Classification Characteristics of a Cyclone Type Classifier with Improved Collection Boxes for Separating Particles near the Wall Surface

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Cyclone separators are used in many processes to remove powders for collection in a wide range of diameters. When the cyclone separator is used as a classification device that requires high effectiveness, the 50% cut-off size (D_{p50}) is restricted to less than several microns owing to the strong centrifugal force. We developed a cyclone-type classifier to effectively classify coarse particles collected by the normal cyclone, as discussed in our previous study. The classifier comprises inner and outer collection boxes with a sloping channel region between the upper sections. The sloping channel could derive the additional air, called blow-up flow, from the tangent nozzle established in the outer box. The blow-up flow becomes confluent with the main swirling flow of the cyclone. In the channel, the fine particles affected by the drag of the blow-up flow were collected in the inner box. Additionally, the coarse particles affected by the centrifugal force induced by the swirling flow were collected in the outer box. The previous study, regarding a classifier with a channel length of 6 mm, demonstrated that D_{p50} and the effectiveness of the classification κ , which is the ratio of the 25% cut-off size to the 75% cut-off size (D_{p25}/D_{p75}), increase linearly with the increase in blow-up flow rate (Δq). In this study, we increased the channel length from 6 to 23 mm. This resulted in the following beneficial characteristics for separating acrylic particles having a size distribution of 15–35 μm . Unlike the previous study, D_{p50} depended on the main flow rate at the entrance regardless of Δq since the increase in Δq increases the centrifugal force, which acts simultaneously on the D_{p50} particles, and the drag force. Meanwhile, κ increased significantly with the increase in Δq . The classifier classified the particles with high effectiveness (κ ranging from 0.75 to 0.92).

Introduction

Cyclone separators possess advantages such as a simple structure and are maintenance free since they have no drives or rotors. The swirling flow is so strong that particles in the air are effectively collected in the collection box due to the inertial force differences. Therefore, the cyclone separator is widely used as a general-purpose collection device in many processes for producing powders such as those of ceramics, inorganic material, metals, resin, food, and toners.

Meanwhile, cyclones have been studied for a 50% cut-off size termed D_{p50} , the collecting efficiency after an examination of the velocity distribution, and the pressure loss within a cyclone separator. Barth (1956) proposed a numerical model for predicting D_{p50} called the Equilibrium–Orbit Model, which depends on a balance between drag and centrifugal forces acting on a particle on a control surface (CS). Barth considered the cylindrical CS that is formed by continuing the vortex finder wall to the bottom of the cyclone.

He estimated the tangential velocity over the CS using the wall velocity as calculated from the inlet gas velocity. These estimations are dependent on the friction factor. Hoffmann and Stein (2008) provided the friction factor that included the influence of the particle laden air flow over a hydraulically smooth cyclone surface. Furthermore, Muschelknautz and Trefz (1990) developed Barth's model in greater detail. They suggested a tangential velocity for the gas at the inner core radius of the CS using a friction factor coefficient.

The coefficient was related to the defined Reynolds number for a cyclone body when taking wall roughness into consideration. These models give the basic method for predicting D_{p50} in the field of a swirling flow in a classification device.

Cortés and Gil (2007) reviewed many past studies on the cyclone separator and examined various models for formulating the velocity distributions and pressure loss. The tangential velocity profile in the cyclone was described as a Rankine vortex combined with forced and free vortices. They proposed the use of the Reydon and Gauvin (1981) model for the accurate estimation of the tangential velocity profile with the forced vortex, and the Meissner and Löffler (1978) model for that of the same for the free vortex. Hoffmann and Stein (2008) also investigated many past studies

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and provided various design techniques for applying cyclone separators to practical processes.

However, the common purpose of these studies was to collect particles, and not to classify them. Generally, when cyclone separators are used as classification devices requiring high effectiveness and flexibility of the cut-off size, the critical diameter is less than several microns for a strong swirling flow in the cyclone separator. The studies in this range of diameters are discussed here. Iinoya *et al.* (1992) extended the cut-off size to the submicron level and improved the classification effectiveness by using the blow-down method. Yoshida *et al.* (1995) tracked the behavior of the particles in a blow-down cyclone separator using computational fluid dynamics (CFD), and explained the mechanism by which the particle cut-off size became small. Yoshida *et al.* (1993) could control the cut-off size to be within the range of 0.45–0.75 μm by installing a movable inlet guide plate that allowed the inlet clearance to change in the cyclone entrance section.

Akiyama *et al.* (2005) lowered the cut-off size and improved the classification effectiveness by increasing the flow rate through the nozzle attached to the top section of the cyclone separator. Additionally, Takeda *et al.* (2014) recently suggested a method to lower the cut-off size while controlling the pressure loss by introducing clean air from an entrance nozzle installed at the inlet guide plate in the cyclone separator. These studies developed methods, by which the tangential velocity in the vicinity of the cyclone wall can be increased, to ensure that a strong centrifugal force acts on a particle and results in improved classification effectiveness.

These studies focused on the classification of particles less than several microns as described earlier. There are no reports that study the classification of coarse particles more than several microns. When the cut-off size is intended to be raised to more than several microns for a conventional cyclone separator, the swirling flow must be weakened. This

weakening reduces the centrifugal force acting on the particle and leads to low classification effectiveness. Additionally, the lowered centrifugal force narrows the range of activities where the cyclone separators can be applied as classification devices.

Oshitari *et al.* (2015) modified a conventional cyclone to install a CS on the wall where particles passing the wall surface were classified. The classifier comprised inner and outer collection boxes having a sloping channel region between the upper sections of the boxes. The channel can derive additional air, called blow-up flow, from the tangent nozzle that is installed in the outer box, thereby creating a confluent flow with the main swirling flow of the cyclone separator. This type of a cyclone separator classifier can utilize the strong swirling flow and establish a wider range of the cut-off size D_{p50} than that by the conventional cyclone separators. It is expected that the modified cyclone will be a versatile classification device and can be widely applied to the production of various kinds of powders.

In this study, we designed the channel to be 23 mm and performed classification of acrylic particles using the same diameter distribution (15–35 μm) as the one in our previous study. However, in the previous study (Oshitari *et al.*, 2015), the channel was designed to be 6 mm. The classifier showed excellent operational characteristics and was unlike the one in the previous study. The effectiveness of the classification improved as did the yield without significantly changing D_{p50} . The purpose of this study was to clarify the classification mechanism by examining the cut-off size D_{p50} and effectiveness.

1. Experimental

A general view of the cyclone type classifier that we call an accelerating cyclone vortex (ACV) is shown in **Figure 1(a)**. The initial parameters of the main air flow are repre-

Fig. 1 Structure of the ACV-cyclone and dimensions of the main part

Fig. 2 Dimensions of the classifying part

sented by the flow rate Q and the blow-up flow Δq . Each dimension is an internal value, and all dimensions are the same as those in the previous study (Oshitari *et al.*, 2015) except for the length of the slitter. **Figure 1(b)** shows the inlet guide vane including the definition of the inlet width ratio G at the entrance of the ACV. The guide vane increases the velocity of the inlet air, allowing the tangential velocity of the air and particles to increase in the vicinity of the wall of the ACV. The experiment was performed with the ratio $G=0.4$, which showed the best classification effectiveness during the previous study. The value of G was examined by Takeda *et al.* (2014), and they concluded that the most suitable value of G is 0.4 from the relation between the pressure loss and the effect on the tangential velocity of a particle. **Figure 1(c)** shows a plane and side view of the classification section as well as the structure of the introduction section with the blow-up flow.

Figure 2 shows an enlarged view of the classification section consisting of the inner and outer collection boxes. The upper section of the inner box is a circular truncated cone shape, called the slitter, and an important section used for separating particles. The slope length l of the slitter was increased to 23 mm, while the length was 6 mm (Figure 2) in the previous study (Oshitari *et al.*, 2015). The upper surface of the slitter forms the channel that separates the particles into the outer collection box. The radius r_2 is the distance from the center of the cyclone to the middle point of the separation channel based on the width at the tip of the slitter. Additional air was driven through the nozzle with a setting angle (θ_q) of 20° and diameter (d) of 6 mm. The blow-up flows into the outer collection box in the tangential direction after collecting in the manifold.

The fundamental principle of classification is shown in **Figure 3**. The particles are first supplied from the inlet, enter the channel along with the air of velocity u_θ by passing through the throat of the cyclone, and rotate at a velocity v_θ along the wall. Then, the particles are separated according to their size by the tip of the slitter. The larger particles on which the centrifugal force F_c acts with greater intensity relative to the drag force F_d , are collected in the outer box. In contrast, the smaller particles, with the reverse relation, are collected in the inner box. F_c and F_d are induced by the

Fig. 3 Schematic diagram of the principle of separation

Fig. 4 Experimental flow diagram of the apparatus

acceleration a and the relative velocity of the air u_r and the particle velocity v_r , respectively. Hereafter, u and v denote the velocity of air and a particle, respectively, while the subscript, which is added as necessary, denotes the direction or the position. The subscripts θ and r denote tangential and radial directions, respectively.

Figure 4 shows the arrangement of the experimental device. The particles were supplied at a constant rate by the feeder (1), and dispersed using a ring nozzle type disperser (Yamada *et al.*, 1994). The blow-up air from the compressor (8) was driven into the outer collection box at a constant flow rate by the flow meter (9). The filter (4) was located at a point after the ACV to obtain the precise material balance. The particle size distribution was measured using a laser diffraction-type instrument (LA-950 manufactured by Horiba Co., Ltd.). The spherical acrylic particles, which were used for our classification, had a size distribution as shown in **Figure 5**. The experiments were performed under various operating conditions defined by Q and Δq . The particles were classified in 5 min at a feed rate of 2 g/min. Additionally, the weight and size distributions of the particles that had collected in the collection boxes were measured for each experimental condition.

The classification performance was evaluated using the partial separation efficiency $\Delta\eta$, which is defined as follows.

Fig. 5 Particle size distribution of the test powder

$$\Delta\eta = \frac{m_c f_c \Delta D_p}{m_c f_c \Delta D_p + m_F f_F \Delta D_p} \quad (1)$$

The yield (E_c) of the coarse particles collected in the outer collection box is defined as follows.

$$E_c = \frac{m_c}{m_c + m_F} \quad (2)$$

Here, m_c and m_F represent the mass of the particles collected in the outer and inner collection boxes, respectively, and $f_c \Delta D_p$ and $f_F \Delta D_p$ are the mass fractions for the range of diameters from $D_p - \Delta D_p/2$ to $D_p + \Delta D_p/2$ in each of the boxes, respectively.

The following equation of Eq. (3) (Dirgo and Leith, 1985) was used as the most suitable fitting curve for $\Delta\eta$ since we had to calculate $\Delta\eta$ for D_{p25} , D_{p50} , and D_{p75} from a limited number of experimental relationships between $\Delta\eta$ and D_p .

$$\Delta\eta = \frac{1}{1 + \left(\frac{D_{p50}}{D_p} \right)^n} \quad (3)$$

Here, the values of D_{p50} and n were determined by the least squares method such that the result from Eq. (3) matched with the measured value.

2. Results and Discussion

2.1 Effect of blow-up flow rate Δq on D_{p50}

Figures 6, 7, and 8 show the partial separation efficiency curves for different values of the blow-up flow rate Δq under constant main flow rates (Q) of 600 L/min, 800 L/min and 900 L/min respectively. In each figure, several curves were omitted to avoid visual complexity. However, the values of D_{p50} , n , and E_c are listed completely in the tables. The curves (Figure 6) show that D_{p50} changed from 23.7 to 24.3 μm only, although Δq was increased from 0 to 80 L/min. On the other hand, the effectiveness notably improved as Δq increased because of the increase in D_{p25} and the decrease in D_{p75} . An improvement in the effectiveness was also confirmed by the increase in the values of n . With the curves of $\Delta\eta$ under the condition of $Q=800$ L/min (Figure 7) and 900 L/min

Fig. 6 Effect of the blow-up flow rate Δq on classification performance

Fig. 7 Effect of the blow-up flow rate Δq on classification performance

Fig. 8 Effect of the blow-up flow rate Δq on classification performance

(Figure 8), the effect of Δq on D_{p50} and the effectiveness is approximately similar to as observed under the condition of $Q=600$ L/min. Primarily, the effectiveness is improved with an increase of Δq without D_{p50} significantly changing, as will be discussed in detail.

Figure 9 shows the plots of D_{p50} against Δq . In the figure, the values of D_{p50} from our previous study ($l=6$ mm) were also plotted for comparison. The cut-off size D_{p50} in this study ($l=23$ mm) is more or less constant. In contrast, D_{p50} increased linearly in the previous study. Furthermore, other

experiments, with $l=6$ mm, were performed. The curves of $\Delta\eta$ obtained from these experiments were similar to those obtained from experiments with $l=23$ mm. Therefore, it can be concluded that the channels of lengths greater than a certain value result in similar $\Delta\eta$ curves.

The classification model to estimate D_{p50} reflects the classification mechanism. We consider the difference in D_{p50} between this study and the previous study that used a particular classification model, and produced a new model to explain how D_{p50} is determined for the long channel in this study. In our previous study, D_{p50} was estimated using a static model where D_{p50} was the diameter of the particle that was balanced by the centrifugal force and drag force at the CS. In that mathematical model, we used the tangential velocity of the airflow for expressing D_{p50} . However, in this study, we decided to directly use the velocity of the particle instead of that of air. Such a method provides insight into the classification mechanisms, and can explicitly relate the behavior of a particle to D_{p50} . The static model equation, which is obtained from Eq. (A1), based on $dv_r/dt=0$ and $v_r=0$ at the CS in the Appendix, is as follows.

$$D_{p50} = \sqrt{\frac{18\mu r_2}{\rho_p S v_\theta^2 \sin\theta}} (\Delta q + q_0) \quad (4)$$

Here, v_θ is the tangential velocity of the particle at the CS and q_0 can be estimated based on results from our previous study (Oshitari *et al.*, 2015) as $q_0=0.275Q$. This key relationship and those obtained from the previous study are summarized and described in **Table 1**.

Fig. 9 Effect of blow-up flow rate Δq on D_{p50}

Table 1 Relational expression and description to use for the estimation of D_{p50} (Oshitari *et al.*, 2015)

No.	Relational expression	Description
1	$q_0 = 0.275Q$	The flow rate q_0 can be estimated based on results from our previous study as $q_0=0.275Q$. The value of q_0 is the significant air-flow rate that determines D_{p50} at $\Delta q=0$. The air enters into the channel and exits with the same flow rate q_0 . We confirmed that the relational expression was completed with respect to δ ranging from 8 to 11 mm, and G ranging from 0.4 to 1.0.
2	$u_{\theta 1} = 1.03u_t$ $= 1.03 \frac{Q}{GS_{in}}$	The tangential velocity $u_{\theta 1}$ can be estimated from the relationship $u_{\theta 1} = 1.03u_t$, as was obtained from the tangential velocity distribution in the cyclone using the Meissner and Löffler (1978) model that has been reviewed by Cortés and Gil (2007). The estimation needed the friction factor coefficient, which was assumed to be 0.0058 based on the study of Muschelknautz and Trefz (1990). Here, u_t is the air velocity at the cyclone entrance. The tangential velocity $u_{\theta 1}$ is exactly equal to the tangential velocity at the radius of the throat r_1 in the tangential velocity distribution (Hoffmann and Stein, 2008).
3	$u_{\theta 3} = \frac{\Delta q}{S_i}$	The velocity $u_{\theta 3}$ is the flow-out air velocity from the blow-up flow nozzle. The contribution of blow-up flow for the tangential velocity of particles can be estimated based on $u_{\theta 3}$.

marized and described in **Table 1**. If the tangential velocity of the particle for $\Delta q=0$ is designated as $v_{\theta 0}$, then $v_{\theta 0}$ can be expressed using the tangential velocity of the air $u_{\theta 1}$ at the throat of cyclone (Figure 2) as follows.

$$v_{\theta 0} = Ku_{\theta 1} \quad (5)$$

Here, K is the ratio of $v_{\theta 0}$ to $u_{\theta 1}$, and $u_{\theta 1}$ can be estimated from the relationship $u_{\theta 1} = 1.03u_t$ (Table 1).

Meanwhile, we express the contribution of the blow-up flow for the particle tangential velocity v_θ as follows.

$$v_\theta - v_{\theta 0} = Au_{\theta 3} \quad (6)$$

Here, $u_{\theta 3}$ is the flow-out air velocity out of the blow-up flow nozzle and A is the parameter related to the shape of the device. Combining Eq. (5), Eq. (6) and the relational expressions in Table 1 yields the following equation.

$$v_\theta = v_{\theta 0} \left(1 + \alpha \frac{\Delta q}{q_0} \right) \quad (7)$$

$$\alpha = 0.267 \frac{GS_{in}A}{KS_i} \quad (8)$$

Here, α is the parameter related to A and K . The values of K and α were obtained as 0.220 and -0.580 , respectively, by the least squares method such that Eq. (4) matched with previous experimental data on D_{p50} . In Figure 9, the dash-dotted and dash-dot-dotted lines show the estimated D_{p50} , which almost coincides with the experimental D_{p50} . Then, Eq. (7) is reasonably accurate for evaluating the contribution of q_0 and Δq to the particle tangential velocity v_θ . The negative value of α (-0.580) indicates that the increase of the blow-up flow rate had weakened the tangential velocity v_θ while increasing D_{p50} , since the drag acting on the particle had become greater than the centrifugal force.

The classification results provided a small value for K , indicating that the particle had spiraled along the wall with a very small velocity relative to the air velocity. The reason is that the particle would have descended spirally through the boundary layer formed in the vicinity of the wall while colliding with the wall. This fact is supported by several studies that involve the measurement of particle velocity near the wall of a cyclone separator (Li *et al.*, 2009) and air-solid two-phase flow through a bend (Tanaka *et al.*, 1988). It is

also supported by the theoretical analysis of collision (Sommerfeld, 2003). According to the analysis, it is inferred that the value of K is influenced by particle–fluid (air), particle–wall, and particle–particle interaction in the vicinity of the cyclone wall. Furthermore, smaller diameter particles have a higher tangential velocity due to a lower frequency of collision with the wall. The value of K primarily depends on particle diameter, particle density, and particle concentration concerning the particle viewpoint. Here, we adopted the same value of K (0.220) that we had obtained in the above case, while considering the following.

Meanwhile, this study provided results that indicate that D_{p50} hardly changes with the blow-up flow rate. The difference in D_{p50} between the studies means that the particles, which entered the channel, were classified through another classifying mechanism. In order to explain this, a new classification model is necessary. **Figure 10** shows schematically the comparison between the behavior of the particle in the new model (dynamic model) and the previous model (static model). In the static model, the particles are instantaneously classified at the tip of the slit; in the dynamic model, the particles, which enter the channel, turnaround and approach the tip of the slit, where the particles are classified. The equation of the dynamic model is obtained from Eq. (A1) with $dv_r/dt \neq 0$ and $v_r = 0$ at CS. The mathematical model derived from the dynamic model is as follows. The derivation process is referred to in the Appendix.

$$D_{p50} = \sqrt{\frac{18\mu r_2}{\rho_p S v_{\theta}^2 \sin \theta} \left(\Delta q + \frac{q_0}{1 - \exp(-q^*/(q_0 + \Delta q))} \right)} \quad (9)$$

Here, the parameter q^* is obtained from the experimental data D_{p50} for the case where $\Delta q = 0$ in Eq. (9). The parameter q^* was determined by the least squares method; hence, Eq. (9) matched with the measured D_{p50} .

Figure 11 shows the experimental D_{p50} and the fitted line obtained using Eq. (9). The D_{p50} estimated from Eq. (9) coincides with the experimental D_{p50} . Additionally, the value of $q^* = 218$ L/min was obtained from the fitted line. **Figure 11** also shows the previous experimental D_{p50} and the calculated D_{p50} from Eq. (4), which were smaller and more sensitive to the main flow Q than that of this study.

In this study, the value of α was obtained as 0.473 by the least squares method and by allowing the value of D_{p50} from Eq. (9) to match with the experimental D_{p50} . The dashed lines and the solid line in **Figure 9** show the estimated D_{p50} , which coincides with the experimental D_{p50} . In the Appendix, we assumed that $m = 0.5$ holds regardless of the value of Δq in the area of the CS, and $S = 2\pi r_2 \delta m \sin \theta$. The assumption was confirmed on the basis of the level of consistency between the estimated D_{p50} and experimental D_{p50} . The dynamic model accommodates the particle behavior and the classification mechanism for the channel length $l = 23$ mm in this study. The positive value $\alpha = 0.473$ shows that the increase of the channel length led the blow-up flow to contribute highly to the increase in the particle tangential velocity v_{θ} . The cut-off size D_{p50} is decided by the main flow

Fig. 10 Schematic diagram comparing dynamic model with static model of classification

Fig. 11 Effect of main flow rate on 50% cut size D_{p50}

Table 2 Experimental-parameter values

l [mm]	K [—]	α [—]	q^* [L/min]
6	0.220	−0.580	∞
23	0.220	0.473	218

rate at the entrance regardless of the blow-up flow rate since the blow-up flow rate increases both the drag force and centrifugal force acting on the D_{p50} particle.

We conclude that t_c/τ is proportional to $1/(q_0 + \Delta q)$, where t_c/τ is the dimensionless residence time turnaround point to the tip of the slit in the channel in the Appendix. This fact was practically confirmed from the linearity of the relationship of t_c/τ using Eq. (A5) and the values of $1/(q_0 + \Delta q)$. The experimental values of the parameters are listed in **Table 2**. Here, Eq. (9) is applicable to the static case since the dynamic model is reduced to Eq. (4) of the static model with $q^* = \infty$.

2.2 Effect of blow-up flow rate Δq on effectiveness

The effectiveness of classification can be evaluated using several methods depending on the requirements. We adopted $\kappa = D_{p25}/D_{p75}$, also called the sharpness index, which is generally used for evaluating the classification as well as the slope of $\Delta \eta$ curve at D_{p50} . **Figure 12** shows each relationship of Δq with κ for $l = 23$ mm and 6 mm. The value of κ for $l = 23$ mm ranged from 0.75 to 0.92 for an increas-

Fig. 12 Effect of blow-up flow rate Δq on sharpness of classification

ing Δq . The curves for $Q=600$ L/min (Figure 6) show that initially, the increase in Δq removes the fine particles from the channel by virtue of the drag force, and subsequently draws the coarse particles out by the centrifugal force into the outer collection box. Therefore, the value of κ gradually increases because D_{p25} increases to within the range of the lower Δq , and then, κ sharply increases in the vicinity of $\Delta q=40$ L/min since D_{p75} decreases. For $Q=800$ (Figure 7) and $Q=900$ L/min (Figure 8), the measurable fine particles have already been removed even when $\Delta q=0$, and the value of κ increases mainly due to the decrease in D_{p75} .

These characteristics show that the classification effectiveness is improved while holding the particle diameter relatively constant. The average D_{p50} and the maximum deviation from the average with $l=23$ mm, and the value of D_{p50} with $l=6$ mm are denoted in Figure 12 to enable the comparison of the κ values. The value of κ ranged from 21.9 to $24.3 \mu\text{m}$ for the average D_{p50} is larger than that for the case where $l=6$ mm when Δq is above approximately 60 L/min.

In the previous channel, for $l=6$ mm, the increase in κ was accompanied by an increase in D_{p50} with an increasing Δq . This characteristic shows that the classification effectiveness was remarkably affected by the particle diameter. For $l=6$ mm, the value of κ did not reach the same level as it did for the case of $l=23$ mm until the cut-off size D_{p50} was approximately $27 \mu\text{m}$. This occurred since Δq did not contribute to increasing the centrifugal force acting on the particles, only to eliminate them from the channel by the drag force in ascending order based on the particle diameter.

Several studies have shown that the values of n are in the range of 2–4 (Hoffmann and Stein, 2008) for conventional cyclone separators, and 6.4 (Dirgo and Leith, 1985) for the most efficient separator. The value $\kappa=0.71$ is obtained using Eq. (3), where $n=6.4$, and $\Delta\eta=0.25$ for D_{p25} and $\Delta\eta=0.75$ for D_{p75} . Considering the value $\kappa=0.71$, the ACV shows a considerably higher effectiveness than other cyclone separators.

Therefore, we identify the suitable operation condition using the dimensionless slope of $\Delta\eta$ as the appropriate effectiveness index. The slope is easily obtained as the dimensionless value $n/4$ for the particular case of D_{p50} by dif-

Fig. 13 Relationship between operating condition and classification effectiveness

ferentiating Eq. (3) with respect to D_p/D_{p50} and substituting $D_p/D_{p50}=1$ into the differentiated equation. The relationship between the effectiveness index and the operation condition $\Delta q/Q$ is shown in Figure 13. This relationship is more straightforward than the relationship shown in Figure 12. The effectiveness index for the case of $l=23$ mm sharply increased from approximately $\Delta q/Q=0.05$ to $\Delta q/Q=0.1$, indicating that the maximum effectiveness is accomplished when $\Delta q/Q$ is above approximately 0.1.

While the increase in the Q value resulted in a decrease in D_{p50} , it also increased the effectiveness. In contrast, the effectiveness index for the case of $l=6$ mm linearly increased with an increasing $\Delta q/Q$. However, there is a natural limit since all particles are removed from the channel when $\Delta q/Q$ is too large. This operational condition should be determined from the relationship between the removing efficiency and the yield of a specified target-particle diameter. This was cited in the previous paper (Oshitari *et al.*, 2015).

As shown above, D_{p50} depends on the centrifugal and drag forces acting on particles. The ACV allowed an increase in Δq to strengthen both the forces at the CS, thereby improving the classification effectiveness while holding D_{p50} approximately constant. The ACV shows desirable characteristics, where particles with specified target-particle diameters are effectively classified without a decrease in the yield.

Conclusions

By classifying the acrylic fine particles with the developed cyclone type classifier (ACV), the following knowledge was obtained.

1. The cut-off size D_{p50} is best accommodated by the dynamic model where the D_{p50} particle turns around in the channel. Additionally, the D_{p50} is determined in the non-equilibrium with respect to the centrifugal force and drag force at the CS.
2. The cut-off size D_{p50} closely depends on the main flow rate Q entering the entrance regardless of the blow-up flow rate Δq , since the increase in Δq results in a simultaneous increase in the drag force and centrifugal force

acting on the particle.

3. The classification effectiveness $\kappa = D_{p25}/D_{p75}$ was significantly improved by the increase in the blow-up flow rate. This increase in the blow-up flow rate resulted in an increasing D_{p25} and decreasing D_{p75} . Consequently, the classifier was able to classify particles by $\kappa = 0.75\text{--}0.92$. These particles would be collected, if conventional cyclones were used.
4. The relationship between the dimensionless slope at D_{p50} and $\Delta q/Q$ permitted a clear evaluation indicating that the maximum classification effectiveness was accomplished when $\Delta q/Q$ is above approximately 0.1.

Appendix

The motion of a particle in the channel was modeled by deriving the equation for estimating cut-off size D_{p50} in terms of the air flow rate and the particle velocity as shown in **Figures A1(a)** and **A1(b)**, respectively. The CS, which determines D_{p50} , was perpendicularly set to the slit at the entrance of the channel. The radius of the CS is represented as r_2 .

With respect to the flow of the air as shown in Figure A1(a), the air flows upward along the vortex slit with a velocity of $u_r + \Delta u_r$. This is based on the situation where the air moves through the throat of the cyclone with a flow rate of q_0 , and then turns around with the velocity u_r while the blow-up air flow rate Δq contributes to the velocity Δu_r in the channel. As for the motion of the particle in Figure A1(b), the particle accompanying the air through the throat enters the channel and also turns around with the velocity v_r , which is assumed to be equal to the air velocity u_r . The particle then moves upwards along the vortex slit with the air at a relative velocity $U' = v_r - (u_r + \Delta u_r)$.

Meanwhile, the particle velocity v_r decreases while moving along the slit depending on the centrifugal acceleration $a = (v_\theta^2/r_2) \sin \theta$, which acts in reverse to the moving direction due to the particle rotation at velocity v_θ around the center of the cyclone. Here, the centrifugal acceleration a and the rotating velocity v_θ are assumed to be constant and the rotating radius is represented by the radius of the CS r_2 . For the conditions stated, D_{p50} is considered as the diameter of the particle where the velocity v_r becomes zero at the CS.

A mathematical model for estimating D_{p50} was derived

Fig. A1 Schematic diagram indicating relative velocity with air and particle

based on the equation of the particle motion. The equation, which has a one-dimensional coordinate taken in the direction along the slit, is as follows.

$$\left(\frac{\pi D_p^3}{6} \right) \rho_p \frac{dU'}{dt} = -3\pi D_p \mu U' - \left(\frac{\pi D_p^3}{6} \right) (\rho_p - \rho_{\text{air}}) a \quad (\text{A1})$$

Here, U' is $v_r - (u_r + \Delta u_r)$, and the particle velocity v_r is the only variable to depend on time. The first item on the right side is the drag force due to the airflow, and the second item is the body force induced by the centrifugal acceleration a . The application of Stokes' law of resistance provides the relationship $C_D = 24/Re_p$ where Re_p is defined as $Re = \rho U' D_p / \mu$.

These relationships were used to derive Eq. (A1). The true density of air, ρ_{air} , is neglected with respect to ρ_p . Rearranging Eq. (A1) yields the following equation.

$$\frac{dU'}{dt} = -\frac{1}{\tau} U' + a \quad (\text{A2})$$

Here, τ , called the relaxation time of the particle, is defined as follows.

$$\tau \equiv \frac{D_p^3 \rho_p}{18\mu} \quad (\text{A3})$$

Integrating Eq. (A2) for $t=0$ at the turnaround point, where the relative velocity U' is Δu since $v_r = u_r$, provides the following equation.

$$(u_r + \Delta u_r) - v_r = \tau a \left(1 - \exp\left(-\frac{t}{\tau}\right) \right) + \Delta u_r \exp\left(-\frac{t}{\tau}\right) \quad (\text{A4})$$

As described above, D_{p50} is the particle diameter when $v_r = 0$ at the CS. In Eq. (A4), replacing τ by Eq. (A3), D_p by D_{p50} , v_r by zero, time t by time t_e , (i.e., the time necessary for a particle to move from the turnaround point to the CS), a by $v_\theta^2 \sin \theta / r_2$, u_r by q_0/S , and Δu_r by $\Delta q/S$, and then rearranging Eq. (A4) with D_{p50} yields the following equation.

$$D_{p50} = \sqrt{\frac{18\mu r_2}{\rho_p S v_\theta^2 \sin \theta} \left(\Delta q + \frac{q_0}{1 - \exp(-t_e/\tau)} \right)} \quad (\text{A5})$$

Here, S is the area of the CS, which can be calculated as $2\pi r_2 \delta m \sin \theta$ where $m = 0.5$ (half of the cross section of the channel). When the blow-up flow rate $\Delta q = 0$, the rate of outflow from the channel is equal to the flow rate q_0 . If the flow entering the channel does not significantly lose its kinetic energy in the channel, $m = 0.5$ is obtained. Additionally, if the kinetic energy is not altered by the blow-up flow, m remains at 0.5. The assumptions are to be confirmed on the basis of the level of consistency between the estimated D_{p50} and experimental D_{p50} . The flow rate q_0 and Δq are transformed to the velocity u_r and Δu_r , respectively, within the area S .

We concluded that t_e/τ is proportional to $1/(q_0 + \Delta q)$, where t_e/τ is the dimensionless residence time turnaround point to the tip of the slit in the channel. Ultimately, we obtained the following equation.

$$D_{p50} = \sqrt{\frac{18\mu r_2}{\rho_p S v_{\theta}^2 \sin \theta} \left(\Delta q + \frac{q_0}{1 - \exp(-q^*/(q_0 + \Delta q))} \right)} \quad (\text{A6})$$

Here, q^* is assumed to be a constant parameter within our experimental conditions and with dimensions of flow rate. The parameter q^* is the value of $q_0 + \Delta q$ corresponding to $t_e/\tau = 1$. Additionally, the value of $1 - \exp(-q^*/(q_0 + \Delta q))$ indicates the attainment level towards the equilibrium point, where the drag force is equal to the centrifugal force. The parameter q^* is obtained from the experimental data D_{p50} for the case where $\Delta q = 0$ in Eq. (A6).

Nomenclature

A	= constant parameter on shape of device	[—]
a	= centrifugal acceleration	[m/s ²]
C_D	= drag coefficient in Stokes' law	[—]
d	= inside diameter of the blow-up nozzle	[m]
D_p	= particle diameter	[m]
D_{p25}	= 25% cut-off size of the partial separation efficiency curve	[m]
D_{p50}	= 50% cut-off size of the partial separation efficiency curve	[m]
D_{p75}	= 75% cut-off size of the partial separation efficiency curve	[m]
E_c	= yield of coarse particles	[—]
F_C	= centrifugal force induced by vortex flow	[N]
F_D	= drag force induced by main flow and blow-up flow	[N]
$f_c(D_p)$	= frequency of coarse particle size distribution	[m ⁻¹]
$f_f(D_p)$	= frequency of fine particle size distribution	[m ⁻¹]
K	= ratio of $v_{\theta 0}$ to $u_{\theta 1}$	[—]
l	= length of slit	[m]
M	= ratio of control surface (CS) area to cross section of channel	[—]
m_b, m_c	= mass of total particles within the inside and outside collection boxes	[kg]
N	= number of blow-up nozzles	[—]
n	= exponent in Eq. (3)	[—]
Q	= rate of inlet air flow into cyclone (primary flow rate)	[L/min] or [m ³ /s]
q_0	= flow rate of air into channel through throat of cyclone	[L/min] or [m ³ /s]
q^*	= constant parameter relative to $t_e/\tau = 1$ in Eqs. (9) and (A6)	[m ³ /s]
r	= radius of tip of slit from center of cyclone	[m]
r_1	= radius of throat of cyclone	[m]
r_2	= representative radius of CS from center of cyclone	[m]
r_3	= radius of outside collection box	[m]
S	= area of CS	[m ²]
t_e	= residence time from turnaround point to CS in Eq. (A5)	[s]
u_i	= velocity within blow-up nozzle	[m/s]
u_{in}	= velocity of air flow at cyclone inlet	[m/s]
u_r	= velocity of air flow along channel	[m/s]
u_t	= velocity of converged air flow by inlet guide vane	[m/s]
u_{θ}	= tangential velocity of air	[m/s]
$u_{\theta 1}$	= tangential velocity of air in throat of cyclone	[m/s]
$u_{\theta 2}$	= tangential velocity of $q_0 + \Delta q$	[m/s]
$u_{\theta 3}$	= tangential velocity of blow-up flow rate Δq	[m/s]
v_r	= velocity of particle along channel	[m/s]
v_{θ}	= tangential velocity of particle at CS	[m/s]
$v_{\theta 0}$	= tangential velocity of particle with $\Delta q = 0$ at CS	[m/s]
α	= constant parameter on shape of device and property	[—]

	of particle	[—]
Δq	= blow-up flow rate of air	[L/min] or [m ³ /s]
Δu_r	= velocity of air induced by blow-up flow along channel	[m/s]
$\Delta \eta$	= partial separation efficiency	[—]
δ	= vertical width of channel	[m]
θ	= inclination angle of slit	[degree]
θ_q	= inclination angle of blow-up nozzle	[degree]
κ	= classification sharpness index ($= D_{p25}/D_{p75}$)	[—]
μ	= viscosity of air	[Pa·s]
ρ_{air}	= true density of air	[kg/m ³]
ρ_p	= true density of particle	[kg/m ³]
τ	= relaxation time of particle	[—]

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