# THE IMPACT OF SCALING RULES ON PARAMETERS OF THE CYCLONE WORKING WITH CFB BOILERS

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**Abstract** – In the paper the impact of scaling rules on the performance of a cyclone separator working with CFB boiler has been investigated. The analysis has been performed with using five sets of scaling relationships and the model proposed by Muschelknautz for calculation the total and the grade separation efficiency of a cyclone. As follows from obtained results both set of scaling relationships as well as scale of a cold model have impact on the total grade separation efficiency of a cyclone separator. However, owing to the high total separation efficiency values calculated for all analyzed sets of scaling relationships there is no need to introduce additional scaling rules typically used for scaling cyclones. This conclusion is of special importance in the case of scaling experiments carried out based on the simplified set of scaling relationships for which a scale of a cold model can be assumed at an arbitrary level.

## INTRODUCTION

Due to the main environmental advantage of burning a diverse range of difficult low grade fuels of varying quality with low emissions of exhaust gases, the Circulated Fluidized Bed (CFB) combustion is still attractive process for converting chemical energy into electricity and heat. From the operational point of view CFB boiler is a high-velocity gas-solid system whose performance is controlled in large part by the bed hydrodynamics (Glicksman et al., 1993). According to van der Meer (1999), assuming that restitution between particles, friction between particles and riser wall as well as electrostatic forces and cohesion could be neglected, the complex flow behavior in CFB risers is assumed to be governed by eight parameters: superficial gas velocity $U_0$, external solids circulation flux $\dot{G}_s$, Sauter mean particle diameter $d_{32}$, particle density $\rho_p$, riser hydraulic diameter $D$, gas density $\rho_g$, gas viscosity $\mu$ and acceleration due to gravity $g$. The relationships between those parameters, known as mathematical models, could be valuable tools for description the transport at work in CFBs (Knowlton et al., 2007). Unfortunately, due to the complex flow behavior that characterizes gas-solid systems and as a consequence a current stage of the theoretical models' development, a complete description of circulating fluidized bed hydrodynamics remains still a challenging task (Detamore et al., 2001). It is no wonder that in this situation the attention of many researchers is focused on development of scaling methods, that have been used with success in engineering application to transfer information from equipment of one size to another similar equipment having different size (Leckner et al., 2011). In case of fluidized beds, the following full set of scaling laws has been developed by Glicksman et al. (1994)

$$\frac{U_0^2}{gH}, \frac{\rho_p}{\rho_g}, \frac{U_0 d_p \rho_p}{\mu}, \frac{U_0 H \rho_g}{\mu}, \frac{\dot{G}_s}{\rho_p U_0}, \varphi, PSD, geometry \tag{1}$$

Set (1) has been derived by nondimensionalizing the governing hydrodynamic equations of motion and conservation of momentum for the gas and solids phases proposed by Anderson and Jackson (1967).

Performing scaling experiments in the conditions of full dynamic similarity of flows is associated with several limitations. The most important is necessity of using particulate materials of a high density (ca. 10 400kg/m$^3$) with a wide size distribution. The other is the smallness of the particles which can cause significant cohesion as well as changing the fluidization regime (Knowlton et al., 2005). Furthermore, it should be noted that when the full set of scaling parameters are used, a cold model of a CFB boiler has linear dimensions approximately one-quarter those of the combustor, which is too large for most laboratories. Therefore, in scaling experiments where it is expected to maintain roughly the macroscopic flow pattern, the fluidization regime as well as the riser solids hold-up by volume and the conditions in the boiler's combustion chamber satisfy the relationship $Re_p \leq 15$ (van der Meer et al., 1999), the set (1) can be relaxed by elimination of second order or insignificant parameters. Thanks to this, it is possible to choose independently of the cold model size as well as of the density of the particles in the scale model. As follows from experimental studies carried out by Kolar and Leckner (2006) and Glicksman et al. (1993), the use of a particulate material of an arbitrary density does not remain without an effect on the quality of the scaling process. The solid density profiles of the two hot and cold beds matched fairly well, especially for particulate materials of higher density. The similar conclusion can be drawn for the arbitrary selected scale of a cold model. As has been reported by Mirek (2016), the agreement between the hot bed and the 1/10 and 1/20 cold models is better for the bigger cold model. This conclusion is in contradiction to the experimental results obtained by Glicksman et al. (1993), who found that the simplified set of scaling relationships gives acceptable results even when the length ratio is as small as 1/16.

Due to the fact that performance of CFB boilers is strongly affected by the cyclone efficiency, the crucial part of a scale cold model is a cyclone separator. Unfortunately, until now, there are no experimental findings on the impact of scaling laws on the cyclone performance working with cold models of CFB boilers. However, this issue is of special importance for two reasons:

- in contrast to CFB boiler in scale down model the finest fraction of particles are very quickly emitted beyond the circulation contour and must be continuously recirculated into the riser,
- since the cyclone efficiency is affected by the scale, the bed hydrodynamics must be in direct relationship with the scaling laws, especially simplified ones.

The purpose of this paper is to study the impact of scaling laws on the cyclone performance in cold models for which the reference model is the Lagisza 966MW$_{th}$ supercritical CFB boiler operating at the company TAURON Wytwarzanie SA - The Lagisza Power Plant, Poland. Of particular interest is the influence of the simplified scaling relationships on the cyclone grade efficiency. The analysis is performed based on Muschelknautz model developed for highly charged cyclones working with CFB boilers.

## REFERENCE MODEL

For the purpose of cold model studies the Lagisza 966MW$_{th}$ supercritical CFB boiler operating at the company TAURON Wytwarzanie SA - The Lagisza Power Plant, Poland has been chosen as a reference facility (Fig. 1).

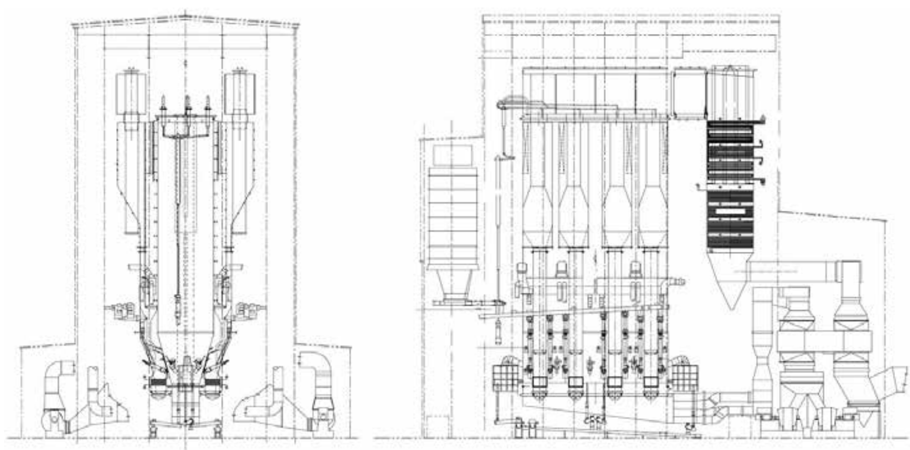

Fig. 1 Schematic diagram of the Lagisza 966MW$_{th}$ supercritical CFB boiler

The cross section of the combustion chamber at the grid level is 27.6×5.3m$^2$, and above the height of 8.95m: 27.6×10.6m$^2$. The total height of the combustion chamber is 48m. The boiler was fired with bituminous coal with properties given in Table 1.

Table 1 Proximate and ultimate analyses of bituminous coal (Ziemowit coal mine, Poland)

| Proximate analysis (as-received) | | | Ultimate analysis (air dried basis) | | |
|---|---|---|---|---|---|
| Component | Unit | Overall range | Component | Unit | Overall range |
| C | wt, % | 54.3-58.7 | LHV | MJ/kg | 21.35-23.48 |
| $S^{combustible}$ | wt, % | 0.95-1.25 | Moisture | wt, % | 12.20-18.45 |

| | | | | | |
|---|---|---|---|---|---|
| H | wt, % | 3.93-4.15 | Volatile matter | wt, % | 26.55-29.72 |
| N | wt, % | 0.85-0.91 | Ash | wt, % | 10.42-18.17 |
| $O^{by\ different}$ | wt, % | 7.82-8.81 | | | |

The operational tests were carried out for steady boiler operation conditions. The particulate material samples were taken from the dense combustion chamber region at the height of 8.3m from the grid. A detailed description of the sampling method can be found in Mirek and Ziaja (2011). Figure 2 presents the particle size distributions (PSD) of the inert material circulating in the Lagisza 966MW$_{th}$ CFB boiler.

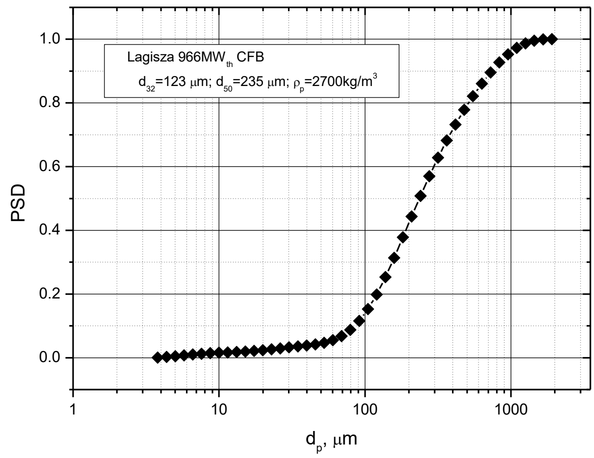


Fig. 2 PSD of inert material circulating in the Lagisza 966MW$_{th}$ CFB boiler

For the purpose of static pressure measurements, a data acquisition system consisted of ADAM-6000 A/C converters, APR-2000ALW smart pressure sensors and DasyLab10.0 software was employed.

## RESULTS AND DISCUSSION

### Scaling relationships

The analysis of the impact of scaling laws on the cyclone performance in cold models for which the reference model is the Lagisza 966MW$_{th}$ has been performed based on five sets of scaling relationships presented in Table 2. In every case a geometrical similarity between reference and scale cold models is preserved.

Table 2 Summary of scaling relationships used in the analysis of the impact of scaling laws on the cyclone performance in scale cold models

| Scaling relationships | Denotation | Parameters chosen independently | References |
|---|---|---|---|
| $\frac{U_0}{u_T}, \frac{\dot{G}_s}{\rho_p U_0}, PSD$ | set (1) | $d_{32}, \rho_p, \rho_g, D, \mu, k$ | van der Meer et al., 1999 |
| $Re_p, \frac{U_0}{u_T}, Ar, PSD$ | set (2) | $\rho_p, \rho_g, D, \mu, k$ | Mirek, 2016 |
| $\frac{U_0}{u_T}, \frac{\dot{G}_s}{\rho_p U_0}, Fr, PSD$ | set (3) | $\rho_p, \rho_g, D, \mu$ | van der Meer et al., 1997 |
| $\frac{U_0}{u_T}, \frac{\dot{G}_s}{\rho_p U_0}, Fr, \frac{\rho_p}{\rho_g}, PSD$ | set (4) | $\rho_g, D, \mu$ | van der Meer et al., 1997 |
| $Fr, Re_p, \frac{\rho_p}{\rho_g}, \frac{\dot{G}_s}{\rho_p U_0}, \frac{d_p}{D}, PSD$ | set (5) | $\rho_g, \mu$ | Glicksman et al., 1991 |

As follows from Table 2, four of five sets of scaling relationships are in simplified forms (set (1)-(4)). For them it is possible to choose some parameters independently. As can be noticed from Table 2, the greater the number of scaling relationships, the smaller the number of parameters which can be chosen independently.

In Table 3 parameters of the reference Lagisza CFB boiler with small-scale equivalents calculated according to sets (1) to (5) have been presented.

Table 3 Operational parameters for maximum loading (100%MCR; PA/SA=1.86) of the Lagisza 966MW$_{th}$ CFB boiler and small-scale corresponding equivalents evaluated according to sets (1) to (5)

| | | **Lagisza CFB boiler** | **Set (1)** | **Set (2)** | **Set (3)** | **Set (4)** | **Set (5)** |
|---|---|---|---|---|---|---|---|
| **$U_o$** | m/s | 5.1 | 2.58 | 1.48 | 1.14 | 1.14 | 2.40 |
| **$u_t$** | m/s | 0.98 | 0.22 | 0.14 | 0.10 | 0.10 | 0.21 |
| **$u_{mf}$** | m/s | 0.0041 | 0.0022 | 0.0019 | 0.0009 | 0.0017 | 0.0019 |
| **D** | m | 11.99 | 0.60 | 0.60 | 0.60 | 0.60 | 2.65 |
| **$\rho_p/\rho_g$** | - | 8724 | 2083 | 2083 | 2083 | 8755 | 8755 |
| **$\mu$** | Pa s | 4.46E-05 | 1.80E-05 | 1.80E-05 | 1.80E-05 | 1.80E-05 | 1.80E-05 |
| **$d_{32}$** | m | 1.23E-04 | 6.00E-05 | 4.41E-05 | 3.84E-05 | 2.57E-05 | 2.72E-05 |
| **$d_{50}$** | m | 2.35E-04 | 1.15E-04 | 8.45E-05 | 7.37E-05 | 4.94E-05 | 5.21E-05 |
| **T** | K | 1123 | 293 | 293 | 293 | 293 | 293 |
| **$G_s$** | kg/(m$^2$s) | 12.38 | 5.81 | 3.33 | 2.56 | 10.77 | 22.64 |
| **$\mu_E$** | kg/kg | 15.69 | 1.88 | 1.87 | 1.87 | 7.87 | 7.86 |
| **k** | | 1 | 1/20 | 1/20 | 1/20 | 1/20 | 1/4.53 |
| **$Re_p$** | - | 4.36 | 10.38 | 4.36 | 2.93 | 1.96 | 4.36 |
| **Ar** | - | 8 | 20 | 8 | 5 | 7 | 8 |
| **Region in Geldart classif. of particles** | | B | A | A | A | B | B |
| **Fuidization regime** | | Fast fluid. bed | Fast fluid. bed | Fast fluid. bed | Fast fluid. bed | Fast fluid. bed | Fast fluid. bed |

As has been demonstrated in Table 3, in sets (1) to (4) the cold model scale has been assumed to be 20 (see column 3 to 6) and the fluidizing medium used in calculations is air with a density of 1.2kg/m$^3$.

## Computation of the separation efficiency

Due to the higher inlet solids loading the cyclone performance in a CFB boiler is not the same as in classical cyclones. The total separation efficiency in CFB boilers is the sum of the two separation efficiencies: at the wall and in the inner vortex, according to the following expression (VDI Heat Atlas, 2010)

$$\eta_{tot} = \eta_{wall} + \eta_{vtx} = 1 - \frac{\mu_{lim}}{\mu_e} + \frac{\mu_{lim}}{\mu_e} \sum_{j=1}^{m} \eta_F(d_j)\, \Delta R_{Ai}(d_j) \tag{2}$$

where the limited loading ratio $\mu_{lim}$ is given by (VDI Heat Atlas, 2010)

$$\mu_{lim} = K_{lim} \cdot \left(\frac{d_e^*}{d_{50,A}}\right) \cdot (10\mu_e)^y \tag{3}$$

and the constant $K_{lim}$=0.02 for fine particles, and 0.03 for coarser particles. For inlet loadings $\mu_e < 2.2 \times 10^{-5}$ the exponent $y$ has the value 0.81 and for $\mu_e > 0.1$ the value 0.15. The cut size for wall separation can be calculated by the following equation (VDI Heat Atlas, 2010)

$$d_e^* = \sqrt{\frac{0.5(0.9\dot{V})}{A_w} \cdot \frac{18\mu}{(\rho_p - \rho_g)\bar{z}_e}} \tag{4}$$

With the total separation efficiency described by Eg. (2), the emission of a cyclone becomes (VDI Heat Atlas, 2010)

$$S = (1 - \eta_{tot})\mu_e \rho_g \tag{5}$$

Due to the fact, that in most cases $\mu_e > \mu_{lim}$ the particle size distribution of the carryover, $R_F(d)$, can be determined in $m$ size fractions using the distribution of the inner feed, the total separation efficiency, and the grade efficiency curve (Muschelknautz and Muschelknautz, 1999)

$$\Delta R_F(d) = \frac{\mu_{lim}}{\mu_e} \cdot \frac{\left(1 - \eta_{F,i}(d)\right)}{(1 - \eta_{tot})} \cdot \Delta R_A(d) \tag{6}$$

Total grade efficiency curve can be determined based on the following expression (VDI Heat Atlas, 2010)

$$\eta_F(d) = 1 - (1 - \eta_{tot})\frac{\Delta R_F(d)}{\Delta R_A(d)} \tag{7}$$

Figure 3 shows the comparison of separation efficiencies at the wall and in the inner vortex calculated with the help of the Muschelknautz model for the reference CFB boiler and scale cold models whose parameters have been calculated based on sets (1)-(5) (Table 2).

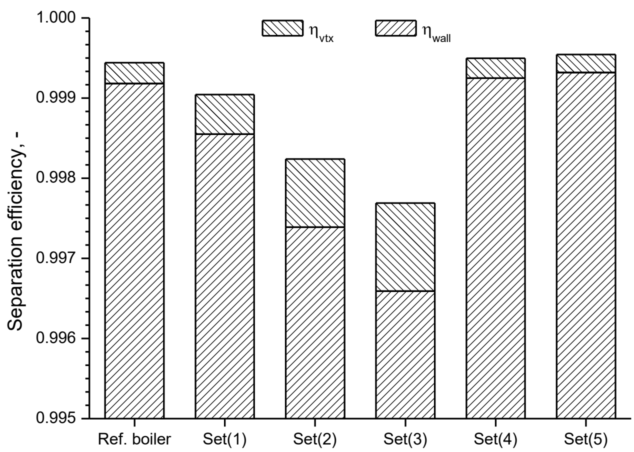


Fig. 3 Separation efficiency at the wall and in the inner vortex calculated for reference CFB boiler and scale cold models based on sets (1)-(5) (see Table 2)

As follows from the obtained results all sets of scaling relationships allow the high separation efficiency (above 99.6%) to be satisfactorily achieved in cyclone separators of the scale cold models. Nevertheless, in comparison to values calculated for the reference boiler the highest total efficiencies have been calculated for set(4) and set(5). Due to the fact that the separation efficiency dramatically increases with solids loading such high separation efficiencies are probably the result of high load ratios $\mu_e$ at inlets.

As can be seen in Table 2, a cold model scale described by the hydraulic diameter $D$ has no impact on hydrodynamic parameters being part of simplified scaling relationships represented by sets (1) to (4). At the same time, since the cyclone efficiency is affected by the scale this parameter must be in direct relation to the total separation efficiency of the cyclone. Figure 4 shows the comparison of grade efficiency curves determined for different cold model scales (k=1/20; 1/15 and 1/10) based on Muschelknautz model and set(1) of scaling relationships.

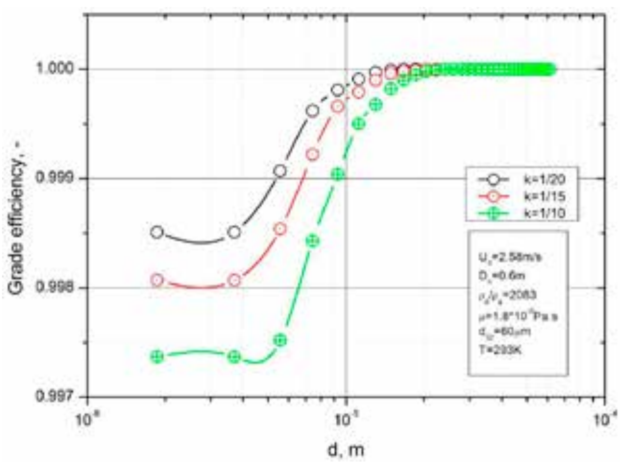

Fig. 4 Influence of a cold model scale factor 'k' on the total grade efficiency curve calculated for set(1) of scaling relationships

As follows from Fig. 4, the fines fraction of the feed is collected with a greater efficiency for cold models of a smaller scale factor *k*. It means that although a cold model scale can be theoretically assumed at an arbitrary level in case of utilizing simplified sets of scaling relationships, its value has impact on total separation efficiency of a cyclone.

Figure 5 depicts the comparison of grade efficiency curves determined for the reference boiler and different sets of scaling relationships calculated based on the Muschelknautz model. As follows from Fig. 5, the total grade efficiency values are greater than 99.4% for all analyzed cases. Analyzing the shape of the curves one can observe that general tendency is that with decreasing particle size the grade efficiency decreases (but not down to zero), goes through a local minimum and again increases for the very small particles. This behavior is observed in different commercial cyclones of 0.3 to 0.5m diameter at temperatures between $20^0$C and $900^0$C, and at pressure up to 30MPa (Muschelknautz and Muschelknautz, 1996).

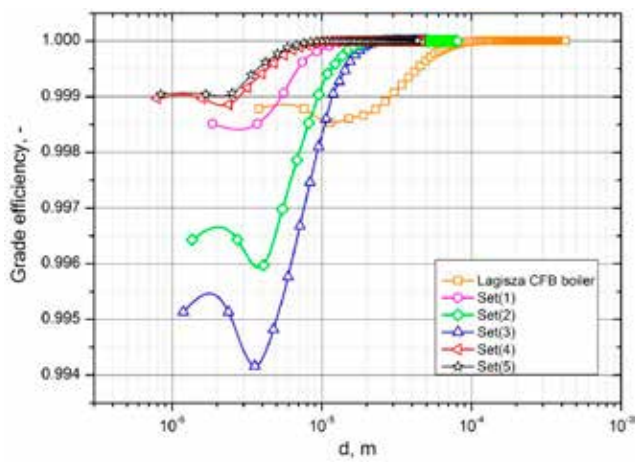

Fig. 5 Influence of the set of scaling relationships on the total grade efficiency curve

The highest total grade efficiency has been calculated for sets (5) and (4) and the lowest for set(3). It is interesting, that the total grade efficiency values similar to that of the reference boiler can be achieved for the simplest set of scaling relationships, i.e. set(1). At the same time, by introducing to this set the additional scaling law (i.e. Froude number) the total grade efficiency is decreased to the lowest value.

## RESULTS AND DISCUSSION

Based on the obtained results, it appears that both a set of scaling relationships and a scale of a cold model has impact on the total grade separation efficiency of a cyclone separator. However, taking into account high grade efficiency values calculated for all sets of scaling relationships there is no need to introduce additional scaling rules typically used for scaling cyclones. The highest total grade efficiency can be achieved for full set of scaling relationships but the use of the simplified set containing only two dimensionless numbers allows achieving a slightly lower value of this parameter. It is worthy to underline that in contrast to a real CFB boiler in scale down model the finest fraction of particles are very quickly emitted beyond the circulation contour. Therefore the above-mentioned conclusions are true only in case of continuously recirculated fines into the riser.

## NOTATION

| | | | |
|---|---|---|---|
| $Ar$ | Archimedes number, $d_p^3\rho_g(\rho_p-\rho_g)g/\mu^2$, - | $R_F(d)$ | residue of the emitted dust, - |
| $A_w$ | area of cyclone wall, $m^2$ | $S$ | particle emission, $kg/m^3$ |
| $d_e^*$ | cut size for separation at wall, m | $T$ | temperature, K |
| $d_p$ | particle diameter, m | $U_0$ | superficial gas velocity, m/s |
| $d_{32}$ | Sauter mean particle diameter, m | $u_{mf}$ | minimum fluidization velocity, m/s |
| $d_{50}$ | mass mean particle diameter, m | $u_t$ | terminal velocity of particle, m/s |
| $d_{50,A}$ | median particle size of feed, m | $\dot{V}$ | gas flow rate, $m^3/s$ |
| $d$ | particle size, m | $y$ | exponent for calculating limited load ratio, - |
| $D$ | riser hydraulic mean diameter, $4A/P$, m | $\overline{z_e}$ | mean centrifugal acceleration at reference radius, $m/s^2$ |
| $Fr$ | Froude number based on $D$ ($U_0^2/gD$), - | $\eta_{tot}$ | total separation efficiency, - |
| $g$ | acceleration of gravity, $m/s^2$ | $\eta_{wall}$ | separation efficiency at wall, - |
| $\dot{G}_s$ | solids circulation flux, $kg/m^2s$ | $\eta_{vtx}$ | separation efficiency in cyclone vortex, - |
| $H$ | combustion chamber height, m | $\eta_F(d)$ | grade efficiency, - |
| $k$ | cold model scale factor, - | $\rho_g$ | gas density, $kg/m^3$ |
| $K_{lim}$ | constant for calculating limited load ratio, - | $\rho_p$ | particle density, $kg/m^3$ |
| $MCR$ | Maximum Continuous Rating, % | $\varphi$ | particle sphericity, - |
| $PA/SA$ | primary/secondary air ratio, - | $\mu$ | gas viscosity, Pa s |
| $PSD$ | particle size distribution | $\mu_E$ | initial load, kg/kg |
| $R_{Ai}(d)$ | residue of the inner feed, - | $\mu_{lim}$ | limited load ratio, - |
| $Re_p$ | particle Reynolds number, - | | |

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