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A SIMPLIFIED METHODOLOGY FOR SCALING HYDRODYNAMIC DATA FROM LAGISZA 460 MW$_E$ SUPERCRITICAL CFB BOILER

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The paper presents the results of model studies on the hydrodynamics of the world's first supercritical circulating fluidized bed boiler Lagisza 460 MW$_e$, carried out on a scale model built in a scale of 1/20 while preserving the full geometrical similarity. To reflect the macroscopic pattern of flow in the boiler's combustion chamber, tests were carried out based on two dimensionless flow dynamic similarity criteria, while maintaining a constant Froude number value between the commercial and the scaled-down units. A mix of polydispersion solids with its fractional composition determined by scaling down the particle size distribution of the boiler's inert material was utilised for the tests using a special scaling function. The obtained results show very good agreement with the results of measurements taken on the Lagisza 460 MW$_e$ supercritical CFB boiler.

Keywords: circulating fluidized bed, scaling, hydrodynamics

1. INTRODUCTION

In modelling Circulating Fluidized Bed (CFB) hydrodynamics using flow dynamic similarity tools, the equality of all mass and pressure forces acting on suspended solids particles are assumed both in the commercial and the scaled-down units. With the effect of mass forces being neglected, the relationships between those forces are described by criterial numbers, and in particular:

- $\mathrm{Re}_d = \rho_s U_0 d / \mu$ - particle inertia/gas viscous force,
- $\mathrm{Re}_D = \rho_f U_0 D / \mu$ - gas inertia/gas viscous force,
- $Fr_D = U_0^2 / (gD)$ - inertia/gravity force,
- ρ_s / ρ_f - solid inertia/gas inertia force.

Performing scaling experiments in the conditions of full dynamic similarity of flows is associated with several limitations, the most important of which involves the need for using a polydispersion solids mix of a density of approx. 10 000 kg/m^3. In such a case, the commercial bed most commonly comprises particles from Group B of Geldart's classification, while the small bed, particles from Group A. As the behaviour of A and B Group particles subjected to fluidization is quite different, a justified fear arises that the same fluidization regime will not be maintained in the small and the commercial beds (Knowlton et al., 2005).

In the majority of cases, scaling of circulating fluidized bed hydrodynamics seeks to reflect the macroscopic flow pattern, for achieving of which only three dynamic similarity criteria are required to be satisfied. These criteria can be the relationships proposed by Glicksman (Glicksman et al., 1993; Glicksman 2003)

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$$\frac{U_0^2}{gD}, \frac{U_0}{U_{mf}}, \frac{G_s}{\rho_s U_0} \qquad (\mathrm{Re}_d < 4) \tag{1}$$

or Horio (Horio et al., 1989)

$$\frac{U_0^2}{gD}, \frac{U_0}{v_t}, \frac{G_s}{\rho_s U_0} \qquad (5 < \mathrm{Re}_d < 15) \tag{2}$$

As follows from sets of Equations (1) and (2), the use of three criterial numbers provides the possibility of making an arbitrary selection of the particle size or density of material on the scaling model and easy determination of the remaining flow parameters (Horio et al., 1997; Kolar and Leckner, 2006; van der Meer et al., 1999). On the other hand, using the relationships proposed by Glicksman and Horio for scaling-down purposes involves the necessity for determining the external solids circulation flux, G_s. As this measurement in a large-scale CFB boiler is difficult to accomplish, there is a need to search for alternative similarity criteria. One of these criteria can be the following set of equations

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

Another one, proposed in the present paper, is a set of dimensionless numbers, in which the Froude number related to the unit's hydraulic diameter is introduced.

2. DERIVATION OF THE SCALED-DOWN MODEL

As follows from (van der Meer et al., 1999), the use of two flow dynamic similarity numbers makes it possible to obtain the terminal velocity and mean diameter of particles close to those determined using three dimensionless numbers. With an unknown value of the parameter G_s, these criteria can be

$$\frac{U_0^2}{gD}, \frac{U_0}{v_t} \tag{4}$$

Considering the fact that in the case of large-scale commercial CFB boilers the flow of the gas-particles mixture takes place within the viscous limits ($Re_d < 4$), the condition of equality of the Reynolds numbers and the Archimedes numbers may be treated less restrictively, which provides some freedom in determining the mean particles diameter used for the tests. The value of the mean particle diameter d can be determined for a known value of v_t by solving a system of equations of the following form

$$\begin{cases} v_t = \sqrt{\frac{4}{3}\frac{d}{C_d}}\left[\frac{\mu(\rho_s - \rho_f) g}{\rho_f^2}\right]^{\frac{1}{3}} \\ C_d = \frac{432}{d^3}\left(1 + 0.022 d^3\right)^{0.54} + 0.47\left(1 - e^{-0.15 d^{0.45}}\right) \end{cases} \tag{5}$$

For a known value of d, the velocity U_{mf} can be determined according to the relationship (Kunii and Levenspiel, 1991)

$$U_{mf} = \frac{Ar \mu \varepsilon^3 \phi_s^2}{150 d \rho_f (1 - \varepsilon)} \tag{6}$$

The use of relationships (4), (5) and (6) enables to determine the basic parameters of scaling model operation, as shown in Table 1. For comparison, parameters determined based on the set of Equations (3) are shown in the last row of Table 1.

Table 1. Parameters of the Lagisza Supercritical CFB boiler (2nd row) and small-scale equivalents according to Equations (4), (5) and (6) (2nd row) used in scaling experiments for $\varphi_s = 1$, $\varepsilon = 0.4$. The small-scale equivalents calculated according to Equations (3) are presented in the last row.

	U_o m/s	d_{32} μm	d_{50} μm	ρ_s kg/m^3	ρ_f kg/m^3	μ Pa s	t ^{0}C	D m	v_t m/s	Re_d -	Ar -	U_{mf} m/s
Lagisza SC-CFBC	5.10 4.17 3.14 2.62	122.99	234.57	2700	0.3095	$4.456 \cdot 10^{-5}$	850	11.99	0.479	4.357 3.562 2.682 2.238	7.68	0.00639
Scale-down model	1.14 0.93 0.70 0.59	38.29	71.39	2500	1.204	$1.813 \cdot 10^{-5}$	20	0.6	0.107	2.900 2.365 1.780 1.501	5.04	0.00141
Scale-down model (3)	1.48 1.21 0.91 0.76	44.05	84.01	2500	1.204	$1.813 \cdot 10^{-5}$	20	0.6	0.139	4.357 3.562 2.682 2.238	7.68	0.00186

As follows from Table 1, the Lagisza CFB boiler operates within the viscous limits, which allows the same fluidization regime, riser solids hold-up by volume and macroscopic movements of solids to be maintained in the scaling model. Moreover, as has been found from the comparison of the values calculated for the model using three criterial numbers, the differences between the values d_{32} and v_t are small.

3. EXPERIMENTAL VERIFICATION OF SCALING RELATIONSHIPS

The verification of the flow similarity model was conducted on a scaled cold model presented in Figure 1. The scaling model of the supercritical CFB boiler operating at the Lagisza Power Plant was made of plexiglass in a scale of 1/20, while preserving the geometrical similarity. Because of the symmetrical construction of the boiler, its model comprises half of the depth of a 0.69×0.53 m^2 cross-section combustion chamber equipped with four cyclone separators (one on each side). The symmetry of inert material distribution along combustion chamber height was confirmed by the measurements of suspended solids density taken for different boiler loads, and by detailed numerical simulations. The test stand is equipped with two independent compressed air systems, the first of which supplies the primary and secondary air channels, while the other delivers air to the Intrex separators and to the loop seals (Fig. 1).

The system of primary and secondary air is equipped with an industrial fan 2 of a maximum capacity of 5500 m^3/h and a total pressure build of 20 kPa. For the other system, the source of compressed air is a set of three compressors 7, each with the following parameters: 29.4 m^3/h and 1.05 MPa. The fluidizing medium used in the tests was air of a density of 1.2 kg/m^3.The tests were carried out for the loads and corresponding primary and secondary air fractions, as shown in Table 2.

Table 2. Fractions of primary and secondary air streams depending on the boiler load

% MCR	100	80	60	40
PA/SA	1.86	2.33	3	5.25

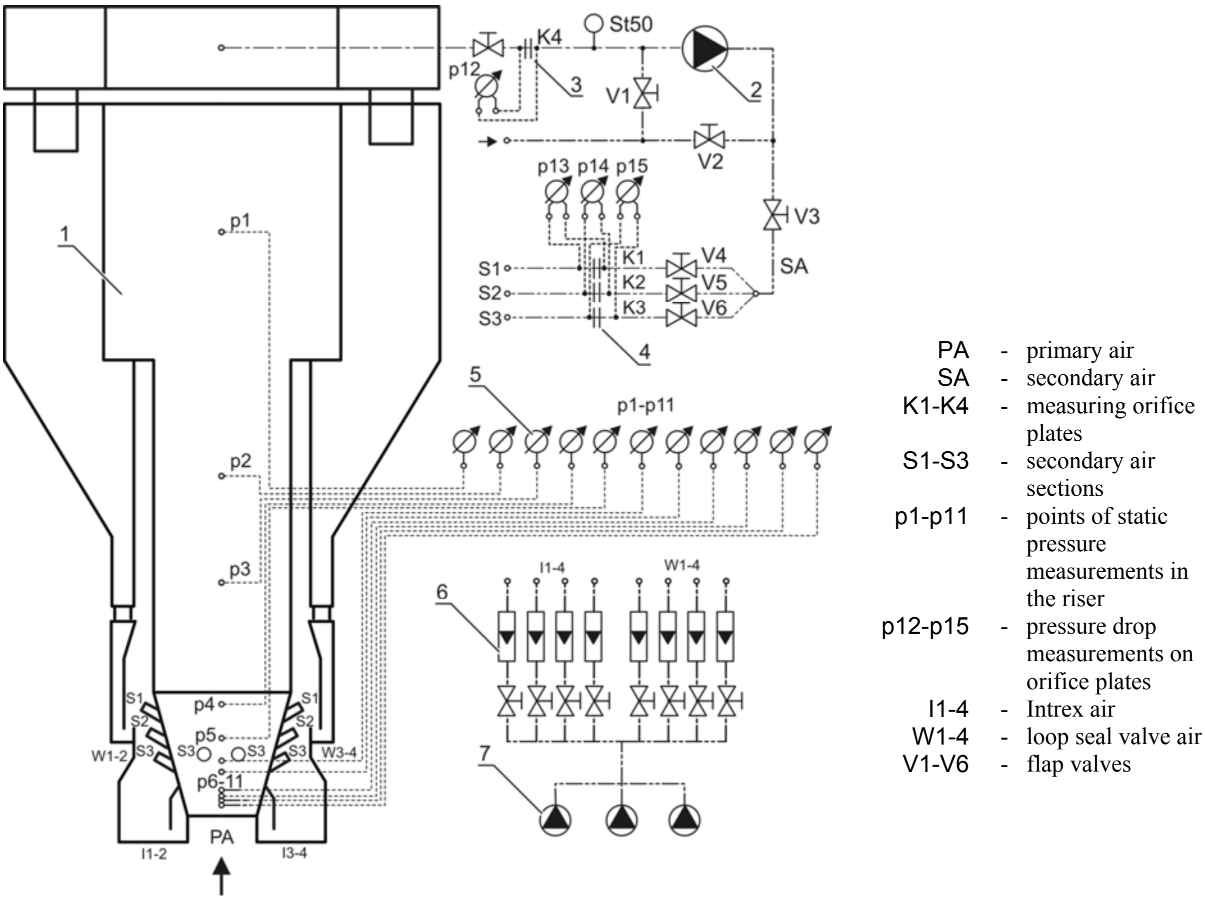

Fig. 1. The scaled-down model of the Lagisza supercritical CFB boiler:
1 – Transparent model, 2 – Industrial fan of 5500 m^3/h, Δp = 20 kPa, 3 – Measuring orifice plate for primary air, 4 – Measuring orifice plates for three secondary air streams, 5 – Digital pressure sensors APR-2000ALW, 6 – Rotameters,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

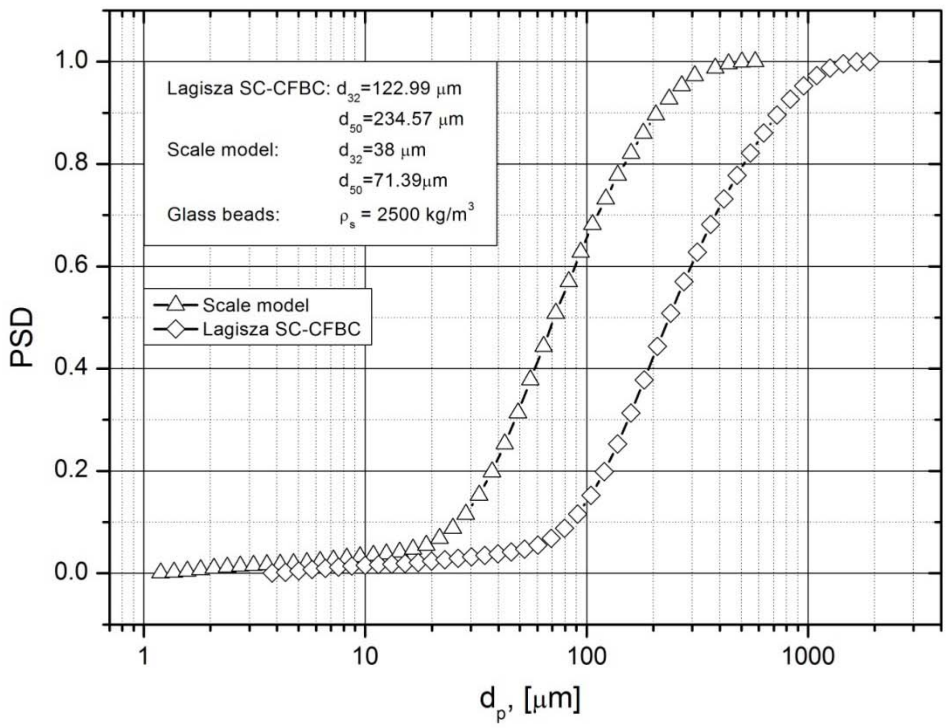

Fig. 2. PSD of inert material circulating in the Lagisza SC-CFBC boiler and in the scaling model

Glass microbead particles with the scaled-down particle size distribution (PSD) of the boiler's inert material presented in Fig. 2 and a mean diameter of d_{32} = 38 μm were used in the experiments.

Maintaining the constant Froude number requires determining the scaling function which defines the relationship between the particle size distribution of the boiler's inert material and the particle size distribution of the material used for the model tests. This function in the range of 1 – 1000 μm is represented by a curve whose equation has been approximated with a polynomial of the third degree. The graph of the scaling function is presented in Fig. 3.

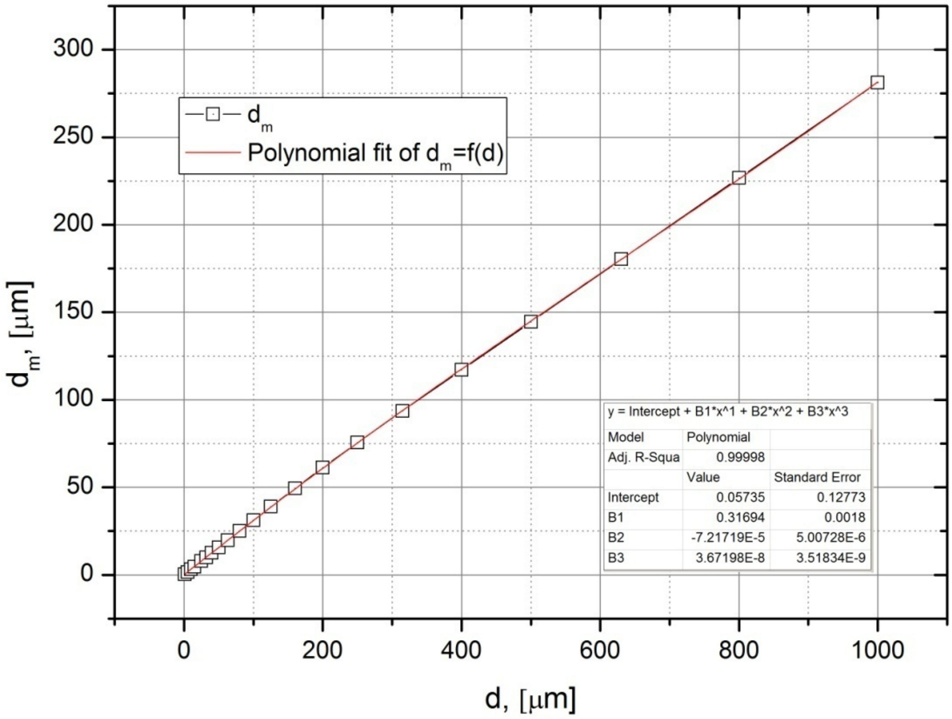

Fig. 3. The function of scaling the particle diameter between the commercial and the scaled units

4. EXPERIMENTAL RESULTS

The experimental test results are represented in the form of a solids hold-up distribution along combustion chamber height, whereas the suspended particles density was determined by measuring pressure gradients following the relationship:

$$\frac{\partial p}{\partial h} = -\rho_s \left(1-\varepsilon\right)\cdot g \qquad (7)$$

To enable a comparison of the obtained results with data provided in the literature, the measured values were related to the maximum value. The measurements were taken for four boiler loads, for which primary air fractions as against secondary air fractions are given in Table 2. Moreover, for each of the boiler load cases, the mass flux of solids circulating in the scale model's recycle system, G_s, was also measured.

Figure 4 shows a comparison of dimensionless solids hold-up distributions determined for the Lagisza supercritical CFB boiler and in the scaling experiments for 100% MCR. As can be seen from the obtained distributions, the differences between the values measured in the boiler's combustion chamber and those on the scale model are small. The exception is the point at a height of 1.825 m, where the effect of the stagnant point which had formed in the cyclone separator inlet zone was noted. In this zone, the values obtained from the model were greater by a maximum of 30 % than the values measured in the commercial unit.

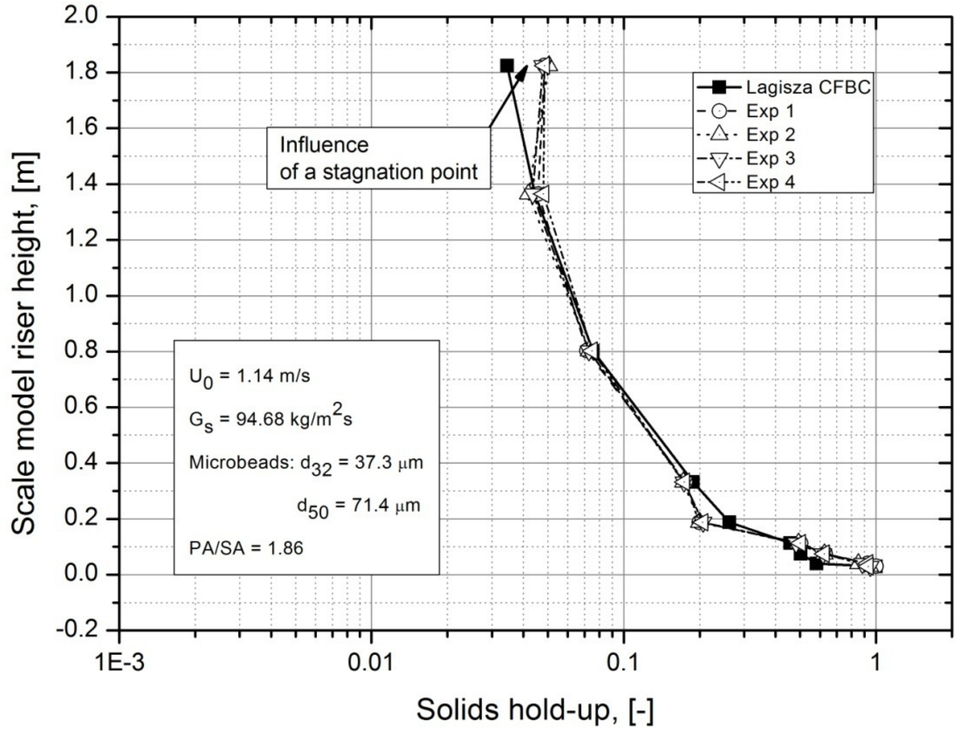

Fig. 4. Dimensionless solids hold-up distributions for the Lagisza SC-CFBC boiler and the scale model at 100 % MCR

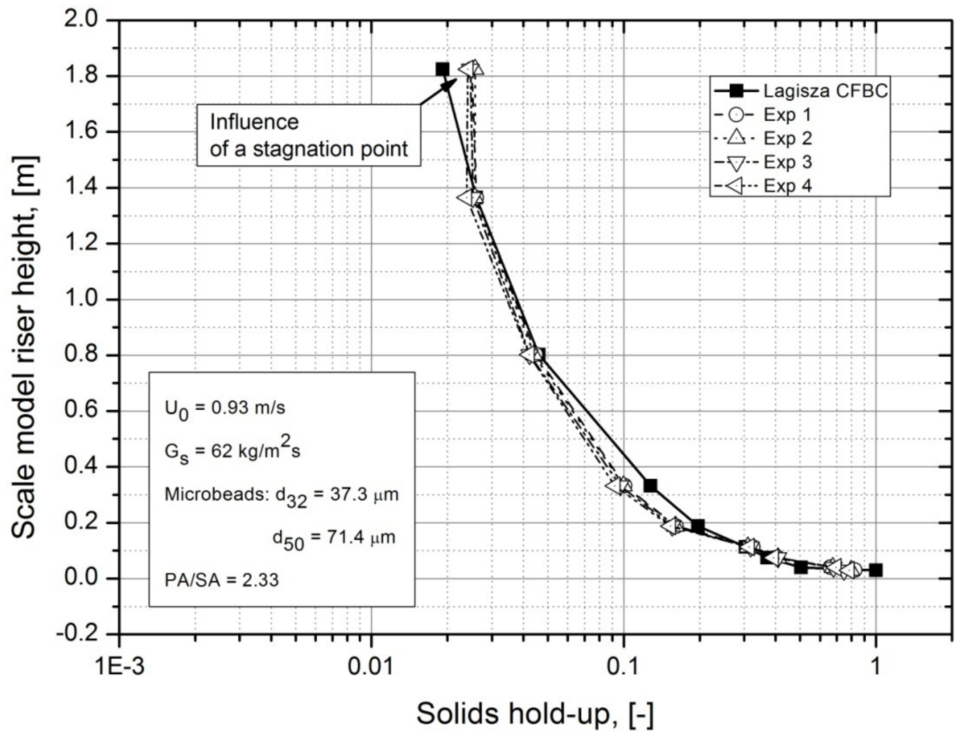

Fig. 5. Dimensionless solids hold-up distributions for the Lagisza SC-CFBC boiler and the model at 80 % MCR

Figures 5 and 6 show solids hold-up distributions obtained on the model and in the Lagisza CFB boiler for 80 % and 60 % MCR, respectively. As indicated by the obtained distributions illustrated in Figs. 5 and 6, there is very good concurrence between the values measured in the boiler's combustion chamber and on the model. The exception are the values measured at the point at a height of 1.825 m, where, similarly as for 100 % MCR, the effect of the stagnant point became visible. The maximum difference between the values obtained at this point on the model and in the commercial unit is 34 % for the case of 80 % MCR and 32 % for 60 % MCR.

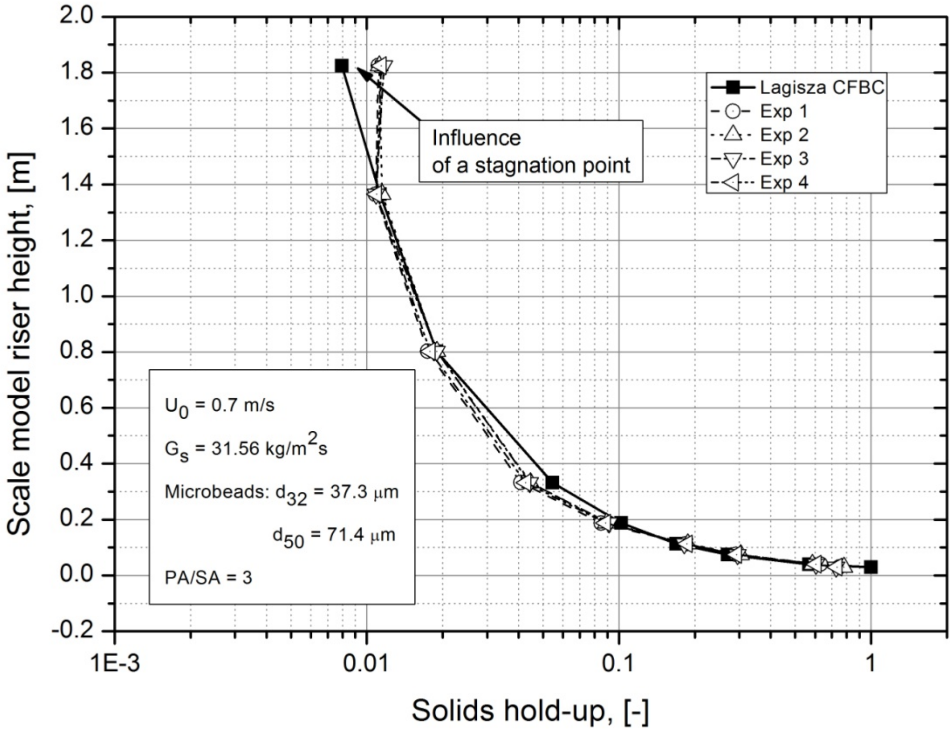

Fig. 6. Dimensionless solids hold-up distributions for the Lagisza SC-CFBC boiler and the model at 60 % MCR

Figure 7 shows a comparison of dimensionless solids hold-up distributions determined for the Lagisza supercritical CFB boiler and in the scaling experiments for a boiler load of 40 % MCR. As can be seen from the obtained distribution, the best consistence between the values measured on the model and in the commercial unit's upper combustion chamber zone was achieved for this load. The exception is the bottom region, where the maximum deviation between the reference values and the values obtained on the model was observed.

As indicated by the graphs shown in Figures 4-7, the use of merely two criterial numbers defined by set of Equations (4) allows the macroscopic solids hold-up distribution in the boiler's combustion chamber to be satisfactorily reflected on the scaled-down model stand. The greatest differences of the values measured in the boiler's combustion chamber were recorded at a height of 1.825 m, that is in the exit zone, and in the bottom zone immediately above the air distributor. In addition, as has been found from a comparison of the results obtained using a set of Equations (3), the effect of secondary air on the concurrence of the obtained results is satisfactory. This implies that the best results in the modelling of large-scale CFB boiler hydrodynamics on a scale model with a scale factor of 1/20 are achieved by using a material of a smaller mean diameter.

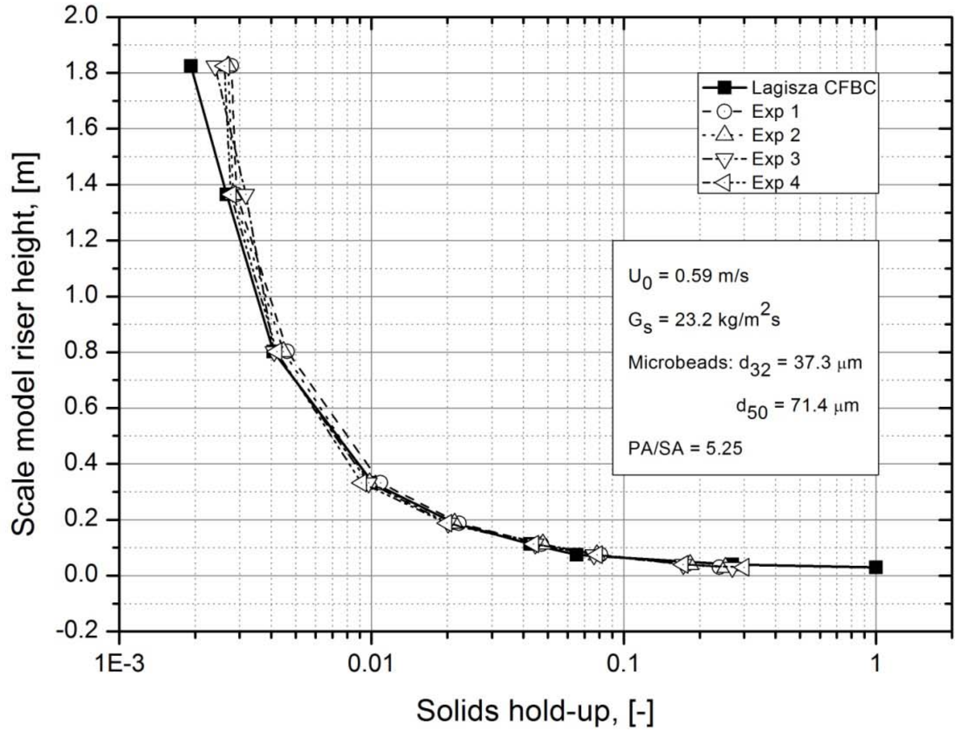

Fig. 7. Dimensionless solids hold-up distributions for the Lagisza SC-CFBC boiler and the model at 40 % MCR

5. CONCLUSIONS

As has been demonstrated by the conducted laboratory tests, the use of two dimensionless dynamic similarity numbers allows the hydrodynamics of the Lagisza 460 MW_e supercritical CFB boiler to be satisfactorily reflected on a scale model with a scale factor of k = 1/20. The obtained solids hold-up distributions are characterised by a very good repeatability and enable a quantitative description of suspended particles behaviour in the boiler's combustion chamber. The average differences between the values measured in the boiler's combustion chamber and on the model do not exceed a dozen or so percent, which can be considered a very good result. Compared with the results obtained for three criterial numbers described by the set of Equations (3), the solids hold-up distributions is in a very good agreement with the values measured in the commercial unit, especially in the secondary air-affected zone.

The proposed dynamic flow similarity criteria make it possible to scale down hydrodynamics of a large-scale CFB boiler. Thanks to this, a large number of experiments can be performed to facilitate alterations and modifications to be made to the operating boiler to improve its performance.

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SYMBOLS

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

D	riser hydraulic mean diameter, m
d_{50}	mass mean particle diameter, m
d_{32}	Sauter mean particle diameter, m
d	particle diameter in commercial unit, m
d_m	particle diameter in scaling model, 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, -
p	pressure, Pa
Re_d	particle Reynolds number, -
Re_D	Reynolds number based on D, -
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
□$_s$	particle sphericity, -
ε	voidage, -
μ	gas viscosity, Pa s
ρ_f	gas density, kg/m^3
ρ_s	particle density, kg/m^3

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