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Particle Collection and Concentration for Cyclone Concentrators

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Four cyclone concentrators were designed and fabricated to compare their particle separation and concentration behavior, such as the major, minor, outlet, and wall deposition fractions. Two of the cyclone concentrators were the conventional type, with the minor flow tube connected to the particle outlet at the bottom of the cyclone. The others were modified cyclone concentrators with a gap between the particle outlet at the bottom of the cyclone and the minor flow tube. The modified cyclone concentrators had different particle outlet and minor tube diameters, with variable minor tube heights.

The particle number fraction of the minor flow for the conventional cyclone concentrator increased and had wider U-shaped curves, in the large particle size range, as the particle outlet diameter increased. In addition, the gap between the particle outlet and minor flow tube of modified cyclone concentrator had an adverse effect on the particle concentration ability of the cyclone concentrator with a small minor tube diameter, in that the wall deposition and particle fraction of the minor flow were increased and decreased, respectively. However, the modified cyclone concentrator with a large minor flow was a better particle concentrator because the gap offered a space for the particles collected on the cyclone wall to gather, preventing the particles from going along the minor flow, especially with high particle concentrations in the inflow.

INTRODUCTION

Cyclones are widely used in the field of air pollution for ambient and source sampling. They are also used for industrial particulate control because of their simplicity of design, low maintenance costs, and adaptability to a wide range of operating conditions. However, cyclones are incapable of collecting fine particles because of their reliance on inertial forces to separate particles from the gas stream. As a result, in industrial particle control applications, they may well serve as a pre-cleaner for the removal of the coarser particles of a heavily loaded stream, which will finally be cleaned by other types of equipment. In addition, in application for ambient and source sampling, cyclones are used as samplers, with large cutoff diameters, due to the flat collection efficiency curve for small particles. Thus, much interest has focused on the high collection efficiencies and sharp collection efficiency curves of cyclones in the small particle size range (DeOtte 1990; Dietz 1982; Dirgo and Leith 1985; Iozia and Leith 1989; Kim and Lee 1990; Moore and McFarland 1996; Smith et al. 1983; Sumner et al. 1987; Zhu et al. 2001).

In a cyclone, particle-laden air is introduced radially into the upper portion of a cylinder and accelerated outward to the cylinder wall, where particles either stick and are retained or swirled down to a collection port at the bottom of the cylinder. The overall gas motion in the cyclone consists of an inner vortex moving toward the cyclone exit, containing the smaller-sized particles, and an outer vortex moving in the opposite direction, carrying the larger-sized particles. Thus, cyclones have been used only for collecting large particles from a gas flow, by centrifugal force, and removing them through the dust hopper. Recently, some studies (Galperin and Shapiro 1999; Kim et al. 2002) have indicated that cyclones could possibly be used as particle concentrators, which were referred to as cyclone concentrators by Kim and colleagues (2002). Although the entire gas is carried away from conventional cyclones through the vortex finder, virtual cyclones have a small portion of the gas flow (minor flow) drawn out through the bottom of the cyclone, which concentrates the particles, as shown in Figure 1. In a cyclone concentrator, the particles collected on the cyclone wall either are retained at the wall or go down to the bottom of the cyclone, as in conventional cyclones, and a small portion of the gas flow (minor

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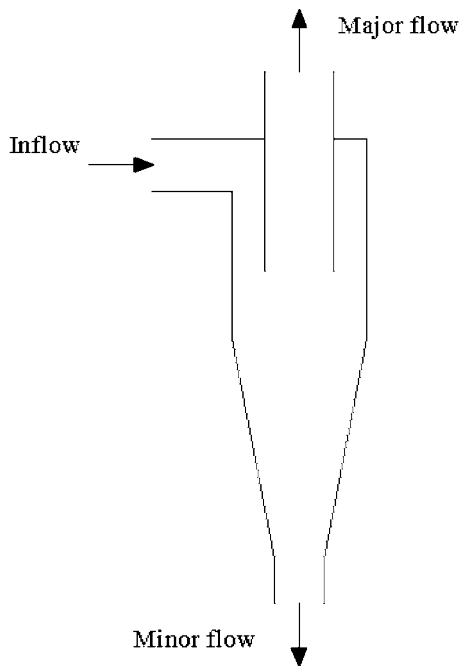


Figure 1. Conventional cyclone concentrator.

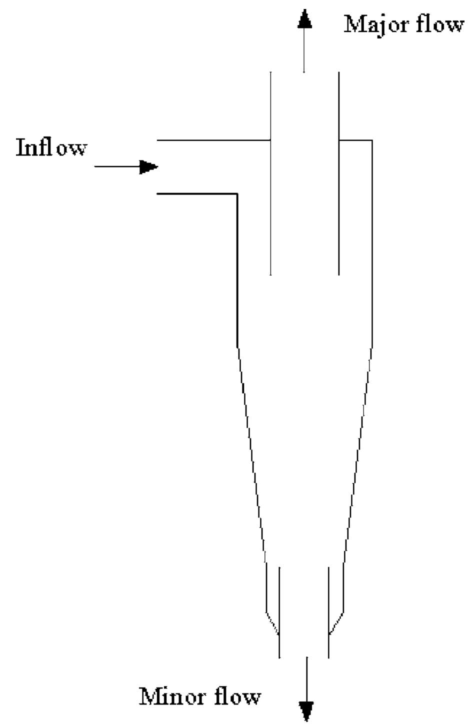


Figure 2. Modified cyclone concentrator.

flow) containing particles is pumped out at the bottom, where the particle concentration is much higher than that at the inlet. The large portion of the gas flow (major flow) that remains contains the small particles, which is carried away from the cyclone through the vortex finder.

The virtual impactor is one of the most commonly used concentrators, with typically S-shaped concentration factor curves, as it can concentrate particles larger than the 50% cut-off diameter. However, the concentration factor curves of cyclone concentrators show reversed U-shaped curves with a maximum in the region of the 50% cutoff diameter (Kim et al. 2002) because most particles larger than the 50% cutoff diameter are collected and retained at the cyclone wall, with small particles following the major flow without being collecting. Galperin and Shapiro (1999) tested two multicyclones, operating as concentrators, by varying the ratios of the minor/major flow volumes. They found that the collection efficiencies of the tested cyclones were higher, and the 50% cut-off diameters lower, than that of conventional cyclones. Kim et al. (2002) also tested two cyclone concentrators with different dimensions and described their higher major flow efficiencies. In addition, they showed that the concentration factor had reversed U-shaped curves, as mentioned above, and that they had the greatest potential for concentrating particles.

This article evaluates the performance of cyclone concentrators, by varying the total flow rates and cyclone bottom diameters (particle exit diameter). The cyclone concentrators used in this study have a gap between the particle exit tube, at their bottoms, and the minor flow tube, as shown in Figure 2, which is expected to provide for different particle collection patterns. In addition, the cyclone concentrator performance and particle concentration factor are evaluated at different minor flow tube heights, to examine the effects of the minor flow tube on the particle concentration factor and the major flow efficiency.

EXPERIMENT

Design and Configuration of the Cyclone Concentrators

Figures 3 and 4 and Table 1 show the dimensions and geometries of the cyclone concentrators used in this study. The cyclone in Figure 3a has the same dimensions as those used by Kim et al. (2002), and the cyclone in Figure 3b has a larger minor flow tube diameter than that in Figure 3a. The modified cyclone concentrators, with a gap between the bottom of the cyclone and the minor flow tube, are shown in Figure 4. The bottom diameters of the cyclones in Figures 4a and 4b are 11 and 20 mm, which are the same as those of the cyclones in Figures 3a and 3b, respectively, but inner diameters of the minor tube are 4 and 13 mm. The distances between the bottom of the cyclone and the minor tube are also 2.5 and 3 mm, respectively; the minor tubes have a thickness of 1 mm. The minor tubes of the cyclone concentrators in Figures 4a and 4b have three different lengths (L), respectively, which are +5 mm, 0 mm, and −5 mm. The cyclone concentrators were designed and fabricated to allow these minor tubes to be interchanged.

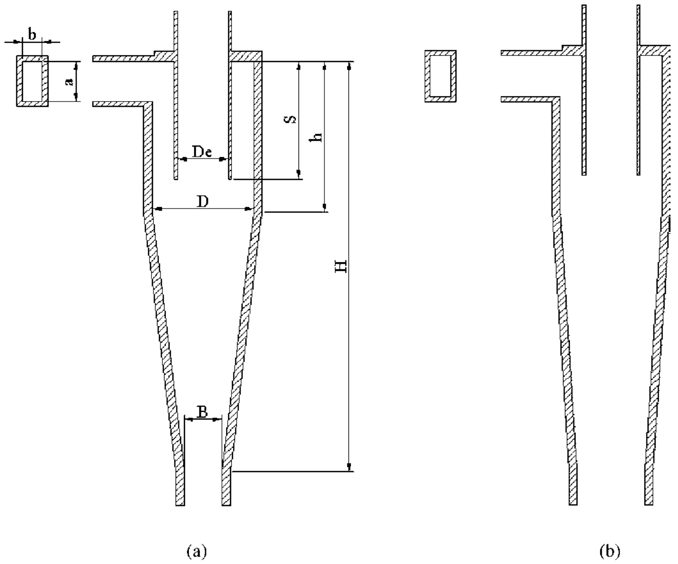


Figure 3. Dimensions and geometry of (a) cyclone I and (b) cyclone II.

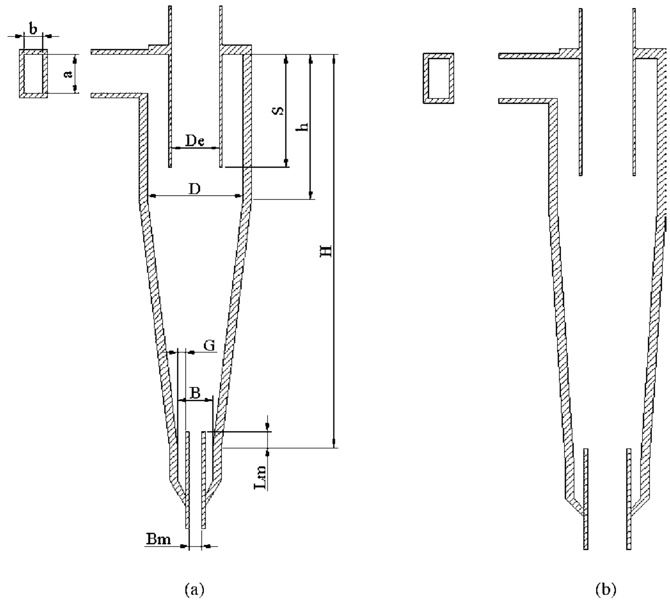


Figure 4. Dimensions and geometry of (a) cyclone III and (b) cyclone IV.

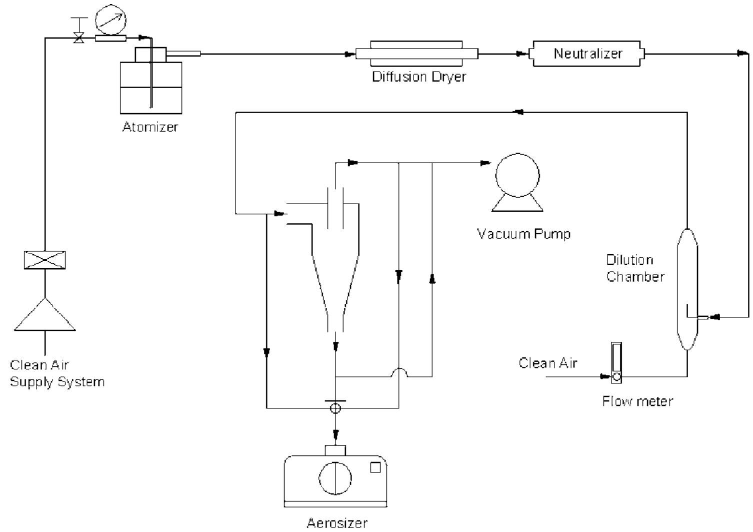
Experimental Setup and Procedure

A schematic diagram of the experimental set-up, with a generation system for polystyrene latex particles (PSL, Duke Scientific Corp., A, density = 1.05 g/cm^3), is shown in Figure 5a. The experimental system consists of a particle generator, a test cyclone, and a particle detector. Monodisperse polystyrene latex particles were generated by an atomizer (TSI Inc., Shoreview, MN, Model 9302), with a geometric standard deviation of less than about 1.16. The generated particles were passed though a Kr-85 neutralizer, diluted with filtered air and introduced to the cyclone at 50 and 70 L/min. The minor and major flows were pumped out of the particle outlet, at the bottom of the cyclone, and the gas outlet (vortex finder), respectively. The minor flow rate was 4 L/min, and the major flow rates were 46 and 66 L/min.

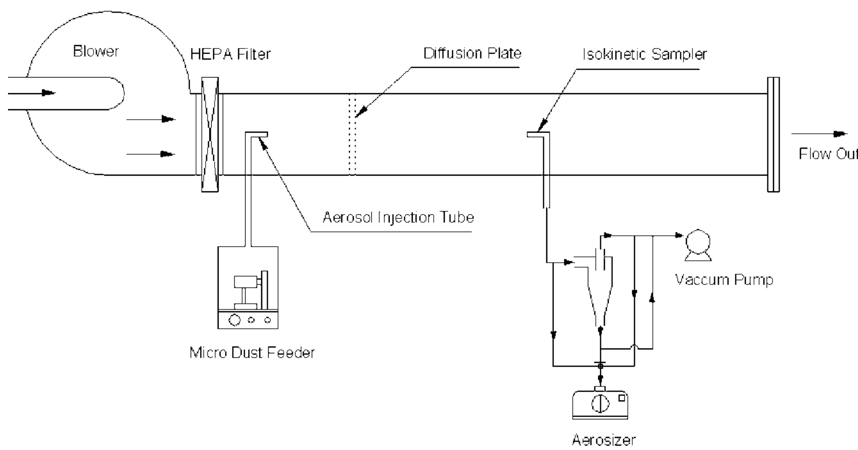
The inlet and outlets (major flow outlet and minor flow outlet) of the cyclones were designed to be connected to an isokinetic sampler with minimal particle losses during the transportation. The pressure drop was checked upstream and downstream. The collection efficiencies and concentration factor of the cyclone

Table 1
Dimensions and operating conditions for the test cyclones

Dimensions and operating conditions	Cyclone I	Cyclone II	Cyclone III	Cyclone IV
A) Dimensions that were different between cyclones				
Particle outlet diameter, B (mm)	11	20	11	20
Minor flow tube inner diameter, Bm (mm)	11	20	4	13
Minor flow tube height, Lm (mm)	0	0	+5, 0, −5	+5, 0, −5
Gap width, G (mm)	0	0	2.5	3
B) Dimensions and operation conditions that were the same between cyclones				
Cyclone diameter, D (mm)	30			
Gas outlet diameter, De (mm)	15			
Inlet height, a (mm)	12			
Inlet width, b (mm)	6			
Gas outlet height, S (mm)	45			
Cyclone height, H (mm)	122			
Cylindrical body height, h (mm)	45			
Flowrate (L/min)	50, 70			
Temperature (K)	293			



(a)



(b)

Figure 5. Schematic diagrams of experimental setups, with (a) PSL and (b) fly ash particle generation systems.

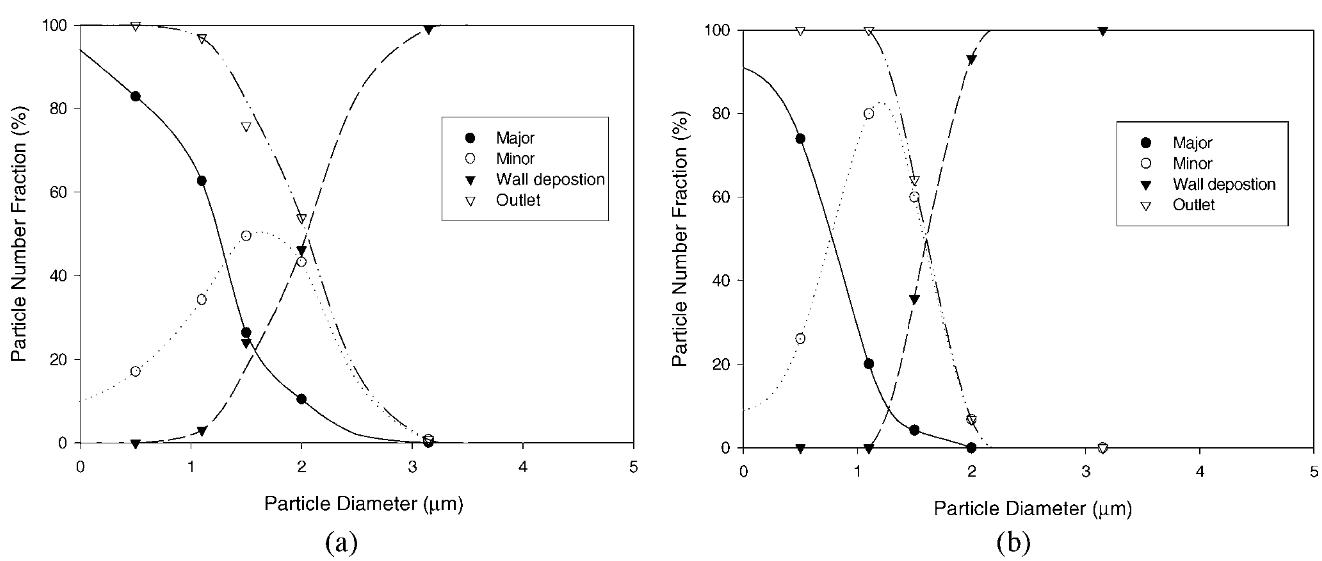


Figure 6. Particle number fractions for cyclone I at (a) 50 L/min and (b) 70 L/min.

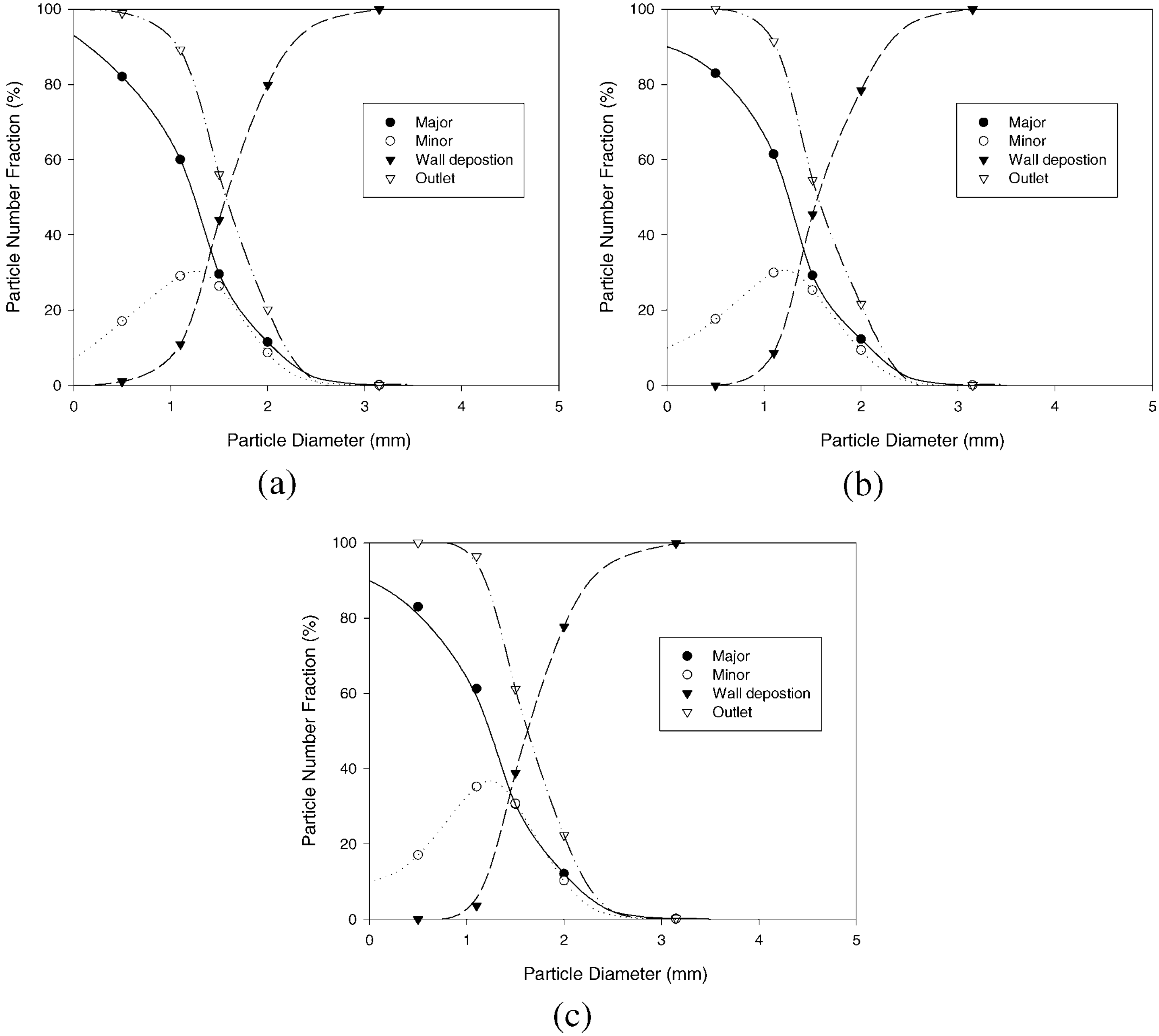


Figure 7. Particle number fraction for cyclone III with (a) +5 mm, (b) 0 mm, and (c) −5 mm minor tube heights at 50 L/min.

concentrators were determined from the particle number concentrations of the inlet and outlet, which were measured by an Aerosizer (API Inc., MN, Model Mach II-LD). The particle number fraction (f) and concentration factor were determined by Equations (1) to (6)

$$N_{in}Q_{in} = N_{major}Q_{major} + N_{minor}Q_{minor} + WD \quad [1]$$

$$f_{major} = \frac{N_{major}Q_{major}}{N_{in}Q_{in}} \quad [2]$$

$$f_{minor} = \frac{N_{minor}Q_{minor}}{N_{in}Q_{in}} \quad [3]$$

$$f_{outlet} = \frac{N_{major}Q_{major} + N_{minor}Q_{minor}}{N_{in}Q_{in}} = f_{major} + f_{minor} \quad [4]$$

$$f_{WD} = \frac{WD}{N_{in}Q_{in}} = 1 - f_{outlet} \quad [5]$$

$$CF = \frac{N_{minor}}{N_{in}} \quad [6]$$

where Nin, Nmajor, and Nminor are particle number concentrations of the inflow, major flow, and minor flow, respectively. Qin, Qmajor, and Qminor are the flow rates of the inflow, major flow, and minor flow, respectively, and WD is wall deposition

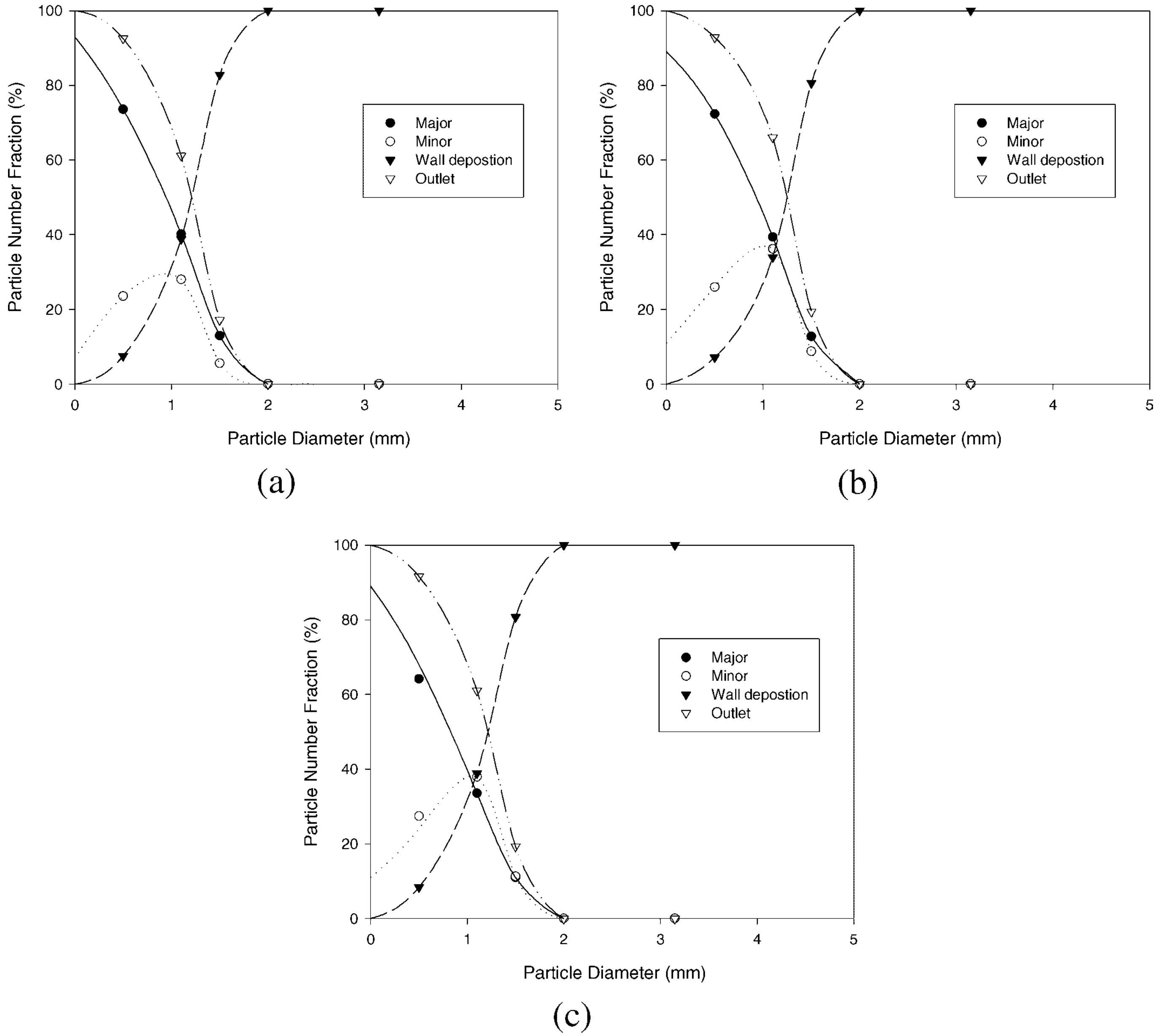


Figure 8. Particle number fraction for cyclone III with (a) +5 mm, (b) 0 mm, and (c) −5 mm minor tube heights at 70 L/min.

of particles. fmajor, fminor, foutlet, and fWD are the particle number fractions of the major flow, minor flow, outlet flow, and wall deposition, respectively.

Figure 5b shows a schematic diagram of the experimental setup, with a generation system for high concentrations of fly ash particles (density $= 2.43$ g/cm^3). The wind tunnel comprised a 3-m single-lane, with a 0.3-m diameter and was made of Plexiglas and operated at ambient temperature. The tests were performed at a wind velocity of 1.1 m/s. The fly ash particles were dispersed using a micro dust feeder (Model MF-2, Sibata Scientific Technology Ltd., Tokyo, Japan), with a geometric standard deviation (GSD) and the geometric mean diameter (GMD) of 1.85 and 4.57 μm, respectively. The fly ash particle number concentration ranged between 1.0×10^9 and 1.0×10^{10} particles/m^3 and the PSL particle number concentration ranged between 1.0×10^6 and 1.0×10^7 particles/m^3. The particle number concentrations were measured by an Aerosizer using the same method described for Figure 5a. In addition, particles were also collected on the 47-mm Zefluor membrane filter (P5PJ047, Pall Corp., NY), with a 2-μm pore size, at the cyclone inflow, major flow, and minor flow, to measure the particle mass and evaluate the total particle mass fraction.

RESULTS AND DISCUSSION

Figure 6 shows the calculated particle number fractions for cyclone I at 50 and 70 L/min (minor flow rate: 4 L/min), which had already been evaluated by Kim et al. (2002). The particle number fractions were in good accordance with those obtained by Kim et al. (2002), and the particle fractions in the minor flow were reversed U-shaped curves, with maxima at 1.5 and 1.0 μm diameters, respectively, as shown in Figures 6a and 6b. In addition, as described by Kim et al. (2002), the particle fraction curves of the minor flow became narrower with increases in the flow rate. Figure 7 shows the particle number fractions for cyclone III at 50 L/min, which has a 2.5-mm gap between the cyclone bottom and minor flow tube with an inner diameter of 4 mm. Cyclone III had various minor flow tube heights, +5, 0 and −5 mm, with Figures 7a, 7b, and 7c showing the particle number fractions of the cyclone with these minor flow tube heights. The major, minor, wall deposition, and outlet particle number fractions of cyclone III, with the three different minor flow tube heights, had similar values, meaning the minor flow tube height does not play an important role in the particle number fraction of cyclone III at 50 L/min. However, compared with cyclone I, the particle number fractions of cyclone III, with the gap, have different curves. For example, the particle fraction of the minor flow for cyclone III was lower than that for cyclone I when the particle sizes were larger than 1.1 μm, and the particle fractions of the minor flow for cyclones I and III show maximum values at 1.5 and 1.1 μm, respectively. In addition, the wall deposition fraction for cyclone III was higher than that for cyclone I, especially with particle sizes larger than 1.1 μm. While the wall deposition fractions of cyclones I and III were about 43% and 78%, with a 2.0-μm particle diameter, their minor flow particle fractions were about 41% and 9%, respectively. This means that, in the case of cyclone III, particles going down the cyclone wall or moving with the gas flow toward the minor flow in cyclone I might be collected in the gap at the bottom of cyclone III. The gap between the cyclone bottom and minor flow tube led to an increase in the wall deposition, but a decrease in the minor flow particle fraction. Thus, the cyclone III was inappropriate for concentrating particles at a flow rate of 50 L/min. Figures 8a, 8b, and 8c also show the particle number fractions for cyclone III with minor flow tube heights of +5, 0, and −5 mm, respectively, at 70 L/min. The particle number fraction of the minor flow for cyclone III was also lower than that for cyclone I, as at 50 L/min, and the difference in the particle number fractions between cyclones I and III was larger at 70 L/min than at 50 L/min. Especially, the particle number fraction of the minor flow for cyclone III with a +5 mm minor flow tube height decreased by over 60%, compared with that for cyclone I. These results indicate that cyclone III can be used as a particle collector with a high efficiency but cannot be used as a particle concentrator with a high concentration factor.

Figure 9 shows the particle number fractions for the cyclone II with a 20-mm cyclone bottom and minor flow tube diameter, at 50 and 70 L/min. The particle number fractions of the minor flow for cyclone II had reversed U-shaped curves that were a little bit higher and wider than those for cyclone I. The particle number fractions for the wall deposition of the cyclone II were lower than those for cyclone I, especially in the larger particle size range. This trend is shown more clearly in Figure 9b. The particle number fraction of the minor flow for cyclone II in Figure 9b (70 l/min) had a peak with a diameter of 1.5 μm, and that for cyclone I had a peak of 1.0 μm. This result means that the particles with a diameter near 1.5 μm are more concentrated in the minor flow than those near 1.0 μm when the bottom and minor tube diameters of the cyclone were increased from 11 to 20 mm. Usually, the collection efficiency of the cyclone wall

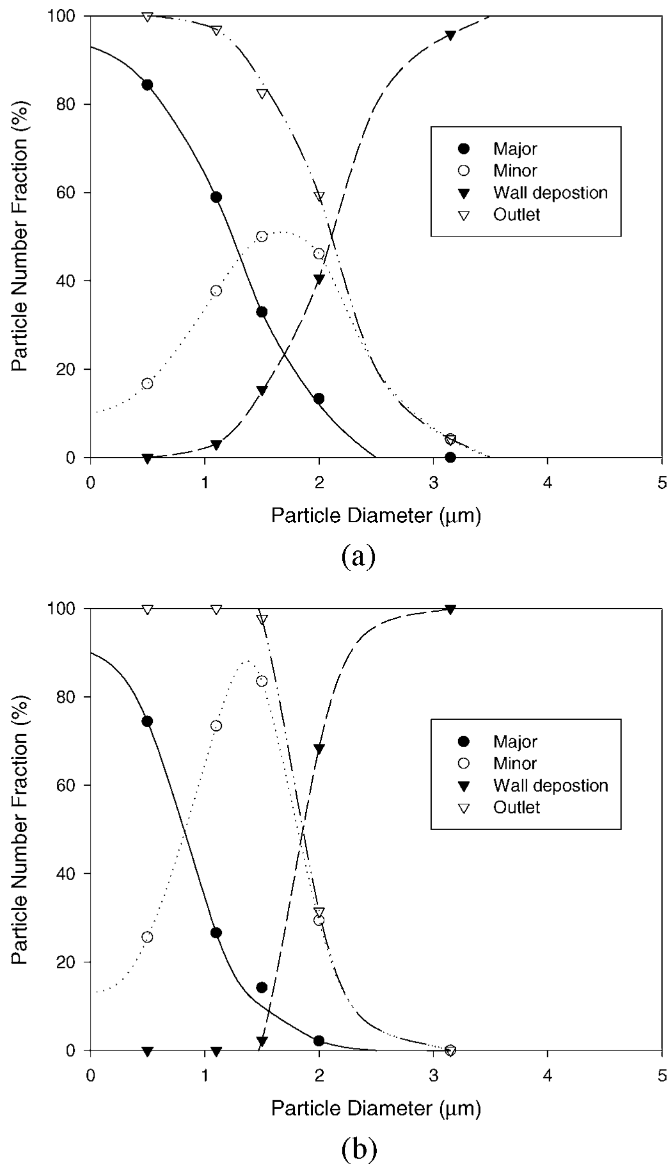


Figure 9. Particle number fractions for cyclone II at (a) 50 L/min and (b) 70 L/min.

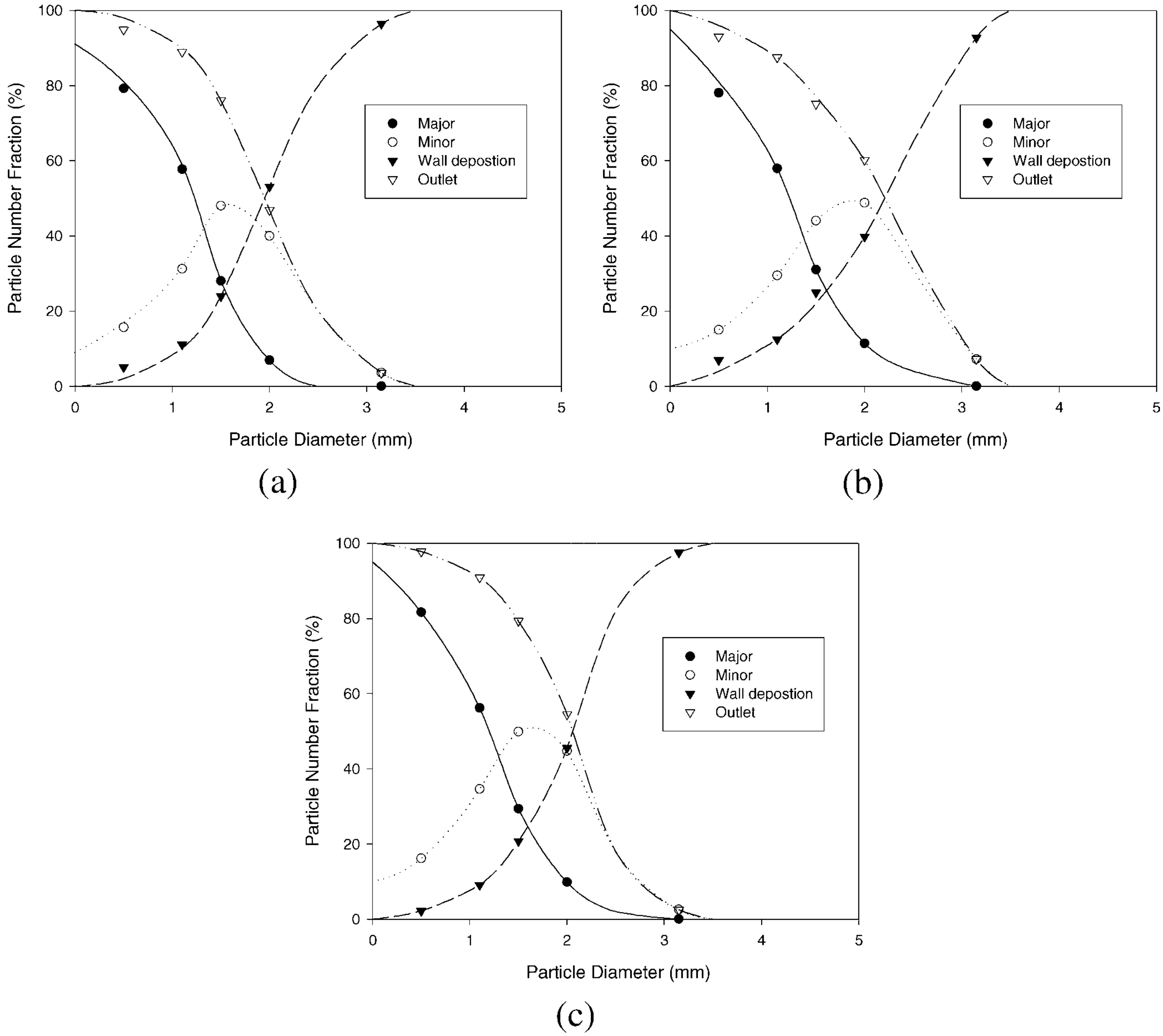


Figure 10. Particle number fraction for cyclone IV with (a) +5 mm, (b) 0 mm, and (c) −5 mm minor tube heights at 50 L/min.

decreased as the bottom diameter increased. Thus, it should be noted that the particles that are not collected on the cyclone wall move along the minor flow due to the large diameter of the minor flow tube.

Cyclone IV had a 3.0-mm gap between the cyclone bottom and the minor flow tube. Figures 10a, 10b, and 10c show the particle number fractions for cyclone IV, with +5, 0, and −5 mm minor tube heights, at 50 L/min. The particle number fractions of the major, minor, outlet, and wall deposition for cyclone IV had similar curves to those for cyclone II, with less than 10% differences, regardless of the minor tube heights, although the wall deposition increased in the small particle size range due to the gap. This trend is shown in Figures 11a, 11b, and 11c for the particle number fractions of the cyclone IV, with +5, 0, and −5 mm minor tube heights, at 70 L/min. However, although the particle number fraction of the minor flow for the cyclone III was 60% lower than that for the cyclone I, the particle number fraction of the minor flow for the cyclone IV was similar to that of the cyclone II. In addition, the particle fraction of the minor flow for cyclone IV had a peak at 1.5 μm as did that for cyclone II. These results indicate that the gap between the bottom of the cyclone and the minor flow tube has little effect on the particle number fraction of the cyclone as long as the cyclone has a large bottom and minor tube diameters, although a large bottom

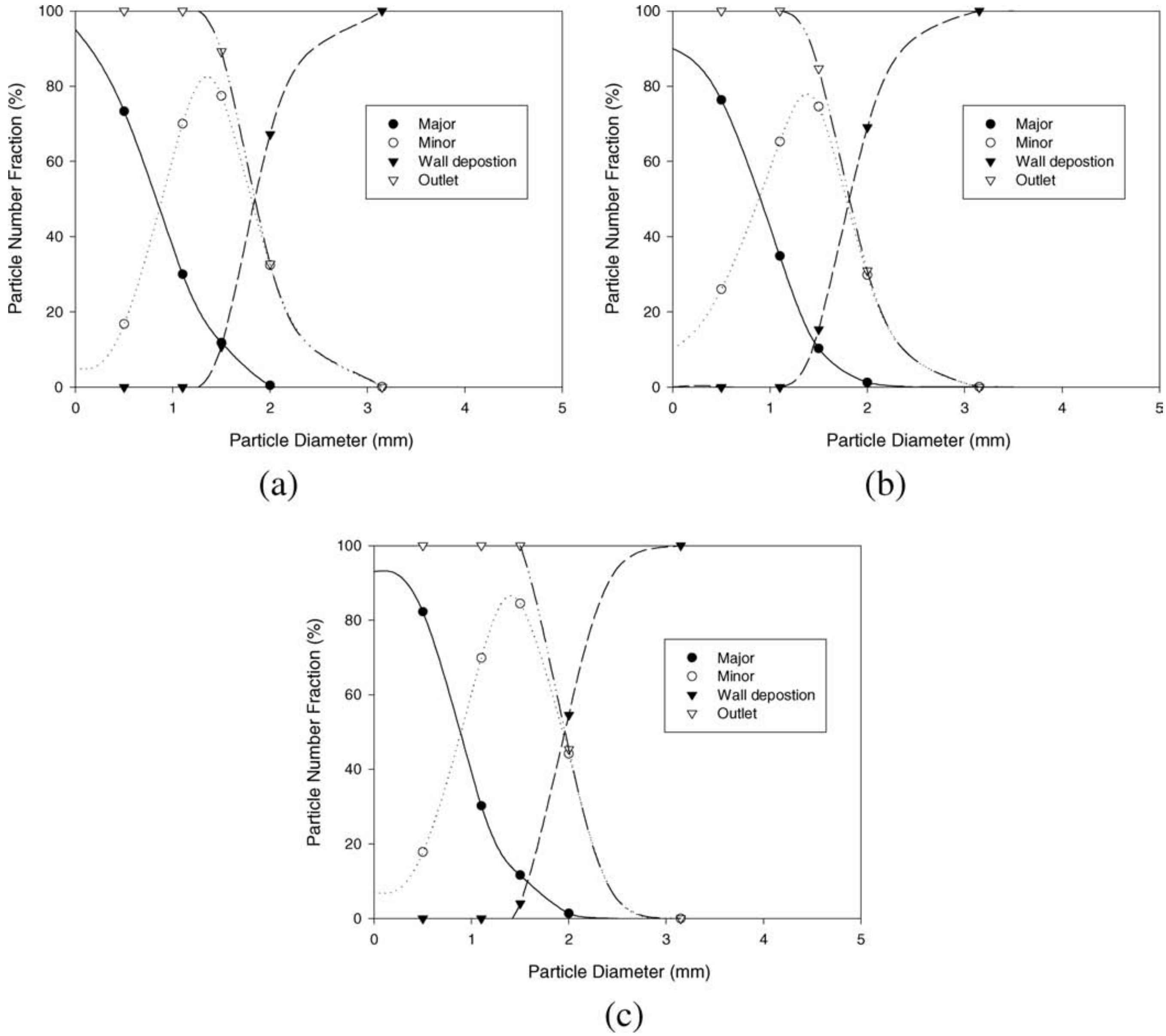
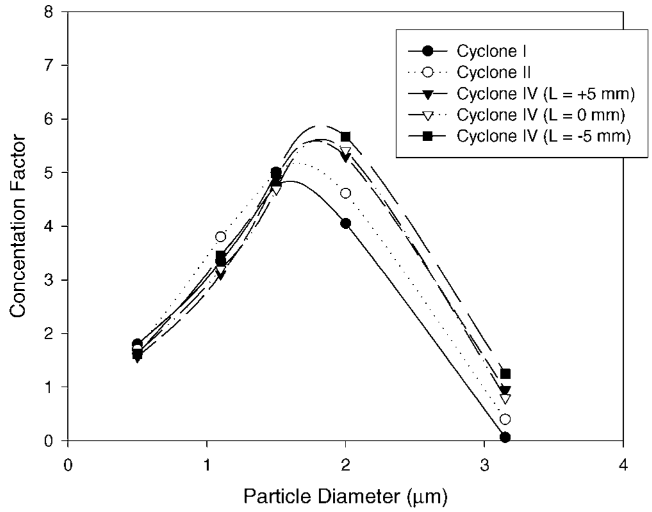


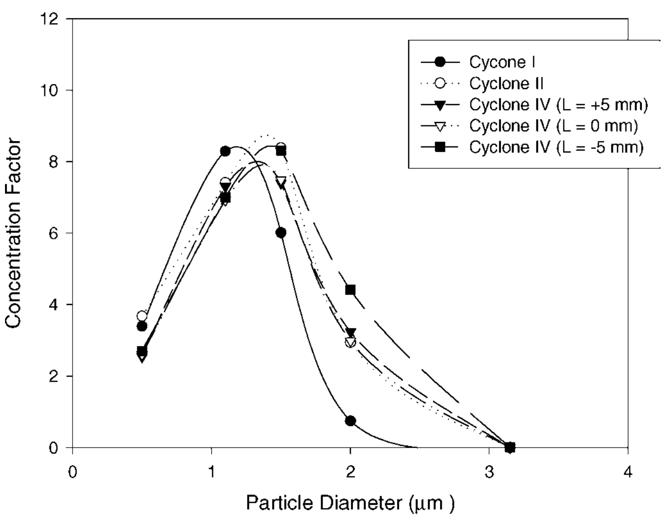
Figure 11. Particle number fraction for cyclone IV with (a) +5 mm, (b) 0 mm, and (c) −5 mm minor tube heights at 70 L/min.

to the cyclone gives different particle number fraction curves, such as a wider reverse U-shaped curve for the minor flow, compared with a small bottom.

The concentration factor of cyclone IV was larger than those of cyclones I and II in the particle size range over 1.5 μm, and showed a higher peak, at 50 L/min, as shown in Figure 12a. The concentration factor of cyclone IV did not show a narrower characteristic curve than cyclone I at 70 L/min, as shown in Figure 12b, meaning that cyclone IV cannot concentrate particles of an appropriate size, any better than cyclone I. However, the high particle concentration at the cyclone inlet resulted in very different particle number fractions for these two cyclones, as shown in Figure 13. For cyclone I, when the particle concentration at the inlet was high, the particles collected on the wall moved down with the minor flow. Thus, most large particles were found in the minor flow, which were collected and stuck on the cyclone wall when low particle concentrations were used. These results may lead to S-shaped particle fraction curves due to the small particles exiting through the vortex finder, with the large particles going down the minor flow tube, which acts as a virtual impactor. However, the particle fraction for cyclone I had no S-shaped curve. It should be noted that the large particles collected on the cyclone wall move down to the cyclone bottom and along the minor flow tube wall, and these particles cannot be sampled by the isokinetic sampler located in the center of the minor tube. Thus, the particle number fraction of the larger



(a)



(b)

Figure 12. Particle concentration factor of the cyclones at (a) 50 L/min and (b) 70 L/min.

particles may not have high values. Using filters, the particle total mass fraction of the minor flow was over 98%, which means that most of the large particles were collected on the filter from the minor flow. The particle number fraction curves for cyclone IV remained unchanged, although they had slightly lower peaks. The particles collected on the cyclone wall did not follow the minor flow but moved into the gap between the particle exit and minor flow tubes. Thus, the particle number fraction of the minor flow for cyclone IV was 0% with large particle sizes, and the total particle mass fraction of the minor flow was below 2%.

For high particle concentrations at the cyclone inlet, cyclone IV can concentrate the particles in a specific size range more steadily than cyclone I. In addition, cyclone IV is more energy efficient because the pressure drop of the cyclone IV was lower

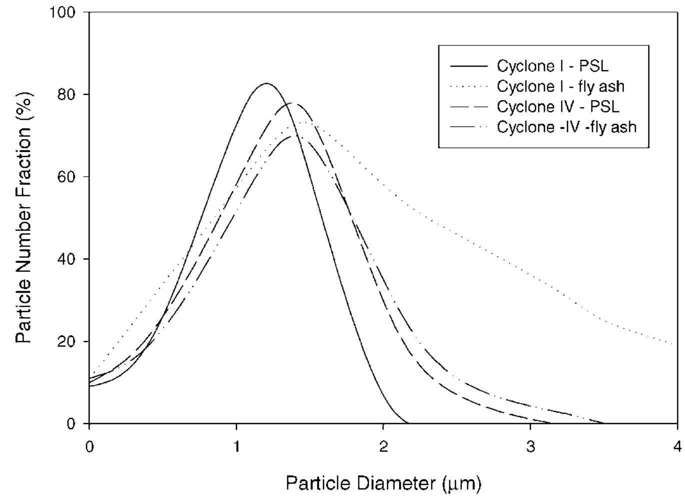


Figure 13. Particle number fractions of the cyclones with fly ash.

than those of the other cyclones, as shown Figure 14. The pressure drop of the cyclone concentrators decreased as the bottom diameter increased. The gap between the bottom and minor flow tube had no real effect on the pressure drop.

While the virtual impactor can concentrate particles larger than the 50% cut-off diameter, the cyclone concentrator can concentrate particles within a narrow range near 50% cut-off diameter. The higher the inflow rate, the smaller the peak concentration particle size and the narrower the concentration factor curve. Thus, the cyclone concentrator can concentrate the particles of particular size. The size range of particle concentration can be turned varying the flow rate and cyclone design, especially in particle size having sharp collection efficiency curve. In addition, the modified cyclone concentrator with a gap can be used for process of high particle concentrations. With this particular particle-concentrating potential, the cyclone concentrator

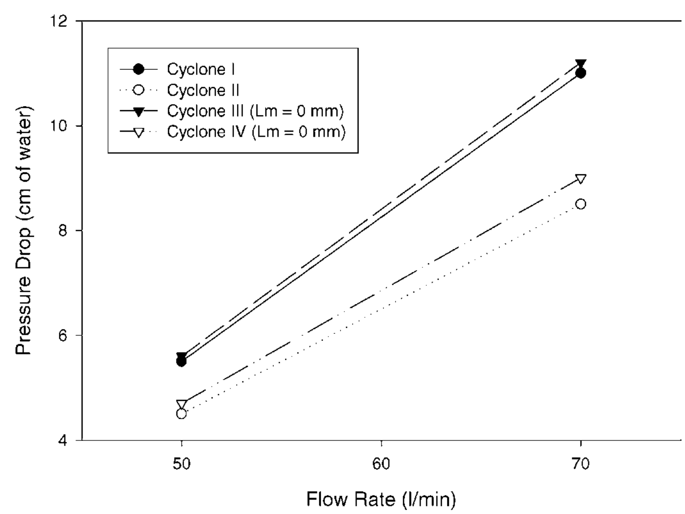


Figure 14. Pressure drop of the cyclone concentrators.

might be useful for concentrating bioaerosols, which are usually found in the appropriate size range between 0.5 and 10 μm and at low concentrations in the air. Cyclone concentrators might also be useful for application as generators for test particles within a desired size range, while two or more virtual impactors in series are required to achieve the same results.

CONCLUSIONS

In this study, the particle number fractions for the modified cyclone concentrators, with a gap between the particle exit tube at the cyclone bottom and minor flow tube, were evaluated and compared with those for conventional cyclone concentrators, and the effects of the gap, on the particle collection and concentration, examined. In addition, this study represented the effects of the heights and diameters of the minor flow on the particle number fraction of the cyclone concentrators.

The particle number fraction of the conventional cyclone concentrator had different curves, according to the gas flow rate at the inlet and the diameter of the particle exit or minor flow tubes. As the flow rate increased, the particle number fractions of the minor flow had narrower reversed U-shaped curves and higher peaks. In addition, as the particle exit or minor flow tube diameters increased, the particle number fractions of the minor flow had wider reversed U-shaped curves.

The cyclone concentrator, with a gap and small minor tube diameter, such as cyclone III, showed lower particle fraction for the minor flow and higher particle fraction for the wall deposition. Thus, the cyclone cannot concentrate more particles in a specific size range than the conventional cyclone concentrator.

The cyclone concentrator with a gap and large minor tube diameter, such as cyclone IV, had slightly lower or higher particle fractions for the minor flow, and at the high flow rate, showed a peak with a larger particle size than the conventional cyclone concentrator. In addition, when a high particle concentration was introduced to the inlet of the cyclone concentrator, it was able to maintain the reversed U-shaped curve for the particle fraction of the minor flow. Thus, the particles can be concentrated more stably than with a conventional cyclone concentrator.

The height of the minor flow tube did not play an important role in the particle number fraction of the cyclone concentrator, such as with cyclone III and cyclone IV although greater height for the minor flow tube sometimes resulted in a slightly larger wall deposition.

REFERENCES

DeOtte, R. E., Jr. (1990). A Model for the Prediction of the Collection Efficiency Characteristics of a Small, Cylindrical Aerosol Sampling Cyclone, *Aerosol Sci. Technol.* 12:1055–1066.

Dietz, P. W. (1982). Electrically Enhanced Cyclone Separators, *Powder Technol.* 3:221–226.

Dirgo, J., and Leith, D. (1985). Performance of Theoretically Optimized Cyclones, *Aerosol Sci. Technol.* 12:673–685.

Galperin, V., and Shapiro, M. (1999). Cyclones as Dust Concentrators, *J. Aerosol Sci.* 30:S897–898.

Iozia, D. L., and Leith, D. (1989). Effect of Cyclone Dimensions on Gas Flow Pattern and Collection Efficiency, *Aerosol Sci. Technol.* 10, 491–500.

Kim, H. T., Zhu, Y., Hinds, W. C., and Lee, K. W., (2002). Experimental Study of Small Cyclone concentrators as Particle Concentrators, *J. Aerosol Sci.* 33:721–733.

Kim, J. C., and Lee, K. W. (1990). Experimental Study of Particle Collection by Small Cyclones, *Aerosol Sci. Technol.* 12:1003–1015.

Moore, M. E., and McFarland, A. R. (1996). Design methodology for multiple inlet cyclones. *Environ. Sci. Technol.* 30: 271–276.

Smith, W. B., Iozia, D. L., and Harris, D. B. (1983). Performance of Small Cyclones for Aerosol Sampling, *J. Aerosol Sci.* 14:402–409.

Sumner, R. J., Briens, C. L., and Bergougnou, M. A. (1987). Study of a Novel Uniflow Cyclone Design, *Canadian J. Chem. Eng.* 65:470–475.

Zhu, Y., Kim, M. C., Lee, K. W., Park, Y. O., and Kuhlman, M. R. (2001). Design and Performance Evaluation of a Novel Double Cyclone, *Aerosol Sci. Technol.* 34:373–380.