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Generalized Performance Characteristics of Miniature Cyclones for Atmospheric Particulate Sampling

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Small cyclones are advantageous for size selective sampling of atmospheric particulate matter because they are capable of collecting large samples and are less subject than impactors to particle bounceoff and reentrainment. However, there has been a lack of an accurate generalized quantitative description of their performance, which has necessitated extensive calibrations of each design. Collection efficiency data for 30 cyclones have been accurately fitted by two simple equations using outlet Reynolds number as a variable rather than flow rates. They also fitted the limited available data for the effects of temperatures ranging from 25 to 204 ° C. Normalized particle sizes plotted on log probability paper vs collection efficiency as a single straight line for all experimental flow rates. Three constants fully described the performance of each cyclone, and these constants could be estimated since they varied over a small range for most of the cyclones. The new generalized empirical equations should facilitate calibration and use of cyclones for air sampling.

Introduction

Because the size of particles strongly influences their degree of deposition in the nose, trachea, and lungs⁽¹⁾ the American Conference of Governmental Industrial Hygienists has defined⁽²⁾ allowable levels of "respirable" dust in terms of the particles remaining after discarding the larger particles in a

presampler according to a standard removal efficiency curve. The cut size for 50% collection was specified as 3.5 μm (aerodynamic diameter). The U.S. Environmental Protection Agency is reviewing^(3,4) the current total suspended particulate standard and is considering an inhalable particle

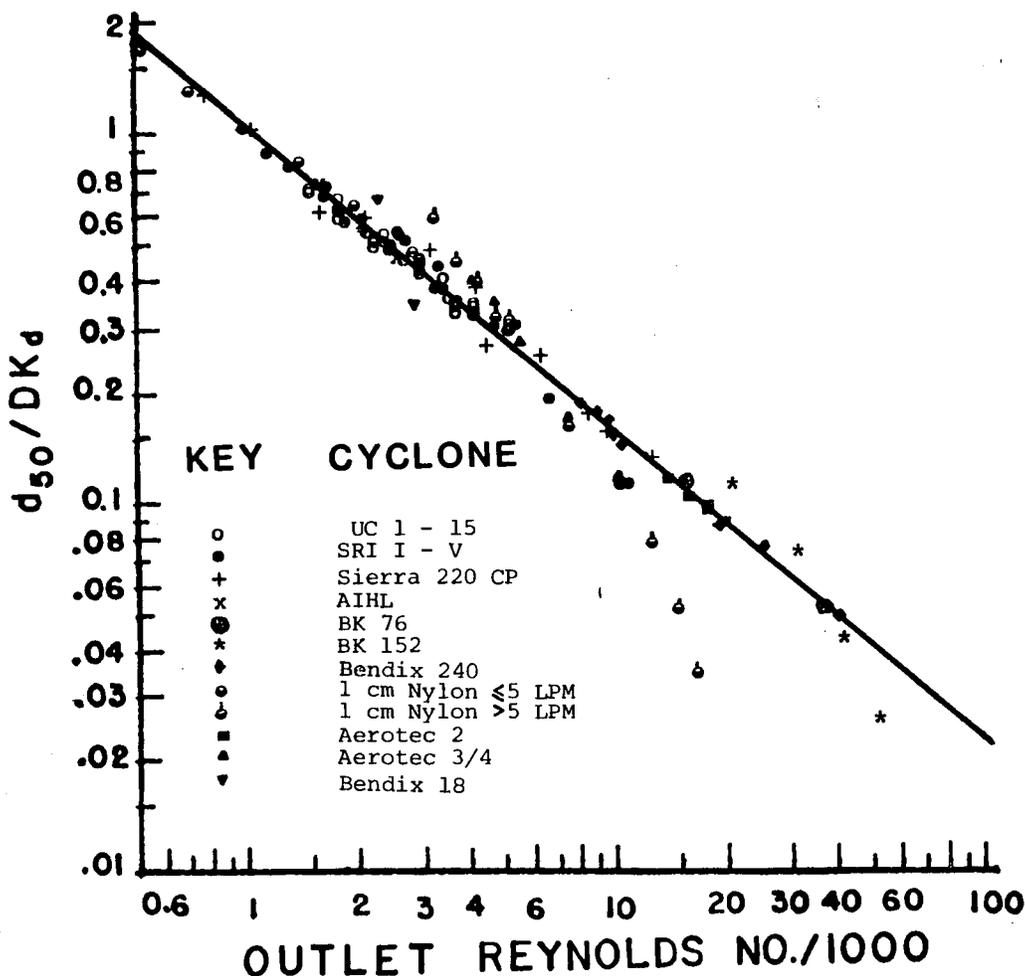


Figure 1 — Relationships between cut sizes and outlet Reynolds numbers for thirty cyclones.

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standard based upon a 50% cut size of 10 μm . Cyclones have certain advantages as presamplers for size-selective particulate sampling over cascade and virtual impactors. They are capable of handling larger flow rates and are less subject to particle bounceoff and reentrainment. However, the empirical nature of cyclone design has been a handicap, requiring extensive calibrations to accurately determine the performance of each design.

Cyclone theory is too complex and involved to be discussed here. Lippmann and Chan^(5,6) summarized various theoretical, semiempirical, and empirical theories describing collection efficiencies of cyclones for various particle sizes in terms of the cyclone dimensions and air flow rates. Most theoretical equations predicted that the cut size (size collected with 50% efficiency) varied with the flow rate raised to the -0.5 power, which was substantially different from the relationships shown by experimental data. They tabulated empirical exponents for 11 cyclones ranging from -0.75 to -2.13. Thus the theoretical approach was not as accurate as an empirical description. They related collection efficiencies to particle sizes with an empirical hyperbolic tangent equation. Besides the value of the exponent, three additional constants were fitted to the data by a computer program to accurately describe the performance of each cyclone. The constants varied over wide ranges, and could not be predicted in advance from the cyclone dimensions. Data for collection efficiency vs the log of particle size were plotted in the form of a series of S shaped curves, one for each flow rate.

Saltzman and Hochstrasser⁽⁷⁾ generalized the empirical description of cyclone performance. Instead of flow rate, the dimensionless Reynolds number, Re , at the cyclone outlet was used as a variable for calculating cut size:

$$Re = \rho_g D_o v / \mu_g = \left[\frac{\rho_g 4}{\mu_g \pi} \right] \frac{Q}{D_o} \quad (1)$$

where ρ_g = density of air
 μ_g = viscosity of air
 D_o = cyclone outlet diameter
 v = air velocity ($= 4Q/\pi D_o^2$)
 Q = air flow rate.

Their results for cut sizes for 15 experimental cyclones were fitted by the following empirical equation:

$$d_{50}/DK_d = (Re/1000)^{-n} \quad (2)$$

where d_{50} = mass median aerodynamic particle diameter (unit density) collected with 50% efficiency
 D = cyclone body diameter
 K_d = a dimensionless constant characterizing each cyclone
 n = empirical constant.

They found that a single value of n ($= 0.713$) fitted all 15 cyclones, (correlation coefficient 0.98) and values of $10^4 \times K_d$ varied over only a small range (2.01 to 2.71).

They showed that plotting normalized particle size (d/d_{50}) against cyclone efficiency on log probability paper condensed performance data for various particle sizes and flow rates into a single line that was straight for most of its length.

TABLE I
 Calculated Performance Constants for
 UC Cyclones⁽⁷⁾ Using $n = 0.830$

Cyclone No.	Dimensions ^A			L/min ^B for $d_{50} =$		
	D_o	t	L_c	$10^4 \times K_d$	3.5 μm	10 μm
9	c	c	c	2.481	(6.47)	(1.83)
8	c	c	b	2.585	(6.80)	(1.92)
7	c	c	a	2.777	(7.42)	(2.09)
14	c	a	b	2.937	(7.93)	(2.24)
5	b	c	b	2.444	(7.95)	(2.24)
6	b	c	c	2.489	(8.12)	(2.29)
15	c	a	c	3.044	(8.28)	(2.34)
4	b	c	a	2.556	(8.39)	(2.37)
11	b	b	b	2.585	(8.50)	(2.40)
12	b	b	c	2.611	(8.61)	(2.43)
13	c	a	a	3.207	(8.82)	(2.49)
10	b	b	a	2.872	(9.65)	(2.73)
2	a	c	b	2.533	9.96	(2.81)
3	a	c	c	2.660	10.56	(2.98)
1	a	c	a	2.668	10.60	(2.99)

^ACyclone diameter, $D_o = 1.905$ cm. Other values (in cm) as follows:

	a	b	c
I.D. of Outlet, D_o	0.952	0.794	0.635
Thickness of outlet tube, t	0.238	0.158	0.079
Cone Length, L_c	4.762	2.381	1.429

^BValues outside experimental range in ().

Since the efficiency also is the probability of capture of each particle, the probit scale was logical. The slope of the line was inversely related to the sharpness of the size separation by the cyclone. This relationship is expressed by the following equation:

$$\log(d/d_{50}) = (\log \sigma_g) Z(e) \quad (3)$$

where d = mass median aerodynamic particle diameter (unit density)
 $Z(e)$ = probit function of probability of capture, e (collection efficiency)
 σ_g = standard geometric deviation.

They also developed a generalized equation closely fitting the pressure drops of 18 cyclones:

$$\Delta PD^2/K_p = (Re/1000)^{2.22} \quad (4)$$

where ΔP = cyclone pressure drop
 K_p = a constant characterizing each cyclone.

Values of K_p in units of $\text{cm H}_2\text{O} \times \text{cm}^2$ ranged from 0.36 to 0.91.

The success of these calculations suggested the present study in which the same methods were applied to collection efficiency data from the literature from a variety of other investigators for 15 other cyclones.

Results

The outlet Reynolds numbers for the data for the 30 cyclones ranged over a hundredfold range from 500 to 50 000. It was

found that a single selected value of $n = 0.830$ in Equation 2 gave a reasonably good fit for 27 of the cyclones. Figure 1 shows a log-log plot of the data for the 120 points for the 30 cyclones. Values of d_{50}/DK_d are plotted vs $Re/1000$. Values of d_{50} were obtained from plots of raw data for each cyclone for each flow rate by interpolation at 50% collection efficiency if reasonably possible. The value of K_d was calculated for each cyclone from Equation 2 with $n = 0.830$ for each pair of values of d_{50} and Q . The geometric mean of these calculated values of K_d was taken as the best value. Values of $10^4 \times K_d$ varied for the different cyclones over a relatively small range of 1.43 to 4.46. Ten points for the 1 cm nylon cyclone ($Q > 5$ L/min) and four for BK-152 were clearly divergent and were excluded from the calculations for the line fitted by the method of least squares to equation 2 in logarithmic form. It had an intercept of 0 and slope of -0.830 . The fit is remarkably good considering the diversity of cyclones and investigators. The correlation coefficient was 0.992, and the standard deviation (s_y) of the points about their mean abscissa ($Re/1000 = 3.73$) was 9.2%. It is especially noteworthy that the data for cyclones SRI-I, II, and III included 3 cut points at 93 °C and 3 at 204 °C, all of which fitted the line closely. There is a scarcity of data for miniature cyclones at elevated temperature, but these results imply that Equation 2 also describes the effect of temperature on cut size. The detailed discussion below shows more data for those cyclones confirming this observation.

For each cyclone a log probability plot according to Equation 3 was made of normalized particle sizes vs cyclone efficiencies for all available raw data. A straight line was fitted to the points by the method of least squares. In a few cases, points at the extreme ends were excluded, since they obviously fitted curved line segments. A slight adjustment

was then made in the value of K_d previously calculated from interpolated d_{50} values to make the fitted line go exactly through $d/d_{50} = 1$ at 50% collection efficiency. The reciprocal of the slope of the line, σ_g , was a measure of the sharpness of the size separation of the cyclone. As a measure of the fit of the points to the line, their standard deviation (s_y) at the mean probit value (usually close to 50% efficiency) was calculated, as well as the correlation coefficient of the line. The % relative standard deviation of d_{50} was approximately computed from the following expression:

$$s_y^2 = \ln(1 + S_r^2) \quad (5)$$

where s_y = standard deviation of natural logarithmic values

S_r = % relative standard deviation of d_{50} .

Table I lists the values of K_d obtained for the fifteen cyclones (UC 1-15) studied by Saltzman and Hochstrasser⁽⁷⁾ over a flow range of 10.0 to 34.8 L/min. These cyclones all had the same body diameter, but differed in outlet diameters, outlet tube thicknesses, and cone lengths. The values of $10^4 \times K_d$ ranged from 2.44 to 3.21. A single plot according to Equation 3, Figure 2, fitted all 15 cyclones. The scatter at the ends resulted from small deviations in experimental measurements. It is exaggerated by the extreme expansion of the probit scale. The 66 points in the range from 5 to 80% efficiency fitted a straight line. The value of the slope, σ_g was 1.31, the correlation coefficient was 0.934, and the % standard deviation of d_{50} was 7.1%. The cyclones with thicker outlet tubes showed the lower efficiencies at the high end. Table I also lists flow rates calculated from Equation 2 to produce cut sizes of 3.5 and 10 μm . The cyclones are arranged to produce ascending values of these. The cyclones with smaller outlets required smaller flows.

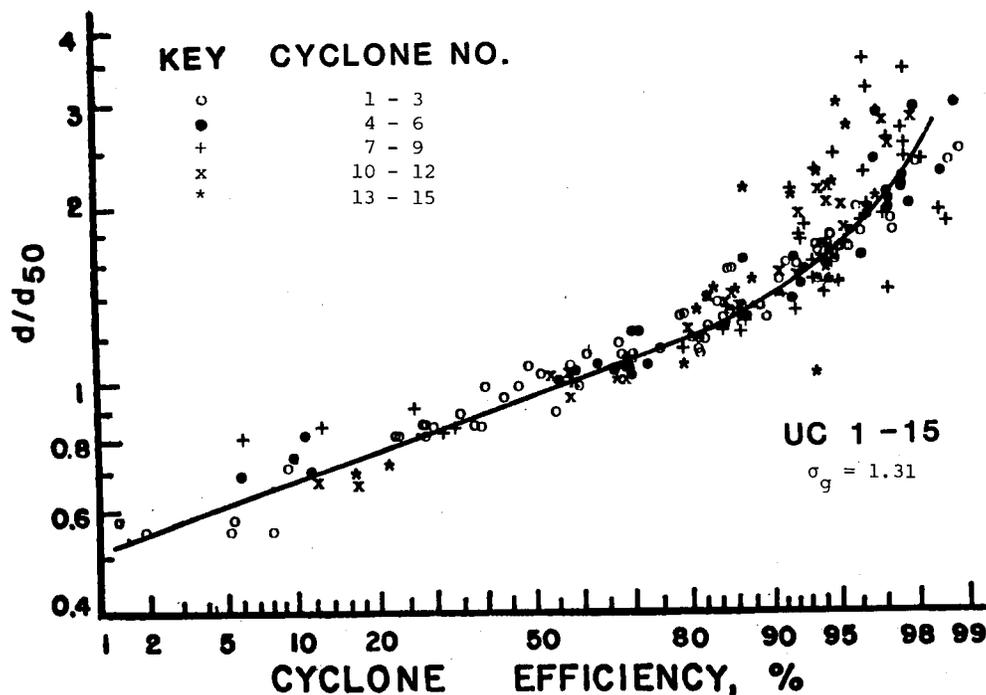


Figure 2 — Generalized plot of normalized particle sizes vs. efficiency of fifteen cyclones, UC 1-15. Data from Saltzman and Hochstrasser.⁽⁷⁾

Saltzman and Hochstrasser⁽⁷⁾ found that cyclones with long cones exhibited unstable transitional flow at low flow rates. Under these conditions the downward turbulent flow

changed in the cone to laminar flow when it reversed to an upward direction, leaving a zone of stagnation at the bottom of the cone and a ring deposit of particles at the reversal

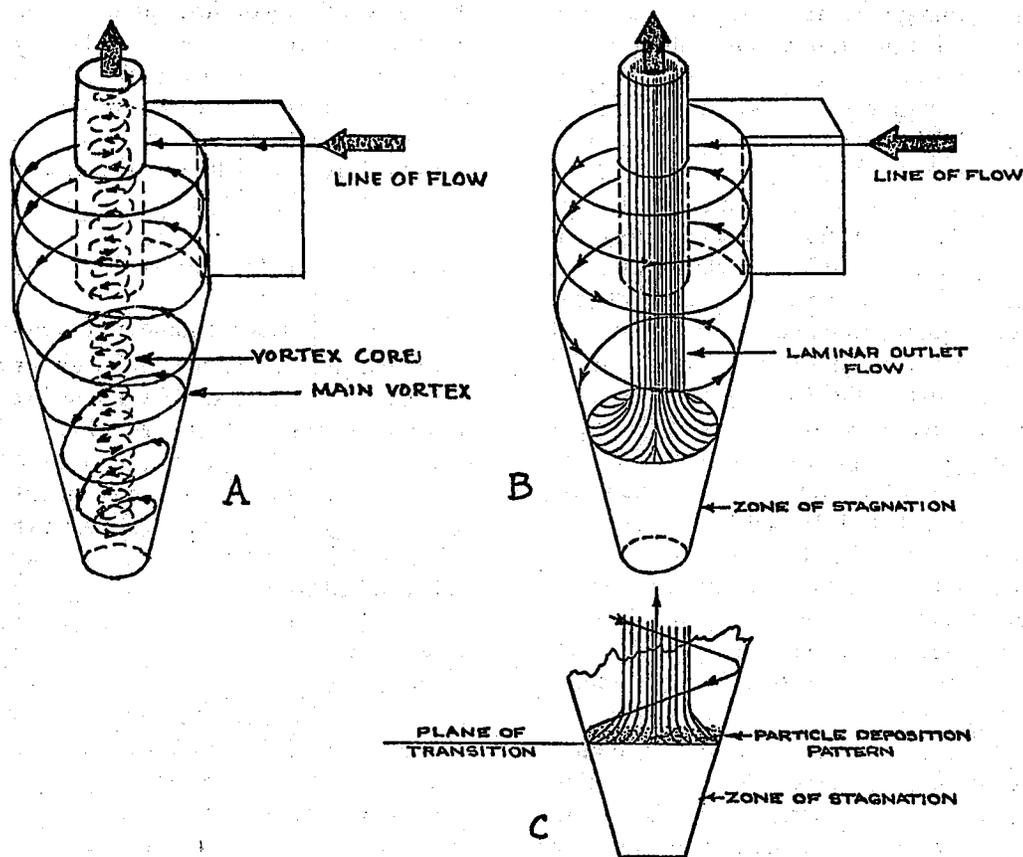


Figure 3 — Flow patterns for cyclones with long cones.⁽⁷⁾ A. Turbulent flow. B. Transitional flow. C. Mechanism of deposition of particles in a ring pattern during transitional flow.

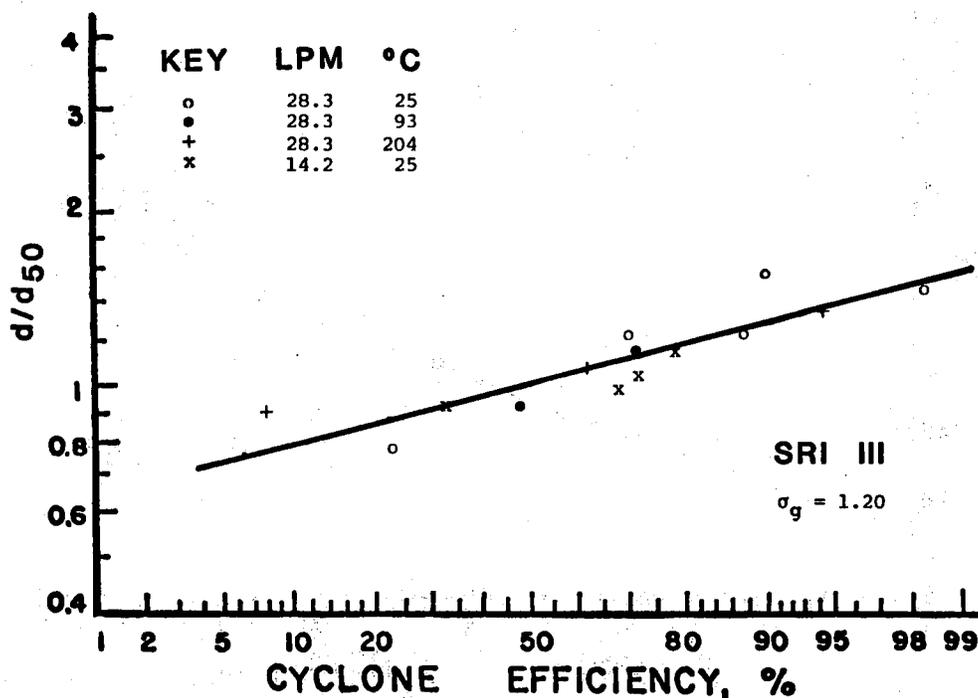


Figure 4 — Collection efficiency of SRI-III cyclone, calculated from data of Smith, Wilson, and Harris.⁽¹⁰⁾

point as illustrated in Figure 3. These data were excluded from the calculations reported here. Aside from this effect, the cone lengths did not appear to have a great influence on performance. The fit of the points in Figure 2 based on the 0.830 exponent was as good as that originally reported for $n = 0.713$.

Figure 4 shows the data for the SRI-III cyclone plotted according to Equation 3 with $n = 0.830$. This is especially interesting because results are given for three temperatures, 25 °C, 93 °C, and 204 °C. Within experimental error all points fitted the same line. This confirms that the outlet Reynolds number expresses the effects of temperature on cyclone performance for the raw data points, as well as for the interpolated d_{50} values as previously indicated in Figure 1. Similar agreement was found in plots containing high temperature data for SRI-I and II, using other optimized values of n . Temperature influences the air density and viscosity terms shown in Equation 1. The SRI-I to V cyclones are commercially available as the Sierra Cyclade Series 280-1 to 5. The Bendix 240 and Aerotec 2 cyclone data are plotted for $n = 0.830$ in Figures 5 and 6. These cyclones have dual inlets and a less efficient design and produce higher values of σ_g , closer to the 1.70 value⁽⁷⁾ for the ACGIH standard curve.

Table II presents the calculated performance constants for 14 cyclones, arranged in order of ascending sizes, using the value of $n = 0.830$. The second column lists the flow ranges within which the raw data were listed in the references^(5,8-13) as listed in the last column. The slopes, σ_g , of the linear portion of the plots for each cyclone are listed in the third column. They may be compared to the ACGIH value of 1.70. With few exceptions, the values were substantially lower indicating a sharper separation of sizes. Values of $10^4 \times K_d$, listed in the fourth column, ranged from 1.7 to 4.5. This is

a remarkably small range, considering the variety of cyclone dimensions. The fifth column lists the number of points within the linear range that were used to fit a straight line to Equation 3 by the method of least squares. The sixth column lists the correlation coefficients obtained, which ranged from 0.712 to 0.993. Six were 0.95 or higher. The seventh column presents the % relative standard deviations of the points in the middle of the plots. These reflect scatter in the raw data, as well as errors in the fit of the empirical equations. Eleven cyclones showed values of 15% or less. The eighth and ninth columns list the dimensions for body diameter and outlet diameter. The tenth and eleventh columns list the flow rates calculated from Equation 2 that would produce cut sizes of 3.5 and 10 μm respectively. The cyclones are arranged in the order producing ascending flow rates for the 3.5 μm cut size. These flows ranged from 2.06 to 419 L/min. There is a good selection of cyclones to achieve either desired cut size for a wide range of flows.

The correlation shown in Figure 1 for $n = 0.830$ was developed in order to determine the best fit for the largest number of cyclones. There are many difficulties in obtaining accurate data, and different investigators have obtained different results for the same cyclones. For example, the AIHL cyclone had the same dimensions as the SRI II cyclone, but somewhat different general constants were obtained as indicated in Table II. Numerous investigators have studied the 10 mm nylon cyclone and reported differing results. At high flow rates (> 5 L/min) the exponent n is substantially higher for this cyclone. It is also much higher for the large (152 mm) Beekmans cyclone (BK 152). In order to obtain the best possible fit for Equations 2 and 3 for each set of data, other calculations were made to optimize values of both n and K_d . Good fits were obtained for all

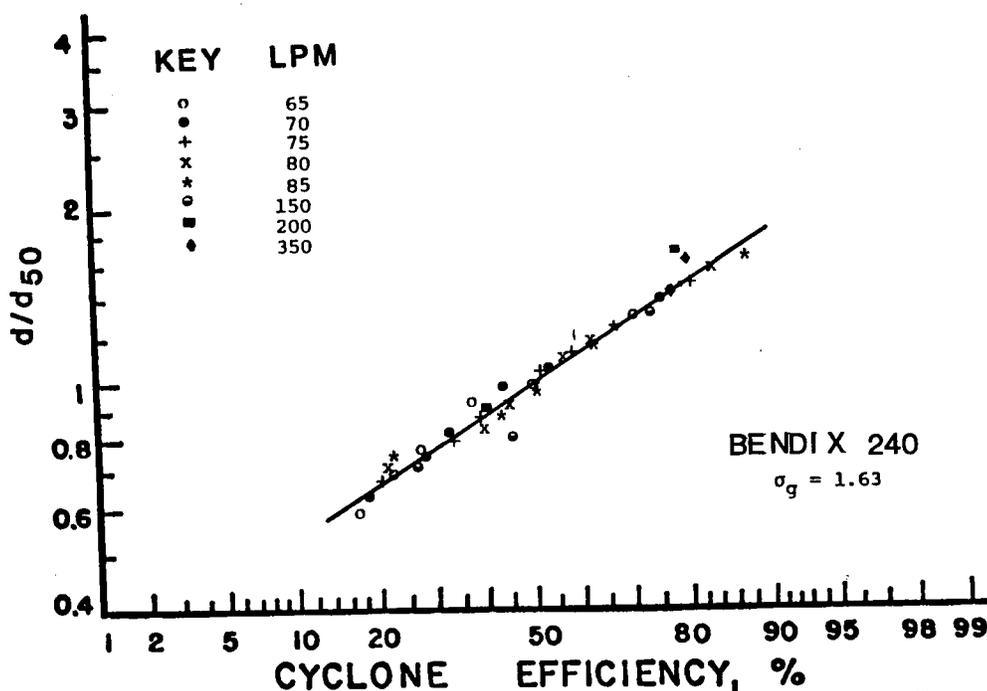


Figure 5 — Collection efficiency of Bendix 240 cyclone (1-inch HASL) calculated from data of Lippmann and Chan.^(5,9)

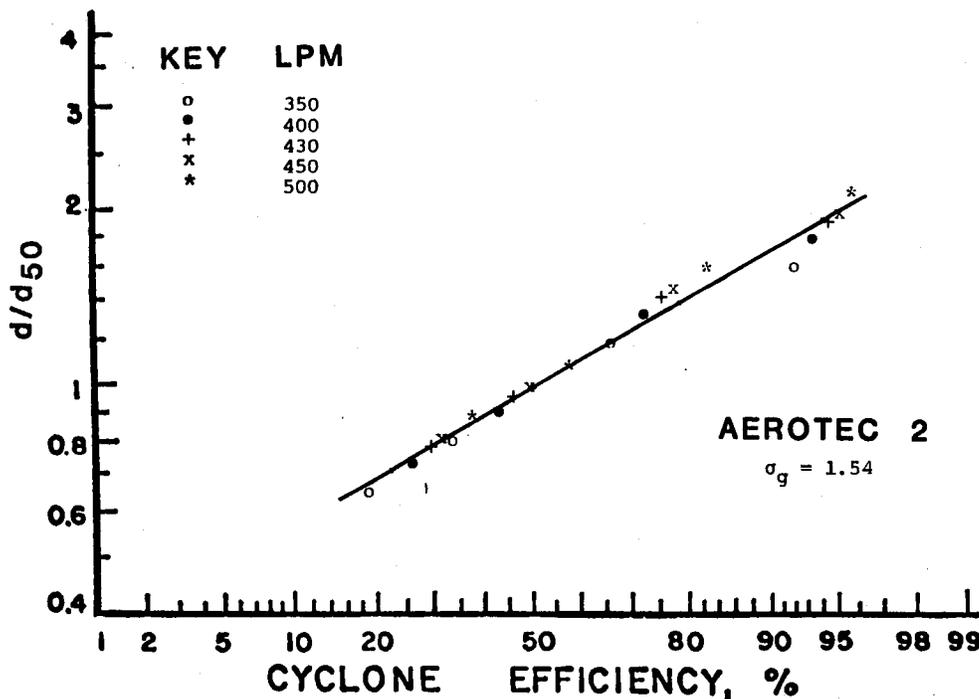


Figure 6 — Collection efficiency of Aerotec 2 cyclone calculated from data of Lippmann and Chan.⁽⁹⁾

cyclones. Table III lists the 10 cases where the best values of n differed from 0.830. In only half of these was the improvement in % S.D. more than 5% over that shown in Table II.

Data plotted using the optimized n and K_d values in Table III are shown in Figures 7-10. Figure 7 shows that the AIHL cyclone data is linear between 10 and 90% collection effi-

ciency. The curvature at the low end suggests the effect of electrostatic charges on the particles. Figure 8 shows that the data for the Aerotec 3/4, a dual inlet cyclone, is linear.

Figures 9 and 10 present data from Lippmann *et al.*^(5,8) for the 10 mm nylon cyclone for flow rates ≤ 5 L/min and > 5 L/min respectively. These widely used cyclones are accu-

TABLE II
Calculated Performance Constants for Cyclones ($n = 0.830$)

Cyclone	Flow Range, L/min	σ_g	$10^4 \times K_d$	No. Points	Corr. Coeff.	% S.D. of d_{50}	Dimensions		L/min ^A for $d_{50} =$		Data Ref.
							D, cm	D_o , cm	3.5 μ m	10 μ m	
10 mm Nylon	0.89 - 5.0	1.31	4.043	33 ^B	0.955	8.9	1.00	0.25	2.11	(0.596)	8
SRI V	7.1 - 28.3	1.14	1.927	9	0.712	19.4	1.52	0.36	(2.06)	(0.582)	10
SRI IV	7.1 - 28.3	1.31	1.429	11	0.854	26.1	2.54	0.59	(4.38)	(1.24)	10
Bendix 18 (1/2" HASL)	8 - 10	1.50	2.462	9	0.891	19.7	2.54	0.495	(7.08)	(2.00)	9
SRI III	14.2 - 28.3	1.20	1.648	14	0.880	9.8	3.11	0.83	(9.33)	(2.63)	10
AIHL	8.4 - 26.6	1.22	1.718	19 ^C	0.938	6.8	3.66	1.05	15.1	(4.27)	11
SRI II	14.2 - 28.3	1.18	1.747	15	0.875	10.2	3.66	1.05	15.4	(4.35)	10
Sierra 220 CP (3/8" outlet)	14.2 - 84.9	1.37	2.301	8 ^C	0.954	8.3	3.81	0.95	20.4	(5.77)	13
Sierra 220 CP (1/2" outlet)	28.3 - 84.9	1.37	2.082	6	0.969	10.8	3.81	1.27	(24.2)	(6.82)	13
Aerotec 3/4 ^D	22 - 55	1.53	2.567	36	0.942	13.0	4.13	0.75	(20.2)	(5.71)	5,9
SRI I	14.2 - 28.3	1.29	2.402	22	0.849	13.4	4.47	1.50	(41.1)	(11.6)	10
Bendix 240 ^D (1" HASL)	65 - 350	1.63	4.461	37	0.984	5.3	5.08	1.09	73.6	(20.8)	5,9
BK 76	427 - 1000	2.62	3.421	5	0.993	9.4	7.6	3.8	(302)	(85.3)	12
Aerotec 2 ^D	350 - 500	1.54	3.190	20	0.992	4.8	11.43	3.51	419	(118)	9

^ACalculated for 21.1 °C (70 °F). Flows outside experimental range indicated in ().

^BFor linear portion from 5% to 95% collection efficiency

^CFor linear portion from 10% to 90% collection efficiency

^DDual inlet

TABLE III
Calculated Performance Constants for Cyclones (Optimal Values of n)

Cyclone	Flow Range, L/min	σ_g	n	$10^4 \times K_d$	No. Points	Corr. Coeff.	% S.D. of d_{50}	Dimensions		L/min ^A for $d_{50} =$		Data Ref.
								D, cm	D_o , cm	3.5 μ m	10 μ m	
10 mm Nylon	0.89 - 5.0	1.33	0.741	4.034	33 ^B	0.976	6.9	1.00	0.25	2.15	(0.521)	8
10 mm Nylon	5.8 - 22.5	2.19	1.475	10.82	46 ^B	0.991	7.8	1.00	0.25	----	----	5,8
SRI V	7.1 - 28.3	1.21	1.117	3.129	9	0.885	15.0	1.52	0.36	(3.36)	(1.31)	10
SRI IV	7.1 - 28.3	1.32	0.974	1.654	11	0.904	21.4	2.54	0.59	(5.05)	(1.72)	10
Bendix 18 ^C (1/2" HASL)	8 - 10	1.85	3.006	18.31	9	0.994	6.3	2.54	0.495	8.31	(5.86)	9
AIHL	8.4 - 26.6	1.23	0.983	1.918	19 ^D	0.982	3.6	3.66	1.05	15.2	(5.21)	11
Aerotec 3/4 ^C	22 - 55	1.57	1.414	7.551	36	0.991	5.1	4.13	0.75	25.0	(11.9)	5,9
SRI I	14.2 - 28.3	1.25	0.641	2.146	22	0.902	9.1	4.47	1.50	(51.4)	(9.98)	10
BK 76	427 - 1000	2.71	0.916	4.389	5	0.996	7.0	7.6	3.8	(316)	(101)	12
BK 152	1146 - 2855	3.73	1.649	63.17	16	0.976	23.2	15.2	7.6	1626	(860)	12

^ACalculated for 21.1 °C (70 °F). Flows outside experimental range indicated in ().

^BFor linear portion from 5% to 95% collection efficiency

^CDual inlet

^DFor linear portion from 10% to 90% collection efficiency

rately injection molded as Dorr-Oliver type TM Dorrclones. The data in Figure 10 was collected using a different experimental system from that in Figure 9. The values for the two highest flow rates, 26.5 and 29.6 L/min did not fit the line and were excluded from the calculations. There is a surprising difference in the two plots for the same cyclone. At the high flow rates the sharpness of size separation was greatly reduced. Blachman and Lippmann⁽⁸⁾ explained this by assuming laminar flow below 5 L/min, and turbulent flow above this rate. They noted that at low flows there were deposits in the first quarter turn, and at high flows there were ring deposits in the long tapered section. The values of n were 0.741 and 1.475, and of σ_g were 1.33 and 2.19 for data in

Figures 9 and 10 respectively. Saltzman and Hochstrasser⁽⁷⁾ also noted transitional flow and ring deposits in their long cone cyclones, and a lower value of n (0.61 vs 0.713) under these conditions. However, the value of σ_g was identical for both. The surprising difference between the two plots may be due to the extremely large range of Reynolds numbers (500-17 000) corresponding to the flow rates used. At very high Reynolds numbers and at large cyclone sizes the relationships appear to be modified.

Discussion

There have been numerous reports of calibrations of the 10 mm nylon cyclone and other cyclones with variable and

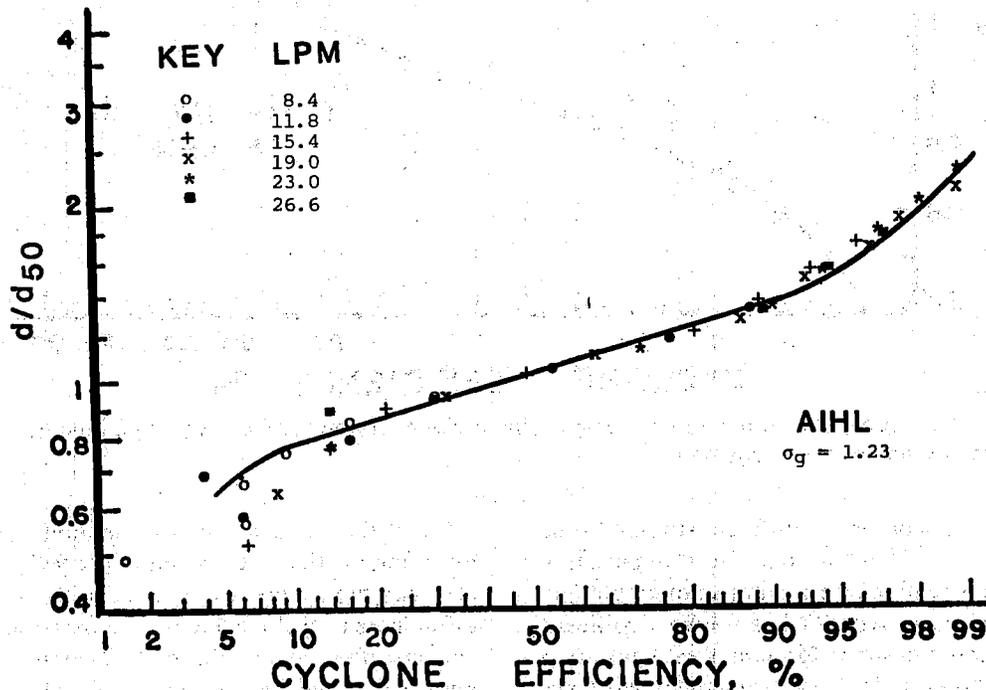


Figure 7 — Collection efficiency of AIHL cyclone, calculated from data of John and Reischl.⁽¹¹⁾

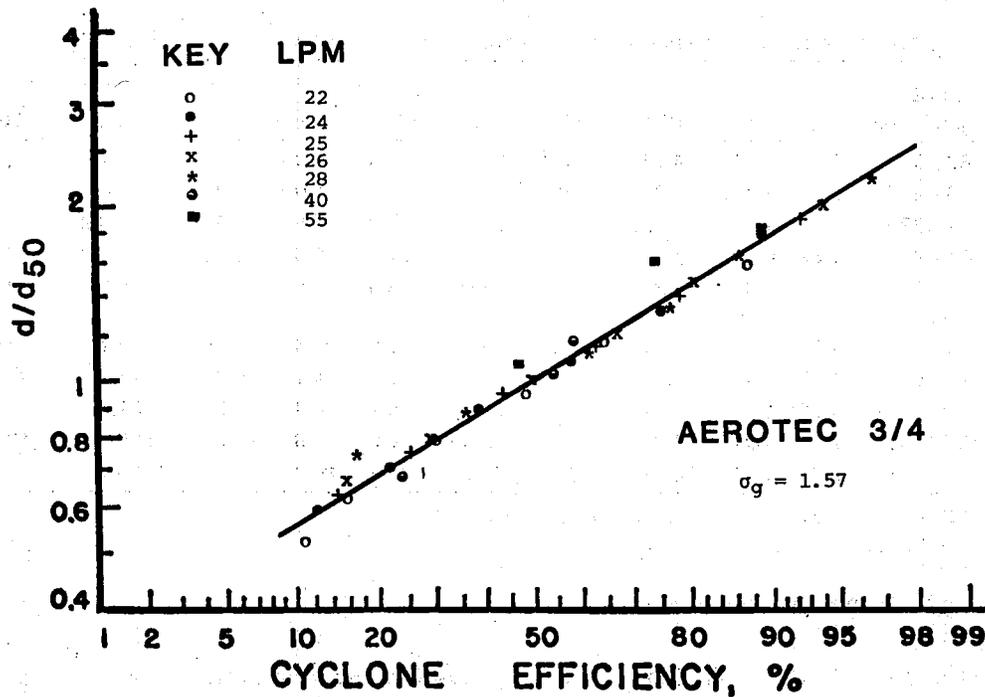


Figure 8 — Collection efficiency of Aerotec 3/4 cyclone calculated from data of Lippmann and Chan.^(5,9)

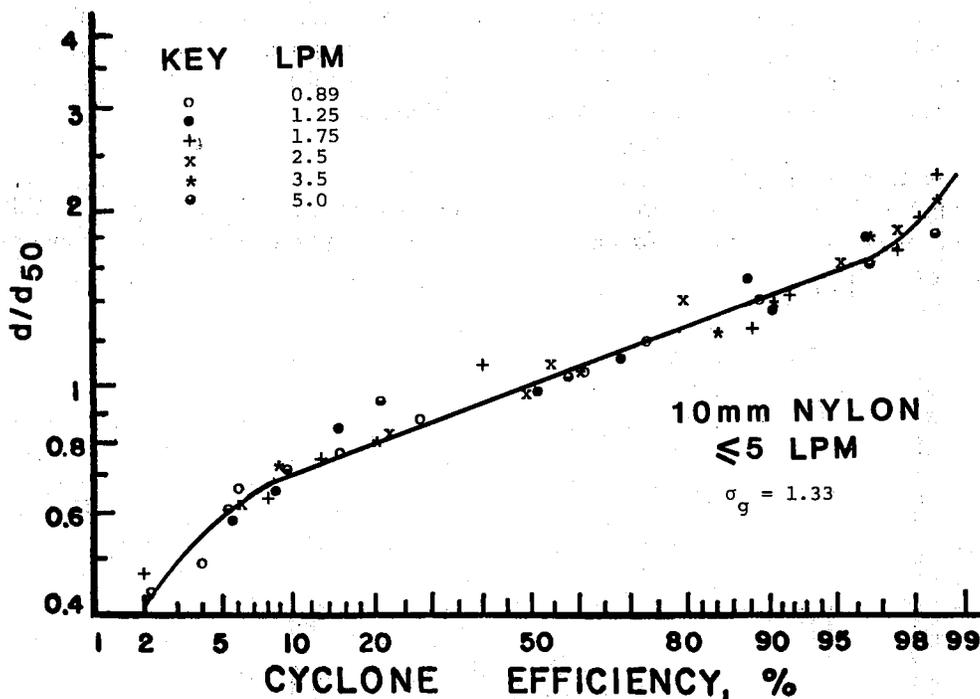


Figure 9 — Collection efficiency of 10 mm nylon cyclone for flows ≤ 5 L/min, calculated from data of Blachman and Lippmann.⁽⁸⁾

inconsistent agreement between the different studies. Some of the earlier discrepancies were traced to effects of pulsating flows produced by some diaphragm pumps not employing pulsation dampers. Recent work⁽¹⁴⁾ has shown significant errors from flow fluctuations even for pumps with pulsation dampers. In some studies of the 10 mm nylon cyclones different outlet connections were used which may have

affected the performance by changing the effective outlet diameter; in others electrostatic charges on the smaller particles may have increased their collection efficiencies. Other differences in cyclone data may have arisen from the different aerosols used, and the methods used for their generation and sizing and for measurement of cyclone efficiency. Lippmann *et al.*^(5,8,9) used a ferric oxide aerosol ($\rho = 2.56$

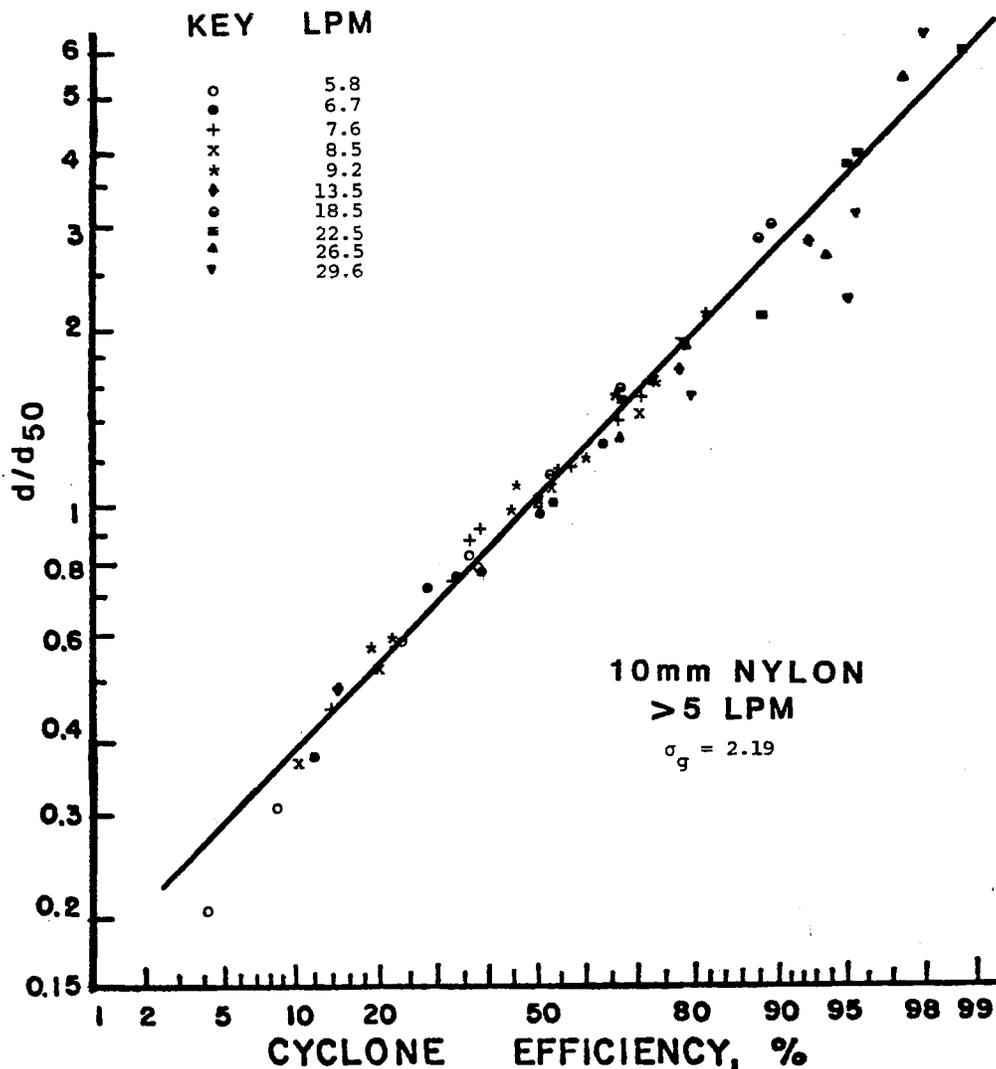


Figure 10 — Collection efficiency of 10 mm nylon cyclone for flows > 5 L/min, calculated from data of Blachman and Lippmann⁽⁸⁾ and Chan and Lippmann.⁽⁵⁾

g/cm³) marked with technetium 99m tracer. Deposits on filters and cyclones were measured without being removed by gamma scintillation counters. Monodisperse particles were generated with a spinning disc generator and sized by optical microscopy. However, the submicron particles (used for the data shown in Figure 10) were generated in an ERC system using air blast atomization and inertial impaction. They were sized with an aerosol centrifuge. The deposits on the foils were gamma counted with a slit collimated scintillation detector. Iron oxide aerosol from a spinning disc generator also was employed by Saltzman and Hochstrasser,⁽⁷⁾ but aerosol deposits were washed out, ashed, and determined by atomic absorption spectroscopy. John and Reischl⁽¹¹⁾ utilized a vibrating orifice to generate monodisperse aerosols of methylene blue and DOP-fluorescein. Deposits were washed off and measured with a spectrophotometer or fluorometer respectively, and sizes were determined with a Climet optical particle analyzer. Smith, Wilson, and Harris⁽¹⁰⁾ used a vibrating orifice aerosol generator for ammonium fluorescein ($\rho = 1.35 \text{ g/cm}^3$) and DuPont Pontamine Fast Turquoise dye ($\rho = 2.04 \text{ g/cm}^3$), and a

Collison nebulizer system for latex spheres ($\rho = 1.027 \text{ g/cm}^3$) for size calibration. Concentrations at the inlet and outlet of cyclones were measured with a Climet particle counter. Beeckmans⁽¹²⁾ used a spinning disc generator for a methylene blue-uranine aerosol ($\rho = 1.42 \text{ g/cm}^3$), and washed out deposits for fluorometric measurement. Particles were sized microscopically. Added to these possible sources of discrepancies are the lack of close dimensional tolerances in the manufacture of some cyclones, the experimental errors in laboratory calibrations, and the differences in performance in laboratory and field environments.

Thus it is not surprising that the calculated flows for a specified cut size in Tables II and III differ substantially in some cases from those in other reports.⁽¹⁵⁾ The value of 2.1 L/min for a cut size of 3.5 μm for the 10 mm nylon cyclone differs substantially from the 1.7 L/min recommended by NIOSH⁽¹⁶⁾ and others. The data set^(5,8) used here was selected because it appeared to be one of the most comprehensive sets. Although they recognized this difference, Chan and Lippmann recommended a flow rate of 1.8 L/min as providing the best overall match to the whole ACGIH curve. No

calculated values can be more accurate than the data upon which they are based. The major advantage of the log probability plotting method proposed here is that it permits condensation of data for different flow rates to a single straight line. This facilitates more accurate calculation of the descriptive parameters n , σ_g , and K_d and highlights deviant data. Furthermore, these parameters vary over only limited ranges. Further studies may shed light on effects of construction dimensions other than the body and outlet diameters.

Conclusions

The proposed empirical equations and method of plotting data on log probability paper have been successfully applied to data for 30 small cyclones from a variety of investigators. The two significant dimensions utilized were the body and outlet diameters. Their sizes ranged from body diameters of 1.0 to 15.2 cm and the flow rates from 0.9 to 2860 L/min. The effects of temperatures ranging from 25 to 204°C on cyclone performance appeared to be adequately predicted. An exponent of 0.830 in Equation 2 fitted 25 of the cyclones reasonably well, and could be used to estimate cut sizes for similar cyclones. The new method of plotting data produces a single straight line for most data at differing flow rates. This should facilitate accurate description of cyclone performance with less experimental calibration data, and selection of flow rates for any desired cut size. The proper operating flows are listed for commercially available cyclones to produce 50% cut off diameters of 3.5 and 10 μm . The method should promote wider use of cyclones for sampling aerosols in air, using a higher range of flow rates, with less problems from bounceoff and reentrainment.

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