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Experimental study of small virtual cyclones as particle concentrators

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Abstract

Two small cyclones, made of aluminum and glass, with different dimensions were employed to understand the effects of minor flow on cyclone efficiency, and then to evaluate their potential usage as particle concentrators. Minor flow is airflow from the bottom of the cyclone where the dust collects in a conventional cyclone. A cyclone having a minor flow is referred to as a virtual cyclone in this study. The difference between a conventional cyclone and a virtual cyclone is that the latter has a minor flow while a conventional cyclone does not. In order to study their performance systematically, both virtual cyclones were tested under different operating conditions. The major flow efficiency curve, 50% cut-off diameter and pressure drop, were measured as a function of the ratio of the minor flow to the inflow. Compared to a conventional cyclone, the virtual cyclone showed a higher major flow efficiency and a smaller 50% cut-off diameter under the same operational conditions. As a final step, the concentration factor, the factor by which a given size is concentrated in the minor flow, was calculated as a function of particle diameter. It was found that at a fixed inflow rate, the concentration factor first increased and then decreased as particle diameter increased. This study shows that the virtual cyclone has the greatest potential for concentrating particles in the region of 50% cut-off diameter.

Keywords: Virtual cyclone; Minor flow; Concentration factor

1. Introduction

Cyclones are devices that utilize the centrifugal force generated by a spinning gas stream to separate particles from the carrier gas. Their simple design, low maintenance costs, and adaptability

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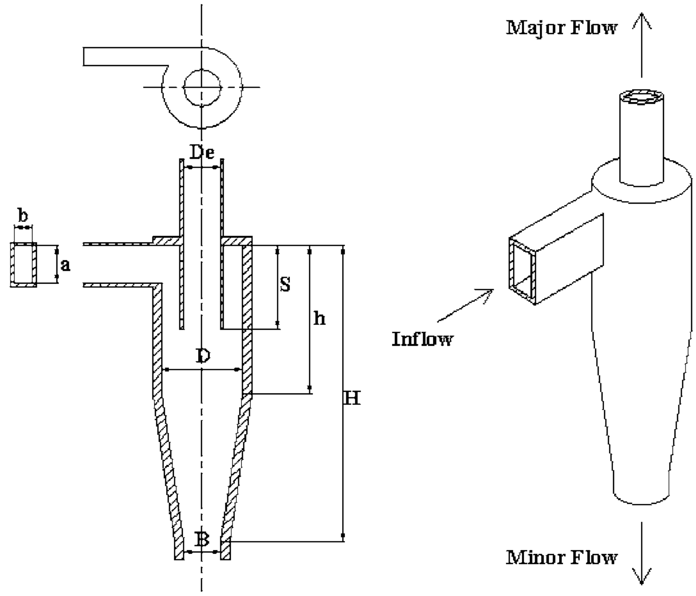

Fig. 1. Cyclone dimensions and flow directions.

to a wide range of operating conditions such as temperature, pressure and flow rate make cyclones one of the most widely used particle removal devices. Large cyclones are used to remove particles from industrial gas streams, while small cyclones are used to separate particles for ambient sampling, particularly, as personal respirable samplers in the field of occupational hygiene (Hinds, 1999; Chen, Yeh, & Rivero, 1998; Gautam & Sreenath, 1997; Liden & Gudmundsson, 1996; Bartley, Chen, Song, & Fischbach, 1994).

A commonly used cyclone design has a tangential horizontal flow inlet, an outlet at the top and a dust container/cup at the bottom, as shown in Fig. 1. It is generally known that the interior flow consists of a double spiral: the outer spiral moving down toward the dust outlet and the inner one moving up toward the gas exit outlet. A complete understanding of the detailed flow field is not well established; therefore, predictions on cyclone performance are rather difficult, and research on cyclone performance and cyclone design has been largely empirical. A number of modifications to the conventional cyclone design have been found to improve the collection efficiency and reduce the pressure drop. These include using a multi-port inlet instead of a single tangential duct (DeOtte, 1990), changing the shape of the gas inlet duct (Liden & Gudmundsson, 1997) and the inner wall of the cyclone body (Kim, Kuhlman, & Lee, 2001). Modifications in cyclone operation include using two or more cyclones in parallel or in series (Grane, Barbaris, & Behrouzi, 1992; Smith, Cushing, & Wilson, 1982; Smith & Wilson, 1979). These can also improve cyclone performance and can be used to size particles.

This paper describes the performance and use of virtual cyclones. The only difference between a conventional cyclone and a virtual cyclone is that the latter has the minor flow pumped out at the bottom, as shown in Fig. 1. A cyclone having a minor flow pumped out from its dust container is referred to as a virtual cyclone in this study although in different studies the terminology has

Table 1
Dimensions of studied cyclones

	Cyclone I	Cyclone II
Inlet height, a (mm)	20	12
Inlet width, b (mm)	10	6
Minor flow outlet diameter, B (mm)	20	11
Cyclone diameter, D (mm)	44	30
Major flow outlet diameter, De (mm)	20	15
Outlet height, S (mm)	45	45
Cylinder body height, h (mm)	80	45
Cyclone height, H (mm)	160	122
Material	Aluminum	Glass

been used for other types of devices (Torczynski & Rader, 1997). The effects of changing size of the different flows, as total, minor and major flows, on particle collection efficiency and particle concentration in the minor flow have been studied. Particles can be concentrated in the minor flow (Galperin & Shapiro, 1999) and thus a virtual cyclone can be used as a particle concentrator. A concentration factor of virtual cyclones has been also compared to that of virtual impactors.

2. Experimental

Two cyclones, one of aluminum and one of glass, were designed and fabricated for this study. Each has a different cylinder height, body diameter and exit tube length. The virtual cyclones tested here have a rectangular inlet and circular outlet similar to the conventional cyclone. The dimensions of these cyclones are shown in Fig. 1 and Table 1. Fig. 1 also shows the direction of airflows. The minor flow is pumped out from the cyclone's dust outlet at the bottom. In order to study the effects of minor flow on cyclone performance, the two cyclones were evaluated under three different operating conditions. First, the inflow (total flow) was fixed at 80 l/min, while the minor flow, starting from 0 l/min, was increased in 4 l/min step up to 16 l/min. Then, the major flow (conventional exit flow) was fixed at 80 l/min, while the minor flow, starting from 0 l/min, was increased in 4 l/min step up to 20 l/min. Finally, the minor flow was fixed at 4 l/min, while the inflow, starting from 40 l/min, was increased by 10 l/min up to 70 l/min. Detailed operating conditions are summarized in Table 2.

Monodispersed polystyrene latex (PSL, Duke Scientific Corporation) particles ranged from 0.5 to 4.0 μm were used for cyclone performance evaluation. For each tested PSL particle size, the measured geometric standard deviation ranged from 1.10 to 1.16. PSL particles were generated by an atomizer (TSI Inc., Model 9302). The material density of PSL is 1.05 g/cm^3. The particle-laden air was drawn by a vacuum pump through a diffusion dryer, a dilution chamber, and the test cyclone at a desired flow rate as shown in Fig. 2. For each particle size and flow rate combination, five replications of particle concentration were alternately, first at inflow and major flow and then minor flow, measured by the Aerosizer/Diluter combination (API Inc., Model Mach II-LD). Isokinetic sampling probes were used to sample representative particle concentrations at inflow, major flow and

Table 2
50% cut-off diameter and pressure drop of tested cyclones under different operating conditions

Cyclone	Inflow (l/min)	Major flow (l/min)	Minor flow (l/min)	Q_{minor}/Q_{in}	Cut-off diameter[a] (μm)	Pressure drop (Pa)
Cyclone I	80	80	0	0	2.02	473.7
	80	76	4	0.05	1.82	478.6
	80	72	8	0.1	1.55	485.4
	80	68	12	0.15	1.45	498.2
	80	64	16	0.2	1.24	510.9
	84	80	4	0.048	1.74	522.7
	88	80	8	0.091	1.51	598.2
	92	80	12	0.13	1.31	672.7
	96	80	16	0.167	1.16	747.3
	100	80	20	0.2	1.05	821.8
Cyclone II	40	36	4	0.1	1.31	299.1
	50	46	4	0.08	1.12	470.8
	60	56	4	0.067	0.96	697.3
	70	66	4	0.057	0.80	1000.3

[a]Based on major flow efficiency curve of virtual cyclones.

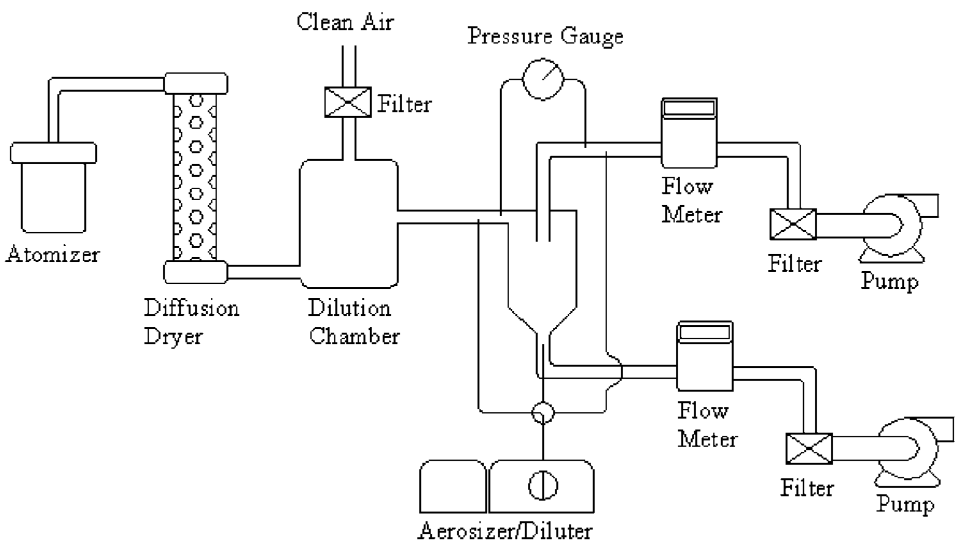

Fig. 2. Schematic diagram of experimental set-up.

minor flow of the cyclone. PSL particle number concentration ranged from 1.0×10^6 to 1.0×10^7 particles/m^3 (corresponding to 0.1–40 μg/m^3). After the highest and the lowest data points were discarded, the remaining data were averaged to obtain the collection or removal efficiency. With this setup the Aerosizer/Diluter was able to measure the total particle number concentration for each PSL size used. It is noted that the Aerosizer's performance during certain aerosol experiments has been of concern for some investigators (Cheng, Barr, Marshall, & Mitchell, 1993; Tsai, Chein, Chang, & Kuo, 1996). In a previous study, it was found that the PSL particle sizes indicated by the manufacturer agreed very closely with the Aerosizer output for particles up to 10 μm (Kim & Lee, 2000). In this study, the Aerosizer served as a PSL particle detector as well as a particle size measurement instrument. All flows were controlled by mass flow controllers (Bronkhorst Hi-Tec Inc., EL-Flow F-112AC) and a mass flow meter (SIERA Instrument, Inc., No. 822S-M-3-OV1-PV1-V1). The pressure change across the cyclone was measured by a magnehelic gauge (Dwyer Instruments Inc.). Short sampling tubes of equal length and diameter were used in the experiments to minimize loss and bias. Throughout the experiments, it was found that the data were reproducible within $\pm 5\%$.

3. Results and discussion

For a conventional cyclone, without a minor flow, and assuming that particle loss except for wall deposition is negligible, the mass balance is written as

$$N_{in}Q_{in} = N_{out}Q_{out} + \mathrm{WD}, \tag{1}$$

where N_{in} and N_{out} are particle number concentrations in the inflow and outflow, respectively. Q_{in} and Q_{out} are flow rates of the inflow and outflow, respectively. WD is wall deposition of particles. The collection efficiency of a conventional cyclone, only by the wall deposition, $\eta_{conventional}$ can be expressed by

$$\eta_{conventional} = \eta_{WD} = \frac{N_{in}Q_{in} - N_{out}Q_{out}}{N_{in}Q_{in}} = \frac{\mathrm{WD}}{N_{in}Q_{in}}. \tag{2}$$

For a virtual cyclone, assuming that except for wall deposition particle loss is negligible, the mass balance becomes

$$N_{in}Q_{in} = N_{major}Q_{major} + N_{minor}Q_{minor} + \mathrm{WD}, \tag{3}$$

where N_{major} and N_{minor} are particle number concentrations in the major and minor flows, respectively. Q_{major} and Q_{minor} are flow rates of the major and minor flows, respectively. The major flow efficiency of the virtual cyclone can be expressed by

$$\eta_{major} = \eta_{WD} + \eta_{minor} = \frac{N_{in}Q_{in} - N_{major}Q_{major}}{N_{in}Q_{in}} = \frac{N_{minor}Q_{minor} + \mathrm{WD}}{N_{in}Q_{in}}, \tag{4}$$

where the collection efficiency by the wall deposition and the removal efficiency by the minor flow are $\eta_{WD} = \mathrm{WD}/N_{in}Q_{in}$ and $\eta_{minor} = N_{minor}Q_{minor}/N_{in}Q_{in}$, respectively. Concentration factor is defined as the ratio of minor flow concentration to inflow concentration for a particular particle size:

$$CF = \frac{N_{minor}}{N_{in}}. \tag{5}$$

3.1. Major flow efficiency

Cyclone I was first tested under two different operating conditions to understand the effect of minor flow on the major flow efficiency. As shown in Fig. 3, when inflow is fixed, major flow efficiency

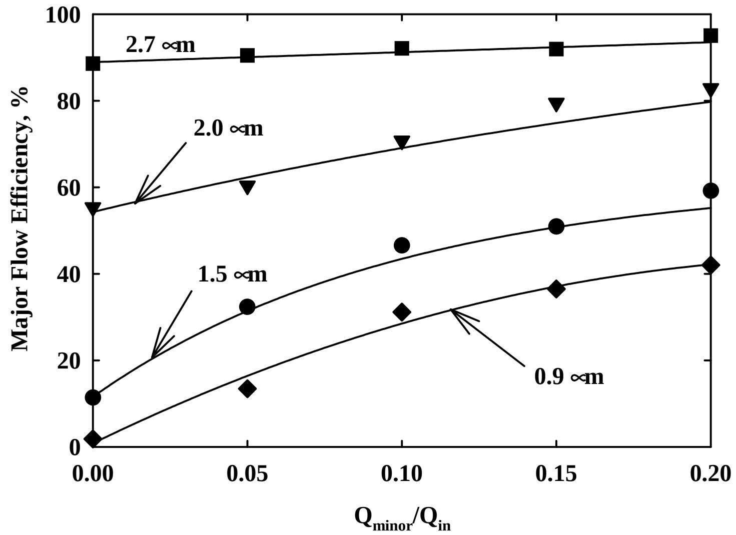

Fig. 3. Comparison of major flow efficiencies for Cyclone I—$Q_{in} = 80$ l/min at different Q_{minor}/Q_{in}.

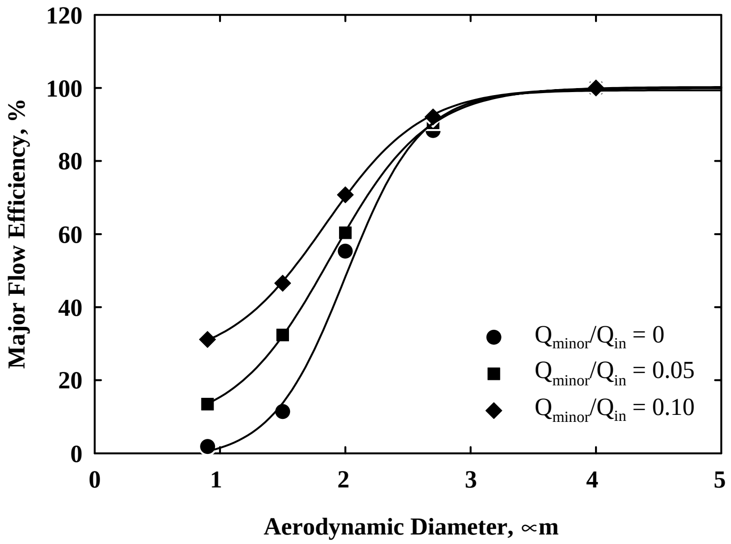

Fig. 4. Major flow efficiency curves for Cyclone I—$Q_{in} = 80$ l/min at different Q_{minor}/Q_{in}.

increases as Q_{minor}/Q_{in} increases. The major flow efficiency of 0.9 μm in diameter increases from nearly 0% to 45%, as the minor flow increases up to 16 l/min. The major flow efficiency curves versus particle diameter are shown in Fig. 4. All curves were fitted based on all experimental data using the four-parameter-sigmoidal equation in SIGMAPLOT version 5.0 software, and 50% cut-off diameters were calculated based on major flow efficiency curves of virtual cyclones. The 50% cut-off diameter decreases as the ratio of Q_{minor}/Q_{in} increases as shown in Fig. 4.

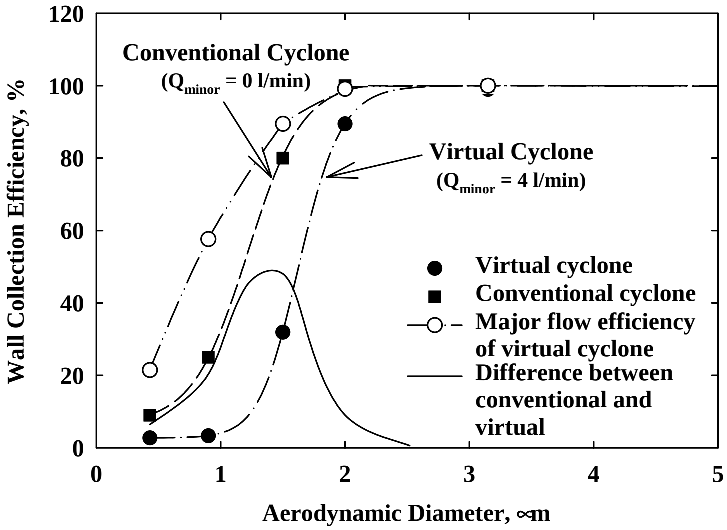

Fig. 5. Particle collection efficiency by wall deposition for Cyclone II at $Q_{\mathrm{in}} = 70$ l/min.

It should be noted that the major flow efficiency shown in Figs. 3 and 4 includes not only the collection efficiency by the wall deposition but also the removal efficiency by the minor flow. If the exiting major and minor flows are combined, particle collection efficiency in virtual cyclones, only by the wall deposition, may be the same as or a little bit lower than that in conventional cyclones. To understand this point more clearly, a small glass virtual cyclone (Cyclone II) was fabricated, whose dimensions are summarized in Table 1. While the major flow efficiency is higher, the particle collection efficiency by the wall deposition is lower for the glass virtual cyclone, as shown in Fig. 5. Fig. 5 also shows the wall collection efficiency difference between the virtual and conventional cyclones. It is noted that the difference is greatest in the size range of 1.5 μm in diameter. Thus, particles with aerodynamic diameter near 1.5 μm are more concentrated in the minor flow. This result indicates that virtual cyclones have the potential to concentrate particles in a specific size range, which is discussed in more detail in the following section. Wall collection efficiency for a virtual cyclone is somewhat lower than a conventional cyclone at the same flow rate. Because particles are concentrated in the minor flow and the minor flow is several fold smaller, the cost of cleaning this minor flow can be many times less than that for the whole gas flow (Galperin & Shapiro, 1999).

3.2. Concentration factor

Fig. 6 shows the calculated particle number fractions for Cyclone II at 50 and 70 l/min, which were calculated based on all experimental data using the mass balance, Eq. (3). The collection efficiency for very small particles by wall deposition is almost zero and the particles follow both major and minor flows perfectly, exiting from the top and the bottom of the virtual cyclone. Thus, the fraction of very small particles in the minor flow is theoretically the same as the ratio of the minor flow to the inflow or total flow. For a fixed minor flow of 4 l/min, the particle number fractions

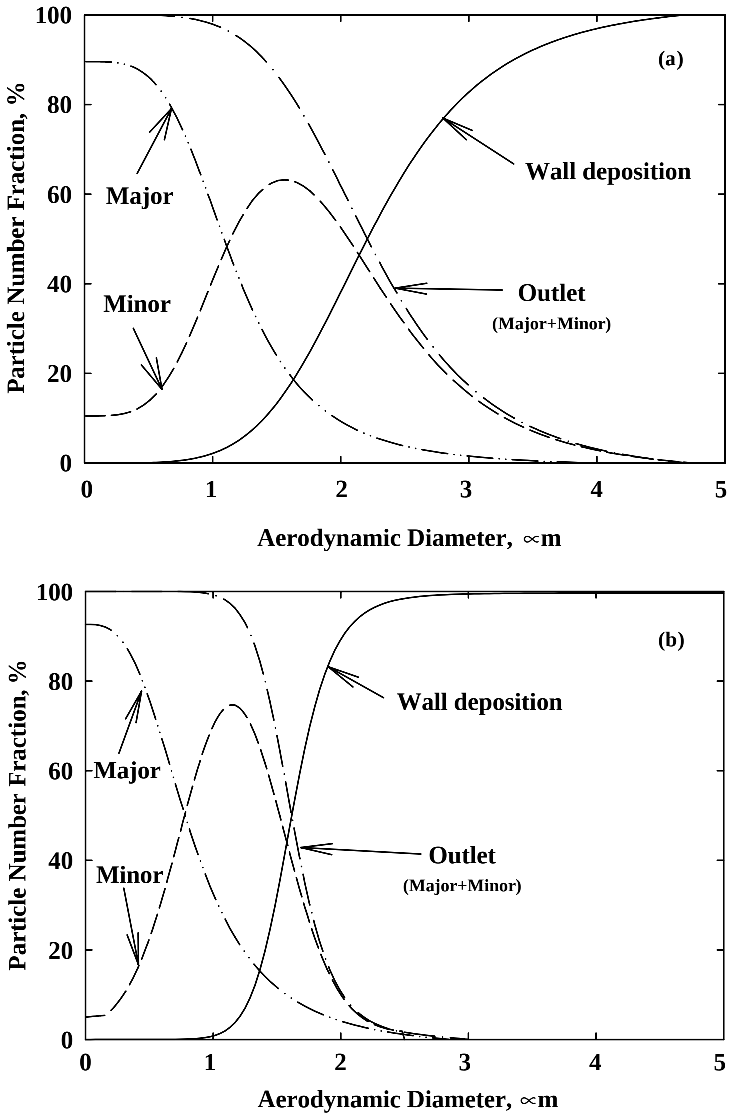

Fig. 6. Calculated particle number fraction versus aerodynamic particle diameter for Cyclone II at $Q_{\mathrm{minor}} = 4$ l/min and $Q_{\mathrm{in}}=$ (a) 50 and (b) 70 l/min.

in the minor flow are 8% and 5.7%, respectively, for an inflow of 50 and 70 l/min. As shown in Figs. 6(a) and (b), the particle fractions in the minor flow are reversed-U shape curves having a peak in the size range of 1.5 and 1.0 μm in diameter, respectively. Furthermore, the higher the inflow rate, the narrower the particle fraction curve of the minor flow because of steep wall deposition versus size. However, the wall deposition fraction, starting from almost zero for very small particle size, increases steeply as the minor flow fraction decreases. Smaller particles with lower inertia are carried out in the major flow, while larger particles with higher inertia are collected by the cyclone

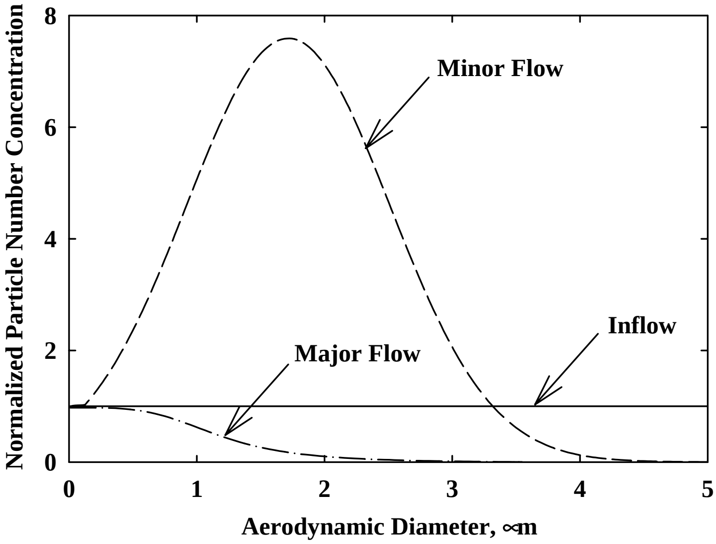

Fig. 7. Normalized particle number concentration for Cyclone II at $Q_{minor} = 4$ l/min and $Q_{in} = 50$ l/min.

wall. Intermediate particles, which are within a certain size range, near the 50% cut-off diameter, are concentrated into the minor flow. Fig. 7 shows this point more clearly. The number concentration of the minor flow is about eight times higher than that of the inflow concentration at the peak of the curve, while the number concentration of the major flow decreases with increasing particle size.

The concentration factor of the virtual impactor is expressed as the ratio of particle concentration in the minor flow to that entering the impactor (Kim & Lee, 2000; Wu, Copper, & Miller, 1989; Barr, Hoover, Kanapilly, Yeh, & Rothenberg, 1983). In this study, the concentration factor for the virtual cyclone was calculated similarly to that for virtual impactors. It should be noted that the concentration factor curve for a virtual cyclone, shown in Fig. 8, looks different from that for the virtual impactor, which is typically expressed as a general S-shaped curve (Wu et al., 1989). As discussed above, particles larger than 50% cut-off diameter are collected by wall deposition, while small particles follow the major flow without any collection or removal. Thus, the concentration factor shows the reversed U-shaped curve with a maximum in the region of 50% cut-off diameter. While the virtual impactor can concentrate particles larger than the 50% cut-off diameter, the virtual cyclone has potential for concentrating particles within a narrow range near 50% cut-off diameter. It is also shown in Fig. 8 that the higher the inflow rate, the smaller the peak concentration particle size and the narrower the concentration factor characteristic curve.

In conventional cyclones the interior flow consists of a double spiral: the outer spiral moving down toward the dust outlet and the inner one moving up along the center axis toward the gas exit. While in virtual cyclones, because of the minor flow, there may be a flow layer going down along the cyclone wall toward the dust container between the cyclone wall and the outer spiral. Intermediate particles reaching this flow region by their inertia, may follow this uniform flow, go down to the bottom and out with the minor flow and thereby be concentrated in the minor flow. More detailed physical analyses of the flow patterns in virtual cyclones will be presented in future studies by using computational fluid dynamics models. With this specific particle concentrating potential, virtual

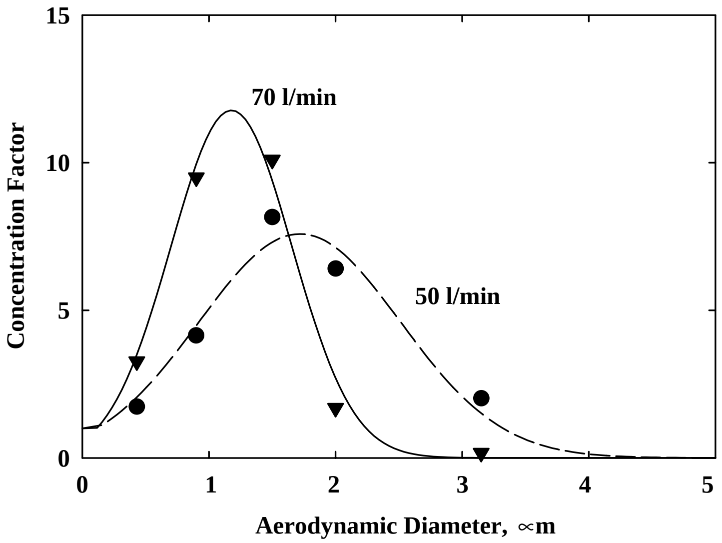

Fig. 8. Concentration factor for Cyclone II at two flow rates.

cyclones can concentrate bioaerosols, which are usually found in the appropriate size range and at low concentrations in the air, into the minor flow. Another possible application of virtual cyclones is that only one of them is needed to generate test particles within a desired size range, while two or more virtual impactors in series is required to achieve the same results (Chen et al., 1988).

3.3. Inflow rate effects and pressure drop

Previous experimental studies have showed that an increase in the inflow rate results in a decrease in cut size diameter (Zhu & Lee, 1999; Iozia & Leith, 1990; Kim & Lee, 1990; Moore & McFarland, 1990; Dirgo & Leith, 1985; Lee, Gieseke, & Piispanen, 1985). The present study shows the same trend. As shown in Fig. 9, for any given particle diameter, the major flow efficiency increases with increasing inflow rate and for any given flow rate, the major flow efficiency increases with increasing particle diameter. Fig. 10 shows 50% cut-off diameter and pressure drop for virtual cyclones versus the ratio of $Q_{\mathrm{minor}}/Q_{\mathrm{in}}$ for Cyclone I at $Q_{\mathrm{in}} = 80$ l/min. The pressure drop increases, while the 50% cut-off diameter decreases as $Q_{\mathrm{minor}}/Q_{\mathrm{in}}$ increases. As listed in Table 2, compared to a conventional cyclone, when inflow is fixed at 80 l/min, the 50% cut-off diameter decreases by 38.6%, while the pressure drop slightly increases by 7.3% with increasing $Q_{\mathrm{minor}}/Q_{\mathrm{in}}$ up to 20%. When major flow is fixed at 80 l/min and minor flow is increased from 0 to 20 l/min, the pressure drop increases by 42.4% with a 48% decrease in the 50% cut-off diameter. At $Q_{\mathrm{minor}}/Q_{\mathrm{in}}$ of 0.2, the pressure drop for the latter is much higher than that for the former showing 38% difference, while the 50% cut-off diameters only change by 15%. The large pressure drops for the experiments with fixed major flow are due to the high inflow rate. At the same $Q_{\mathrm{minor}}/Q_{\mathrm{in}}$, the pressure drop is more dependent on the inflow than the 50% cut-off diameter is. It should be note that even the largest pressure drop listed in Table 2, 1000.3 Pa, is much smaller than the 2000–2500 Pa, which is the maximum pressure drop generally allowed in cyclones (Jaroszczyk & Ptak, 1985).

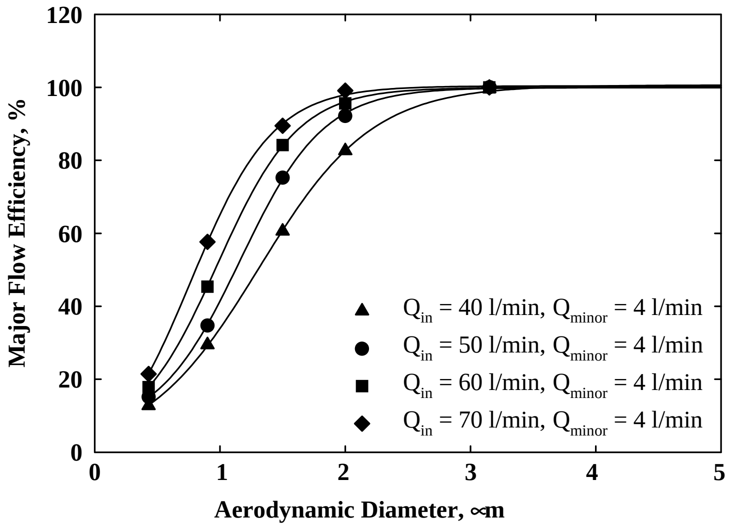

Fig. 9. Major flow efficiency curves for Cyclone II at different flow rates.

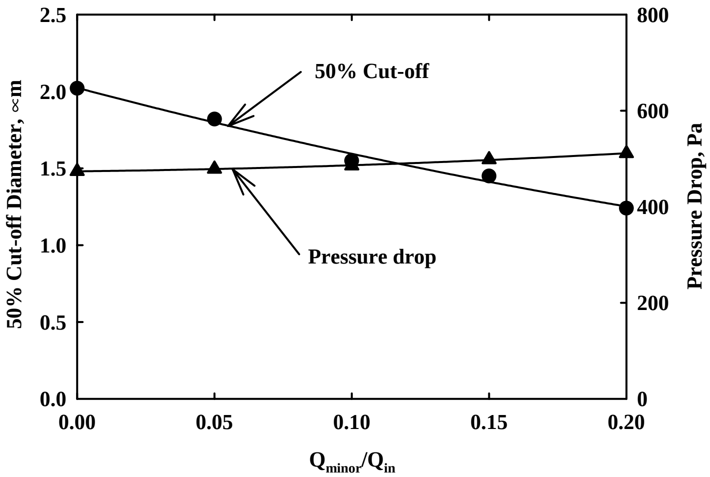

Fig. 10. 50% cut-off diameter and pressure drop for Cyclone I—$Q_{in} = 80$ l/min.

4. Conclusions

In this study, two small virtual cyclones with different dimensions were employed to investigate the effects of minor flow on cyclone performance and particle concentration. The conclusions from this study are summarized below:

1. For fixed inflow or fixed major flow, major flow efficiency increased with increasing the ratio of the minor flow to the inflow up to 20%. When the ratio of the minor flow to the inflow was fixed, however, a higher inflow rate gave a higher major flow efficiency, as has been observed for conventional cyclones.

2. Particle collection efficiency in a virtual cyclone, which occurs only by wall deposition, is a little bit lower than that in conventional cyclones. However, compared to conventional cyclones, major flow efficiency for a given particle size in a virtual cyclone is higher and the 50% cut-off diameter is smaller. This is because most of the intermediate particles are concentrated and removed in the minor flow.

3. The concentration factor of the virtual cyclone had a reversed U-shaped curve with a maximum in the region of 50% cut-off diameter. Thus, the virtual cyclone is able to concentrate particles into its minor flow within a certain size range near the 50% cut-off diameter.

Further investigation using computational fluid dynamics concepts is needed to understand the detailed fluid flow in virtual cyclones, and to model the effects of minor flow on virtual cyclones.

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