Classification of silica fine particles using a novel electric hydrocyclone

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Abstract

A novel electric hydrocyclone is developed and tested. Aqueous suspensions of silica with a median diameter of 754 nm and 0.2% volumetric concentration are tested using a 20-mm-diameter hydrocyclone. The ratios of tested underflow rate to throughput are: 0, 0.1, 0.2 and 0.3. The tested volumetric flow rates are 0.083 $\times$ $10^{-3}$, 0.117 $\times$ $10^{-3}$ and 0.167 $\times$ $10^{-3}$ m$^3$/s (5, 7 and 10 l/min). The conical part of the electric hydrocyclone is connected to a cylindrical dust box having 42 mm diameter. This dust box has a central metal rod cone and a cylindrical metal wall between which the desired 50-volt DC electric potential or no potential is applied. The investigated lengths of the dust box are 53 and 106 mm. The three different conditions investigated are: (a) no applied electric potential, (b) positive potential applied at the central rod side and negative potential at the side wall, and (c) positive potential applied at the side wall and negative potential at the central rod side. In both the absence and presence of the underflow, the hydrocyclone with a long dust box is found to give better classification efficiency than that with a short dust box. Interestingly, the effect of electric potential is reversed with respect to the presence and absence of the underflow. The presence of the underflow unexpectedly increase the 50% particle cut size when electric potential is applied. However, the effect of electric potential is reversed when there is no underflow. The electric potential can reduce the 50% particle cut size by up to 10% compared to the absence of electricity. It is found that condition (c) exhibits a stronger effect than condition (b). As expected, the higher the flow ratio, the smaller the particle cut size becomes. Based on the experimental results, an empirical correlation for the 50% particle cut size has been obtained.

Keywords: Classification; Silica; Particles; Electric; Hydrocyclone

1. Introduction

Silica is a hard abrasive mineral used in numerous industries. Grinding is a common important process to produce silica fine particles. In the dry grinding process, fugitive dust is easily created. When people inhale the fine dust of crystalline silica, it can lead to silicosis, a potentially fatal lung disease. Wet grinding not only eliminates fugitive dust but also gives higher grinding efficiency. The coarse oversize particles have to be separated out and sent back for regrinding. The conventional hydrocyclone is suitable for the classification of relatively fine, though not too fine, particles unclassifiable by sifting.

A hydrocyclone [1,2] is simple in construction, has no moving parts, requires low installation and maintenance investment for the separation, classification and thickening in many solid–liquid processes. Though originally designed to promote solid–liquid separations, they are also used for solid-solid [3], liquid–liquid [4], and gas–liquid separation [5]. Although the first patent on a hydrocyclone is about 115 years old, research works are still in progress aiming at developing new applications [6–10] or understanding the complex phenomena inside it.

Two well-known theories for particle separation in hydrocyclones are the equilibrium orbit theory [11] and the residence time theory [12]. The former assumes that particles of a given size will reach an equilibrium radial orbit position inside the hydrocyclone where their outward terminal settling velocity is equal to the inward radial velocity of the liquid. Accordingly to this theory, larger
particles will attain a radial orbit position near the wall, where the axial fluid velocity has a downward direction. These particles will leave the cyclone through the underflow. The radial orbit position of smaller particles will be located near the center, inside the region where the axial fluid velocity is upward. These particles will escape through the overflow. The cut size is defined as the particle size whose equilibrium orbit is coincident with the locus of zero vertical velocity of the fluid. Such a particle will have equal chances to escape the hydrocyclone either through the underflow or through the overflow. According to the residence time theory, a particle will be separated as a function of both the position it enters the cyclone and the available residence time. The cut size will be the size of the particle which entering the equipment exactly in the center of the inlet pipe will just reach the wall in the residence time available. Several authors have used either theory to derive different equations for predicting the cut size [13–16].

The study of size classification performance, in terms of both fundamental and operational variables has been undertaken by several authors [17–20]. Empirical models have been developed [18–21] which are used for predicting hydrocyclone performance in terms of capacity, cut size and water split. With respect to the empirical modeling of small diameter hydrocyclones, some studies [22–24] describe hydrocyclone performance with new correlations for the capacity, cut size and water split. The flow pattern in hydrocyclones has been examined experimentally [18,23,25] and theoretically [12,18,26]. Expressions for \( d_{50} \) have been obtained empirically [27–30] and theoretically [31,32]. The purpose of this study is to verify the collection efficiency of a new type of electric hydrocyclone with and without underflow under applied electric potential at the dust box. The simple correlation for the 50% cut size is discussed.

2. Materials and methods

Silica is used as the test powder which has the particle size distribution as shown in Fig. 1. The median diameter is 754 nm. The density of powder is 2210 kg/m\(^3\). Deionised water is used in all experiments. Suspensions of 0.2% solid content by weight are tested in hydrocyclone of 20 mm body diameter. All design proportions are as shown in Table 1.

The ratios of tested underflow rate to throughput are: 0, 0.1, 0.2 and 0.3. The tested volumetric flow rates are 0.083 \( \times 10^{-3} \), 0.117 \( \times 10^{-3} \) and 0.167 \( \times 10^{-3} \) m\(^3\)/s. The operating time is 20 min to assure that the system is in steady state.

The simplified experimental apparatus is shown in Fig. 2. As can be seen, it consists of a tank equipped with impeller for mixing at constant speed of 250 rpm. The discharged underflow and overflow are returned to the feed tank. The flow meter and pressure gauge are installed to measure flow rate and pressure drop. The suspension temperature in the tank is constantly controlled at 30 °C by using cooler and heater.

The conical part of the electric hydrocyclone is connected to a cylindrical dust box having 42 mm diameter. This dust box has a central metal rod cone and a cylindrical metal wall between which the desired 50-volt DC electric potential or no potential is applied. The investigated lengths of the dust box are 53 and 106 mm. The three different conditions investigated are: (a) no applied electric potential, (b) positive potential applied at the central rod side and

![Fig. 1. Particle size distribution of the feed materials.](image-url)
negative potential at the side wall, and (c) positive potential applied at the side wall and negative potential at the central rod side.

The particle size analyses of both effluent streams are carried out by Laser Scattering Particle Size Distribution Analyser, HORIBA LA-920 with (NaPO₃)₆ 0.3 g as a dispersing agent. The concentrations of solids in the underflow and overflow samples are measured by evaporation and weighing. The grade efficiency, $G$, and the cut size, $d_{50}$, are evaluated according to the procedure recommended by Svarovsky [2].

3. Results and discussion

Fig. 3 shows the effect of dust box length in the absence of underflow. The hydrocyclone with a longer dust box exhibits higher separation efficiency because coarse particles have less chance to escape from the vortex finder than that with a short one. At steady state, the 50% cut size are 2.260 and 1.858 $\mu$m for the short dust box at flow rate $0.117 \times 10^{-3}$ m$^3$/s and $0.167 \times 10^{-3}$ m$^3$/s, respectively but decreases by 10.22% to 2.029 $\mu$m and by 11.52% to 1.644 $\mu$m for the long dust box.

Figs. 4 and 5 show the particle separation efficiency when electric potential is applied to the long dust box of the hydrocyclone in the presence and absence of the underflow, respectively. The effect of electric potential is reversed with respect to the presence and absence of the underflow. More specifically, the electric potential for positive pole at both the central rod and side wall increases the 50% particle cut size when compared with no application of electric potential in the presence of the underflow. The trend is reversed in the absence of the underflow. Both in the absence and presence of the underflow, effect of the potential when the positive pole is connected to the side wall is stronger than when the positive pole is connected to the central rod.

Fig. 6 shows the relationship between 50% particle cut size, $d_{50}$, and the underflow to throughput ratio, $R_f$, by using the long dust box at feed flow rate $0.117 \times 10^{-3}$ m$^3$/s with and without electric potential. As expected, the higher the flow ratio, the smaller the particle cut size becomes. The choice is between high flow ratios at low-pressure drops, or low flow ratios at high-pressure drops. However,
a higher flow ratio results in a lower solid concentration and vice versa. Depending on the particle size of the feed solids and the cost of further dewatering of the solids in the underflow, the two running costs of dewatering of the solids in the underflow and pressure drop should be weighed against each other and the operating conditions optimized accordingly.

Fig. 7 shows the relationship between $d_{50}$ and suspension feed flow rate, $Q$, for either the short or long dust box at operating flow ratio 0.1 with and without electric potential. As anticipated, the higher the feed flow rate, the smaller the particle cut size. The results confirm both the effect of dust box length in Fig. 3 and trend of electric potential effects in Figs. 4 and 6. Similarly, Fig. 8 shows the relationship between $d_{50}$ and $Q$ for short or long dust boxes with no underflow in the absence and presence of electric potential. The higher feed flow rate reduces the smaller particle cut size. The results again confirm both effects of dust box length in Fig. 3 and trend of electric potential in Fig. 5. In order to obtain the smallest cut size the long dust box should be selected and the system operated with positive electric potential at the wall and no underflow.

Fig. 9 shows the correlation results for the $d_{50}$ in the presence and absence of underflow using parameters $K_1$, $C_1$ and $C_2$ (see Appendix A) compared with experimental results in the presence and absence of underflow, respectively. The estimated parameters are agreed well with experimental results.

4. Conclusion

In both the absence and presence of the underflow, the hydrocyclone with a long dust box is found to give better classification efficiency than that with a short dust box. Interestingly, the effect of electric potential is reversed with respect to the presence and absence of the underflow. The presence of the underflow unexpectedly increase the 50% particle cut size when electric potential is applied. However, the effect of electric potential is reversed when there is no underflow. The electric potential can reduce the 50% particle cut size by up to 10% compared to the absence of electricity. It is found that condition (c) with positive potential applied at the side wall and negative potential at the central rod side exhibits a stronger effect than condition (b) with positive potential applied at the central rod side and negative potential at the side wall. As expected, the higher the flow ratio, the smaller the particle
cut size becomes. Based on the experimental results, an empirical correlation for the 50% particle cut size has been obtained as Eqs. (A.3)–(A.6).

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**Appendix A**

The correlation derived from equation of motion is

\[ m \frac{du}{dt} = -3\pi \mu D_p (u_t - v) + \frac{m v_r^2}{r} \]  

(A.1)

where \( u \) and \( v \) are particle and fluid velocity that respect to coordinate, respectively. At steady state the left hand term is zero, so that:

\[ D_p = \sqrt{\frac{18 \mu (u_t - v)}{(\rho_p - \rho) v_r^2}} \]

At critical particle velocity, \( u_t = 0 \):

\[ D_{pc} = \left[ \frac{18 \mu v_r}{(\rho_p - \rho) v_r^2} \right]^{1/2} = \left[ \frac{18 \mu (v_R)}{(\rho_p - \rho) v_r^2} \right]^{1/2} \]

Normally, \( v_0 = v_r \), \( v_R = \alpha v_r v_t = 4Q/10D^2 \) and \( r = D/2 \)

\[ D_{pc} = (7.07\alpha)^{1/2} \left( \frac{\mu D_p D_t^2}{(\rho_p - \rho) Q} \right)^{1/2} \]

\[ = K \left( \frac{\mu D_p D_t^2}{(\rho_p - \rho) Q} \right)^{1/2} \]  

(A.2)

Substitute with the cyclone dimensions and property:

\[ d_{50} = K \left( \frac{0.8328 \times 10^{-3} \times 20 \times 10^{-3} \times (3.9 \times 10^{-3})^2}{(2210 - 995.647)Q} \right)^{0.5} \]  

\[ d_{50} = K \left( \frac{2.0862 \times 10^{-13}}{Q} \right)^{0.5} \]  

(A.3)

The semi-empirical constant \( K \) is denoted by:

\[ K = K_1 + C_1 + C_2 \]  

(A.4)

where \( K_1 \) is a constant. \( C_1 \) and \( C_2 \) denote the dust box length effect and electric effect respectively. The correlation for the presence of the underflow is:

\[ K_1 = \frac{15338}{Q^{0.0245} R_f^{0.359}} \]  

(A.5)

The correlation for the absence of the underflow is:

\[ K_1 = 79746Q^{0.0599} \]  

(A.6)

The constants for the presence and absence of the underflow in Eq. (A.4) are shown in Table A1.

| \( C_1 \) | \( C_2 \) |
|---|---|
| **Presence of underflow** | **No** | **Center** | **Wall** |
| Short dust box | 3067 | 0 | 744 | 1698 |
| Long dust box | 0 | 0 | 1036 | 1815 |
| **Absence of underflow** | **Short dust box** | 5836 | 0 | −2759 | −4045 |
| Long dust box | 0 | 0 | −2114 | −4323 |

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