A Down-Exhaust Cyclone Separator

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In this paper we report on the development of a down-exhaust cyclone separator suitable for use as a primary device for gas−particle separation in circulating fluidized-bed (CFB) boilers. It consists of a cylindrical shell which is joined by an inclined cone, a guide body, and a downward exhaust pipe. The principle of solids separation is similar to that in reverse flow cyclones, except that in this separator the gas leaves the separator axially at the bottom. It has been shown that this separator is capable of achieving a separation efficiency of around 99% in handling high solids loadings such as those in CFB boilers, at a pressure drop of around 400 Pa. A model based on the mechanism of radial solids mixing is proposed, which assumes that the slip between gas and particles in the tangential direction is negligible and that the particles are well-dispersed. This model enables prediction of grade separation efficiency, total separation efficiency, and cut diameter. It may be used in conjunction with a pressure drop model to optimize the design and operating parameters.

Introduction

The cyclone separator has been widely used to remove small particles or droplets from a gas or liquid stream. The principle is that the centrifugal acceleration, resulting from strong rotation of the flow, forces particles of a higher density than the fluid to move toward the outside wall where they are subsequently removed from the flow. For the so-called tangential or reverse flow cyclone, the flow enters tangentially into a cylinder or pipe section which produces a strong rotation. The direction of the flow is reversed in the cyclone; the fluid exits axially at the top and the particles are collected at the bottom. For detailed accounts of the separation principle and design criteria, one may refer to the literature such as Stairmand,[1] Panton,[2] Dirgo and Leith,[3] and more recently Muschelknautz and Greif.[4,5] The advantage of this type of cyclone is that it usually has a high separation efficiency (typically above 99.5%). However, the pressure drop is also high (around 2000 Pa), which is partly due to the flow reversal. For large-scale industrial applications, for example, in circulating fluidized-bed (CFB) boilers, where the cyclone is a key component, the performance of the cyclone directly affects operational safety and capital costs of the plant. A necessary condition of the cyclone for use in CFB boilers is that it has a high separation efficiency, enabling achievement of satisfactory combustion, heat transfer, and sulfur retention. On the other hand, the pressure drop in the cyclone must be low to reduce the running cost. In addition, the cyclone should be simple in structure and compact in size. The use of a traditional cyclone in handling the high solids loading in CFB systems causes a dramatic increase in the pressure drop and decrease in the separation efficiency.[6]

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The design engineers of CFB boilers are often more concerned with the pressure drop rather than the separation efficiency. This is because particles which escape from the primary cyclone can be captured, relatively easily, using the traditional secondary cyclone operated at the low solids loadings. A general guideline for the design of the primary cyclone should be that the required separation efficiency be achieved at a minimum pressure drop. The first author of this paper (H.P.C.) has worked for the past 10 years on testing and improving the design of cyclone separators. The motivation of his work was to minimize the pressure drop while satisfying the requirement of the separation efficiency. In this paper we present our work in developing a down-exhaust separator now in operation in a number of CFB boilers in Southern China. We also present a mechanistic model to aid the design of such types of separators.

Principles

A schematic of the down-exhaust cyclone separator[7] is shown in Figure 1. It has a rectangular inlet, a cylindrical shell, a guide body, and an exhaust pipe. After entering the separator tangentially, the gas-particle mixture rotates downward in the gap between the cylindrical shell and the guide body. Most of the gas rotates until the inlet of the exhaust pipe while a small amount of the gas continues to rotate and reaches the surface of the inclined cone. The particles, after being separated from the gas by centrifugal forces, move downward and enter an ash bunker.

It has been shown[8] that the tangential gas velocity (W_t) consists of a quasi-forced vortex near the guide body and quasi-free vortex near the cylindrical shell. The tangential particle velocity (V_t) is approximately the same as W_t, indicating that the slip between gas and particles in the tangential direction is negligible.

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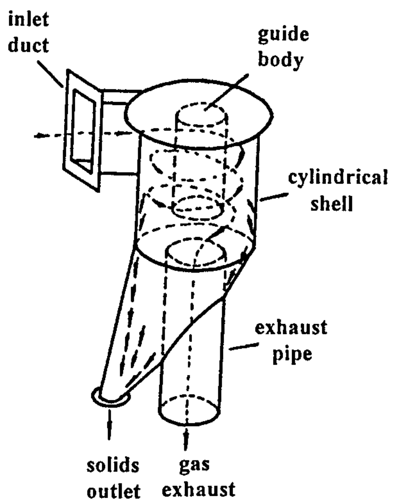

Figure 1. Schematic of the solids separator.

The radial gas velocity (W_r) is about an order lower than the tangential gas velocity. It consists of an inward quasi-sink flow near the guide body and an outward quasi-source flow near the cylindrical shell. Quasi-sink flow is detrimental to solids separation, since particles are forced to move toward the quasi-forced vortex region where they could be dragged into the exhaust pipe. Quasi-source flow, on the other hand, enhances solids separation as particles are forced to move toward the quasi-free vortex region where they fall along the cylindrical shell.

The axial gas velocity (W_a) is downward everywhere above the inlet of the exhaust pipe. Below this, it is downward near the surface of the inclined cone (which joins the cylindrical shell) and is upward near the exhaust pipe. The downward velocity near the cylindrical shell causes particles to move downward along the shell, thus enhancing solids separation. The downward velocity near the guide body and the upward velocity near the exhaust pipe both cause particles to move toward the inlet of the exhaust pipe, thus reducing the separation efficiency.

Experimental Facility and Method

Tests have been conducted extensively on down-exhaust separators of various dimensions. The results reported in this paper were obtained using a cyclone separator with the following dimensions: diameters of the cylindrical shell and the exhaust pipe are 0.4 and 0.2 m, respectively, inlet height and width are 0.28 and 0.09 m, respectively, and the height of the cylindrical shell is 1.0 m. The particles used were fly ash from a fluidized-bed boiler, which were 0−200 μm in size with a mean diameter of 75 μm and particle density of 1200 kg/m^3.

The total and grade separation efficiency were determined by sampling, sieving and weighing the particles at the inlet, outlet, and also ash bunker of the cyclone separator. Solids concentrations were measured in situ by an isokinetic probe, while the particle size distribution was determined using a laser Mastersizer. Our laboratory tests show that the total separation efficiency obtained by in-situ sampling was within 2% of that obtained by directly weighing the input and collected particles. Experimental errors were kept below 1% in the laboratory and 3% in the plants. If the errors were above these, then new measurements had to be made. The results were found to be reproducible, and the relative standard deviations between different tests under the same conditions were generally below 1%.

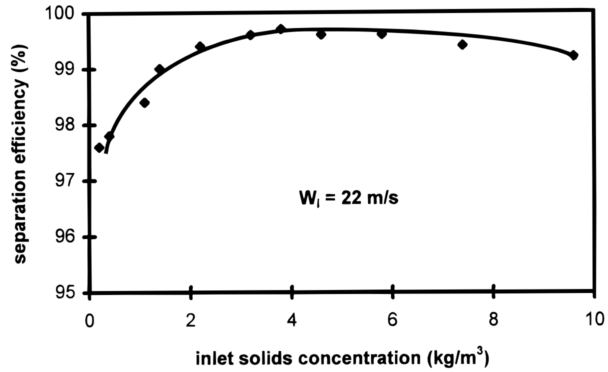

Figure 2. Variation of separation efficiency with inlet solids concentration.

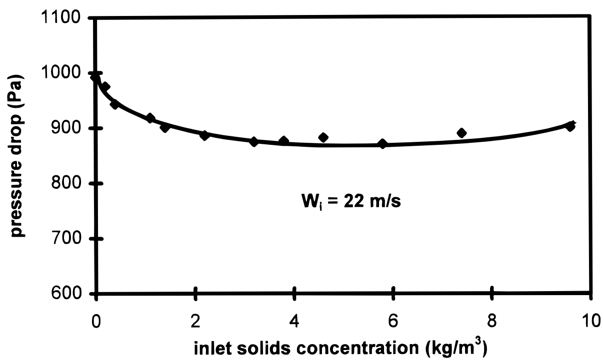

Figure 3. Variation of pressure drop with inlet solids concentration.

Experimental Results and Plant Operation

Examples of the results are shown in Figures 2−5. As the inlet solids concentration increases, the separation efficiency first increases and then decreases (Figure 2), while the pressure drop decreases initially and increases slightly afterward (Figure 3). Therefore, a critical inlet solids concentration exists for both the separation efficiency and pressure drop. This agrees with the observations of Baskakov et al.[9] and Lewnard et al.[6] using reverse flow cyclones. We find that this critical solids concentration depends on the design as well as operating conditions. The separation efficiency also increases with an increasing inlet gas velocity until a critical value is reached (Figure 4); it then decreases as the gas velocity is further increased. This may be explained by the effects of particle entrainment and rebound, such as those suggested by Kalen and Zenz[10] for reverse flow cyclones. As the inlet gas velocity increases, the centrifugal particle velocity increases, which causes the separation efficiency to increase. If the inlet gas velocity is too high, then the momentum of the particles in the radial direction could be so high that rebounding at the cylindrical shell becomes significant, which results in a decrease in the separation efficiency. The pressure drop increases with increasing inlet gas velocity as for a reverse flow cyclone (Figure 5).

The design concept of the down-exhaust cyclone separator is now incorporated in a number of CFB

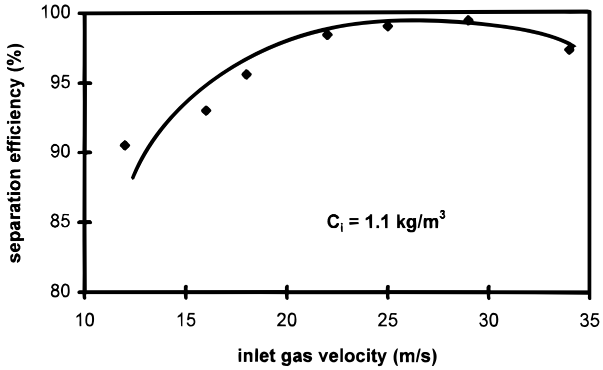

Figure 4. Variation of separation efficiency with inlet gas velocity.

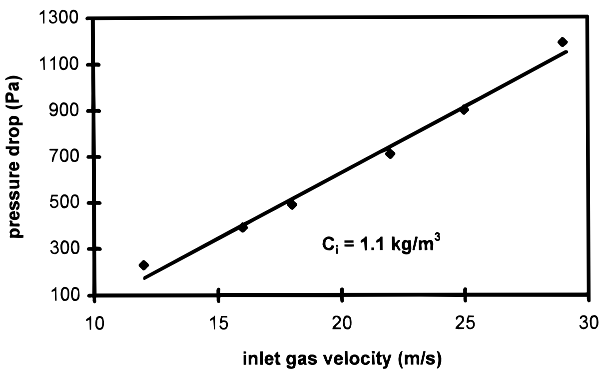

Figure 5. Variation of pressure drop with inlet gas velocity.

boilers in operation in Southern China. The separation efficiencies achieved in these plants are typically in the range from 98.6 to 99.5% at a pressure drop of around 400 Pa. We expect that, after careful adjustment of operating conditions, the performance of these separators can be further improved. The experimental results and plant operation therefore demonstrate that the down-exhaust cyclone separator indeed has the advantage of a high separation efficiency and a low pressure drop.

A Mechanistic Model

In this section, we present the development of a mechanistic model of the down-exhaust cyclone separator. We incorporate in this model a lateral (radial) mixing theory of Ma,[11] which assumes that particles are evenly distributed in any cross-section of the cyclone due to highly turbulent and vortical flow of the gas, and that all the particles are captured when they enter a boundary layer near the cylindrical shell. The main assumptions of our model are (1) There is no slip between gas and particles in the tangential direction (i.e., $V_t = W_t$). (2) The particles are spherical in shape. (3) All the particles are captured in a boundary layer near the cylindrical shell.[12] (4) The particles are well-dispersed so that the particle–particle interaction and the effect of particles on the gas are negligible. This last assumption may be reasonable when solids loadings are relatively low, such as those commonly used in CFB boilers. For applications where a higher solids loading (e.g., above 30 kg/m^3) is used, then the calculated results will need correction by a solids loading factor.[11]

Figure 6 shows particles at time τ and angle θ of the separator. The radii of the guide body and the cylindrical shell are r_1 and r_2, respectively. After time $d\tau$ the

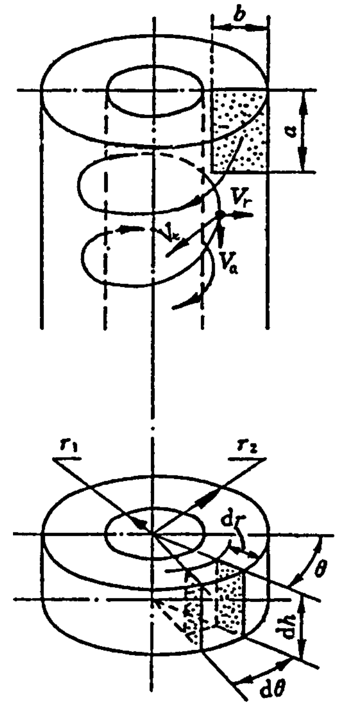

Figure 6. Diagram outlining the strategy of the model.

particles rotate for an angle $d\theta$. The particles near the cylindrical shell move in three directions: tangentially the movement is $r_2\ d\theta = V_{t2}\ d\tau$, where V_{t2} is the tangential velocity of particles near the cylindrical shell; radially it is $dr = V_{r2}\ d\tau = (V_{r2}/V_{t2})r_2\ d\theta$, where V_{r2} is the radial velocity of particles near the cylindrical shell; axially, it is dh. Particles are captured when their distance from the cylindrical shell is less than dr ($2r_2 \gg dr$). In angle $d\theta$ the mass of captured particles of diameter δ can be expressed as

$$-dm(\delta) = C_a\ dh[r_2^{\ 2} - (r_2 - dr)^2]\frac{d\theta}{2} \tag{1}$$

where C_a is the concentration of particles of diameter δ in angle $d\theta$. The total mass of particles of diameter δ in angle $d\theta$ is

$$m(\delta) = C_a\ dh(r_2^{\ 2} - r_1^{\ 2})\frac{d\theta}{2} \tag{2}$$

Therefore, the mass fraction of the captured particles in angle $d\theta$ is

$$-\frac{dm(\delta)}{m(\delta)} = \frac{2r_2\ dr - (dr)^2}{r_2^{\ 2} - r_1^{\ 2}} \approx \frac{2r_2\ dr}{r_2^{\ 2} - r_1^{\ 2}} = \frac{V_{r2}}{V_{t2}}\frac{2r_2^{\ 2}}{r_2^{\ 2} - r_1^{\ 2}}\ d\theta \tag{3}$$

Integrate eq 3 along the route of gas flow (θ changes from 0 to $2\pi N$), and we obtain

$$\frac{m_o(\delta)}{m_i(\delta)} = \exp\left(-\frac{V_{r2}}{V_{t2}}\frac{4\pi N r_2^{\ 2}}{r_2^{\ 2} - r_1^{\ 2}}\right) \tag{4}$$

where subscripts i and o represent the inlet and outlet of the separator, respectively, and N is the number of rotations of gas in the separator. If the effective separation height and the inlet height of the separator are h and a, respectively, then $N = h/a$. The grade separation efficiency for particles of diameter δ can be expressed as

$$\eta(\delta) = 1 - \frac{m_o(\delta)}{m_i(\delta)} = 1 - \exp\left(-\frac{V_{r2}}{V_{t2}}\frac{4\pi N r_2^{\,2}}{r_2^{\,2} - r_1^{\,2}}\right) \quad (5)$$

To calculate the grade separation efficiency using eq 5, we will need to find the tangential and radial velocities of the particles near the cylindrical shell (i.e., V_{t2} and V_{r2}, respectively).

A mass balance of gas through the section of the separator may be expressed as

$$abW_i = \int_{r_1}^{r_2} aW_t \, dr \quad (6)$$

where a and b are the inlet height and width of the separator, respectively, and W_i is the inlet gas velocity. For quasi-free vortex flow,

$$W_t r^k = C_1 \quad (7)$$

where C_1 is a constant, r is the radius of rotation, and k is a rotation index. The value of k may be obtained through flow measurement or using the following empirical correlation:[13]

$$k = 1 - (1 - 0.74 r_2^{\,0.14})\left(\frac{t + 273}{283}\right)^{0.3} \quad (8)$$

where t is the temperature of the gas in °C. For quasi-forced vortex flow,

$$W_t = C_2 r(1 - C_t r) \quad (9)$$

where C_2 and C_t are constants. The value of C_t is related to the dimensions of the cyclone and the rotation index by the following correlation:[14]

$$C_t = \frac{1}{4}\frac{r_2 + (1 + k)r_e + kr_1}{1 + k} \quad (10)$$

Let r_t be the radius which divides the quasi-free vortex and quasi-forced vortex regions; the following correlation holds:[14]

$$C_t r_t = \frac{1 + k}{2 + k} \quad (11)$$

Equations 10 and 11 were established following rigorous tests using 25 cyclones of different geometries (with the shell diameter varying from 0.1 to 3 m). Let $r = r_t$ and combine eqs 7, 9, and 11; we find

$$C_2 = \frac{2 + k}{r_t^{\,1+k}} C_1 \quad (12)$$

The right-hand side of eq 6 may be rearranged to show the contributions of the quasi-forced vortex and quasi-free vortex regions, that is,

$$abW_i = a\int_{r_1}^{r_t} C_2 r(1 - C_t r)\, dr + a\int_{r_t}^{r_2} \frac{C_1}{r^k}\, dr \quad (13)$$

From eqs 12 and 13 we find

$$C_1 = \frac{W_i b}{r_t^{\,1-k}}\left(\frac{2 + k}{2}[1 - (r_1/r_t)^2] - \frac{1 + k}{3}[1 - (r_1/r_t)^3] - \frac{1}{1 - k}[1 - (r_2/r_t)^{1-k}]\right)^{-1} \quad (14)$$

The tangential gas and particle velocities near the cylindrical shell ($r = r_2$) can then be found from eq 7, that is,

$$V_{t2} = W_{t2} = \frac{W_i b}{r_2^{\,k} r_t^{\,1-k}}\left(\frac{2 + k}{2}[1 - (r_1/r_t)^2] - \frac{1 + k}{3}[1 - (r_1/r_t)^3] - \frac{1}{1 - k}[1 - (r_2/r_t)^{1-k}]\right)^{-1} \quad (15)$$

The motion of particles in the field of centrifugal forces can be described as

$$m_p \frac{dV_r}{d\tau} = m_p \frac{V_t^{\,2}}{r} - C_D A_p \frac{\rho_g (V_r - W_r)^2}{2} \quad (16)$$

where m_p is the mass of a single particle (i.e., $\pi\delta^3\rho_p/6$), V_r is the radial velocity of the particle, C_D is the drag coefficient, A_p is the projection area of the particle (i.e., $\pi\delta^2/4$), and ρ_g is the gas density. C_D may be expressed as

$$C_D = \frac{C}{Re_\delta^{\,n}} \quad (17)$$

Re_δ in eq 17 is the particle Reynolds number, defined as $Re_\delta = V_r\delta/\nu$, in which ν is the kinematic viscosity of gas. The use of a drag coefficient in the form of eq 17 enables the determination of an explicit expression for the grade separation efficiency as a function of particle diameter and dimensions of the cyclone. The values of C and n in eq 17 may be found by regression based on the range of Re_δ and C_D. The term $(V_r - W_r)$ in eq 16 can be reduced to V_r, as the radial velocity of gas is at least an order lower than that of particles.[14] Equation 16 can therefore be solved for V_r, assuming $dV_r/d\tau = 0$, that is,

$$V_r = [4\rho_p\delta^{1+n}V_t^{\,2}/(3\rho_g C\nu^n r)]^{1/(2-n)} \quad (18)$$

The radial particle velocity near the cylindrical shell, V_{r2}, can be obtained by replacing r with r_2 in eq 18, that is,

$$V_{r2} = [4\rho_p\delta^{1+n}V_{t2}^{\,2}/(3\rho_g C\nu^n r_2)]^{1/(2-n)} \quad (19)$$

The values of V_{t2} and V_{r2} obtained above enable calculation, using eq 5, of the grade separation efficiency for a given particle diameter and operating conditions. The total separation efficiency can be calculated by eq 20 when the particle size distribution is known:

$$\eta = \sum_i [\eta_i(\delta) f_i(\delta)] \quad (20)$$

where $\eta_i(\delta)$ and $f_i(\delta)$ are the grade separation efficiency and mass fraction of particles, respectively, in the ith particle size interval. Let $\eta(\delta) = 50\%$, and then the cut

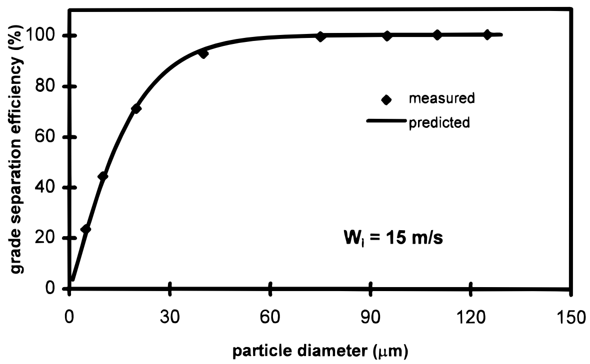

Figure 7. Example of the comparison between predicted and measured grade separation efficiency.

diameter, δ_{50}, can also be obtained. The relationship between the cut diameter and grade separation efficiency is given in eq 21.

$$\eta(\delta) = 1 - \exp\left[-\ln 2\left(\frac{\delta}{\delta_{50}}\right)^{(1+n)/(2-n)}\right] \qquad (21)$$

Results and Discussion

We now have a mechanistic model which enables prediction of the principal indices of the down-exhaust cyclone separator, including grade separation efficiency, total separation efficiency, and critical separation diameter. Figure 7 shows an example of the comparison between model prediction and measurements of the grade separation efficiency as a function of particle diameter. Dimensions of the separator based on which the comparison was made are as follows: $r_1 = 0.05$ m, $r_2 = 0.1$ m, $a = 0.14$ m, and $b = 0.04$ m. The particles used were in the size range from 0 to 100 μm, with a mean diameter of 45 μm and particle density of 2100 kg/m^3. It can be noted that the agreement between model prediction and measurements is very encouraging.

The proposed model may be applicable for a wide range of flow conditions, because of the use of a general correlation for the drag coefficient (eq 17). Many researchers (e.g., Ma,[11] Ogawa,[15] and Basu and Fraser[16]) have used the drag coefficient $C_D = 24/Re_\delta$ to calculate the separation efficiency of reverse flow cyclones, assuming that the flow is in the Stokes region. For application in CFB boilers, however, these models may no longer be applicable. This is because the particle Reynolds number in CFB cyclones is in the range from 1 to 1000 and, therefore, the Stokes law no longer accurately describes the flow resistance. We find that the values of C and n which give rise to a calculated grade separation efficiency in agreement with measurements of down-exhaust cyclones of various geometries, while being valid for the particle Reynolds number typical of CFB boilers, are 30 and 0.625, respectively. These values may therefore be recommended for general use.

The model presented above may be used together with a pressure drop model, which is summarized in the Appendix, of Chen et al.[17] to optimize the design of the down-exhaust cyclone separator. In the design, the dimensions of the separator are optimized using a computer program which yields minimum pressure drop while satisfying the required separation efficiency. As an example, some of the design parameters of the 6 and 12 MWe CFB boilers, in operation in Southern China, obtained using the computer program, are given below.

For the 6 MWe CFB boiler:

$$r_2 = 1.1\text{ m},\quad a = 1.37\text{ m},\quad b = 0.65\text{ m},\quad W_i = 20\text{ m/s},\quad \delta_{50} = 21\ \mu\text{m}$$

For the 12 MWe CFB boiler:

$$r_2 = 1.4\text{ m},\quad a = 2.0\text{ m},\quad b = 0.8\text{ m},\quad W_i = 22\text{ m/s},\quad \delta_{50} = 21\ \mu\text{m}$$

Both cyclones are in satisfactory operation.

Concluding Remarks

Development of a purpose-orientated cyclone separator is presented. A distinct feature of this cyclone separator is that it has a downward exhaust, which makes it possible to achieve a separation efficiency of around 99% in handling solids loadings which are much higher than those for traditional cyclones, at a pressure drop of about 400 Pa. Because of the use of a downward exhaust, the separator also has the advantage of being more compact and thus requires less space for plant installation as compared to the reverse flow cyclones. This design is particularly suitable for use in CFB systems as a first-stage gas−particle separator. It has been incorporated in 6 and 12 MWe CFB boilers in operation in Southern China and the performance of these cyclones is considered to be superior to that of reverse flow cyclones. The proposed model enables prediction of the principal indices of the separator including grade separation efficiency, total separation efficiency, and cut diameter. This model also enables optimum design of the down-exhaust cyclone separators, on the basis of achieving the required separation efficiency at a minimum pressure drop, when used together with a pressure drop model developed earlier by the authors.

Nomenclature

a = height of separator inlet, m
A_p = particle projection area, m^2
b = width of separator inlet, m
C = constant in the expression of drag coefficient
C_1 = constant, eq 7
C_2 = constant, eq 9
C_a = concentration of particles of diameter δ, kg/m^3
C_D = drag coefficient
$f_i(\delta)$ = mass fraction of particles in the ith particle size interval
h = effective separation height, m
k = rotation index, eq 7
m_p = mass of a single particle, kg
$m(\delta)$ = mass of particles of diameter δ, kg
N = number of rotations of gas in the separator
ΔP = pressure drop in the separator, Pa
r = radius of rotation, m
r_1 = radius of guide body, m
r_2 = radius of cylindrical shell, m
r_e = radius of the exhaust pipe, m
r_t = radius of the boundary dividing quasi-free and quasi-forced vortex regions, m

Re_δ = particle Reynolds number
t = temperature, °C
V_r = radial particle velocity, m/s
V_{r2} = radial velocity of particles near the cylindrical shell, m/s
V_t = tangential particle velocity, m/s
V_{t2} = tangential velocity of particles near the wall, m/s
W_a = axial gas velocity, m/s
W_i = inlet gas velocity, m/s
W_r = radial gas velocity, m/s
W_t = tangential gas velocity, m/s
δ = particle diameter, m
δ_{50} = cut diameter at which the grade separation efficiency is 50%, m
η = total separation efficiency
$\eta(\delta)$ = grade separation efficiency
$\eta_i(\delta)$ = grade separation efficiency of particles in the ith particle size interval
ν = kinematic viscosity of gas, m^2/s
θ = angle, rad
ρ_g = gas density, kg/m^3
ρ_p = particle density, kg/m^3
τ = time, s

Appendix

The pressure drop for gas flow in the down-exhaust cyclone separator (ΔP_0) consists of a pressure drop due to the flow of gas (ΔP_r) and a pressure drop due to flow area reduction at the inlet of the exhaust pipe (ΔP_e), that is,

$$\Delta P_0 = \Delta P_r + \Delta P_e \tag{A1}$$

ΔP_r and ΔP_e can be found from

$$\Delta P_r = \xi_r \frac{\rho_g W_i^2}{2} \tag{A2}$$

$$\Delta P_e = \xi_e \frac{\rho_g W_i^2}{2} \tag{A3}$$

where ξ_r and ξ_e are resistance coefficients due to the flow of gas and due to the flow area reduction, respectively. Expressions of ξ_r and ξ_e are given in eqs A4 and A5, which were based on regression of experimental results, obtained from 25 cyclones of different dimensions at various inlet gas velocities and solids concentrations.

$$\xi_r = 0.884B^2\{(k^2 + 6k + 11)(r_2/r_t)^{2k}/6 + [(r_2r_t)^{2k} - 1]/k\} \tag{A4}$$

$$\xi_e = 0.803(ab/r_e^2)^2(1 - r_e^2/r_2^2)^{0.651} \tag{A5}$$

B in eq A4 is a dimensionless number, defined as

$$B = \frac{b}{r_2}\left(\frac{r_2}{r_t}\right)^{1-k} \Bigg/ \left(\frac{2+k}{2}[1 - (r_1/r_t)^2] - \frac{1+k}{3}[1 - (r_1/r_t)^3] - \frac{1}{1-k}[1 - (r_2/r_t)^{1-k}]\right) \tag{A6}$$

The pressure drop for gas–particle flow with a solids concentration of C_i (in kg/m^3) is given by

$$\Delta P = \Delta P_0/(1 + 0.346C_i^{0.45}) \tag{A7}$$

Literature Cited

(1) Stairmand, C. J. The Design and Performance of Cyclone Separators. *Trans. Inst. Chem. Eng.* **1951**, *29*, 356.

(2) Panton, R. L. *Incompressible Flow*; Wiley: New York, 1984.

(3) Dirgo, J.; Leith, D. Design of Cyclone Separators. In *Encyclopedia of Fluid Mechanics, Vol. 4, Solids and Gas–Solids Flows*; Cheremisinoff, N. P., Ed.; Gulf Publishing Co.: Houston, TX, 1986.

(4) Muschelknautz, E.; Greif, V. Fundamentals and Practical Aspects of Cyclones. In *Circulating Fluidized Bed Technology IV*; Avidan, A. A., Ed.; AIChE: New York, 1994; p 20.

(5) Muschelknautz, E.; Greif, V. Cyclones and Other Gas–Solids Separators. In *Circulating Fluidized Beds;* Grace, J. R., Avidan, A. A., Knowlton, T. M., Eds.; Blackie Academic & Professional: London, 1997; p 181.

(6) Lewnard, J. J.; Herb, B. E.; Tsao, T. R.; Zenz, J. A. Effect of Design and Operating Parameters on Cyclone Performance for Circulating Fluidized Bed Boilers. In *Circulating Fluidized Bed Technology IV*; Avidan, A. A., Ed.; AIChE: New York, 1994; p 525.

(7) Chen, H. P.; Lin, Z. J.; Liu, D. C. Recirculating fluidized bed boiler fly ash separator. Chinese Patent 91,100,364.9, 1991.

(8) Lin, Z. J.; Chen, H. P.; Liu, D. C. The Design of a CFB Boiler with Downward-Exhaust Solids Separator. *J. Huazhong Univ. Sci. Technol.* **1994**, *22* (3), 16.

(9) Baskakov, A. P.; Dolgov, V. N.; Goldobin, Y. M. Aerodynamics and Heat Transfer in Cyclones with Particle-laden Gas Flow. In *Circulating Fluidized Bed Technology;* Basu, P., Large, J. F., Eds.; Pergamon Press: Oxford, 1988; p 233.

(10) Kalen, B.; Zenz, F. A. Theoretical-Empirical Approach to Saltation Velocity in Cyclone Design. *AIChE Symp. Ser.* **1974**, *70* (137), 388.

(11) Ma, G. D. *Calculation of Cyclones*; China Environmental Science Press: Beijing, 1990.

(12) Leith, D.; Licht, W. The Collection Efficiency of Cyclone Type Particle Collectors–A New Theoretical Approach. *AIChE Symp. Ser.* **1972**, *68* (126), 196.

(13) Alexander, R. M. In *Proc. Aust. Inst. Min. Met. (N. S.)* **1949**, 152/3, 202.

(14) Chen, H. P.; Huang, L.; Lin Z. J.; Liu, D. C. The Separating Mechanism of a Cyclone Separator with Downward Exhaust Gas in a CFB Boiler. *J. Huazhong Univ. Sci. Technol.* **1995**, *23* (3), 111.

(15) Ogawa, A. *Separation of Particles from Air and Gases*; CRC Press: Boca Raton, FL, 1984.

(16) Basu, P.; Fraser, S. A. *Circulating Fluidized Bed Boilers Design and Operations*; Butterworth-Heinemann: Boston, 1991.

(17) Chen, H. P.; Huang, L.; Lin Z. J.; Liu, D. C. On the Pressure Drop of a New-Type Cyclone Separator with Downward Exhaust Gas. *J. Huazhong Univ. Sci. Technol.* **1995**, *23* (8), 28.

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