Particle separation in cyclones of circulating fluidized bed systems

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Abstract. Circulating fluidized bed (CFB) plants are widely used in energy, petrochemicals, aluminum production (alumina firing), and other industrial sectors. The CFB technology is characterized by relatively high reactor velocity that exceed the transport velocity of medium-sized particles, and the presence of separators (mainly of the cyclone type) with a system for returning trapped particles to the reactor. This ensures a long residence time of the particles in the reaction zone, a high circulation rate, and a stable and relatively low temperature in the reactor. In fact, it is the cyclone capture efficiency that directly determines the multiplicity of circulation and the flow rate of circulating particles and their size characteristics. The report discusses the current state of development and methods for cyclones calculating. Data from our and foreign studies are reviewed and the dependence of the correction on the mass concentration of particles is proposed. A brief description of the test rigs and the results of our own studies of particle separation in cyclones are given. Experimental data on the effect of dust on the capture efficiency are presented in the form of a dependence of the relative entrainment of particles (1-efficiency) on the mass concentration of particles at the entrance to the cyclone. Entrainment is noticeably reduced when the concentration increases, as small particles are attracted by larger ones to the wall of the cyclone.

Introduction

Circulating fluidized bed (CFB) plants are widely used in energy, petrochemicals, aluminum production (alumina firing), and other industrial sectors. The CFB technology is characterized by relatively high reactor velocity that exceed the transport velocity of medium-sized particles, and the presence of separators (mainly of the cyclone type) with a system for returning captured particles to the reactor. This ensures a long residence time of the particles in the reaction zone, a high circulation rate, and a stable and relatively low temperature in the reactor. In fact, it is the cyclone capture efficiency that directly determines the multiplicity of circulation and the flow rate of circulating particles and their characteristic size. Not only is the overall capture efficiency important, but the fractional efficiency is also important. High fractional efficiency for small particles allows to significantly reduce the size of circulating particles, thereby increasing their concentration in the
reactor and the conductive component of heat exchange in CFB boilers. High-temperature cyclones are the most common in CFB boiler schemes. For large boilers, they have a diameter of up to 10 m and are lined by refractory. Some boilers are equipped with steam-cooled cyclones, and the surface of the cyclone is protected by a ceramic coating. Numerous studies have been carried out recently in China, which allowed us to create our own design of high-performance separators and CFB boilers [1].

The report discusses the current state of development and methods for cyclones calculating. It should be noted that many experts have expressed doubts about the possibility of achieving an efficiency of more than 90% in high-temperature large diameter cyclones. The reason for this was the traditional knowledge about the capture of small particles coming from the gas stream in small concentrations (about 10 g/m$^3$). In CFB furnaces, the average particles size entering the ash separators is 170 - 250 microns, and the dust content of the flow reaches 10 kg/m$^3$.

Cyclones pressure drop during the movement of a gas stream with high dust content is significantly reduced compared to a non-dusty stream. Data from our and foreign studies are reviewed and the dependence of the correction on the mass concentration of particles is proposed. The issues of increasing the fractional efficiency due to the installation of the exhaust pipe eccentrically to the cyclone axis are considered [2]. The use of such a solution on a bench installation significantly increased the efficiency of capture in a cyclone with a diameter of 0.3 m and allowed to obtain total capture efficiency at the level of 99.99%. Such a high efficiency is associated both with relatively large particles and with their high concentration [3]. Experimental data on the effect of dust on the capture efficiency are presented in the form of a dependence of the relative entrainment of particles (1-efficiency) on the mass concentration of particles at the entrance to the cyclone.

**1 Effect of Solids Loading on Cyclone Performance**

At low solid-to-gas mass loading ratios solid particles are clustered as thin strands on the cyclone walls and are transported in the downward direction in a spiral path, while at high mass loadings, a major portion of wall surface area is covered with a layer of solid particles (also know as a dense strand in [10]). For the calculation of the solids separation in the gas cyclone the model of [11] has been taken as a basis very often. In this model the separation mechanism in the cyclone is divided into two parts. At first, immediately near the inlet that part of the solids loading $\mu_e$, which exceeds a limiting value $\mu_g$ is forming a strand, which flows directly into the underflow. The remaining part of the solids is undergoing the separation in the vortex. Both mechanisms are described by semi-empirical correlations, which are based on a large number of measurements, including measurements at large-scale industrial cyclones. The overall separation efficiency versus inlet solids loading of selected experimental studies is presented in Figure 1.
In this figure, the improvement of separation efficiency with the cyclone Reynolds number can be observed from the experimental data of [12] for a fixed value of particle kinematic response time. The kinematic response time of particles used in the study of [8] is somewhat higher compared to the particles of other studies presented in Figure 1, leading to a very high efficiency of separation. For the rest of the studies, no conclusive argument can be stated regarding the effect of this parameter. Despite available experimental studies on the effect of solids loading on the separation efficiency, there is no consensus regarding the exact mechanism of this improvement [12].

Limiting value of the solids loading $\mu_g$ in different studies differ significantly – from 0.005 to 0.05. In [13] complex dependences are given for this quantity. The calculation results given in [13] showed that an increase in the average particle size leads to growth of $\mu_g$. For large solids loading $\mu_e$, the limit values are higher. With increasing cyclone size and temperature, the ultimate value of the solids loading increases. According to data [13], with respect to a cyclone with a diameter of 90 mm, the capture efficiency of particles with dimensions of 0.01 mm for solids loading $\mu_e=0.05$ is about 86%, and for $\mu_e=10$ it reaches 99.6%.

2. Experimental setup and methods

A detailed description of the test rig and layout of reactors was given in [14]. CFB reactor is a vertical column with cross-section $0.2 \times 0.3$ m and 5.4 m height, to the top of column the inlet cyclone duct is attached. The air is discharged from the cyclone to the settling chamber, at the top of which installed the removable filter. To the conical part of cyclone attached the riser with cross-section $0.1 \times 0.1$ m. In the middle part of the riser is installed shut-off rotary valve, which is used to determine the flow rate of material through the circulation loop. The riser is connected to the upper loop seal. The design of the loop seal allows releasing one part of the material directly to the CFB reactor, and the other part to the lower part of FB reactor through the riser with L-valve with $44 \times 94$ mm cross-section and 420 mm length in horizontal part. FB reactor has a lower section with $0.28 \times 0.2$ m cross-section and a height of 0.5 m, a transition cone section and an upper section of $0.4 \times 0.4$ m cross-section and 1.5 m height. It is connected to pipe with loop seal placed in the conical part of reactor and providing feed of the material to lower section of CFB reactor.
The cyclone design is shown in Figure 2. To increase the efficiency of capturing fine particles, the exhaust pipe of cyclone is installed eccentrically with a displacement from the inlet duct [15].

![Cyclone design](image)

**Figure 2.** Cyclone design

During the research, solid flow rates in the standpipe riser under cyclone were measured with a cut-off valve. The flow rates of all air flows were measured using pre-calibrated flow-rate orifice plate and rotameters. The pressure drop of cyclone was determined from the pressure differences between the upper part of CFB reactor and the exhaust pipe before entering fine filter, in addition, the pressure drop across sections of reactor - the cylindrical part of cyclone and cylindrical part of cyclone - exhaust pipe were measured. The amount of entrainment from cyclone was determined by the weight method. After 1 hour of operation, the accumulated material was unloaded and weighed. The samples of entrainment and circulating material were subjected to the determination of the fractional composition after each experiment. The small particles of entrainment were analyzed on a Fitch device.

2 Experimental results and discussion

The capture efficiency in cyclone proved to be very high - more than 99.99%. This is due to both relatively large particles and their high concentration. Therefore, it is better to analyze the influence of factors on the full efficiency of the cyclone through the amount of entrainment from the cyclone. In Figure 3 shows the dependence of relative entrainment on mass concentration. Mass concentration, that is, the ratio of the flow rate of solid particles to the total flow rate of solid particles and gas, in our opinion, is the best criterion in comparison with mass loadings. This approach is often used in the analysis of data on two-phase flows. At \(\mu = 0\) it is a gas flow, at \(\mu = 1\) it is a heavy phase flow.
Figure 3. The mass concentration of a stream against relative entrainment of particles (1-efficiency)

In [16], the calculations of fractional capture efficiency were performed for 4 models. The first two models are based on force balance and the following two on a combination of force balance and residence analysis. For most options, calculation model [17] gives maximum efficiency values. Approximately 1.5 times smaller is the diameter of particles captured by 50% compared with other models.

Fractional efficiency of the cyclone is determined by the method of VTI [18] when processing the experimental data. This method is based on the three-zone model proposed in [19] and got its development in [20] for high-temperature cyclones. In this model, three zones are considered: the entrance zone, the down flow and the lifting flow. Turbulent mixing is determined by the profile of radial concentrations in each zone, taking into account the exchange of particles. The proposed in [19] system of equations for each zone under the appropriate assumptions and transformations performed by the authors [20] leads to the following set of dependencies for the calculation of fractional efficiency:

\[
\eta = 1 - \left( k_0 - \sqrt{k_1^2 + k_2} \right) \cdot \exp\left( - f(d) \right) \tag{1}
\]

where \( k_0, k_1 \) and \( k_2 \) – depend on the ratio of the diameters of the cyclones and the exhaust pipe, as well as on the function of the particle diameter.

The function of the particle diameter \( f(d) \) was determined on the basis of generalization of data on high-temperature cyclones and own experimental data. As a result of processing this data, the following dependence was obtained:

\[
f(d) = 0.565 \left( \frac{h_e - \frac{q}{l}}{l} \right)^{0.44} \cdot \left( \frac{t_g + 273}{293} \right)^{0.3} \cdot \left( \frac{d_i}{d_p} \right)^{10.4} \tag{2}
\]

where \( h_e \) is the height of the exhaust pipe, m; \( t_g \) – gas temperature in the cyclone, °C; \( d_i \) and \( d_p \) – current and calculated particle size, m

The calculated particle size is determined by the formula:
where \( H_c \) – height of the cylindrical part of the cyclone, m; 
\( U_e \) – gas velocity at the cyclone inlet, m/s; 
\( a \) – the height of inlet duct, m; 
\( b \) – the width of inlet duct, m.

The calculation results according to the above formulas are in good agreement with the model for the experimental conditions. It should be noted that dependence 2 was obtained by processing numerous data on fractional efficiency, including for high dust conditions, as well as for industrial cyclones. Thus, the calculation to some extent takes into account the influence of solids loading.

A traditional approach is used to determine the overall capture efficiency:

\[
\eta = \frac{1}{2} \left[ 1 + \varphi(x) \right] 100
\]

where \( \varphi(x) \) is the probability integral (tab. value) at

\[
x = \frac{\lg \frac{d_m}{d_{\infty}}} {\sqrt{\lg^2 \sigma_\eta + \lg^2 \sigma_q}}
\]

where \( d_m \) is the average particle diameter at the inlet, m

\( lG \sigma_q \) - standard deviation in the distribution function of particles at the entrance to the cyclone.

The values \( d_m \) and \( lG \sigma_q \) are determined by the construction in normal-logarithmic coordinates from the known fractional composition of particles at the entrance to the cyclone.

The calculated values of the total capture efficiency are very large, which is associated with both a long residence time and a narrow range of particle sizes with their high average diameter. Comparison of calculated and experimental data on the total capture efficiency showed that the calculated values are always lower than the experimental ones. Noticeable differences are observed when \( m \) is greater than 0.5. The difference is only 0.004 - 0.005%. Thus, we can conclude that for cyclones with very high efficiency, the inclusion of the mass concentration at the inlet lies within the possible errors of both calculation and experiment.

It is known that the pressure drop of a cyclone decreases with increasing mass concentration. The presence of solids in the cyclone, forming particle strands that descend to the collection device (dipleg or hopper) produces this effect in cyclones. For low-to-medium inlet solid loadings and constant geometry, cyclone non-dimensional pressure drop (Euler number) decreases monotonically with solids concentration. Nevertheless, the curve has a minimum (a critical solid inlet loading) and for very high solid loadings (such as in CFB) the opposite process has usually been detected. The cyclone pressure drop can be calculated by following formula:

\[
\Delta P = \psi_c \cdot \xi_c \cdot \frac{U_e^2 \rho_s}{2}
\]

where \( \psi_c \) is correction for the influence of inlet flow concentration, \( \xi_c \) is the cyclone resistance coefficient, reduced to the velocity in it \( (U_e) \).

To calculate the correction for solid concentration, several dependencies are proposed. The most representative form of dependence is proposed in [21]. This form gives a correction value of 1 for a pure gas flow, with a minimum correction at mass concentrations (as solid flow rate to summ of solid
and gas flow rates - $\mu$) of about 0.3 and a further increase in its value with increasing concentration. This form of dependence was also used in the description of our investigations in previous works [16]. In a paper [22], a series of dependencies are analyzed to calculate the correction for mass concentrations. Experimental data [22] showed the absence of influence of gas velocity and particle sizes. Figure 4 shows our data and data [22]. They are summarized by a formula:

$$\psi_c = \frac{1}{25.8 \cdot \mu^{1.71} + 1} + 0.72 \cdot \mu$$  \hspace{1cm} (7)

![Figure 4. The correction on dust content of the flow against mass concentration of particles](image)

1 – Velocity in CFB reactor: U = 3.06 - 3.1 m/s; 2 - U = 3.55 - 3.8 m/s; 3 - U = 4.29 - 4.42 m/s; 4 - U = 4.7 m/s; 5 - data [22] ($d_p = 0.08 - 0.111$ mm); 6 - data [22] ($d_p = 0.111 - 0.5$ mm); 7 - formula (7)

**Conclusions**

The effect of mass loading at the inlet of the cyclone on the fractional capture efficiency is considered. According to experimental results, this effect is especially large at a mass concentration of more than 0.5. The calculated values of the total capture efficiency are very large, which is associated with both a long residence time and a narrow range of particle sizes with their high average diameter. Comparison of calculated and experimental data on the total capture efficiency showed that the calculated values are always lower than the experimental ones.

The presence of solids in the cyclone, forming particle strands that descend to the collection device (dipleg or hopper) produces this effect in cyclones. To calculate the correction for solid concentration, new dependence is proposed.

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