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Experimental Study of Particle Collection by Small Cyclones

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A new set of experimental data on the particle collection characteristics of small cyclones is reported. The collection efficiency for particles ranging from 2 to 10 μm in diameter was measured systematically for nine cyclones at flow rates ranging from 8.8 to 18.4 L/min. Special emphasis was given to the effects of the exit tube size and of the cyclone body size on the particle collection efficiency. The size ratio of the exit tube to the cyclone body was varied from 0.24 to 0.80. The experimental results show that the stiffness of the particle collection cutoff with size does not change noticeably with a change in the cyclone body size while operation of a cyclone at a low flow rate can cause the particle collection characteristics to become less stiff. It was also found that the exit tube diameter influences the particle collection efficiency substantially, with results showing that as the exit tube size is decreased, the collection efficiency increases. A large cyclone body size increases the efficiency. However, when the cyclone body is increased excessively, the collection efficiency appears to decrease somewhat. The experimental data were compared with existing cyclone theories and Barth's (1956) theory was found to be in good agreement. Finally, the exit tube was found to affect substantially the pressure drop of cyclones. As the exit tube size increased, the pressure drop decreased. However, when the exit tube size was further increased until it approached the body size, the pressure drop increased again.

INTRODUCTION

Cyclones are one of the most popular and commonly used inertial devices for removing particulates from gas streams and for measuring the size distribution of airborne particles. The working principle of cyclones is that particulate-laden gas enters the upper part of a cyclone tangentially through an inlet tube, creating a spiral flow around the exit tube. As this spiral moves down, particles are deposited onto the cyclone body wall by centrifugal force. The gas that reaches the lower part of the cyclone moves towards the exit tube to form an inner spiral.

Cyclones are very rugged in design and reliable in performance. For this reason they are widely used to control particulate matter for a variety of applications. Cyclones range in size from a miniature cyclone having a body diameter of < 2 cm, for collecting submicrometer range inhalable particles in industrial hygiene applications, to a cyclone of several meters in diameter for removing particulate matter from gases in industrial plants.

While cyclones have been used extensively in various industries for a long time, the exact mechanisms of removing particulates are still not fully understood. The reason for the lack of complete understanding of the cyclone operating principle is partially because the fluid flow in a cyclone is rather complex. The geometry of a seemingly simple cyclone involves more than half a dozen dimensions, including cyclone body diameter, inlet tube diameter, exit tube diameter, exit tube length, cyclone height, cyclone cone size, dust collection cup size, etc. Exact description of the complete three-dimensional flow field in this geometry and

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modeling of particle motion in such a flow field can become highly complex. Therefore, most cyclone theories are based on a simplified model or depend upon empirical correlation equations. Theoretical studies of cyclone performance include Lapple (1950), Barth (1956), Sproull (1972), Leith and Licht (1972), Theodore and DePaola (1980), and Dietz (1981). While some of these theories were developed about 30 years ago, they have not been well validated. Therefore they remain not fully utilized for practical applications, and design of cyclones still relies upon experience, trial, and on a design guide. Stairmand (1951) presented one of the most popular design guides. His standard design guide suggested that the exit tube diameter be half of the cyclone body diameter for designing a cyclone termed as a high efficiency cyclone and 0.75 for a medium efficiency cyclone. While this standard cyclone design guide has been widely used, it does not have any firm theoretical or experimental grounding. In fact, the effects of each cyclone dimension are poorly understood. For this reason, some of the above existing cyclone theories involve as many as eight cyclone dimensions (Barth, 1956; Leith and Licht, 1972; Dietz, 1981) while others consider only three or four dimensions (Lapple, 1950; Theodore and DePaola, 1980). The purpose of the present work is to help better understand the working principle of cyclones by exploring experimentally the effects of both cyclone body and exit tube size on cyclone performance in a systematic way. The particle collection efficiency for a series of cyclones whose dimensions do not follow those suggested by classical design guides has been measured. In addition, the ability of cyclone theories to predict cyclone performance is evaluated by comparing the experimental results with existing theories.

EXPERIMENTAL

Nine cyclones were specially designed for this study and made of glass. The dimensions of these cyclones are shown in Figure 1 and Table 1. As shown in the table, three body sizes and four different exit sizes were covered. In order to specifically examine the effects of the exit tube size and the body diameter, all other dimensions were designed to remain the same. The cross section of the cyclone inlet tube attained an approximately elliptical shape with a major axis of 1.29 cm and a minor axis of 0.71 cm as shown in Figure 1. The schematic diagram of the experimental system is shown in Figure 2. The system consisted of an aerosol generator, a test cyclone, and an aerosol detector. Throughout the experiment, particles of a uniform size produced by the Berglund-Liu aerosol generator (model 3050, TSI Inc., St. Paul, MN) were used. The material of the particles was dioctyl phthalate (DOP) whose density is 0.98 g/cm^3. The operating principle of the particle generator is referred to Berglund and Liu (1973). In order to ensure that the solvent used in this generation method evaporated completely, a drying chamber was placed after the aerosol generator. All the experiments were carried out at room temperature.

The experimental procedures for measuring cyclone efficiencies were designed to first generate particles of a desired size, then to pass the particle-laden air through a test cyclone at a desired flow rate, and then to measure particle concentrations upstream and downstream of the cyclone. For measuring the particle concentrations, an aerodynamic particle sizer (model 3300, TSI Inc.) was used. The aerodynamic particle sizer is capable of measuring not only the total concentration but the particle size distribution over 50 different size classes. The size of the particles produced was controlled by the operating conditions of the Berglund-Liu aerosol generator. Throughout the experiments, it was found that the particles were very uniform in size. Flow rates were measured with a hot wire mass flow meter which was calibrated against a wet test meter. A sampling flow rate of

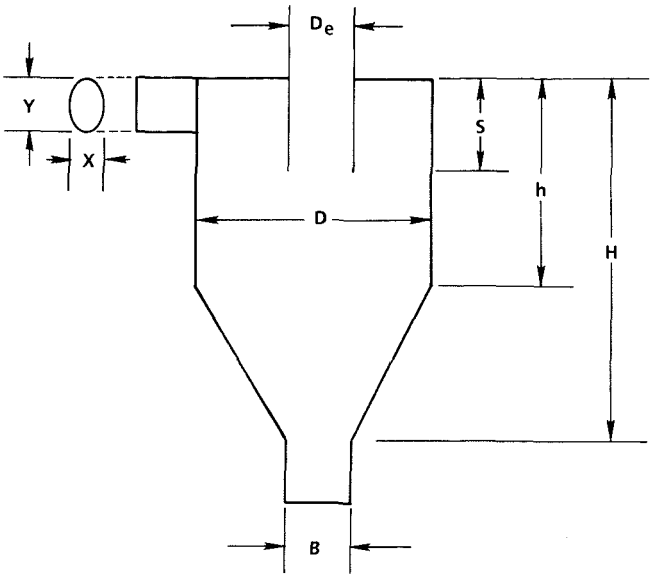

FIGURE 1. Cyclone dimension.

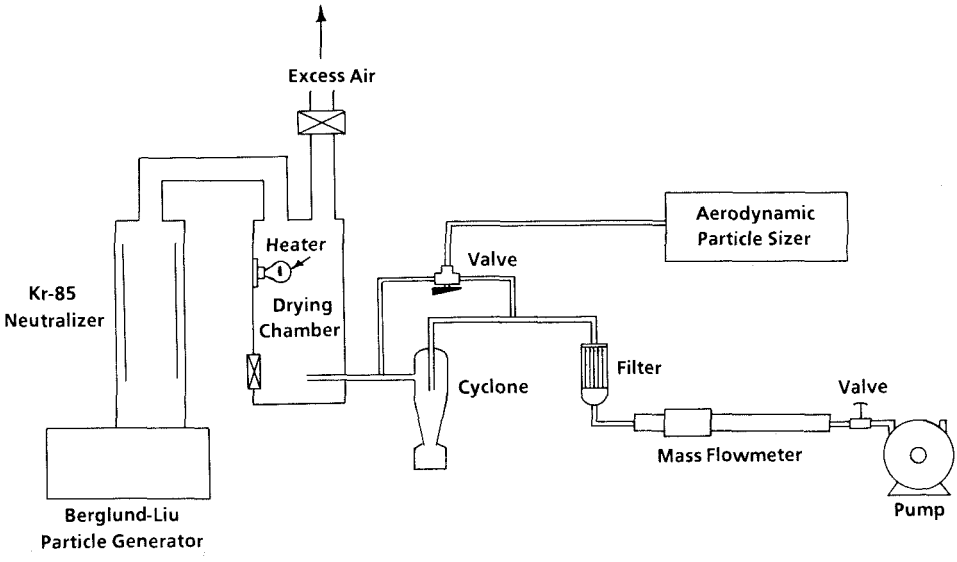

FIGURE 2. Schematic diagram of experimental setup.

5 L/min, as needed by the aerodynamic particle sizer, 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 cyclone exit ducts due to swirling motion of air. In swirling flows the particle concentration distribution may not be uniform. In the present experiment, the exit tube was relatively small and the sampling flow rate was on the same order of magnitude with the flow rate through the

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TABLE 1. Dimensions of Tested Cyclones

Cyclone no.	Cyclone body, I.D. (cm)	Exit tube, I.D. (cm)	Common for all cyclones, (cm)
I-1	2.19	0.8	$X = 0.71$
I-2	2.19	1.0	$Y = 1.29$
I-3	2.19	1.36	$S = 3.6$
I-4	2.19	1.75	$h = 4.5$
II-1	3.11	0.8	$H = 9.5$
II-2	3.11	1.0	$B = 1.5$
II-3	3.11	1.36	
II-4	3.11	1.75	
III-2	4.11	1.0	

TABLE 2. List of 50% Particle Cut Diameter

Cyclone no.	Flow rate (L/min)		
	8.8	12.4	18.4
I-1	6.7	5.1	3.3
I-2	7.3	6.0	4.3
I-3	—	7.2	6.0
I-4	—	8.5	6.7
II-1	6.2	4.7	2.9
II-2	6.2	4.7	2.9
II-3	6.9	5.9	4.4
II-4	8.1	6.7	5.4
III-2	7.1	5.1	3.6

exit tube. Further, the sampling point was located about eight times the tube diameter downstream of the cyclone. Therefore, the effect of swirling flows on particle concentration measurements is not expected to be significant.

RESULTS AND DISCUSSION

Figures 3–5 present the collection efficiency data obtained from the measurements for the nine cyclones. The 50% particle cut diameter for each experimental condition is summarized in Table 2.

In Figure 3, the measurement results of the 2.19-cm cyclone, designated cyclone I in Table 1, are presented for four different exit tube sizes. Three flow rates of 8.8, 12.4, and 18.4 L/min were used for measurements for the first two exit tube sizes, and two flow rates were employed for the two remaining exit tube sizes. Most of the measurement data are seen to be well accommodated by a so-called "S"-shape curve, with little scatter. Reproducibility of the data was found to be very good with about $\pm 3\%$ agreement on a weekly basis. It is believed that the ability of the Berglund-Liu generator to precisely control the size of particles, combined with the accurate concentration measurement technique provided by the aerodynamic particle sizer, produced such high-quality, reproducible data. As expected, the collection efficiency is seen to increase as either the particle size or the flow rate increases. With respect to exit tube size, the particle collection efficiency is found to decrease with increasing exit tube size.

It should be noted that an increase in the exit tube size by approximately twofold can result in doubling the particle cut size in the case of 18.4 L/min in Figure 3. A change in the particle cut size of this magnitude, which can be caused by simple modification of the exit tube size, has not been widely recognized previously. This is because for most cyclone design applications the ratio of the exit tube size to the cyclone body size is kept roughly the same. The effect of the exit tube size on the particle collection efficiency may be important due to its role in controlling both the outer and inner spiral flow patterns. If, for example, we have a very large exit tube whose size is almost as large as the cyclone body size, it is likely that the spiral pattern is not as sharp, and that some particles may enter the exit tube without reaching the lower part of the cyclone. With a small size exit tube however, a well-defined outer spiral flow and a small and long inner spiral flow are expected to form, forcing an increased number of particles to travel to the lower part of the cyclone. There is some evidence that the small exit tube also increases the chance for particles to be de-

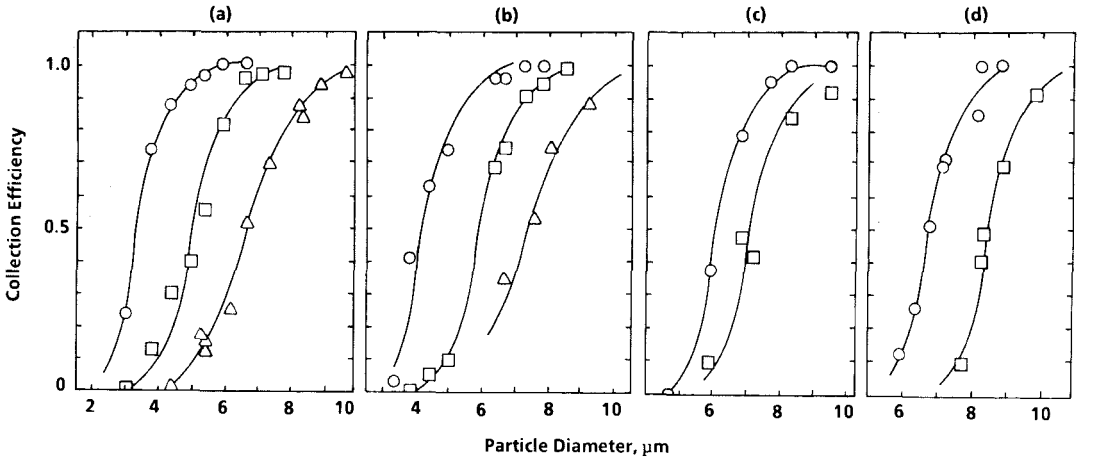

FIGURE 3. Measured collection efficiency as a function of particle size for (*a*) cyclone I-1, (*b*) cyclone I-2, (*c*) cyclone I-3, and (*d*) cyclone I-4. (○) 18.4 L/min; (□) 12.4 L/min; (△) 8.8 L/min.

posited onto the inner exit tube surface. This point will be discussed in more detail later.

Figure 4 presents the results of the particle collection efficiency measurement for cyclone II, which has a body size of 3.11 cm. Generally, the trends regarding the influences of the particle size, the flow rate, and the exit tube size on the efficiency of cyclone I apply equally here. When Figures 3 and 4 are compared for an identical condition, it is noted that the particle collection efficiency for a cyclone having a larger body diameter is higher than that for a smaller

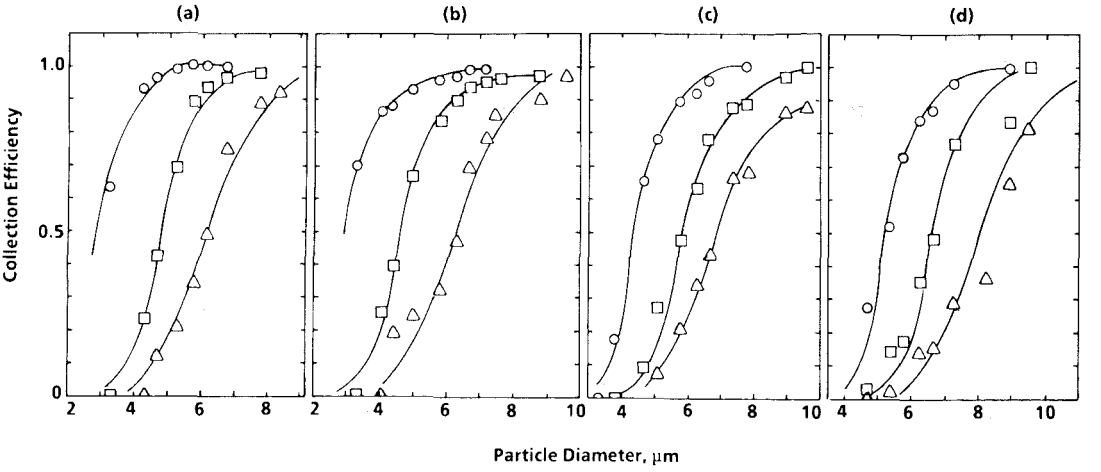

FIGURE 4. Measured collection efficiency as a function of particle size for (*a*) cyclone II-1, (*b*) cyclone II-2, (*c*) cyclone II-3, and (*d*) cyclone II-4. (○) 18.4 L/min; (□) 12.4 L/min; (△) 8.8 L/min.

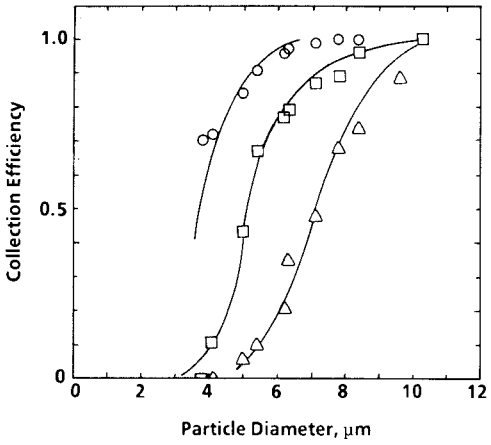

FIGURE 5. Measured collection efficiency as a function of particle size for cyclone III-2. (○) 18.4 L/min; (□) 12.4 L/min; (△) 8.8 L/min.

cyclone. When all the other dimensions are kept equal, a large body diameter is thought to provide particles with a longer residence time, thereby increasing the chance to be deposited. In order to confirm this hypothesis, a cyclone with an even larger body size was tested. Figure 6 presents the results for cyclone III-2, which has a body size of 4.11 cm. When Figures 4 and 5 are compared, efficiencies for III-2 are seen to be generally lower than those for cyclone II-2, whose body size is smaller. Therefore, the above attempt to explain the body size dependence with the residence time alone does not appear to be adequate. While the residence time for particles will become longer with a larger body size, an excessively large body diameter may begin to unfavorably affect the pattern of spiral flows, either by reducing the number of flow turns in the cyclone or by reducing the tangential flow velocity near the wall surface. Body size effects will be discussed in more detail later.

Figures 3 through 5 show that the collection efficiency curve is sharper as the air flow rates increase, but the shape of collection efficiency curves for a fixed flow rate is seen to remain roughly the same regardless of cyclone body size and exit tube size. To further confirm this observation, the efficiency data in Figures 3 through 5 were shifted along the particle size axis until they fell on a single curve that depends upon only the flow rate. The results are shown in Figure 6, illustrating the discussed observa-

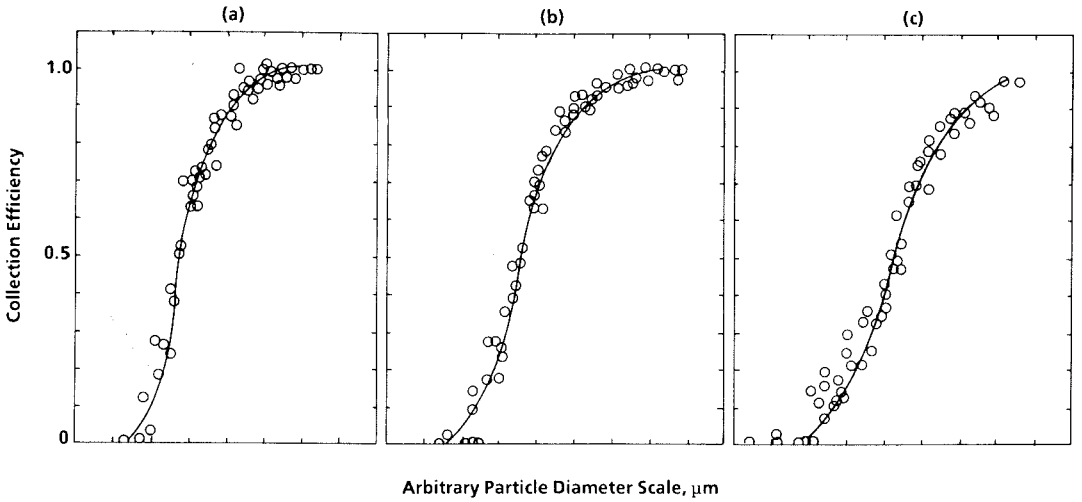

FIGURE 6. Collection efficiency data for a given flow rate shifted along particle size axis. (*a*) 18.4 L/min; (*b*) 12.4 L/min; and (*c*) 8.8 L/min.

tion. This is an important point, because for a given flow rate it is possible to alter the particle cut size without deteriorating the sharpness simply by adjusting the exit tube size. Past practice was of course to try a cyclone of different body size, keeping the ratio of the exit tube to body size approximately the same.

An important interest in cyclone studies, for both experimental and theoretical purposes, is the determination of the location within the inner structure of a cyclone where the predominant deposition of particles occurs. An additional qualitative experiment was performed to address this question. The inner surface of cyclone I-1 was first coated with mineral oil. Carbon black particles were then passed through the cyclone at a flow rate of 12.4 L/min. The reason for coating the walls with oil is, of course, to prevent the shift of particles from the position of their original deposition. In order to roughly control the size of the carbon black particles entering the cyclone, cyclone I-3, whose particle cut diameter is a few microns higher as seen in Table 2, was placed upstream of cyclone I-1. Carbon black particles were passed continuously until the deposition pattern became visible.

A significant amount of deposit was found in the lower part of the cyclone body as expected. A large portion of the particles that are transported to this region by the downward spiral flow may become deposited by centrifugal force. In addition, a sudden change in the flow direction in this region would cause large particles to deviate from air stream lines and deposit onto walls. The results also showed slight particle deposits on the upper wall of the cyclone immediately after the tip of the inlet tube. Apparently some particles entering the cyclone tangentially through the inlet tube become deposited on the cyclone wall by the impaction mechanism before fully turning around the annular gap between the exit tube and the inner wall of the cyclone body. Finally, some additional deposit was observed at the entrance region inside the exit tube. Apparently the particles following the inner spiral flow became deposited on the exit tube by centrifugal force. The deposit was heaviest at the entrance and rapidly diminished within the next 1 cm length.

It has been widely accepted that particle collection in cyclones occurs mainly by centrifugal force in the main cyclone body section. Therefore, most theoretical studies take this deposition mechanism as the only particle collection mechanism. This study suggests that there may be additional collection mechanisms that are potentially important in cyclones. These are impaction onto the cyclone wall from the inlet and deposition inside the exit tube. A quantitative study on the magnitude of these mechanisms remains as future work.

COMPARISON WITH THEORIES

Since the present study has provided experimental data for a total of nine different cyclone configurations at three different flow rates as a function of particle size, it will be useful and informative to compare the present results with existing theories. Dirgo and Leith (1985) measured the particle collection efficiency for a relatively large cyclone of one design at five different flow rates and compared the measurement results with several cyclone theories. The theories used for their comparison study included Lapple (1950), Barth (1956), Leith-Licht (1972), and Dietz (1981). They found that the Barth theory, with simple modification, and the Leith-Licht theory were better than the others for the cyclone configuration they used in their study. Only the Barth and Leith-Licht theories, which Dirgo and Leith (1985) found to best predict efficiencies, will be used here.

Barth's theory is based on the assumption that there is an imaginary central core that extends from the cyclone exit tube down to the cyclone bottom. The theory further defines a critical particle size for which its

centrifugal force is equal to the drag force on the edge of the core. While particles smaller than the critical size will be swept into the core and escape the cyclone, larger particles will be collected out toward the cyclone wall by their large centrifugal force. The collection efficiency, η is expressed as follows:

$$\eta = \frac{1}{\left[1 + (V_{ts}/V_{ts}^*)^{-3/2}\right]}. \quad (1)$$

Here, V_{ts} is particle terminal settling velocity and V_{ts}^* is terminal settling velocity of the critically sized particle whose force towards the wall is balanced by the inward radial drift.

$$\frac{V_{ts}}{V_{ts}^*} = \frac{\pi \cdot h^* \cdot V_t^2 \cdot \rho_p \cdot d^2}{9Q \cdot \mu} \quad (2)$$

$$h^* = H - S \qquad \text{for } De \le B$$

$$h^* = \frac{(H-h)(D-De)}{(D-B)} + (h - S) \qquad \text{for } De > B$$

$$V_t = V_0\left[\frac{(De/2)(D-b)\pi}{2ab\alpha + h^*(D-b)\lambda\pi}\right]$$

$$\lambda = 0.02$$

$$\alpha = 1 - 1.2(b/D),$$

where D, De, H, h, S and B are shown in Figure 1, and d is the particle diameter, h^* is the height of the central core, b is the width of the cross-section of the inlet, a is the height of the cross section of the inlet, Q is the flow rate, μ is the gas viscosity, V_0 is the gas outlet velocity, and ρ_p is the particle density.

The Leith-Licht (1972) theory is a direct calculation without employing the critical central core concept upon which Barth's theory is based. This theory calculates the collection efficiency using the assumption that uncollected dust is uniformly mixed throughout the entire height of the cyclone and then calculating an average residence time for particles. The collection efficiency is given by an equation that is similar to the Barth theory in complexity. The exact features of the model and final expression for the efficiency may be referred to in Leith and Licht (1972) or Dirgo and Leith (1985). Dirgo and Leith (1985) also includes a good review of other theories.

The modification of Barth's theory that Dirgo and Leith (1985) found necessary to better fit their data is quadruplication of V_{ts}/V_{ts}^* in Eq. (1). They found that this simple modification enables Barth's theory to give efficiency values higher than the original theory, providing a better fit to their data. In this study, such a modification was not made and the efficiency values predicted by Barth's original theory were used.

Both theories are based on a design of the cyclone inlet whose cross section attains a rectangular shape. The cyclones used in this study have an inlet whose cross section is an elliptical shape. For comparison purposes, a rectangle with a width of 0.7 cm and a height of 1.03 cm was assumed for the inlet tube. It should be noted that the cross section area for the above dimensions is the same as that of the elliptical shape attained by the tested cyclones.

Figure 7 compares both theories with the data obtained for one of the experimental conditions employed in this study. The theoretical prediction based on Barth's model is seen to yield a curve very similar to the data. Barth's model matches the experimental data more closely than the Leith-Licht theory, which yields a collection efficiency curve that differs substantially from the data. Further comparisons for other experimental conditions have shown that Barth's model was consistently superior. It should also be mentioned that in general, Barth's model tends to give an efficiency curve higher than, or a particle cut diameter smaller than, the present data. Therefore the modification Dirgo and Leith (1985) made for improving the agreement with their data would cause the agreement to deteriorate in the present case.

In order to compare an increased number of the data sets with the theories in a systematic way, a 50% particle cutoff size will be utilized. Table 2 summarizes particle

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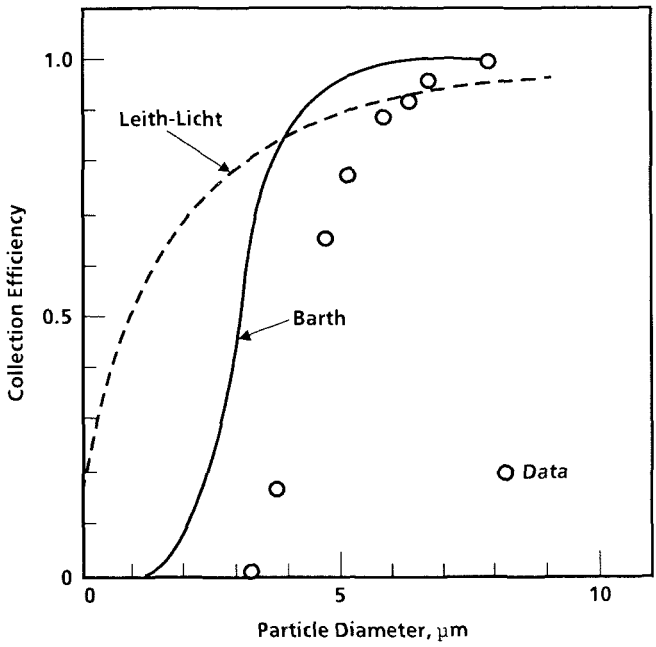

Figure 7. Comparison of cyclone theories with measured data for cyclone II-3 at a flow rate of 18.4 L/min.

cut size for each experimental condition. Figure 8 shows the relationship between the 50% cutoff size (d_{50}) and the cyclone exit tube size ratio. In the figure, the experimental data demonstrate that the particle cut diameter increases with increasing cyclone exit diameter, *De*. While agreement between Barth's theory and the data is reasonable, the Leith-Licht theory predicts d_{50}'s much smaller than the data.

In order to observe the effects of the cyclone body diameter on cyclone efficiency, the particle cut diameters are plotted against the cyclone size in Figure 9. It is noted from the experimental data that as the cyclone body size is increased from 2.19 to 3.11 cm, d_{50} appears to decrease first. When the body size is further increased, the particle cut diameter appears to increase. A possible interpretation of this has been discussed in a previous section. The theories, however, predict that d_{50} will monotonically decrease. Again Barth's theory is shown to be superior in predicting the data.

According to both theories, the collection efficiency curve will become stiffer as the exit tube size decreases and as the cyclone body size decreases. As discussed along with Figure 6 the current experimental data do not show the predicted trend, at least for the range of exit tube and body sizes covered by the experiment. It might be possible that the range of both the exit tube and the body sizes covered by the experiment was not wide enough to observe the predicted change in the curve sharpness.

Lee et al. (1985) studied experimentally the effects of gas density on the performance of cyclones. In their study, they found that a high gas density causes the cyclone efficiency to increase. In an attempt to empirically correlate their experimental data, they plotted the particle cut size against the Reynolds number which was defined as $Re = v_i De\rho/\mu$, where v_i is the inlet gas velocity, *De* is the cyclone exit tube diameter, ρ is the gas density, and μ is the gas viscosity. They claimed that with an increase in the Reynolds number or with an increasing exit tube diameter the cyclone efficiency improves. The reason for using *De* in defining the Reynolds number and for the

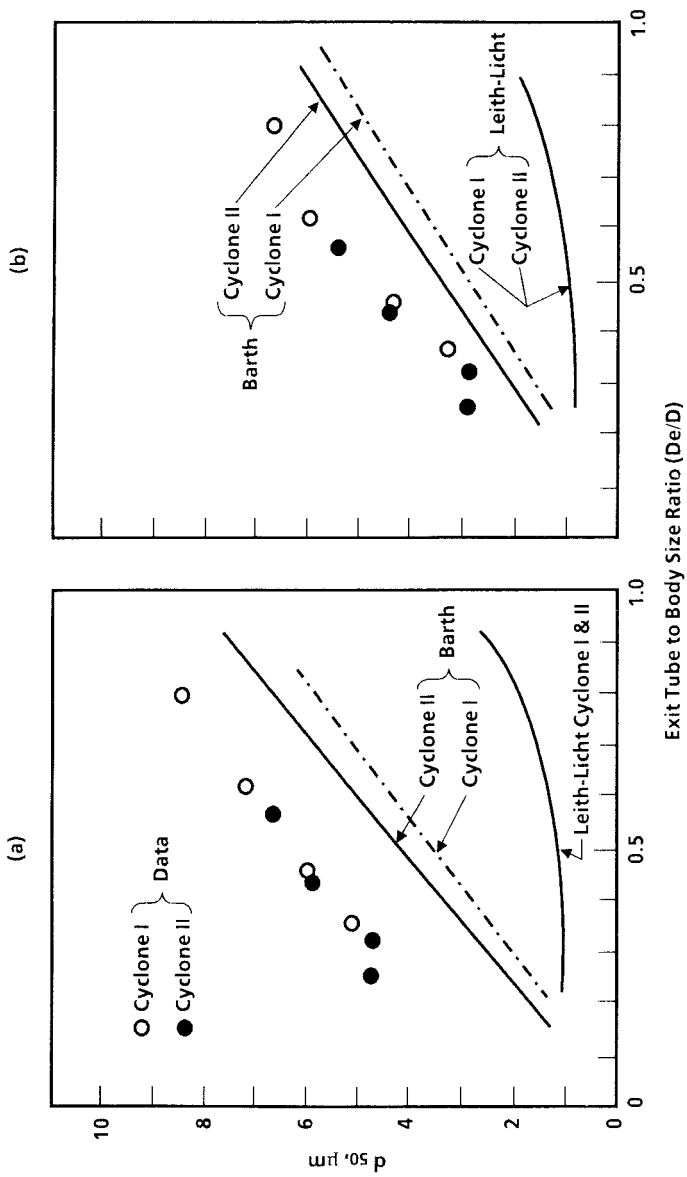

FIGURE 8. 50% cut particle diameter as a function of the ratio of exit tube to cyclone body. (*a*) 12.4 L/min; and (*b*) 18.4 L/min.

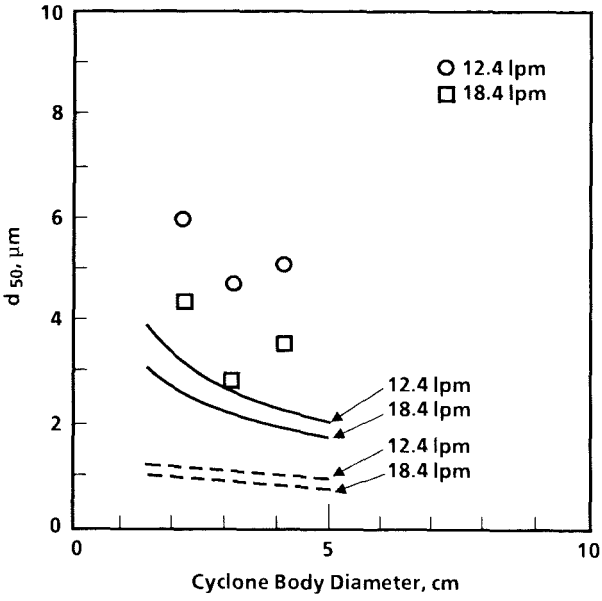

Figure 9. 50% cut diameter as a function of cyclone body size for exit tube size of 1.0 cm. (—) Barth theory; (---) Leith-Licht theory.

acceptable correlation results in their study was probably that the ratio of the exit tube to cyclone body sizes was kept roughly constant. The present study has just revealed that the Reynolds number they defined is not experimentally or theoretically justified. Therefore, it is recommended that the Reynolds number based on the cyclone body size rather than the exit tube size be used for future data correlation purposes.

EXIT TUBE SIZE EFFECTS ON PRESSURE DROP

As a final step in this study, the pressure drop was measured at flow rates of 12.4 and

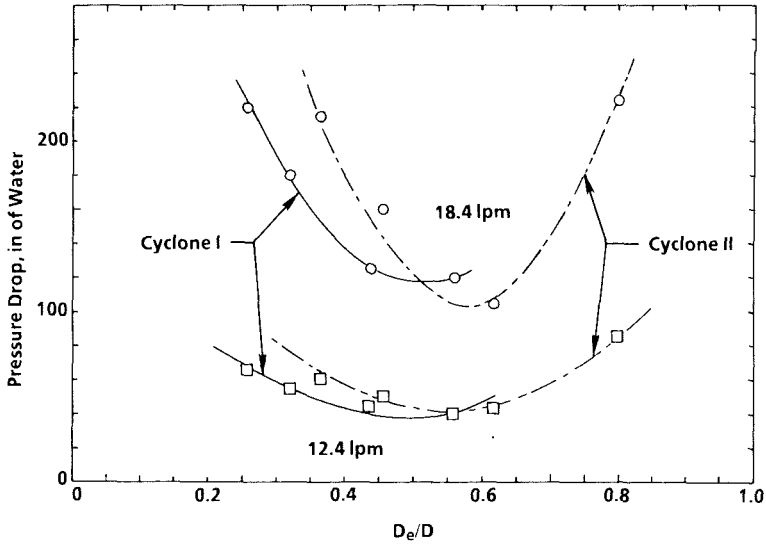

FIGURE 10. Measured pressure drop as a function of D_e/D.

18.4 L/min for cyclones I and II. Figure 10 depicts the pressure drop versus De/D. As shown in this figure, the pressure drop decreases as the dimensionless factor De/D increases. As the factor increases further, the pressure drop is seen to increase again. As a result, the pressure drop is at a minimum for values of De/D of about 0.5–0.6. This probably occurs because in low De/D, a significant portion of the pressure drop occurs inside the exit tube. As De/D increases further, the pressure drop takes place in the annular gap between the exit tube and the cyclone wall. As expected, the pressure drop is seen to be larger when the flow rate is higher and when the cyclone body becomes smaller.

Comparing Figure 10 to Figure 8, the pressure drop curves are parabolas attaining a minimum value in the middle of the range of De/D, and the d_{50} increases monotonically when the exit tube size increases. Therefore, the common expectation that the particle collection efficiency will be proportional to the pressure drop would not apply in this case.

In general, pressure drop is a measure of the energy which the cyclone uses. Therefore, cyclones which have De/D of 0.5–0.6 would need the smallest energy. It is interesting to note that this ratio of De/D coincides roughly with Stairmand's design for a high efficiency cyclone which has a De/D of 0.5. It is further noticed from Figure 8 that a value of De/D smaller than 0.5 does not reduce the particle cut diameter substantially.

CONCLUSIONS

In this study, particle collection efficiency data have been presented as a function of particle size, flow rate, cyclone exit tube size, and body size. From the present study, the following conclusions can be drawn:

1. The exit tube size is one of the important dimensions affecting cyclone performance significantly. Particle collection efficiency increases as the exit tube size becomes smaller. It is believed that the exit tube size plays a critical role in defining the flow field inside the cyclone, including the pattern of the outer and inner spiral flows.
2. If all other dimensions are held constant, an increase in cyclone body size results in an increase in particle collection efficiency. However, if the body size is increased excessively relative to the exit tube size, the collection efficiency ceases to increase or even decreases somewhat. This observation needs further investigation with an increased number of cyclones.
3. The sharpness of the particle collection curve does not alter noticeably with changes in exit tube diameter or body size at least for the range of experimental conditions covered in this study. The only observed condition under which the slope of the curve deteriorates is a decrease in the flow rate. For this reason, it was possible to collapse all efficiency measurement data on a single curve which depends only on a flow rate.
4. Qualitative visual observation indicated that particles deposit mostly at the lower section of the cyclone body. This confirms the conventional theoretical approach that particles are collected mainly by centrifugal force in cyclones. However, it was found that deposition also takes place in the inner wall of the exit tube and on the upper wall immediately after the inlet tube. Therefore it might be necessary to investigate these further to quantify their importance relative to the deposition on the lower wall. Currently, none of the existing cyclone theories accounts for these types of deposition mechanisms.
5. The pressure drop measurements indicate that the exit tube size substantially affects the energy loss. As the exit tube size increases, the pressure drop was

found to decrease and the particle collection efficiency decreased as expected. When the exit tube size is further increased until it approaches the cyclone body in size, the pressure drop increases again, indicating that the energy loss occurs in the annular gap between the exit tube and the cyclone wall. However, the particle collection efficiency does not increase substantially in this regime.

6. When the pressure drop and particle collection efficiency data are compared, a cyclone design value of 0.5 as given by Stairmand (1951) for the ratio of the exit tube size to the cyclone body size appears to be quite reasonable.
7. Comparison of the experimental data with existing theories indicated that Barth's theory predicts cyclone behavior far better than the Leith-Licht theory. This conclusion is based on experimental data obtained in this study only. Due to its simplicity in form and good ability to predict cyclone efficiency, Barth's theory is potentially useful in many cyclone studies. It is recommended that Barth's theory be given increased attention, to validate it further and to utilize it as a valuable tool for designing cyclones and predicting cyclone performance.

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REFERENCES

Barth, W. (1956). *Brennst. Waerme Kraft*, 8:1.

Berglund, R. N., and Liu, B. Y. H. (1973). *Environ. Sci. Technol.* 7:147.

Dietz, P. W. (1981). *A.I.Ch.E.J.* 27:888.

Dirgo, J., and Leith, D. (1985). *Aerosol Sci. Technol.* 4:401.

Lapple, C. E. (1950). *Ind. Hyg. Q.* 11:40.

Lee, K. W., Gieseke, J. A., and Piispanen, W. H. (1985). *Atmos. Environ.* 19:847.

Leith, D., and Licht, W. (1972). *A.I.Ch.E. Symp. Ser.* 68:196.

Sproull, W. T. (1972). *Air Pollution and Its Control*, 2nd ed., Exposition Press, Jericho, NY.

Stairmand, C. J. (1951). *Trans. Inst. Chem. Eng.* 29:356.

Theodore, T., and DePaola, V. (1980). *J. Air Pollut. Control Assoc.* 30:1132.

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