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A collection of experimental data for aerosol monitoring cyclones

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ABSTRACT

Cyclone behavior is complex and difficult to model. Recent years have seen the development of new and better predictive models for cyclone performance, which are providing new insights into how cyclone performance is affected by cyclone geometry. Experimental data are essential for verification of such models. In this article we present a dataset of more than 250 experimental determinations of cyclone penetration. The dataset includes cyclones with a wide range of sizes and geometries, tested at a wide range of flow rates. We illustrate some empirical, semi-empirical and mathematical approaches to modeling these cyclone data. For our data, we show that mathematical modeling approaches developed for large gas-cleaning cyclones can also be applied to small aerosol monitoring cyclones, to diverse cyclone geometries, and laminar flow operating conditions.

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Introduction

Cyclones have a very wide range of uses in aerosol monitoring and gas cleaning applications; consequently many investigators have sought to develop models to describe cyclone performance. Good predictive models, whether empirical, semi-empirical or mathematical, can be used to design new cyclones for new applications, or to improve existing designs. Thorough reviews of historical cyclone modeling approaches, and comparisons with experimental cyclone data, have been published by Moore and McFarland (1993), Lidén and Gudmundsson (1997) and Hsiao et al. (2015).

This article presents a large, previously unpublished experimental dataset, characterizing the performance of small, short-coned, circular-inlet cyclones having a wide range of geometries. The dataset has been collected over a period of 25 years and is included as online supplementary information (SI) to this article. We illustrate the conformity of our data with selected predictive cyclone models

The dataset attached to this article concerns cyclones developed over many years for a wide range of aerosol monitoring applications. For these applications the aerosol penetration through the cyclone must follow a predetermined characteristic or convention, e.g., PM10, PM2.5, PM1, respirable or thoracic sampling conventions (ACGIH 1998; CEN 1993; ISO 1995; USEPA 1997). The cut point (defined as the particle aerodynamic diameter at which penetration or collection efficiency is 50%, D_{50}), and the steepness of the selection curve, are the key performance characteristics for aerosol monitoring applications (Peters et al. 2001). The stability of the penetration curve with progressive cyclone dust loading is also an important consideration, particularly for ambient aerosol monitoring (Gussman et al. 2002; Kenny et al. 2004). For the dataset described, whose design flow rates were intended for either personal, static or ambient monitoring applications, tested flow rates typically range from 1 to 20 liters/min with only a few data outside this range. Design cut points at these flow rates are typically in the range 1 to 10 μm. Particle Stokes numbers, at the cyclone inlet velocities tested, are generally below 1 for particles with aerodynamic diameters below 5 μm, but can be as high as 5 for 10 μm particles in some cases.

New aerosol monitoring cyclones are still needed to meet new challenges in both personal and ambient aerosol monitoring. The challenge, for example, of monitoring personal exposure to hazardous dusts at very low

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concentrations requires compact, lightweight cyclones that operate at high flow rates (Lee et al. 2010, 2016). Separating diesel exhaust particles from co-present mineral particles in a mixed aerosol requires cyclones with a precise, sub-micron cut point that remains stable under high dust loadings (Cauda et al. 2014). Chemical speciation and source apportionment of ambient aerosols requires PM1 and PM2.5 cyclones that perform well over long time scales under considerable load (Budisulistiorini et al. 2013; Petit et al. 2015). Predictive cyclone models have played an important role in developing the cyclones for these and other applications.

Gas cleaning cyclones are generally larger than aerosol monitoring cyclones and operate at higher flow rates. For gas cleaning applications, overall efficiency of aerosol collection and pressure drop are key performance parameters, i.e., collection of dust should be maximized for least energy expended (Hoffman and Stein 2008). Cyclone cut points in the range 1–10 μm are also desirable. Gas cleaning cyclones usually have rectangular rather than circular inlet cross-section, but in other respects the cyclone geometry is similar to aerosol monitoring cyclones. Much of the recent and current research on cyclones, both practical and theoretical, focuses on gas-cleaning applications. There have been considerable advances recently in the development of mathematical models of gas-cleaning cyclones. A mathematical cyclone model developed by Avci and Karagoz (2003) has been refined over time through comparison with experimental data (Kaya et al. 2011; Surmen et al. 2011; Karagoz et al. 2013; Tan et al. 2016). In this article we examine whether this model could also be useful to describe the performance of small, circular-inlet aerosol monitoring cyclones.

Experimental data are essential for model verification. We hope that the dataset published with this article will prove useful for this purpose, and will help advance both mathematical and Computational Fluid Dynamic modeling of cyclones.

Description of the cyclone dataset

Aerosol penetration data

The dataset (see the SI) includes more than 250 determinations of the aerosol penetration through specified cyclones at specified flow rates. Each tested cyclone is identified by its physical dimensions as set out in the key to Figure 1, and a summary of the available data is given in Table 1. All tested cyclones had circular tangential inlet tubes, and both inlet and outlet tubes were thin walled (their wall thicknesses are not documented). The cyclones were all machined from aluminum and in some cases the surface was also nickel-plated. The cyclones included in the dataset are all short-coned (i.e., $H/D_c \leq 3$) and are intended for use at flow rates low enough for use with portable pumps.

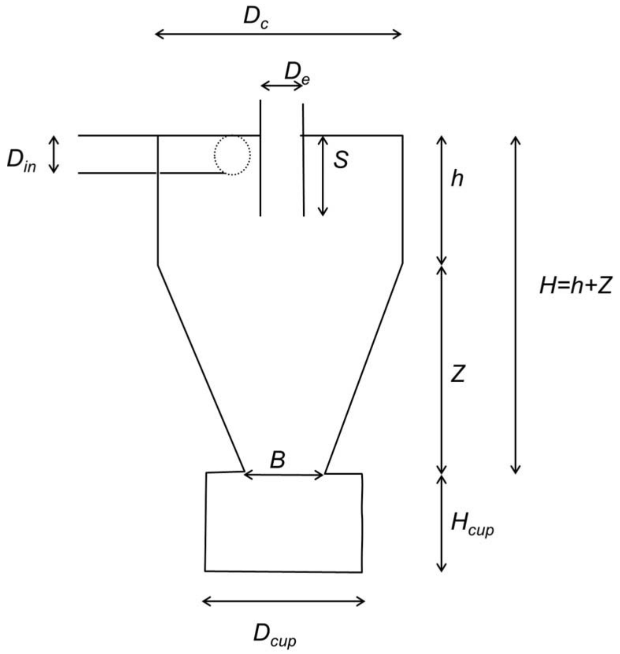

Figure 1. Schematic diagram of a round-entry cyclone, showing the principal dimensions.

The majority of the data are for established cyclone families, designated by the ‘family names’ GK, SCC, ESCC or VSCC. A cyclone family is defined as a group of cyclones whose relative dimensions are in fixed proportions to the body diameter D_c. Early experimental results on some members of these cyclone families were published by Kenny and Gussman (1997) and by Kenny et al. (1999), but the collected dataset is now considerably larger than in these previous articles.

The GK, SCC and VSCC families were developments of the SRI cyclones originally described by Smith et al. (1979). The GK cyclone family was based on the SRI-IV cyclone, the SCC on the SRI-III and the VSCC on the SRI-II. There are small differences in geometry between the original SRI versions and the ‘family’ versions; these were introduced during the product design work in order to optimize the performance for specific aerosol monitoring applications. Since that original development work, the cyclone families have grown by the addition of many new family members intended for different aerosol monitoring applications. Where these new family members have been characterized and those data are publically available they are included in the dataset. Cyclones with the GK, SCC and VSCC family geometries are now commercially available from BGI by Mesa Labs, 10 Park Place, Butler, NJ, USA.

Table 1. Summary of the data in the supplementary information.

Cyclone type	Dc values (mm)	Din/Dc	De/Dc	B/Dc	H/Dc	h/Dc	Z/Dc	S/Dc	Hcup/Dc	Dcup/Dc	Penetration values	Pressure drop values
GK	8 values 11.47 to 41.62 mm	0.200	0.230	0.200	1.300	0.400	0.900	0.230	0.870	0.200	53	ΔP vs. Q for 3 GK sizes
ESCC	9 values 7.46 to 34.91 mm	0.143	0.229	1.000	1.903	1.000	0.903	0.514	0.000	0.000	31	
VSCC	1 value 29.46 mm	0.276	0.296	0.348	1.920	0.633	1.280	0.693	0.614	0.842	12	ΔP vs. Q for 1 VSCC
SCC	13 values 2.24 to 66.34 mm	0.240	0.270	0.250	1.560	0.430	1.130	0.350	0.870	0.635	70	ΔP vs. Q for 5 SCC sizes
Modular	1 value 17.5 mm	Three values: 0.14 to 0.26	Three values: 0.14 to 0.37	Three values: 0.1 to 1.0	Six values: 1.14 to 3.0	Two values: 0.4 and 1.0	Three values: 0.74 to 2.0	Three values: 0.23 to 0.86	Two values: 0 and 0.86	Three values: 0.2 to 1.0	88	

The dataset also includes the results for a set of non-standard cyclones that could be assembled in a range of different shape combinations from a set of modular cyclone parts - tops, inlets, cones and bases. The original work to characterize the resulting cyclone combinations was reported by Kenny and Gussman (2000). The purpose of that study was to evaluate the relationships between cyclone geometry and cyclone performance, in particular the geometry effects on the cut point and the steepness of the penetration curve. Each modular combination of cyclone parts was tested at just two flow rates, 2 and 4 liters/min. This work produced useful insights on how to adjust and optimize the design of an aerosol monitoring cyclone in order to meet a specific design intention. The ESCC cyclone family, whose geometry gives a particularly steep penetration curve, resulted from that study.

Penetration measurement methodology

With a few exceptions the measurement methodology used to generate the penetration data is based on that described in detail by Maynard and Kenny (1995), which has since found widespread application. In this method, cyclones are tested in an aerosol chamber using a test aerosol consisting of solid, spherical glass microspheres of known density. The chamber aerosol is sampled alternately through the cyclone and through a reference inlet, into an aerodynamic particle sizer (APS 3300, 3310, 3320 or 3321, TSI Inc, Shoreview, MN, USA), situated directly below the working section, outside the chamber. The aerosol penetration through the cyclone is calculated by taking the ratio of the two (with and without cyclone) aerosol size distributions. Experimental errors are minimized by ensuring that the concentration of the test aerosol is uniform in space and time, and that other effects such as inlet and transfer losses are, so far as possible, identical in both sampling lines. The size distribution of the test aerosol and the sampling time are selected to ensure, where possible, that sufficient particles are counted in the size ranges of interest. Using solid, spherical particles of known density ensures that the APS software correctly relates aerosol particle size to aerodynamic diameter.

The APS counts are processed to calculate the penetration curves. For each aerodynamic diameter bin, the average particle number counted with the cyclone present is divided by the average number counted without the cyclone present, giving the aerosol penetration for that diameter range. In the case of the dataset presented here, the raw penetration values were analyzed using curve fitting software in order to interpolate the data points and locate the D_{50}, D_{84} and D_{16} aerodynamic diameters (i.e., diameters at which the penetration through the cyclone is 50%, 84%, and 16%, respectively).

The accuracy and precision of the APS methodology for aerosol penetration measurement is reasonably well understood and it has been quantified through inter-laboratory collaborative experiments (Lidén 2000; Kenny et al. 2005). Apart from flow measurement errors, experimental errors in the penetration values can arise from a number of sources, some of which are readily avoidable. Poor calibration of the APS would lead to systematic errors on the aerodynamic diameter axis. Other factors, for example limited sensitivity of the APS to both very small and large particles, non-optimal test aerosol size distribution, or instability in concentration, can introduce both systematic and random errors on the penetration axis. The APS software and the corrections it applies have changed over time and with the different models of APS used. Also, post-processing (for example normalization) and curve fitting of the penetration data can vary within and between different investigators. As there is no absolute reference standard available for aerosol penetration measurements. The quality assurance procedure used in this laboratory throughout the period over which these cyclone data were collected was to regularly repeat tests on selected cyclone specimens. This allowed us to verify that updates in hardware, software or data analysis had no measurable effect on the penetration values obtained. We also regularly participated in comparisons with other laboratories.

Despite its known limitations the APS methodology generally has good reliability and repeatability for cyclones whose cut points are in the range 1–10 μm. Above this range random errors become larger, and systematic errors can also occur unless careful additional steps are taken to correct for inlet and transfer losses (Maynard et al. 1999). Our cyclone dataset does contain a small number of results outside the reliable range, which we have identified and eliminated from analysis.

Pressure drop data

A second more limited dataset is included in the SI documenting measurements of the pressure drop across a number of the 'family' cyclones at different cyclone flow rates. The data, which are summarized in Table 1, have not previously been published but are included for completeness.

The pressure drop measurements were made with a Dwyer inclined/vertical manometer. Flow rate was measured using a series of traceable critical flow Venturi tubes having an average uncertainty of 0.35%.

Barometric pressure was measured using a Meriam Precision absolute electronic barometer, which also served to measure the absolute pressure upstream of the Venturi. The temperature entering the Venturi was measured with a thermistor calibrated against a reference thermometer. All flow rates were normalized to sea level atmospheric pressure and standard temperature 20°C.

Modeling the penetration data

Empirical modeling

Kenny and Gussman 1997 demonstrated that a true family of cyclones can be described with an empirical function of the form

$$\ln(D_{50}) = a + b\ln(D_c) - (b-1)\ln(Q) \qquad [1]$$

Or, more economically

$$\ln(D_{50}\ /\ D_c) = a - (b-1)\ln(Q\ /\ D_c) \qquad [2]$$

where D_{50} is the penetration cut point, D_C is the cyclone body diameter, Q is the flow rate, and a, b are numerical constants determined using non-linear least squares regression.

D_c is the only cyclone dimension included as all other cyclone dimensions are in fixed proportion to D_c for a cyclone family. The values of the numerical constants differ for each cyclone family. Values for parameters a and b determined for the GK, SCC and ESCC families were published in Kenny and Gussman (2000), and those for the VSCC family were published in Kenny et al. (2004).

A statistical modeling approach was used by Kenny and Gussman (2000) to analyze the data for the modular cyclones, since they have diverse geometry and hence are not a family. Multiple regression and factor analysis were used to predict the D_{50}, D_{16} and D_{84} values as a linear function of the cyclone geometrical parameters. Separate regression models were fitted to the data at each of the two tested flow rates. The model parameters are tabulated in Kenny and Gussman (2000). These regression models can be used in principle to estimate the empirical parameters for arbitrary "family" models, however Kenny and Gussman demonstrated that for the known, characterized cyclone families this method was only usable as a first approximation. Its utility is limited because the regression models are fitted at only two different flow rates, the absolute minimum needed to estimate family model parameter values. A re-analysis of normalized data (e.g., flow rate transformed to inlet velocity) with D_{50} values slip-corrected, may prove worthwhile but is not included in this article.

Semi-empirical modeling

For a wide range of cyclones, Moore and McFarland (1993) identified the annular Reynolds number of the flow within the cyclone body to be the principal determinant of the D_{50}. The annular Reynolds number depends on the geometry of the cyclone inlet and outlet and is defined as:

$$\mathrm{Re}_{ann} = \frac{V_i(r_c - r_e)}{\nu_g} \qquad [3]$$

where r_c is the cyclone body radius ($D_c/2$), r_e is the exit tube radius ($D_e/2$), V_i is the average gas velocity in the cyclone inlet and ν_g the kinematic gas viscosity, in this case for air. In a later article Moore and McFarland (1995) showed that the relationship between the cut point and the annular Reynolds number was different for 'short coned' and 'long coned' cyclones.

Lidén and Gudmundsson (1997) analyzed 140 D_{50} determinations for several different cyclone designs having diverse geometry and extended Moore and McFarland's approach to include a wider range of cyclone dimensional parameters. For their dataset the only additional cyclone dimension making a statistically significant contribution to the D_{50} was the vortex finder length, S. Lidén and Gudmundsson's data were fitted by the following relationship:

$$\ln(sD_{50}\ /\ D_c) = c_0 + c_1\ln(\mathrm{Re}_{ann}) + c_2(S\ /\ Dc) \qquad [4]$$

where s is the square root of the Cunningham slip correction factor, S is the cyclone vortex finder length, and $c_0 = ln(0.0414)$, $c_1 = -0.713$ *and* $c_2 = -0.172$ are empirical constants.

Mathematical modeling

Mathematical models of gas cleaning cyclones have been developed to describe and quantify the influence of cyclone geometry on the aerosol separation efficiency and pressure drop. Avci and Karagoz (2003) developed a mathematical model describing the particle separation mechanisms operating along the spiral flow path of the vortex within the body of a cyclone. Their model considers surface-friction-induced deceleration of the flow along the path of the vortex, which affects the position at which the vortex reverses back to flow towards the vortex-finder exit tube. The distance between this turning position and the bottom of the vortex finder exit tube is known as the vortex length.

Avci and Karagoz (2003) derived a mathematical relationship (Equation 26 in their 2003 article) giving the D_{50} cut point as a function of the inlet Reynolds number, the vortex length and the frictional losses, all of which depend on the cyclone geometry and the flow rate. Approximations were proposed for the friction coefficient and the vortex length. More recent work (Avci et al. 2013; Karagoz and Avci 2005) has provided better estimates for the vortex length, which have been validated by experimental studies of vortices within plexiglass cyclones whose geometry can be varied (Avci et al. 2013; Tan et al. 2016).

To illustrate the application of the Avci and Karagoz (2003) model to our dataset we used the following approximations for the critical ‘unknown’ parameters. The friction coefficient depends on the Reynolds number of the flow through the cyclone inlet:

$$\mathrm{Re}_{in} = \frac{D_{in} V_i}{\nu_g} \qquad [5]$$

where ν_g is the kinematic air viscosity and V_i the inlet velocity. The friction coefficient *f* was estimated using different expressions for laminar and turbulent inlet flow:

$$f = \frac{64}{\mathrm{Re}_{in}} \text{ for } Re_{in} < 2300 \text{ and } f \approx \frac{6.4}{[\ln(\mathrm{Re}_{in})]^{2.4}} \text{ for } Re_{in} > 2300 \qquad [6]$$

The length of the spiral path of the vortex, L_{vs}, was estimated using the following relationship from Surmen et al (2011):

$$L_{vs} \approx 1.5 \frac{D_s H}{D_d} \qquad [7]$$

where D_s and D_d are dimensionless geometrical parameters. They relate the cyclone body diameter to that of a cylinder with equivalent frictional surfaces and height *H* - the cyclone height. Using the nomenclature for the cyclone dimensions given in Figure 1:

$$D_d = \frac{h}{H} + 0.5\left(1 + \frac{B}{D_c}\right).\left(0.25\left(1 - \frac{B}{D_c}\right)^2\left(\frac{D_c}{H}\right)^2 + \left(1 - \frac{h}{H}\right)^2\right)^{0.5} \qquad [8]$$

and

$$D_s = D_d + \frac{2D_e S}{D_c H} \qquad [9]$$

following Avci et al (2013). These quantities are used to calculate a dimensionless parameter *cs* (Avci and Karagoz 2003, Equation 27) relating the vortex length to the height of the cyclone. Again, using the nomenclature from Figure 1:

$$cs = 0.5 \frac{f L_{vs}}{D_{in} - 0.1B} \qquad [10]$$

where the calculated value for this parameter exceeds 1, Avci and Karagoz (2003) suggest substituting the approximation $cs \approx 1$. This was the case for the ESCC (and similar modular combinations), and for a small number of other values in our dataset.

Modeling pressure drop data

There is a considerable body of work exploring how pressure drop depends on cyclone geometry, which is reviewed by Hsiao et al. (2015). These authors carried out pressure drop experiments with their own modular cyclone to study the relationships between dimensionless pressure drop and cyclone geometrical ratios. Their work demonstrates that pressure drop is determined by a wide range of geometrical factors and varies strongly with cone height, cone shape and vortex finder length and diameter.

Karagoz and Avci (2005) also developed their mathematical cyclone model to predict pressure drop as a function of cyclone geometry. As with their penetration model, pressure drop is predicted to depend on vortex length, friction coefficient and hydraulic diameter, all of which parameters vary as a function of cyclone geometry. They compared their model predictions with those of four alternative pressure drop models, using experimental data for 12 different cyclones. All the data were for larger gas-cleaning cyclones operating at high flow rates.

Our pressure drop data cover a limited range of distinct cyclone geometries, and there is little overlap between our dataset and the data utilized in these other studies. For these reasons we have included the dataset in the SI for completeness but have not carried out any more than basic analysis, which is included in the SI.

Results for the penetration data

Empirical models

Figure 2 shows the D_{50}/D_c plotted against Q/D_c for the four cyclone families. Power relationships corresponding to Equation (2) using the previously—published family model parameter values are also shown.

In comparing the published family models with our enlarged dataset we can see significant divergences between expected and measured D_{50} values above

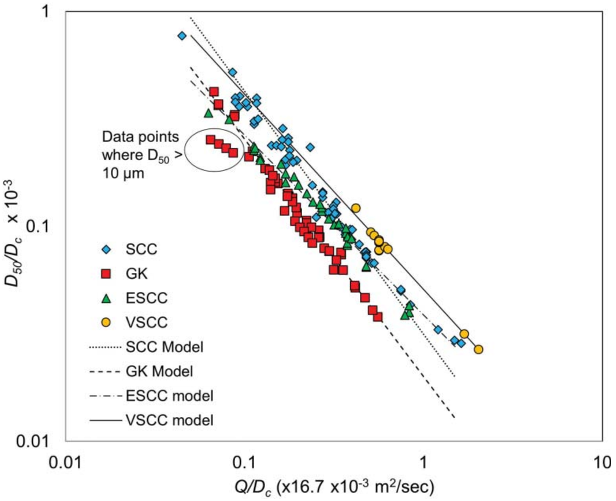

Figure 2. Data for the SCC, GK, ESCC, and VSCC cyclone families, and published family models.

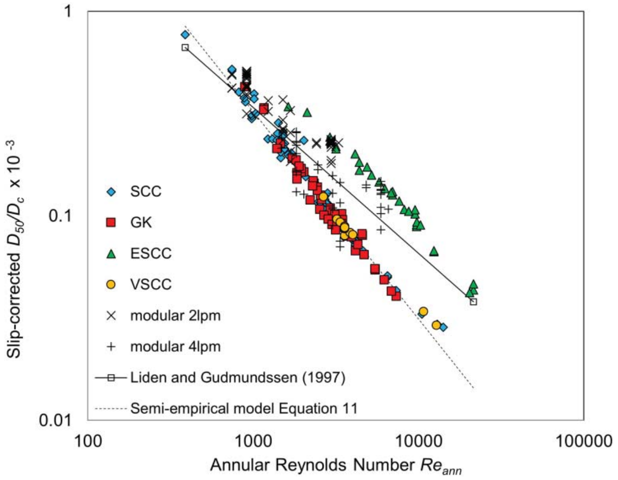

Figure 3. Data for all cyclones, and semi-empirical models.

10 µm. It is not possible, without independent verification using an alternative experimental method, to say whether these stem from experimental error or failure of the models, however we think it likely that these data points reflect limitations in the experimental methods used. For this reason, we have excluded from further analysis the experimental determinations where the expected D_{50} value is above 10 µm. This excludes five values from the SCC dataset and six values from the GK dataset. The model parameter values and the Root Mean Square Errors between the observed and modeled D_{50} values are given in Table 2.

Semi-empirical model

Figure 3 shows D_{50}/D_c plotted against Re_{ann} for both the cyclone families and the modular combinations. The power relationship corresponding to Equation (4), with the parameter values published by Lidén and Gudmundsson (1997), is also shown for the case where $S/D_c = 0.5$, which is mid-range for the cyclones in our dataset (S/D_c varies from 0.23 to 0.85). This relationship is not a good fit to our data. Only four of the ~250 data points in our dataset were included in the dataset analyzed by Lidén and Gudmundsson (1997).

Table 2. Model fit parameters and root mean square errors.

Cyclone type	Published Family model parameters	RMSE – new dataset vs. published family model	RMSE – new dataset vs. semi-empirical model Equation (11)	RMSE – new dataset vs. Avci-Karagoz model
GK	a = 0.936 b = 2.105	0.339 µm	0.391 µm	0.837 µm
ESCC	a = 0.976 b = 1.837	0.219 µm	1.398 µm[1]	0.61 µm
VSCC	a = 1.415 b = 1.908	0.119 µm	0.101 µm	0.571 µm
SCC	a = 1.447 b = 2.131	0.502 µm	0.287 µm	0.713 µm
Modular	n/a	n/a	1.48 µm[1]	1.872 µm

These data were not included when fitting the semi-empirical model.

For the SCC, GK and VSCC cyclone families only, the following power relationship (fitted using least squares regression) is the best fit to our data:

$$\ln(sD_{50}\ /\ D_c) = \ln(0.4753) - 1.014\ln\left(\frac{Q(D_c - D_e)}{D_{in}^2}\right) \qquad [11]$$

and this is also plotted in Figure 3. The R^2 value for this regression is 0.976. For the numerical constants given, D_{50} is in units of micrometers, cyclone dimensions are in millimeters and flow rate Q is in liters/min. Slip correction s is the square root of the Cunningham slip correction factor. Residuals between measured and predicted slip-corrected D_{50} values using this relationship are shown in Figure 4, and the root mean square error in prediction of the slip-corrected D_{50} is given in Table 2, for different cyclone families.

Mathematical models

D_{50} values predicted using the Avci and Karagoz (2003) model, with approximations as set out in Equations (5)–(10), are shown in Figure 5 for both the cyclone family data and the modular cyclone data.

Figure 6 shows the D_{50} residuals plotted as a function of the inlet Reynolds number Re_{in}, which determines the friction coefficient f. Residuals were also analyzed in relation to other model parameters (L_{vs}, D_d, D_s, cs) but are not presented here. Again, the Root Mean Square Errors

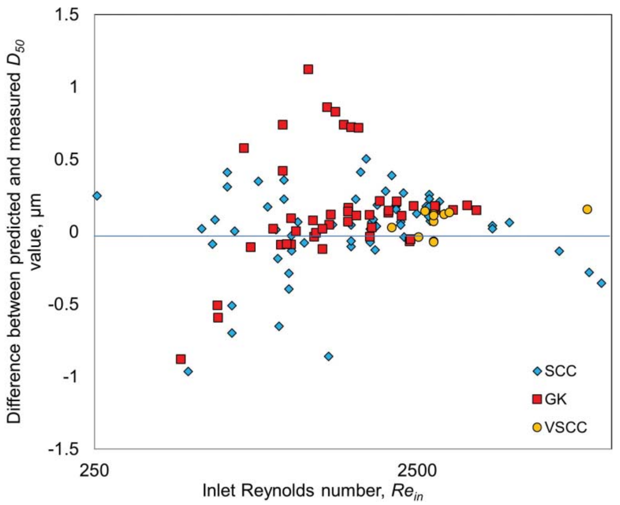

Figure 4. Semi-empirical model (Equation (11)) residuals as a function of inlet Reynolds number.

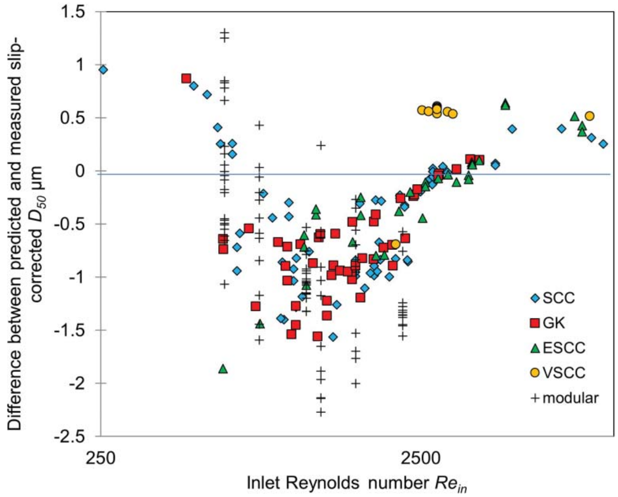

Figure 6. Avci-Karagoz model residuals as a function of inlet Reynolds number.

in predicting the slip-corrected D_{50} values are given in Table 2.

Discussion

In this article we have presented a dataset of penetration determinations for small, circular inlet cyclones with a wide range of sizes and geometries, tested at a wide range of flow rates. The dataset, which is given in full in the SI, includes the cyclone geometrical parameters, measured D_{50} values for all cyclones, plus D_{16} and D_{84} values where these are also available. We have also included data on pressure drop at different flow rates for a restricted selection of these cyclones in the SI. Our principal aim in publishing this dataset is to make these experimental data available to other researchers with an interest in cyclone modeling and design.

We have used our dataset to demonstrate the capabilities of different predictive models for the cut point or D_{50} of a cyclone at a given flow rate. Our results show that simple, empirical family models are robust and reasonably accurate but can only be used for a particular cyclone design having fixed proportions (a cyclone family). They can be used to scale cyclones up or down, for example to match the cyclone's cut point to a desired value at a desired flow rate. Optimizing cyclone performance in other ways, for example increasing the steepness of the penetration curve or reducing the pressure drop, requires a fuller understanding of the influence of cyclone geometry, and changes to the cyclone's proportions. That optimization would generate a new cyclone family with distinct empirical model parameters.

The semi-empirical approach proposed by Moore and McFarland (1993), which includes the inlet and outlet dimensions as well as body diameter, is a more generalizable treatment that works well for different cyclone families having typical geometry. For conventional cyclone designs such as the GK, SCC, and VSCC families, the semi-empirical relationship given in Equation (11) provides a simple predictive model for D_{50} that is only marginally less accurate than the family-specific models. The semi-empirical approach only considers cyclone inlet and outlet geometry, and parameter values have been shown to vary for different cyclone datasets. Experimental studies with multi-inlet and long-coned cyclones (Moore and McFarland 1995), and with modular cyclones (Kenny and Gussman 2000; Hsiao et al. 2015) has generated data for a wider range of more diverse cyclone shapes. These studies confirm that while the inlet and

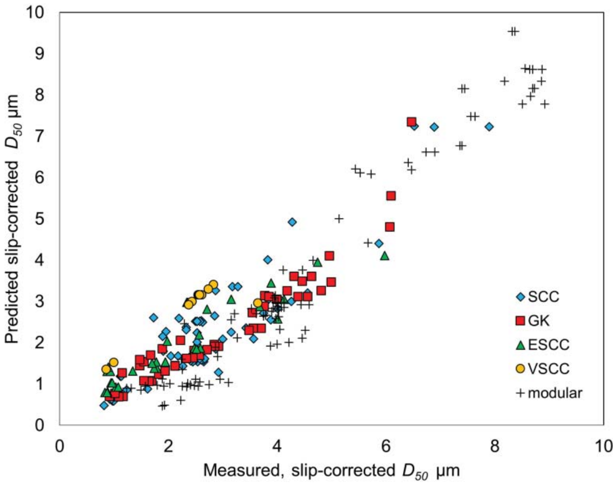

Figure 5. Cyclone cut points predicted by the Avci-Karagoz mathematical model, parameter values calculated using Equations (5)–(10).

outlet geometry dominate cyclone performance, the cone base diameter *B*, cyclone height *H* and vortex finder insertion length *S* are important secondary factors having significant effects. This is also seen in our data for the ESCC cyclone.

The Avci and Karagoz (2003) mathematical model for gas cleaning cyclones, with later parameter refinements by Surmen et al. (2011), considers the contribution of particle separation within both the inlet/outlet portion and the cone, and has potential application to cyclones with a wide range of geometries. For the GK, SCC and VSCC cyclone families the residual errors between observed and predicted D_{50} values (Figure 6) using this model, particularly at lower flow rates where the frictional coefficient could not be estimated well, were larger than those obtained with the simpler semi-empirical model (Figure 4). The Avci-Karagoz model does appear to encompass the geometrical diversity of our dataset better than the semi-empirical approach. This is interesting since recent work by Avci, Karagoz and co-workers to develop the mathematical model and to validate its approximations experimentally has included cyclones with a cylindrical shape similar to the ESCC (Avci et al. 2013; Tan et al. 2016).

The Avci-Karagoz mathematical model is also, to an extent, successful at predicting the D_{50} values for many of the modular combinations. This is remarkable given the very wide range of cyclone geometries included, and considering that for this dataset the model is 'stretched' to flow conditions outside its intended field of application. Notably, the model was developed for large gas-cleaning cyclones with rectangular inlets, operated at high flow rates, but is here applied to small, short, circular-inlet cyclones operated at very low flow rates. A better method to estimate the friction coefficient for the swirling flow inside cyclones, particularly at these lower flow rates, would develop the model's utility for aerosol monitoring cyclones.

Hsiao et al. (2015), in their study of a set of rectangular-entry modular cyclones based on the Stairmand design, also observed good agreement between experimental data and the Avci-Karagoz model predictions. Like the modular cyclones discussed in this article, Hsiao's cyclones could be assembled in a variety of configurations in order to quantify the effects of geometry on efficiency and pressure drop. Hsiao et al. (2015) however tested their modular cyclones at a higher flowrate (30 l/min) and were able to use the turbulent flow approximation to estimate the friction coefficient. Their work provides independent confirmation that the mathematical model developed by Avci, Karagoz and co-workers can be usefully applied to a wide range of cyclone geometries.

Conclusions

Recent years have seen the development of new and better predictive models for cyclone performance, which are providing new insights into how cyclone performance is determined by cyclone geometry. These efforts are building a better understanding of how to optimize cyclone designs for particular applications. The large experimental dataset we have collected over several years has enabled us to compare and contrast some different predictive modeling approaches for cyclones. These range from empirical models that apply only to one fixed cyclone geometry (i.e. a specific cyclone family), to generalizable mathematical models that - in principle - apply to any cyclone.

Empirical models for well-known cyclone families have proved robust over time for predicting the performance of new family members, at least for cut points in the range of 1 to 10 μm. It is more difficult to assess their usability outside this range due to the limitations in our experimental methods.

Our data confirm the observation by Moore and McFarland (1993) that for different cyclone designs having conventional cyclone geometry, it is possible to predict the cut-point/flow relationship using a small subset of key dimensional parameters. For the GK, SCC and VSCC cyclones in our dataset this approach enabled us to fit a single semi-empirical model that is only marginally less accurate than the specific family models. However our semi-empirical fit does not have universal application to any cyclone.

Finally we have shown that the mathematical model developed by Avci and Karagoz (2003) for large gas-cleaning cyclones can also be applied to small aerosol monitoring cyclones. It can be applied to a wide range of cyclone geometries and over a wide range of operating conditions extending beyond its intended field of application. It is particularly useful for cylindrical cyclones that do not have a conical base, and other non-standard cyclone configurations.

Nomenclature

D_c	cyclone body diameter
D_{in}	cyclone inlet diameter
D_e	cyclone outlet (vortex finder) diameter
S	vortex finder length
h	height of the cylindrical part of the cyclone body
Z	height of the conical part of the cyclone body
H	cyclone height $\mathrm{H} = \mathrm{h}+\mathrm{Z}$
Q	flow rate
Re_{in}	Reynolds number of the flow through the cyclone inlet

Re_{ann}	annular Reynolds number of the flow in the cyclone body
v_g	kinematic gas viscosity (in this case, air)
V_i	inlet velocity
s	square root of the Cunningham Slip Correction factor
f	frictional coefficient
L_{vs}	path length of the cyclone vortex, streamwise along the spiral
D_s	dimensionless parameter for the equivalent friction surface in the cyclone body, including the vortex finder surface
D_d	dimensionless parameter for the equivalent friction surface in the cyclone body
cs	dimensionless parameter relating the vortex length to the cyclone height

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