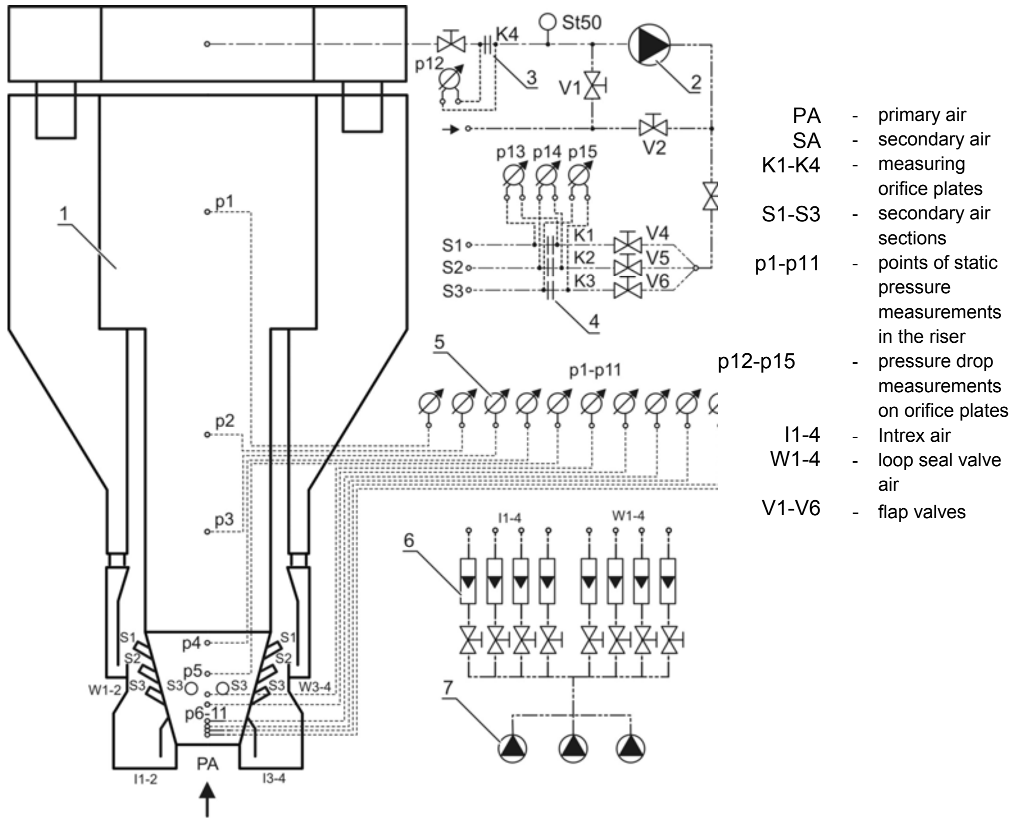

Fig. 5. Scale model of Lagisza supercritical CFB boiler:
1 – Transparent model, 2 – Industrial fan *5500m^3/h*, Δp*=20kPa*, 3 – Measuring orifice plate for primary air, 4 – Measuring orifice plates for three streams of secondary air, 5 – Digital pressure sensors APR-2000ALW, 6 – Rotameters, 7 – Air compressors

The symmetry of inert material distribution along combustion chamber height was confirmed by the measurements of suspended solids density taken for different boiler loads. A detailed description of the test stand can be found in (Mirek, 2011). During the tests, pressures along combustion chamber height were recorded at eleven measurement points corresponding to the pressure measurement points in the real boiler. Depending on the boiler load, the fluidising gas velocity was varied in the range 0.76-1.48 m/s (Tab. 2). In the tests glass bead particles with a density ρ_p=2500kg/m^3 have been used.

Figure 6 illustrates a comparison of the solids suspension density distributions obtained for the materials BA, CM1 and SF8.3m with the distribution recorded in the boiler CFB 966MW$_{th}$ in its full load state. The obtained distributions show that the best fitting with respect to the distribution recorded in the boiler is exhibited by two inert material samples: those of BA and SF8.3m. As can be noticed from Fig. 4, these samples contain the broadest spectrum of particle diameters, for which the velocity is $U_0 \in (v_{t\ min},\ v_{t\ max})$. This means that in circulating fluidisation process a part of the granular material particles remained on the grid forming a dense bubble bed, typical of this state, with a turbulent bubble bed; another part was suspended with the fine particle stream forming a diluted bed; and the remaining part was transported in the gas stream towards the exit region.

Figure 6 demonstrates that the lowest degree of fitting with respect to the distribution recorded in the boiler is shown by the CM1 material sample. This sample is made up of circulating material particles separated out in the cyclones without the coarse fractions which, under normal boiler operation conditions, are transported in the lower and dense zone, that is in the combustion chamber contraction.

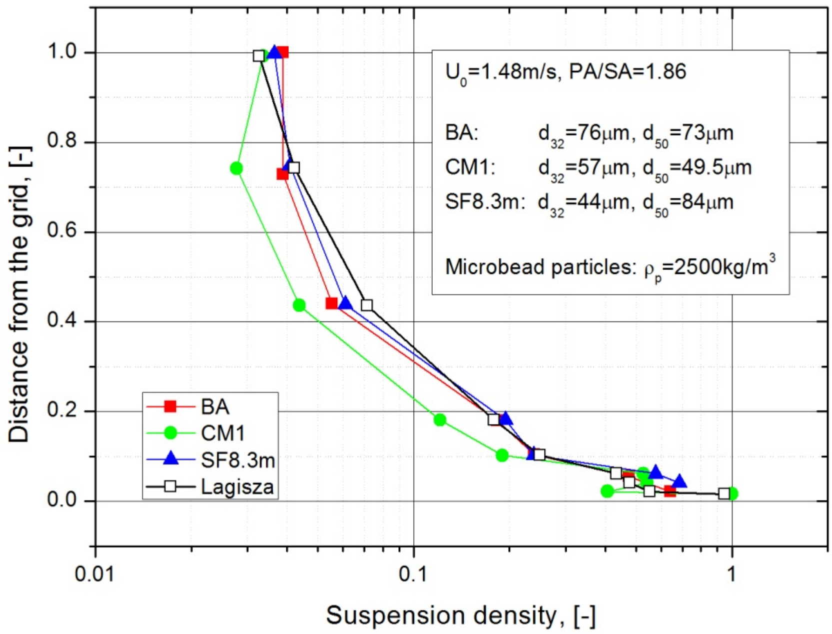

Fig. 6. Suspension density distributions for Lagisza test, for bottom ash (BA), circulating material (CM1) and material taken at a height 8.3m from grid at 100%MCR

5. CONCLUDING REMARKS

One of the CFB hydrodynamics scaling-down criteria is the correct selection of the particle size distribution of granular material designed for testing in laboratory conditions. As indicated by the laboratory tests, due to the complex nature of the CFB, knowing the scaling-down function between the boiler material and the material to be used in the scaling model is insufficient. There is an additional need for an experimental determination of the location on the boiler's circulation contour for sampling granular material, whose particle size composition will allow the state of the boiler's bed hydrodynamics to be reflected in the scaling model. The performed experiments have shown that granular material should be taken from the dense combustion chamber region, where both fine particles separated out in the cyclones and coarse particles transported in the gas stream within the contraction region occur. Out of the three analysed granular material samples taken, from the Intrex superheater (CM1), the dense region (BA) and the combustion chamber bottom (SF8.3m), the sample taken from the dense combustion chamber region exhibited the best representativeness. As a result, the solids suspension density distribution obtained from the solids taken at the combustion chamber height of 8.3m most closely approximated the distribution obtained from the operational tests on the 966MW_{th} CFB boiler.

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SYMBOLS

Ar	Archimedes number, $d^3\ \rho_f(\rho_s - \rho_f)g/\ \mu^2$, dimensionless
C_D	drag coefficient, dimensionless

D	riser hydraulic mean diameter, m
d_{50}	mass mean particle diameter, m
d_{32}	Sauter mean particle diameter, m
d	particle diameter, m
d^*	dimensionless particle diameter, m
Fr	Froude number
g	acceleration of gravity, m/s^2
G_s	external solids circulation flux, kg/m^{2}s
h	height, m
k	scale factor, dimensionless
p	pressure, Pa
Re_d	particle Reynolds number, dimensionless
RH	reheater
SH	superheater
t	temperature, ^{0}C
U_0	superficial gas velocity, m/s
U_{mf}	minimum fluidization velocity, m/s
U^*	dimensionless velocity, m/s
v_t	terminal velocity of particle, m/s

Greek symbols

$\partial p/\partial h$	time-averaged pressure gradient, m
φ_s	particle sphericity, dimensionless
ε	voidage, dimensionless
μ	gas viscosity, Pa s
ρ_f	gas density, kg/m^3
ρ_s	particle density, kg/m^3
ρ_{sus}	suspension density, kg/m^3

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