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Design and Performance Evaluation of a Novel Double Cyclone

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A novel cyclone design, named double cyclone, adds an extra cylinder wall into a conventional reversed flow cyclone. The physical performance of the double cyclone has been experimentally compared to a widely used conventional cyclone by measuring the particle concentrations both upstream and downstream of each cyclone with an Aerosizer. Tests with monodisperse polystyrene latex (PSL) particles with diameters ranging from 0.60 μm to 8.8 μm have shown that the double cyclone provides higher collection efficiency than the conventional cyclone for a tested flow rate range of 10–40 L/min. In addition, the collection efficiency difference between the double cyclone and the conventional cyclone becomes even larger as the airflow rate increases. Sharper particle-size separation characteristics were also observed for the double cyclone. Furthermore, it was found that the double cyclone operates at a lower pressure drop than the conventional cyclone at the same normalized cut size.

INTRODUCTION

Cyclones, one of the most widely used industrial dust collectors, are very rugged in design, reliable in performance, and easy to maintain. Over the years, many different types of cyclones have been built (Figure 1). In a reversed flow cyclone, or cylinder and cone design with a tangential inlet as shown in Figure 1a, aerosol enters the cyclone at the cylinder top, where the configuration of the entry causes the gas to spin forming a vortex. The high tangential velocity exerts a centrifugal force on the particles entrained in the gas, throwing them to the cyclone wall for collection. Below the bottom of the gas exit tube, the spinning gas gradually migrates inward to a central core along the cyclone axis and, from there up, finally out through the gas exit. Dust collected at the wall descends to the collection trap at the bottom of the cone, primarily due to the downward component of the gas velocity at the cyclone wall rather than to gravity.

Although the reversed flow cyclone is the most popular cyclone design, several limitations are inherent in its design. First, the collection efficiency of fine particles is not high enough when a reversed-flow cyclone is operated at ordinary flow rates. Generally, the cut size of conventional cyclones is about 5 μm (Dirgo and Leith 1985; Iozia and Leith 1989). Second, cyclones generally do not provide sharp particle-size separation between the collected and uncollected particles (Willeke et al. 1998). In addition, when the turbulent rotational flow migrates up in the cone, the separated dust has the possibility of escaping from the exit tube with the upward rotational gas flow (Ogawa 1984).

The axial flow cyclone is another frequently used cyclone design. Figure 1b shows a typical once through axial flow cyclone. The rotational flow is created by the guide vanes (Daniels 1957). Centrifugal force acts as the particle removal power and clean gas flows out through the annular space. Since there is no reversed flow in this design, the possibility of particle reentry due to the upward vortex is diminished. However, the collection efficiency is generally lower than the tangential inlet cyclones because of the relatively weak rotational gas flow achieved by means of the guide vanes.

Figure 1c shows a reversed axial flow cyclone in which the dust laden air flows axially into the cyclone. After it passes through the guide vane, it rotates to form a vortex. Again, the particles are thrown to the wall by centrifugal force. The clean air escapes from the exit tube. Both types of axial flow cyclones are used in multicyclone banks for gas cleaning.

Since cyclones have been used extensively in industry, both theoretical and experimental studies on cyclones were carried

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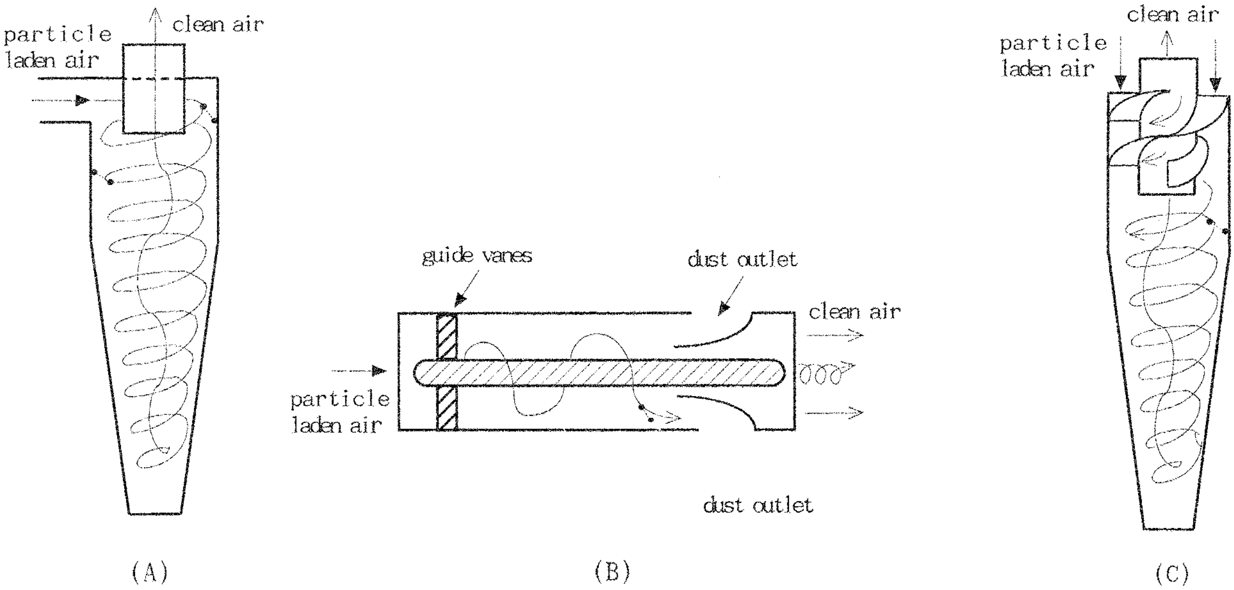

Figure 1. Schematics of different cyclone designs: (a) reversed flow cyclone; (b) once through axial flow cyclon; (c) reversed axial flow cyclone; —— gas trajectory; - - - - - particle trajectory.

out from the early 1940s to the present (Stairmand 1951; Dietz 1981; Boysan et al. 1982; Dirgo and Leith 1985; Lee et al. 1985; Iozia and Leith 1989; Li and Wang 1989; Iozia and Leith 1990; Kim and Lee 1990; Coker 1993; Liden and Gudmundsson 1997; Zhu and Lee 1999). Although our knowledge of flow and particle capture mechanisms operating inside a cyclone has increased over the years, the exact mechanisms of removing particles are still not fully understood. Thus designs of cyclones still rely largely upon experience, trial, and design guides.

In this study, a new cyclone design is introduced in an effort to increase the particle collection efficiency and to overcome some of the limitations of conventional cyclones. In the new design, an additional cylinder wall was introduced into the cyclone body which separates the total inner space into two annular sections. One is between the cyclone wall and the cylinder wall and the other is between the cylinder wall and a removable exit tube, which exits downward rather than upwards, as in a regular cyclone design. Due to this design feature, entrained air is forced to flow one more vortex inside the cyclone body and particles may be collected both on the cyclone wall and on the cylinder wall. Deposited particles descend to the lower part of the device and may be collected by removing the exit tube. This device has the appearance of two cyclones combined coaxially together and is called the double cyclone.

The objective of the present study is to compare the performance of the double cyclone with that of a conventional cyclone. Since the centrifugal force plays a very important role in cyclone performance and since one more vortex is introduced in the double cyclone, the double cyclone is expected to provide a higher collection efficiency than that of the conventional cyclone and thus work as a better aerosol sampling device.

EXPERIMENTAL

Double Cyclone

A prototype of the double cyclone was constructed out of glass. Since there is no theory that is sufficiently accurate to serve as a basis for small cyclone design, the dimensions of the double cyclone were selected to be comparable to those of conventional cyclones that had been previously evaluated. Figure 2 shows the detailed design dimensions (mm) of the double cyclone. The particle laden air enters the double cyclone tangentially on the top part of the cylinder and forms a downward vortex along the cyclone wall surface. When the vortex reaches its end, air then flows upward in the annular space between the exit tube, which faces down, and the cylinder wall to the top of the cyclone. Since there is no way for air to escape at the apex of the cone, it finally flows down again and escapes through the exit tube. Thus instead of the traditional two vortexes, the new design incorporates three vortexes in one cyclone design. Particles may be collected on the surface of both cyclone wall and cylinder wall due to the strong centrifugal force generated by the vortexes. Since the double cyclone is intended to be used as a small sampling device, not too much aerosol mass load is expected and thus no grit pot is introduced in the design. This design has a significant advantage. Due to the additional vortex, centrifugal force is strengthened and the residence time inside the cyclone body is lengthened. Both contribute to a higher collection efficiency.

The evaluation of most air sampling devices is not straightforward, and therefore the utility of new instruments is frequently assessed by comparative tests with widely used and well-characterized standard samplers. In this work, the performance

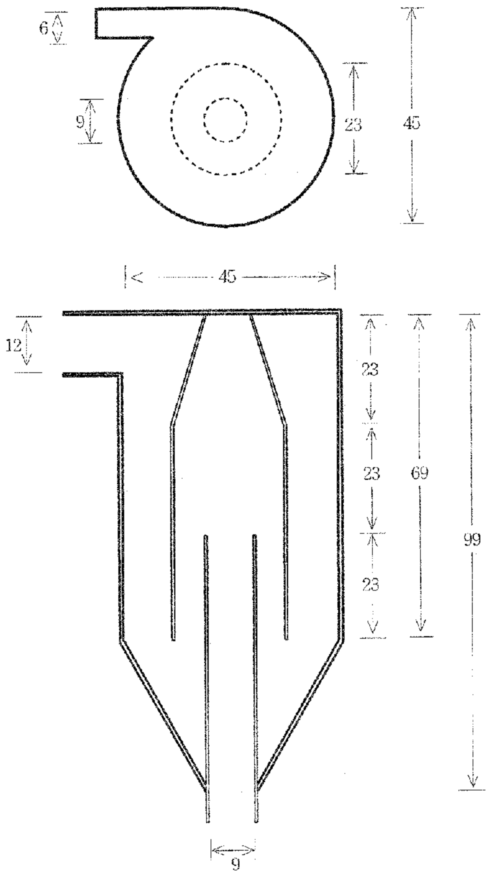

Figure 2. Schematic of the double cyclone (above dimensions are all in mm).

of the double cyclone is evaluated by comparing the particle collection efficiency of double cyclone with that of a conventional cyclone, namely, a high efficiency Stairmand cyclone.

High Efficiency Stairmand Cyclone

The performance of the double cyclone has been compared with that of the widely used glass high efficiency Stairmand cyclone, which has been used as a reference sampler for collecting airborne particles since the 1950s (Stairmand 1951). This kind of cyclone (shown in Figure 1a) is a typical reversed flow or cone-under-cylinder design. The performance of the high efficiency Stairmand cyclone has been studied extensively through both laboratory and field works (Dietz 1981; Boysan et al. 1982; Dirgo and Leith 1985; Lee et al. 1985; Iozia and Leith 1989; Li and Wang 1989; Iozia and Leith 1990; Kim and Lee 1990; Coker 1993; Liden and Gudmundsson 1997; Zhu and Lee 1999). Several other cyclone designs have been evaluated by comparing their performance with that of the high efficiency Stairmand cyclone (Razgaitis and Gusenther 1981; Jaroszczyk and Ptak 1985; Moore and McFarland 1990). The dimensions of the high efficiency Stairmand cyclone used in this study are shown in Figure 3.

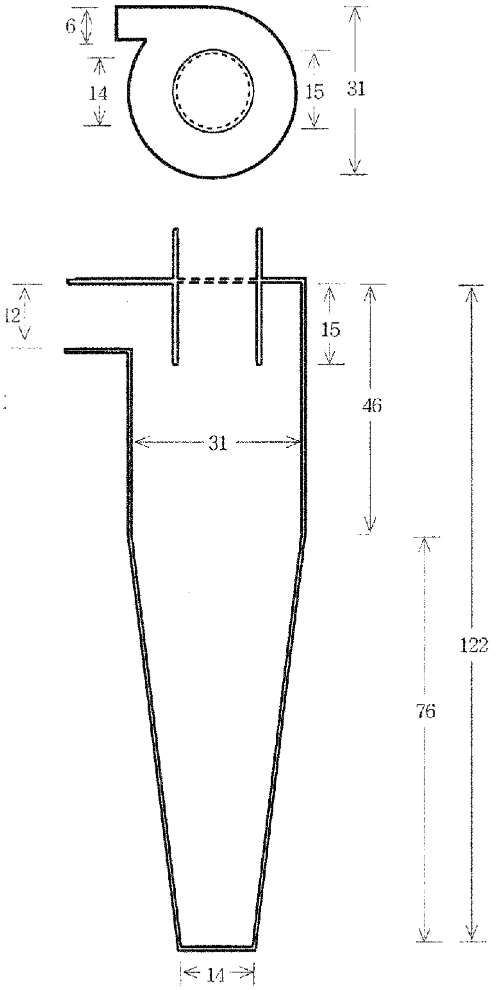

Figure 3. Schematic of the test high efficiency Stairmand cyclone (above dimensions are in mm).

Experimental Setup

A diagram of the experimental system is shown in Figure 4. The main system components consist of an aerosol generator, a test cyclone, and an aerosol detector. Monodisperse polystyrene latex (PSL) particles (Bangs Laboratories, Carmel, IN) were employed for all experiments. Aerosols containing PSL particles ranging from 0.60 μm to 8.8 μm in diameter were produced by an atomizer (TSI, Model 9302). The material density of PSL is 1.05 g/cm^3. A drying chamber was placed in-line after the aerosol generator so that the liquid in the droplets containing a PSL particle was evaporated completely before the particle entered the particle detector. By doing so, the PSL particles were clearly distinguished from the residue particles of the droplets that did not contain any PSL particle (Grinshpun et al. 1997). All the experiments were carried out at room temperature and atmospheric pressure.

The experimental procedures for evaluating the particle collection efficiencies of these cyclones follow. After particles of a desired size were generated, the particle-laden air was drawn

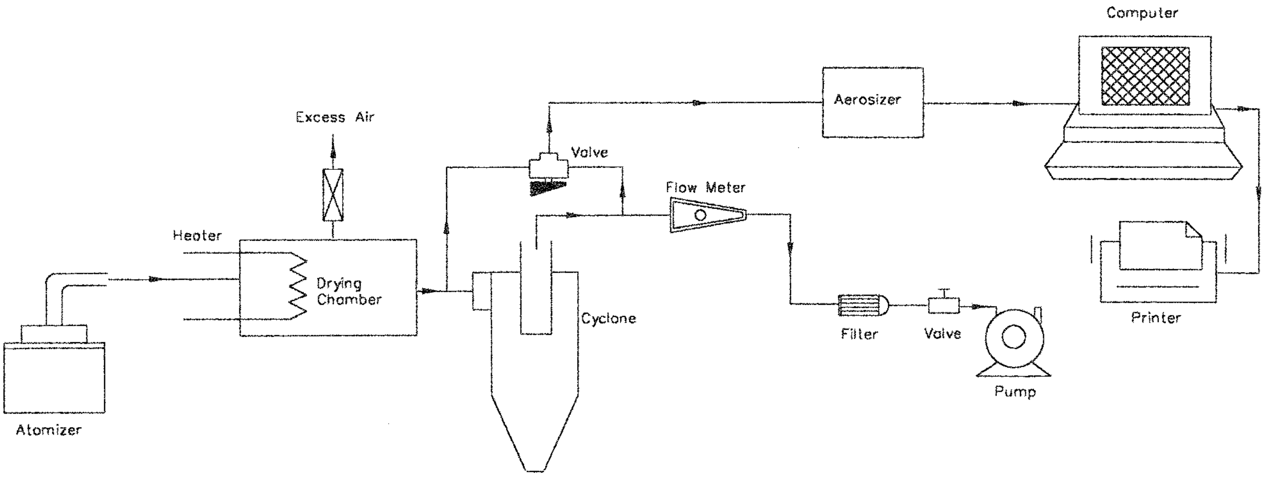

Figure 4. Schematic diagram of experimental system setup.

through a test cyclone at a desired flow rate using a vacuum pump. The flow rates employed in this study ranged from 10 L/min to 40 L/min in 10 L/min increments. Flow through the cyclone was measured by a rotameter that was calibrated against a wet test meter. Pressure drop across the cyclone was measured by a Megnehelic gauge (Dwyer Instruments Inc., Michigan City, IN). The tested particles were sampled alternately through one of two sampling lines: one upstream and the other downstream of the test cyclone. Since both sampling lines were identical, any losses that may have occurred in the sampling lines were assumed to be the same. In this study, an Aerosizer/Diluter (Amherst Process Instruments, Inc., Amherst, MA) combination was used to measure the aerosol concentrations both upstream, C_u, and downstream, C_d, of the test cyclone. The collection efficiency, E_c, of the test cyclone was determined through measurements of the upstream and downstream aerosol concentrations:

$$E_c = \frac{C_u - C_d}{C_u} = 1 - \frac{C_d}{C_u}. \qquad [1]$$

The Aerosizer was interfaced with a personal computer capable of measuring not only the total concentration, but also the particle size distribution over the desired size ranges. The instrument did not have any coincidence losses over the measured aerosol concentration range of 0.1–300 particles/cm^3 (Ulevicius et al. 1997). It was also noted that the PSL particle size indicated by the Aerosizer was in excellent agreement with the nominal PSL particle size value. The sampling flow rate of 1.0 L/min drawn by Aerosizer was taken into account when adjusting the flow rate through the cyclone. For large cyclones, a simple sampling probe may not measure the particle concentration accurately in the cyclone exit tube because the swirling motion of the air tends to decrease the uniformity of particle concentration distribution. However, in the present experiment the cyclone and the exit tube were relatively small. In addition, the sampling point was located about eight times the tube diameter downstream of the cyclone. Therefore the effect of swirling flow on particle concentration measurements was not expected to be significant. To obtain statistically significant results, for each case (cyclone dimension, flow rate, and particle diameter), five replicate experiments were conducted. After the highest and the lowest measurement efficiency data were discarded, the three remaining data sets were averaged to obtain the particle collection efficiency. Throughout the experiments, it was found that the reproducibility of the data was with approximately ±5% agreement.

RESULTS AND DISCUSSION

To compare the performance of the double cyclone and the conventional cyclone, Figure 5 shows the particle collection efficiency versus particle diameter for both cyclones at 10 L/min and 40 L/min. As indicated by many researchers (Dietz 1981; Boysan et al. 1982; Dirgo and Leith 1985; Iozia and Leith 1989,

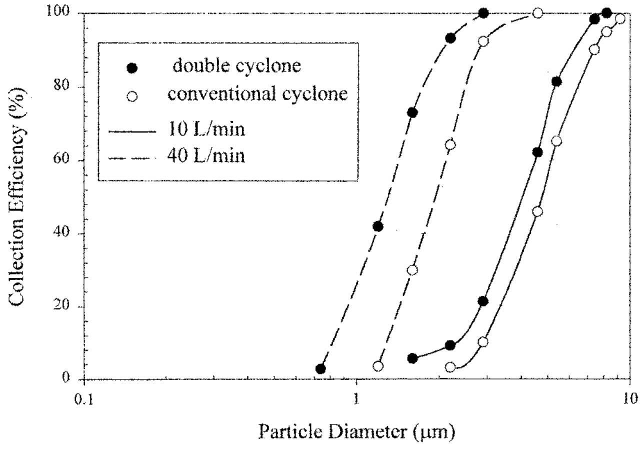

Figure 5. Particle collection efficiencies of the double cyclone and the Stairmand cyclone tested at 10 L/min and 40 L/min.

1990; Kim and Lee 1990; Coker 1993; Liden and Gudmundsson 1997; Zhu and Lee 1999), the collection efficiencies, shown in Figure 5, increased significantly with increasing particle size or gas flow rate. All the measurement data of 10 L/min also are well described by the so-called "S" shape curve. Figure 5 indicates that at a fixed flow rate of 10 L/min, the efficiency curve of the double cyclone is seen to be to the left of that of the conventional cyclone, indicating a higher collection efficiency or a lower 50% cut size (d_{50}). It is also noted that, as the flow rate increases (40 L/min), the "S" shape curve of the double cyclone moves further left of the conventional cyclone, which implies an even higher collection efficiency.

In order to systematically compare the performance of the double cyclone and the conventional cyclone, Figure 6 was generated to depict cut sizes versus all tested flow rates for both the double cyclone and the conventional cyclone. For all four flow rates, the cut sizes for the double cyclone were consistently much smaller than those of the conventional design. In addition, the difference became more and more significant as the flow rate increased, indicating that the double cyclone provided higher collection efficiency than the conventional cyclone, especially at relatively high flow rates.

Most recently, researchers found that d_{50} was not the best indicator for evaluating cyclone performance. They found that a smaller cyclone tended to have a higher collection efficiency than a larger cyclone with the same dimensional design ratios. To compare cyclones with different dimensions, d_{50}/Dc (where Dc is cyclone body diameter) may be a better parameter to use (Moore and McFarland 1993, 1995; Kenny and Gussman 1997; Liden and Gudmundsson 1997). Since the body diameters for the double cyclone and the test Stairmand cyclone were not identical in this study, Figure 7 was generated to plot normalized cut sizes, d_{50}/Dc, versus flow rates. To evaluate the performance of the double cyclone in a comprehensive way, data from several previously published experimental studies were included. Except for the lowest flow rate region (Kenny and Gussman 1996) and the highest flow rate region (Zhu and Lee 1999), the double cyclone provided smaller normalized cut sizes than other conventional cyclones in the tested flow rate region. As mentioned before, cyclones generally have difficulty in providing a sharp particle-size separation. In fact, the sampling effectiveness of a cyclone is characterized not only by the normalized cut size, but also by a slope which is the square root of the ratio of the diameter of particles removed by the cyclone with an 84% efficiency (d_{84}) to the diameter removed with a 16% efficiency (d_{16}) as shown in Equation (2).

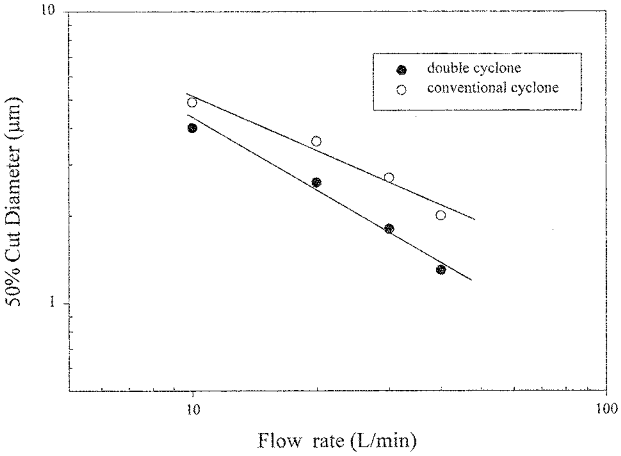

Figure 6. Comparison of cut sizes for the double cyclone and the conventional cyclone at different flow rates.

$$S_c = \sqrt{\frac{d_{84}}{d_{16}}} \qquad [2]$$

A slope of 1 indicates a step function, while a slope that exceeds 2 does not provide a definitive size cut slope. Slopes of 1.3–1.5 are considered to provide a well-defined particle size separation (Watson and Chow 1993). The slopes of both the double cyclone and the test conventional cyclone at different flow rates were calculated using Equation (2) and are listed in Table 1. According to Table 1 the slopes of the double cyclone were always smaller than those of the conventional test cyclone, which indicates a sharper particle-size separation is achieved. Thus at a fixed flow rate, the double cyclone provided a smaller normalized cut size and a better designed particle-size separation curve. Both of these features contribute to a more efficient cyclone design.

Another important issue in cyclone design is energy consumption, which may be indirectly evaluated by examining the pressure drop across the cyclone (Jaroszczyk and Prak 1985; Kim and Lee 1990; Griffiths and Boysan 1996; Zhu and Lee 1999). Generally speaking, the pressure drop, ΔP_c, in a cyclone can be defined as the pressure difference between the mean total pressure (static pressure plus dynamic pressure) in the inlet, P_{iT}, and the mean total pressure in the exit tube, P_{eT}, as follows:

$$\begin{aligned}\Delta P_c &= P_{iT} - P_{eT}\\ &= \left(P_{is} + \rho \cdot \frac{V_i^2}{2}\right) - \left(P_{es} + \rho \cdot \frac{V_{e\theta}^2 + V_{er}^2}{2}\right), \qquad [3]\end{aligned}$$

where P_{is} is the static pressure in the inlet tube, P_{es} is the static pressure in the exit tube, ρ is the gas density, V_i is the inlet velocity, $\rho \cdot (V_i^2/2)$ is the dynamic pressure in the inlet tube, $V_{e\theta}$ is the tangential velocity of gas in the exit tube, V_{er} is the axial velocity of gas in the exit tube, $V_{e\theta}^2 + V_{er}^2$ is the square of the mean velocity in the exit tube, and $\rho \cdot ((V_{e\theta}^2 + V_{er}^2)/2)$ is the dynamic pressure in the exit tube.

It is almost impossible to exactly measure V_i, $V_{e\theta}$, and V_{er} in such a small cyclone design. Thus the mean velocity in the inlet tube, V_i, and in the exit tube, V_e, is assumed to be the ratio of the flow rate passing through the cyclone to the cross-section area of the inlet tube and the exit tube, respectively.

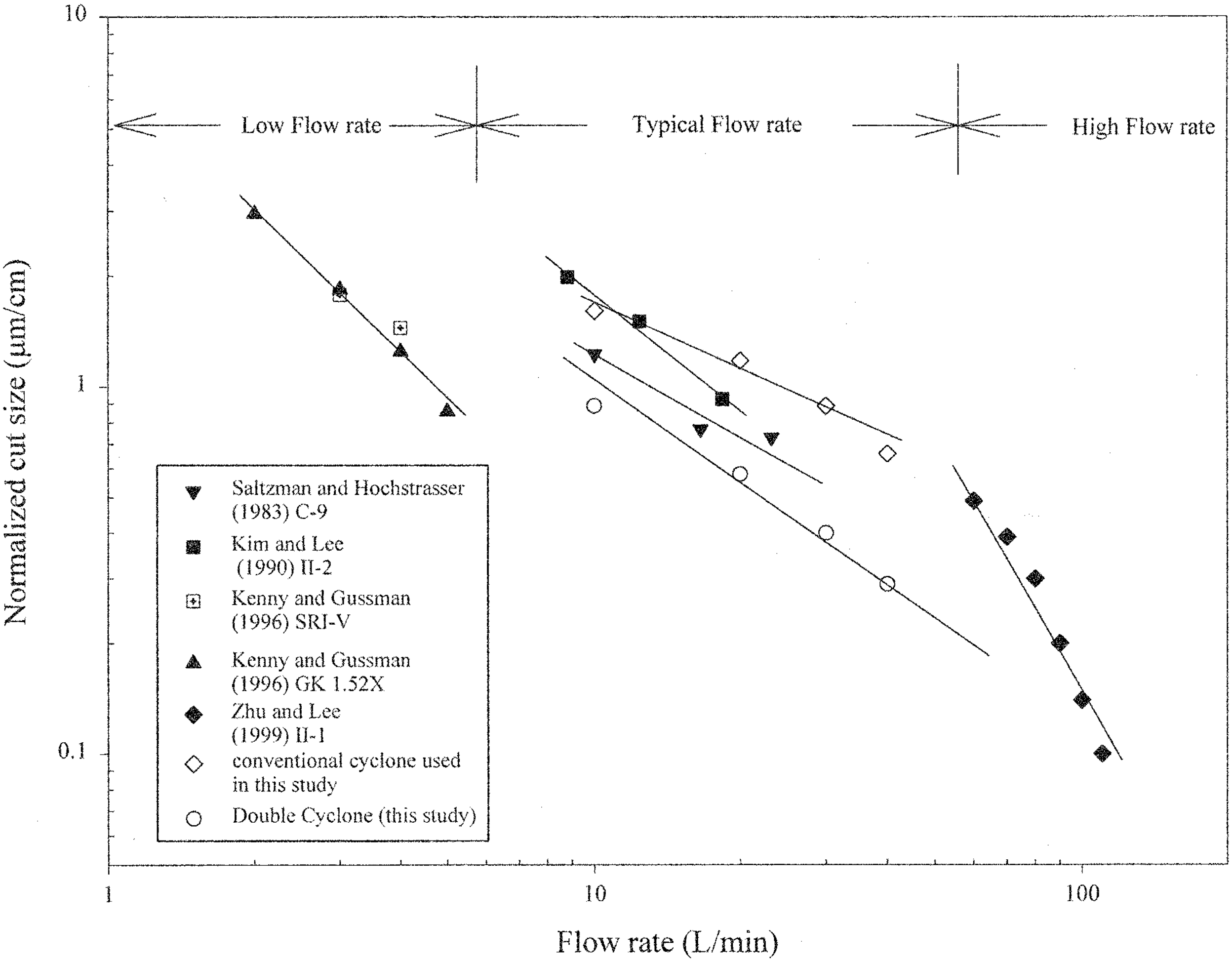

Figure 7. Flow rates versus normalized cut sizes for different cyclones.

Equation (4) follows:

$$V_i = \frac{Q}{A_i} \text{ and } V_e = \frac{Q}{A_e}, \qquad [4]$$

where Q is the flow rate passing through the cyclone, A_i is the cross-sectional area of the inlet tube, and A_e is the cross-sectional area of the exit tube. Therefore Equation (3) is reduced to Equation (5) as follows:

$$\begin{aligned} \Delta P_c &= P_{iT} - P_{eT} \\ &= P_{is} + \rho \cdot \frac{(Q/A_i)^2}{2} - P_{es} - \rho \cdot \frac{(Q/A_e)^2}{2} \\ &= (P_{is} - P_{es}) + \rho \cdot \frac{Q^2}{2} \cdot \left(\frac{1}{A_i^2} - \frac{1}{A_e^2}\right). \qquad [5] \end{aligned}$$

The static pressure difference, $(P_{is} - P_{es})$, is measured by the megnehelic gauge, and the dynamic pressure difference is calculated and added to $(P_{is} - P_{es})$ to yield the total pressure drop. The total pressure drops of the double cyclone and those of the conventional cyclone at different flow rates are listed in Table 2. As observed by prior researchers, the pressure drop became larger as the flow rate is increased (Jaroszczyk and Ptak 1985; Kim and Lee 1990: Griffiths and Boysan 1996; Zhu and Lee 1999). As expected, at a fixed flow rate, the pressure drop across the double cyclone was greater than that across the conventional cyclone. This occurs because the pressure drop is mainly due to the formation of the vortex, thus an enhanced rotational flow or

Table 1
Slopes of particle-size separation characteristics for the double cyclone and the conventional test cyclone at different flow rates

Flow rate (L/min)	Double cyclone	Conventional cyclone
10	1.39	1.58
20	1.38	1.57
30	1.37	1.55
40	1.37	1.53

Table 2
Pressure drops (Pa) of the double cyclone and the conventional test cyclone at different flow rates

Flow rate (L/min)	Double cyclone (Pascal)	Conventional cyclone (Pascal)
10	12.5	5.4
20	32.5	12.3
30	82.5	20.9
40	145.0	45.2

an additional vortex in the double cyclone ensures a higher collection efficiency, which will cause an increase in pressure drop. Since pressure drop is basically a measure of the energy that a cyclone consumes and the normalized cut size characterizes the effectiveness of a cyclone design, a correlation of these two factors to examine their relationship should provide useful data. Figure 8 depicts the total pressure drop versus of the normalized cut size for both the double cyclone and conventional cyclones studied by previous researchers and in this study. A linear relationship is observed for most cyclone designs in Figure 8. In addition, the regression line for the double cyclone is located to the left of those for conventional cyclones, indicating a better cyclone design in that the double cyclone allows lower pressure drop or consumes less energy at the same normalized cut size. Thus it can be concluded that the double cyclone is indeed a more efficient and less costly design than conventional cyclones.

The reason that the double cyclone is superior to the conventional cyclones can be explained as follows. First, the additional cylinder wall separates the cyclone body space into two annular sections. Recently, several researchers found that the annular dimension value is the key radial design factor in determining cyclone performance (Moore and McFarland 1993, 1995; Kenny and Gussman 1997; Liden and Gudmundsson 1997). Therefore an additional cylinder wall separates one big annular section in a conventional cyclone design into two smaller annular sections in the double cyclone design and may help to enhance the collection efficiency. The added cylinder wall also serves as a particle collection surface providing additional surface for particles to deposit. Second, due to the design, particle-laden air is forced to migrate an additional vortex inside the double cyclone. Since centrifugal force is the main particle-removing mechanism inside a cyclone, an additional vortex provides added

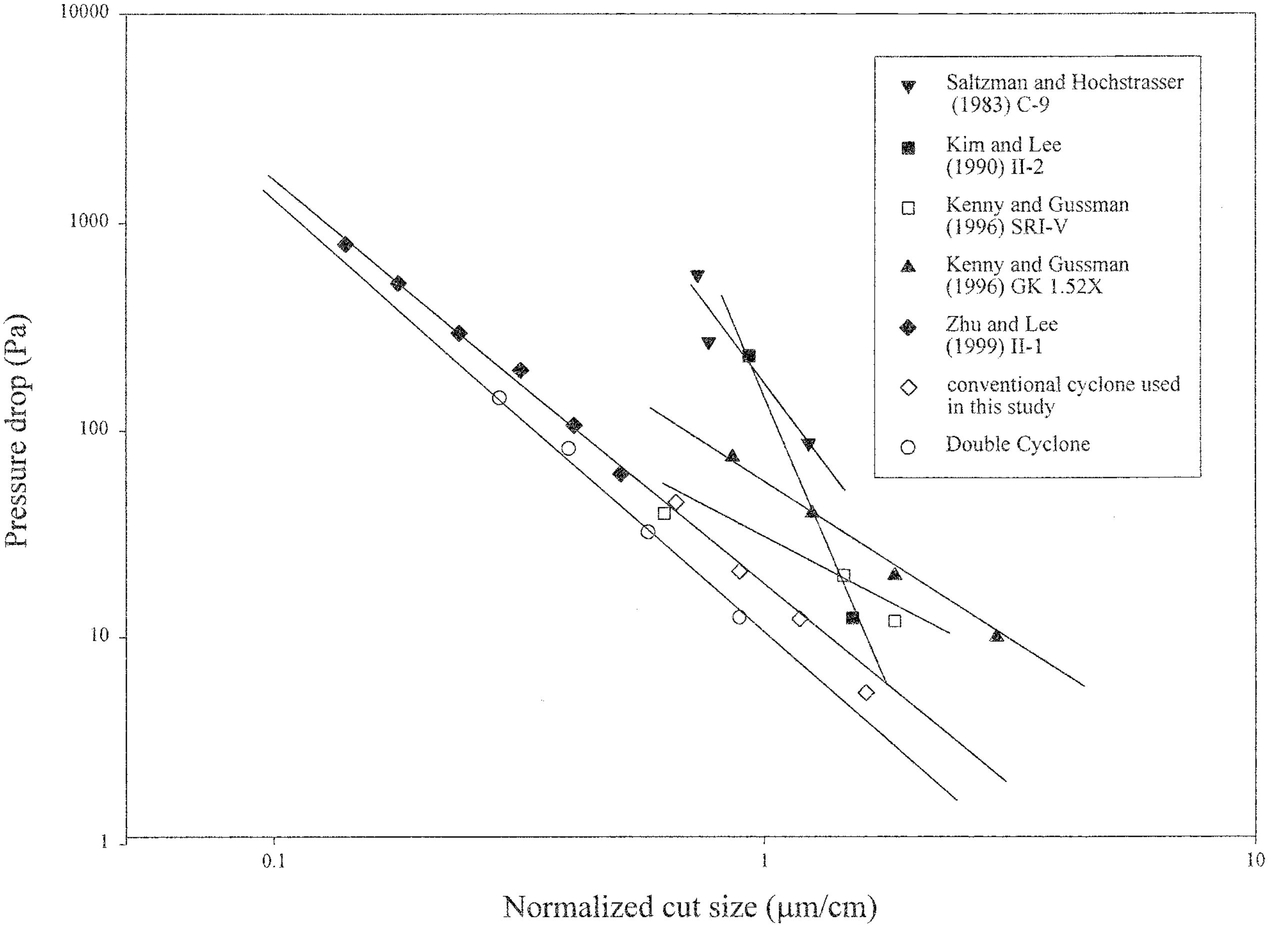

Figure 8. Pressure drop versus normalized cut size for the different cyclones.

centrifugal force to collect more particles. Thus the development of this additional vortex contributes significantly to particle collection efficiency. To fully develop the vortex, a higher flow rate is preferable in that it provides stronger rotational motion of the air. This may be the reason that the double cyclone provides increasingly higher collection efficiency than the conventional test cyclone when the airflow rate is increased as shown in Figures 5, 6, and 7. Finally, the lower pressure drop inside the double cyclone may be explained as follows. Due to the double cyclone design, at the inlet into the second cyclone the air stream does not enter through a single inlet port, but along the entire perimeter of the middle cylinder. Thus the pressure drop at the inlet to the second cyclone is reduced in relation to what it should have been for an ordinary single-port tangential inlet at the same diameter (23 mm).

CONCLUSION

The experimental results in this study provide convincing evidence that the double cyclone is a superior design compared to conventional cyclones. The double cyclone has a higher collection efficiency, a sharper separation curve, and consumes less energy to achieve the same normalized cut size. It is believed that all of these advantages are due to the added cylinder wall in the double cyclone design that separates the limited cyclone body space into two annular sections and forces the particle-laden air to travel three vortexes before it leaves the cyclone.

REFERENCES

Boysan, F., Ayers, W. H., and Switherband, J. (1982). A Fundamental Mathematical Modelling Approach to Cyclone Design, *Trans. ICHEME* 60:222–230.

Coker, A. K. (1993). Understand Cyclone Design, *Chem. Eng. Prog.* 51–55.

Daniels, T. C. (1957). Investigation of a Vortex Air Cleaner, *Engineering (London)* 8:258.

Dietz, P. W. (1981). Collection Efficiency of Cyclones Separators, *AICHE J.* 27:888–892.

Dirgo, J., and Leith, D. (1985). Cyclone Collection Efficiency: Comparison of Experimental Results with Theoretical Predictions, *Aerosol Sci. Technol.* 4:401–411.

Griffiths, W. D., and Boysan, F. (1996). Computational Fluid Dynamics (CFD) and Empirical Modelling of the Performance of a Number of Cyclone Samplers, *J. Aerosol Sci.* 27/2:281–304.

Grinshpun, S. A., Willeke, K., Ulevicius, V., Juozaitis, A., Terzieva, S., Donnelly, J., Stelna, G. N., and Brenner, K. P. (1997). Effect of Impaction, Bouncing, and Reaerosolization on the Collection Efficiency of Impingers, *Aerosol Sci. Technol.* 26:326–342.

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

Ioza, D. L., and Leith, D. (1990). The Logistic Function and Cyclone Fractional Efficiency, *Aerosol Sci. Technol.* 12:598–606.

Jaroszczyk, T., and Ptak, T. (1985). Experimental Study of Aerosol Separation using a Minicyclone, *Powder and Bulksolid Confer.* (10th Annual), pp. 611–622.

Kenny, L. C., and Gussman, R. A. (1995). Characterization and Modelling of a Family of Cyclone Aerosol Preseparators, *J. Aerosol Sci.* 26:S777–S778.

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

Lee, K. W., Gieseke, J. A., and Piispanen, W. H. (1985). Evaluation of Cyclones Performance in Different Gases, *J. Atmospheric Env.* 19/6:847–852.

Li, E., and Wang, Y. (1989). A New Collection Theory of Cyclone Separators, *AICHEJ* 35:666–669.

Liden, G., and Gudmundsson, A. (1997). Semi-Empirical Modelling to Generalise the Dependence of Cyclone Collection Efficiency on Operating Conditions and Cyclone Design, *J. Aerosol Sci.* 28:853–874.

Moore, M. E., and McFarland, A. R. (1990). Design of Stairmand-Type Sampling Cyclones, *Am. Ind. Hyg. Assoc.* 51/3:151–159.

Moore, M. E., and McFarland, A. R. (1993). Performance Modelling of Single-Inlet Aerosol Sampling Cyclone, *Environ. Sci. Technol.* 27:1842–1849.

Moore, M. E., and McFarland, A. R. (1995). Design Methodology for Multiple Inlet Cyclones, *Environ. Sci. Technol.* 30:271–276.

Ogawa, A. (1984). Cyclone Dust Collectors. In *Separation of Particles from Air and Gases*, edited by J. Beddow. CRC Press, Inc., FL.

Razgatis, R., and Gusenther, D. A. (1981). Separation Efficiency of a Cyclone Separation with Turbulence Suppressing Rotating-Insert, *J. Eng. Power.* 103:566–571.

Stairmand, C. J. (1951). The Design and Performance of Cyclone Separators, *Trans. Instn. Chem. Engrs.* 29:356–383.

Ulevicius, V., Willeke, K., Grinshpun, S. A., Donnelly, J., Lin, X., and Mainelis, G. (1997). Aerosolization of Particles from a Bubbling Liquid: Characteristics and Generator Development, *Aerosol Sci. Technol.* 26:326–342.

Watson, J. G., and Chow, J. C. (1993). Ambient Air Sampling. In *Aerosol Measurement: Principles, Techniques and Applications.*, edited by K. Willeke and P. A. Baron. Van Nostrand Reinhold, New York, pp. 622–639.

Willeke, K., Lin, X., and Grinshpun, S. A. (1998). Improved Aerosol Collection by Combined Impaction and Centrifugal Motion, *Aerosol Sci. Technol.* 28:439–456.

Zhu, Y., and Lee, K. W. (1999). Experimental Study on Small Cyclones Operating at High Flow Rates, *J. Aerosol Sci.* 30:1303–1315.