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Research article

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 a 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 of the total and the grade separation efficiency of a cyclone. As follows from the obtained results both the set of scaling relationships as well as the scale of a cold model have an 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 into sets of scaling rules additional formulas 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.

1. 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 Circulating Fluidized Bed (CFB) combustion is still attractive process for converting chemical energy into electricity and heat. From the operational point of view a CFB boiler is a high-velocity gas-solid system whose performance is controlled in large part by the bed hydrodynamics [1]. 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 ρ_p, riser hydraulic diameter D, gas density ρ_g, gas viscosity μ and acceleration due to gravity g [2]. The relationships between those parameters, known as mathematical models, could be valuable tools for description the transport at work in CFBs [3]. 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 the circulating fluidized bed hydrodynamics remains still a challenging task [4]. It is no wonder that in this situation the attention of many researchers is focused on development of scaling methods. They have been in use with success for many years in engineering application to transfer information from equipment of one size to another similar equipment having different size [5]. In case of fluidized beds, the following full set of scaling laws has been proposed [6]

$$\frac{U_0^2}{gD}, \frac{\rho_p}{\rho_g}, \frac{U_0 d\rho_p}{\mu}, \frac{d}{D}, \frac{\dot{G}_s}{\rho_p U_0}, \varphi, PSD, geometry \tag{1}$$

Set (1) has been derived by nondimensionalizing the governing hydrodynamic equations of motion and conservation of momentum for gas and solids phases proposed by Anderson and Jackson [7].

Performing scaling experiments in the conditions of the full dynamic similarity of flows is associated with several limitations. The most important one is in many cases the necessity of using particulate materials of a high density (ca. 10,400 kg/m^3) with a wide size distribution. The other is the smallness of particles which can cause significant cohesion as well as changing the fluidization regime [8]. 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 a 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 $Re_p \leq 15$, the set (1) can be relaxed by elimination of the second order or insignificant parameters [2]. Thanks to this, it is possible to choose independently a cold model size as well as a density of the particles in a scale model. As follows from experimental studies, the use of a particulate material of an arbitrary density does not remain without an effect on the scaling process quality [1,9]. 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

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scale of a cold model. As has been reported by Mirek, the agreement between the hot bed and the 1/10 and 1/20 cold models is better for the larger cold model [10]. This conclusion is in contradiction to the experimental results obtained by Glicksman et al., who found that the simplified set of scaling relationships gives acceptable results even when the length ratio is as small as 1/16 [1].

Due to the fact that the performance of CFB boilers is strongly affected by a cyclone efficiency, the crucial part of a scale cold model is a cyclone separator. For the purpose of scaling experiments, the main input parameters of this device are calculated based on the selected (full or simplified) set of scaling rules at a silent assumption, that this set does meet the requirements of the effective scaling of cyclones. Unfortunately, as can be noticed the full set of scaling relationships (1) does not contain any dimensionless number typically used for scaling of cyclones, especially the Stokes number. For this reason, the question arises: how does the lack of such an important relationship affect the cyclone separation efficiency in a scale cold model? The problem becomes more severe when using simplified scaling formulas. In that case, some parameters such as: linear dimensions, a particle diameter or a particle density, can be chosen independently of the scaling rules. These parameters affect a cyclone separation efficiency and can change significantly the hydrodynamics conditions occurring in a scale cold model. Unfortunately, until now there are no experimental findings on the impact of scaling rules typically used for hydrodynamic scaling of circulating fluidized beds on the cyclone performance working with cold models of CFB boilers.

The purpose of this paper is to study the impact of scaling rules on parameters of the cyclone working with cold models for which the reference object 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 the Muschelknautz model developed for highly charged cyclones working with CFB boilers.

2. 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 the reference facility (Fig. 1).

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

The operational tests were carried out for steady boiler operation conditions at 100% MCR. The particulate material samples were taken from the dense combustion chamber region at the height of 8.3 m from the grid. A detailed description of the sampling method can be found in [11]. Fig. 2 presents the particle size distributions (PSD) of the 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.

3. Results and discussion

3.1. Scaling relationships

The analysis of the impact of scaling rules on the cyclone performance in cold models for which the reference model is the Lagisza 966MW$_{th}$ CFB boiler 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 assumed.

As follows from Table 2, sets (1) to (4) are simplified versions of set (5). The simplifications allow reducing the number of scaling relationships and as a consequence to increase the flexibility in the scaling process. 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,
- for sets (1) to (3) following parameters can be chosen independently: ρ_g, D, μ and g,
- the Sauter mean diameter can be chosen independently only in the case of set (1).

In Table 3 parameters of the reference Lagisza 966MW$_{th}$ CFB boiler with small-scale equivalents calculated according to sets (1) to (5) have been presented.

As has been demonstrated in Table 3, in sets (1) to (4) the cold model scale has been assumed to be 1/20 (see column 3 to 6) and the fluidizing medium used in calculations is air with a density of 1.2 kg/m^3 and a temperature of 293 K.

3.2. 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 [13]

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

where the limited loading ratio μ_{lim} is given by [13]

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

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 the wall separation can be calculated by the following Eq. [13]

$$d_e^* = \sqrt{\frac{0.5(0.9\dot{V})}{A_w}\bullet\frac{18\mu}{(\rho_p - \rho_g)\overline{z_e}}} \tag{4}$$

With the total separation efficiency described by Eq. (2), the emission of a cyclone becomes [13]

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

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 [14]

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

The total grade efficiency curve can be determined based on the following expression [13]

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

Fig. 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).

As follows from the obtained results all sets of scaling relationships allow the high separation efficiency (above 99.7%) to be satisfactorily achieved in cyclone separators of the scale cold models. Nevertheless, in comparison to values calculated for the reference boiler the highest values of the total separation efficiency have been obtained for set (4)