# Controlling the particle cut size of a dry cyclone using acetone

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## Abstract

In this study, we investigated the interaction between particles and the wall in the presence of mist to improve the particle classification performance of a dry cyclone. The interaction between a silica particle and a mica surface in the presence of a flowing acetone mist was measured by performing atomic force microscopy (AFM), which showed that an attractive force was generated and became stronger as time passed while acetone was mist supplied to the system, probably because of static electricity. In a dry cyclone system, this attractive force could enhance the classification performance. In particular, when acetone mist was supplied into the cyclone from the upper part of the dust box at higher flow rates, the classification performance was enhanced. Because acetone is highly volatile and has a low viscosity, the classification performance was improved by the evaporated acetone even when a cyclone with a dust box filled with acetone was used instead of a nozzle supplying the mist. In this case, the ratio of the mass of the particles collected by the upper part of the cyclone to the total mass of the feed powder was increased, probably because of the attractive force between the silica particles and the wall of the cyclone. Moreover, the cut size of the dry cyclone could be controlled by changing the amount of acetone in the dust box of the cyclone.

***Keywords*****:** Classification, Cyclone, Cut size, Acetone, AFM

## 1. Introduction

The improvement of particle classification techniques has been indispensable for industrial applications, because the performance of various products can be enhanced through control of the size distribution of the material particles. One such classification device is the dry cyclone, for which various attached parts have been developed using experiments and numerical calculations to improve its classification performance. These attachments include, for example, a cylindrical part (Yoshida et al. 2009) and an apex cone (Yoshida et al. 2010). In addition, in a cyclone scrubber, injection of mist generated by spray nozzles is effective for particle separation (Yang and Yoshida. 2004). The present study focuses on the role of the mist in the classification apparatus. In particular, we investigated the interaction between particles and the inside wall of a dry cyclone in the presence of mist and the role of the mist in improving the particle classification performance of a dry cyclone.

## 2. Experimental

Silica powder (Denka Fused Silica, Denki Kagaku Kogyo, Co., Ltd.) with a mass median diameter of 2.01 μm was used as the test powder in the present study. Acetone (Wako Pure Chemical Industries Co., Ltd.) and ethanol (Wako Pure Chemical Industries Co., Ltd.) were used as typical organic solvents to generate the mist.

The particle size distributions of the fine and coarse classified particles were measured using a particle size distribution analyzer (LA-950, Horiba Co., Ltd.) according to its standard operation procedure. The size distribution of the original silica test powder for the classification experiments was measured using the same method and is shown (Figure 1).

An atomic force microscope (AFM) (Nanoscope IIIa, Digital Instruments) was used to measure the force curves of a particle in the mist. The interaction forces between a particle and the mica surface were measured using a contact-mode procedure, as shown (Figure 2). The atmospheres were prepared using an AFM liquid cell and an ultrasonic nebulizer (NE-U17, Omron) with acetone mist supplied into the liquid cell. The tested particle had a diameter of ca. 6 μm and was glued to the top of the AFM probe tip with a nominal spring constant of 9 N/m (Weisenhorn et al. 1989; Ducker et al. 1991; Butt et al. 2005). To measure the interactions, the approaching speed of the probe was fixed at 4000 nm/s. All AFM measurements were carried out at room temperature, i.e., 20 ± 2 °C.

Classification experiments were carried out using the dry cyclone system shown (Figure 3). The total flow rate was fixed at 40 L/min using a flow meter and a blower. The linear velocity in the inlet of the cyclone was set at 8.89 m/s, which means that the velocity in the present study is much slower than that typically used in a cyclone (Yoshida et al. 1991, 2009, 2010, 2005). This led to a longer residence time of the particles in the cyclone, which allowed us to clarify the effect of the mist on the classification performance of the cyclone. The original powders were supplied into the cyclone from a feeder with a mass flow rate of 0.7 g/min, and the classification apparatus was operated for 10 minutes. All classification experiments were carried out at room temperature, i.e., 20 ± 2 °C.

The finer particles were collected from the filter, and the larger (coarser) particles were collected from the dust box of the cyclone. Then, the mass and distributions of the fine and coarse particles were measured. From these distributions, the partial separation efficiency, $\Delta\eta$, which is defined by Eq. (1), was used to evaluate the particle classification performance of the cyclone:

$$\Delta\eta = \frac{m_c f_c(D_p) \Delta D_p}{m_f f_f(D_p) \Delta D_p + m_c f_c(D_p) \Delta D_p} \qquad (1)$$

In the above equation, $m_c$ and $m_f$ represent the mass of the coarse silica powder and the fine powder, and $f_c$ and $f_f$ represent the size distributions of the coarse silica powder and the fine powder, respectively.

## 3. Results and Discussion

### *3.1 Interactions between silica particle and mica surface in the mist*

The interactions between the silica particles and the mica surface were measured in the AFM liquid cell with acetone mist flowing at 0.276 g/min from an ultrasonic nebulizer. The time dependence of the approaching force curves between the silica particle and the mica plate under an acetone mist is shown (Figure 4a). It is clear that the attractive force between the silica particle and the mica surface became stronger as $t_r$ increased. After $t_r$ = 10 min, no change in the force curve was found. Although the mechanism that generated the attractive force was not verified in the present study, the force curves were very similar to those that originate from static electricity (Kanda et al. 2002). Hence, the attractive force might be attributed to the static electricity generated by the supplied acetone mist. This attractive force generated in the presence of the acetone mist might have interesting applications, especially because this kind of force can be used in a dry cyclone system to enhance its classification performance. This kind of force curve was also observed between a silica particle and a silica particle with a diameter of 100 µm (Figure 4b). In addition, the similar attractive force was generated using either ethanol or water mist.

### *3.2 Effect of the mist on the classification performance of a dry-cyclone*

The inside wall of the dry cyclone was covered with silica particles during its operation, because the particles were subjected to centrifugal forces and collected by the wall, which could then be approximately regarded as a silica surface. Thus, it is possible that an attractive force between the flowing particles and the inside wall of the cyclone will be generated in the presence of the acetone mist from the nebulizer. Hence, an acetone mist was supplied into the cyclone from the upper part of the dust box by a pump. The effect of the mass flow rate of the acetone mist $q$ on the partial separation efficiency curve of the cyclone at a total flow rate of $Q$ = 40 L/min is shown (Figure 5). It was found that the cut size of the cyclone became smaller with increasing mass flow rate $q$, probably because the attractive force between the particles and the inside wall of the cyclone increased the amount of the particles collected by the cyclone in the presence of the acetone mist.

### *3.3 Control of the cut size of the dry-cyclone with its dust box filled with the organic solvents*

In the above section, the effect of the acetone mist generated by a pump on the classification performance was clarified. However, it would be preferable to construct a classification system that can generate mist without a pump, so in the next experiments the dust box was filled with the organic solvents acetone and ethanol, and the original powder was supplied into the cyclone. Here, the ratio of the height of the organic solvent liquid level to the height of the dust box is defined as $Z$. The partial separation efficiency curves obtained using the dry cyclone at $Z$ = 0.25 is shown (Figure 6). The total amounts of ethanol and acetone that evaporated during each operation were 0.24 g and 1.69 g, respectively, suggesting that mist is indeed generated in the cyclone. When ethanol was used, however, there was no clear difference in classification performance from the standard case in Figure 6. If mist is generated when ethanol is used in the cyclone, a difference in classification performance would be expected (Yang and Yoshida. 2004). Therefore, mist was likely not generated in the cyclone when ethanol was used. On the other hand, the use of acetone improved the classification performance. Although the density and surface tension of acetone are almost the same as those of ethanol, the viscosity of acetone is much smaller, as shown in Table 1. As the viscosity of a liquid becomes lower, it becomes easier for a smaller droplet to be generated as the liquid phase is broken up under the shear flow (Ferguson et al. 1991; Nukiyama et al. 1939). Thus, a mist with smaller droplets would be more easily generated and vaporized for acetone at a higher saturated pressure. Such a mist would enable easier generation of the attractive force between the particles and the inside wall of the cyclone, as observed in our AFM measurements, which would be more useful for improving the classification performance.

To further investigate the causes of the enhancement of the classification performance with acetone at $Z = 0.25$, the mass of the three powders collected by the different parts of the dry cyclone, as shown in Fig. 3b, were measured by an electric balance. Then, the ratios of the masses of the three powders to the total mass of the feeding powder were calculated, as listed in Table 2. It was found that the collection ratio of the upper part of the cyclone was dramatically different before and after acetone was added to the cyclone. Thus, it is clear that this difference is an important factor in the enhancement of the classification performance. The classification at the upper part of the cyclone is not influenced easily by the upward flow in the tapered part of the cyclone, which usually scatters the coarse particles collected by the wall of the cyclone and allows them to mix with fine particles, which is known as the re-entrainment phenomenon (Yoshida et al.

2010). Thus, it was found that classification performance was enhanced as the ratio in the upper part was increased.

An increase in $Z$ increased the average rate of acetone evaporation from the dust box, because the liquid level was so high that the thickness of the fluid film between the air and the acetone liquid was reduced. The particle size from the partial separation efficiency curve at $\Delta\eta = 0.5$, the 50% cut size, became smaller as the amount of acetone evaporation increased (as $Z$ was changed) for 10 minutes of operation of the cyclone, as shown (Figure 7). Thus, interestingly, the cut size can be controlled by changing only $Z$ at $Q = 40$ L/min, which could be a simple classification technique, as the linear velocity at the inlet of the cyclone was extremely slow. In addition, this attractive force will also appear between the silica particles in the cyclone, which might lead to particle coagulation. Coagulated particles would be collected easily by the wall of the cyclone because of the centrifugal force, which would also contribute to the increase in the collection ratio of the cyclone and make the cut size smaller.

## 4. Conclusions

It was found that the interactions between silica particles and the mica surface became more attractive as time passed when acetone mist was generated by a nebulizer and supplied into the system, probably because of static electricity. Thus, a dry cyclone system taking advantage of this attractive force was used to enhance the classification performance. When the acetone mist was supplied into the cyclone from the upper part of the dust box, increases in the acetone mist flow improved the classification performance. Because acetone is easily vaporized and has a low viscosity, the classification performance was enhanced even when the dust box was just filled with acetone, without a pump supplying the mist. With this system, the ratio of the mass of the powder collected by the upper part of the cyclone to the total mass of the feeding powder was enhanced by the attractive force that appeared between the silica particles and the wall of the cyclone. Moreover, the cut size of the dry cyclone could be controlled by changing the amount of acetone in the dust box of the cyclone.

## Acknowledgement

This study was financially supported in part by the Hosokawa Powder Technology Foundation and by Grants-in-Aid for Young Scientists (B) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 23760721).

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## Nomenclature

| | |
|---|---|
| $D_p$ | particle diameter (μm) |
| $f_c(D_p)$, $f_f(D_p)$ | particle size distributions of the classified coarse silica and fine particles, respectively (%) |
| $h$ | separation distance between the silica particle on top of the probe tip and the mica plate (nm) |
| $m_c$, $m_f$ | masses of the classified coarse and fine particles, respectively (g) |
| $P_{sat}$ | saturated pressure (Pa) |
| $Q$ | total flow rate ($m^3$ $s^{-1}$) |
| $q$ | mass flow rate of the acetone mist supplied to the dust box of the cyclone (g $s^{-1}$) |
| $t_r$ | time passed since acetone was supplied into the AFM liquid cell (s) |
| $Z$ | ratio of the height of the organic solvent liquid level to the height of the dust box (-) |
| $\Delta D_p$ | small difference in particle diameter (μm) |
| $\Delta \eta$ | partial separation efficiency (-) |

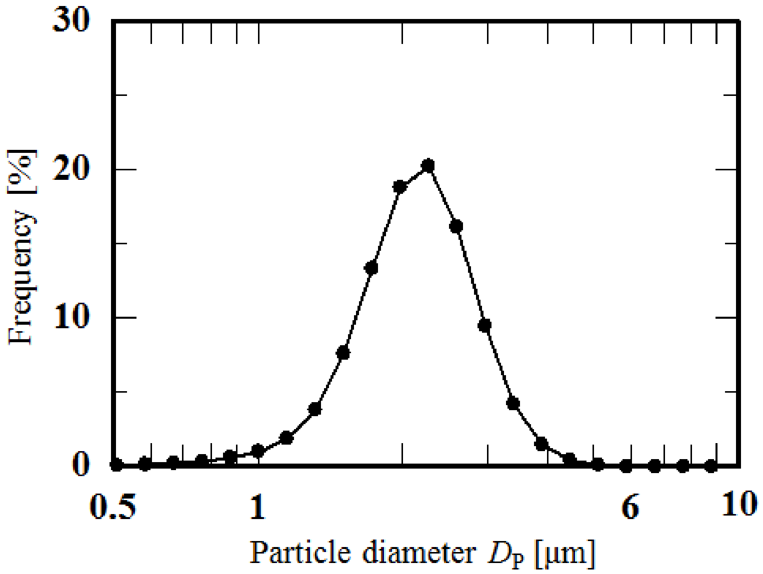

**Figure 1** Particle size distribution of the original silica powder.

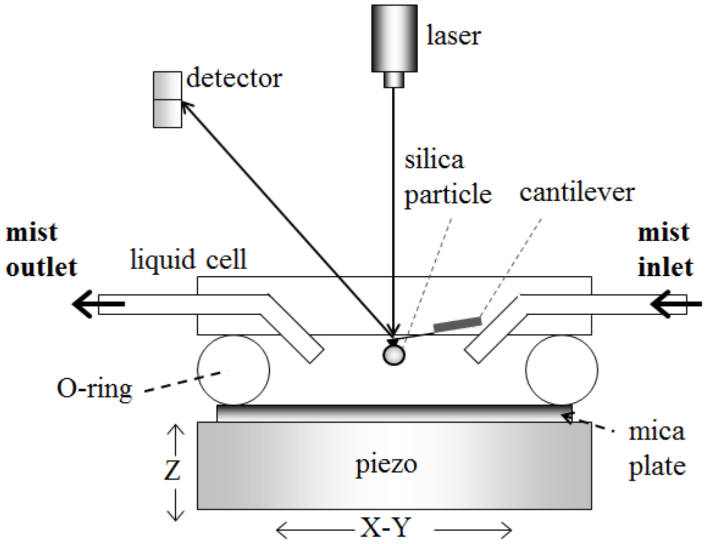

**Figure 2** AFM measurement of interaction between a silica particle and a mica surface in the mist.

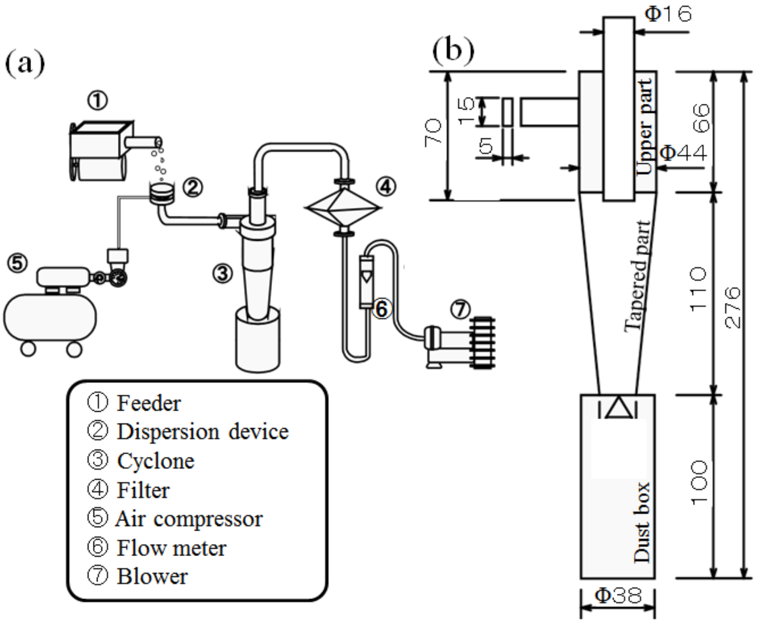

**Figure 3** Cyclone system for classification: (a) overview and (b) details of the cyclone.

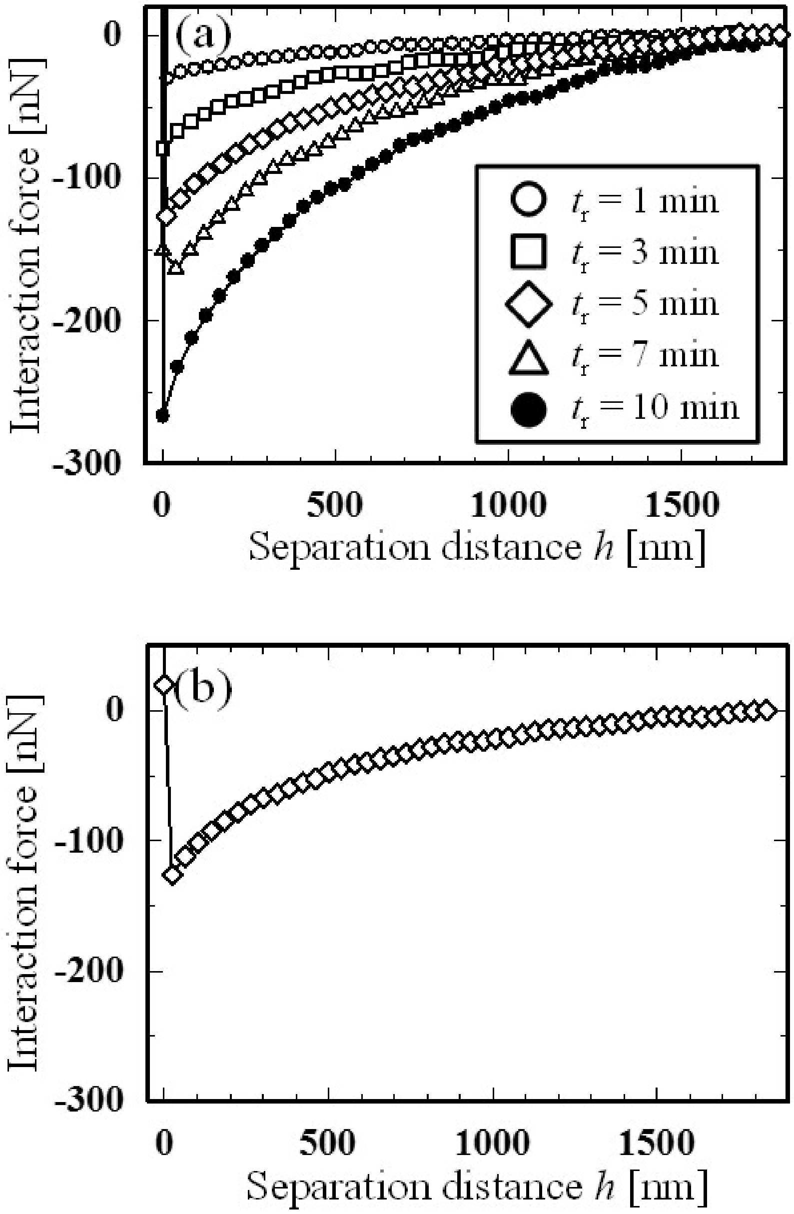

**Figure 4** AFM measurement of force curve. (a) Time dependence of approaching force curves between a silica particle and a mica surface and (b) force curve between a silica particle and a silica particle with a diameter of 100 μm with acetone mist supplied at 0.276 g/min

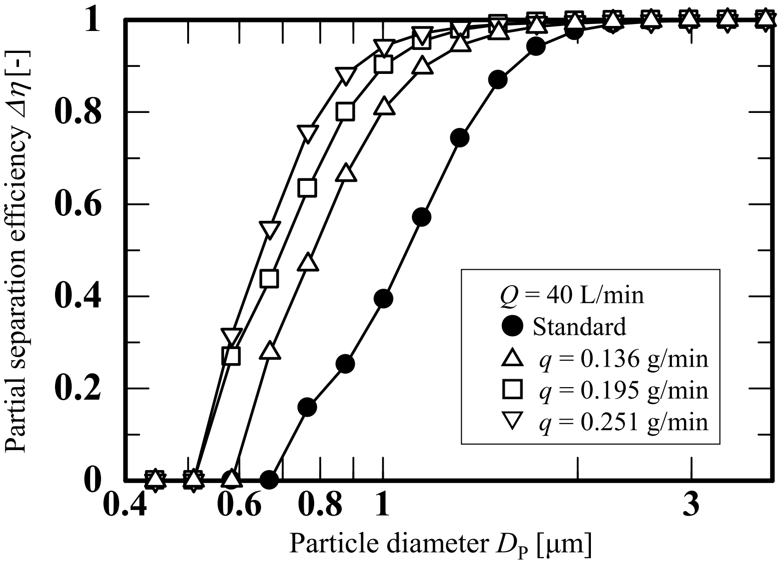

**Figure 5** Effect of the acetone mist's mass flow rate on the classification performance of the dry cyclone, as shown by partial separation efficiency curves. "Standard" means the cyclone was operated without acetone mist.

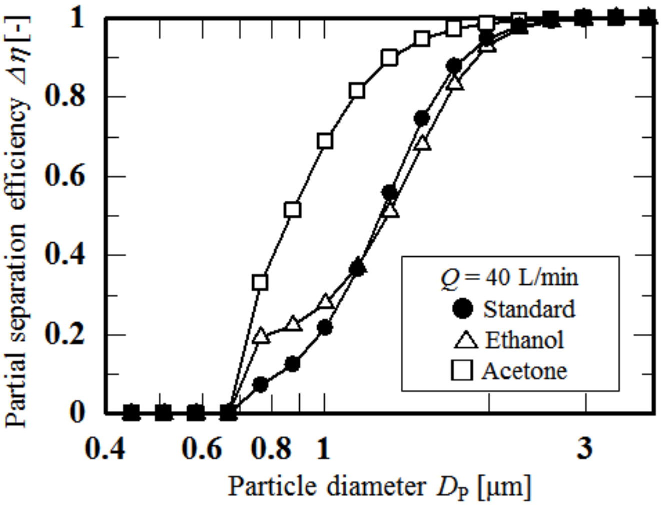

**Figure 6** Partial separation efficiency curves of a dry cyclone whose dust box was filled with organic solvents at $Z = 0.25$. “Standard” means the cyclone was operated without organic solvent.

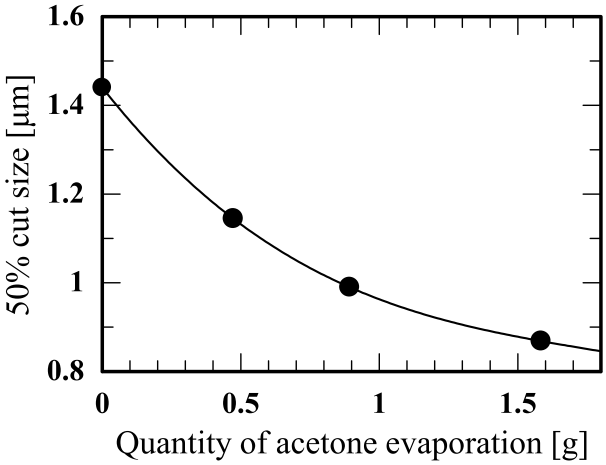

**Figure 7** Effect of quantity of acetone evaporation from the dust box of the cyclone on the 50% cut size for 10 minutes of operation at *Q* = 40 L/min.