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A practical model for estimating pressure drop in cyclone separators: An experimental study

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ABSTRACT

An experimental study regarding the effects of body height (h_b), conical height (h_c), and vortex finder height (S) on cyclone pressure drop was performed. Pressure drops were measured at six different inlet velocities in the range of 10 to 24 m/s. The dimensions of h_b, h_c, and S were in the range of D to $2D$, $2D$ to $3D$, and $0.5D$ to $0.7D$, respectively. The experimental results suggested that the pressure drop decreases with an increase in h_b and h_c, while it increases as S increases. Several models in current literature were tested for their performance in explaining the pressure drop components in cyclones. Besides, a new model was suggested to estimate cyclone pressure drop. Agreement between experimental and calculated pressure drops were weak to moderate for all models in current literature. In contrast, the new model fitted the experimental data very well and this model is suggested for clean pressure drop in cyclone separators. Ratios of predicted to measured pressure drops for the new model ranged between 0.388 and 1.785. The average value was 1.059. The residuals from the new model were normally distributed around the mean value of zero with a negligible positive skewness. The new model can be confidently used for estimating clean pressure drop with $R^2 = 0.976$.

1. Introduction

In air pollution control field, cyclone separators are one of the most commonly used control devices used for removing particulate matter (PM) from the gaseous flow. The main purpose of a cyclone separator is to collect particulate matter prior to emission to the atmosphere or to reduce particulate loading into subsequent control devices. Elsayed and Lacor [1,2] listed major advantages of cyclone separators for particulate control as their simplicity in construction, low cost of operation and maintenance, and most importantly their capability of adaptation to extreme operating conditions such as high temperature, high pressures, high PM loads, and corrosive gasses.

A cyclone separator is composed mainly of four parts: the inlet part, the body, the conical part, and the outlet part. The gas–solid flow enters to the cyclone inlet at very high velocities, best practices of which have been reported as between 6 and 15 m/s [3]. A higher range of inlet velocities between 15 and 25 m/s was also reported [4]. Most of inlet structures are designed so that the gas flow starts its swirling motion with a minimal pressure drop at the inlet side. The most commonly used type of inlet parts is reported as tangential inlet [1]. The body provides outer boundary for the swirling motion within the cyclone separator. Being heavier than the gaseous phase, the particles drift toward and collide with the body wall due to the centrifugal forces. The purpose of the conical part is to divert the gas flow toward the vortex finder and the particles are collected in the dust bin. The cleaned gas forms an inner vortex through the vortex finder and leaves the cyclone separator.

The performance of a cyclone separator is expressed by collection efficiency and pressure drop. These two performance criteria are intimately related with each other. Usually collection efficiency increases with increasing pressure drop. Therefore, prediction of pressure drop is an essential step in cyclone design.

Chen and Shi [5] reported that the pressure drop in cyclones consists of local and frictional losses. The local losses are due to the expansion of the gaseous flow at the inlet and the contraction at the vortex finder. Cortes and Gil [6] reported that the former one is of minor importance when compared to the losses at the cyclone wall and outlet. Although experimental and numerical study showed that cyclone pressure drop is also a function of variables other than cyclone geometry such as gas temperature [7,8] and high solid loading [9,10], most of the researchers have focused on the effects of geometry on cyclone performance and a great number of cyclone geometries with varying collection efficiencies and pressure drops have been proposed [11–15]. On the other hand, many researchers have developed various procedures to estimate pressure drop in cyclones [5,16–21], some of which offer simple ways to predict pressure drop while others are somewhat complicated. In the last decade, however, Computational Fluid Dynamics (CFD) applications to predict flow and pressure fields became more popular [22–29]. Although CFD models have proven to be useful in explaining complex

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Nomenclature

a	Inlet height (mm)
A	Inside surface area of cyclone (mm^2)
A_S	Area of contact surface. See Eq. (8c)
b	Inlet width (mm)
B	Cone-tip diameter (mm)
D	Cyclone diameter (mm)
D_e	Vortex finder diameter (mm)
D_h	Hopper diameter (mm)
e_e	Parameter for accounting losses due to inlet and friction
e_i	Parameter for accounting losses at the outlet
f	Parameter for calculating pressure drop by Alexander's model. See Eq. (3c)
h_b	Body (cylindirical) height (mm)
h_c	Conical height (mm)
h_h	Hopper height (mm)
k	Swirl exponent. See Eq. (8a)
k_i	Correction coefficient to account for the contribution of axial expansion loss. See Eq. (8a)
m	Parameter for calculating pressure drop by Barth's model. See Eq. (6d)
n	Parameter for calculating pressure drop by Alexander's model. See Eq. (3c)
N_H	Number of velocity heads
R_A	Inlet area ratio. See Eq. (8b)
r_c	Radius of core flow. See Eq. (8d)
Re	Reynolds number
S	Vortex finder height (mm)
T	Gas temperature (K)
V_I	Gas inlet velocity (m/s)
V_T	Tangential velocity at cyclone wall (m/s)
Y	Constant related with inlet type. $Y = 0.5$ for no inlet vane; $Y = 1.0$ for neutral inlet vane; $Y = 2.0$ for inlet gas touches external surface of vortex finder. See Eq. (5).
α	Parameter for calculating pressure drop by Barth's model. See Eq. (6e)
ΔP	Pressure drop (N/m^2)
λ	Friction coefficient
ρ_G	Gas density (kg/m^3)
φ	Parameter for calculating pressure drop by Stairmand's model. See Eq. (4b)

phenomena in cyclone separators, application of these models requires high computational capacity as well as time. Therefore, field engineers and cyclone designers often need practical approaches to estimate cyclone pressure drop.

The aim of this study is experimental and numerical investigation of the effects of geometry such as body height (h_b), conical height (h_c), and vortex finder height (S) on clean pressure drop in cyclones and to formulate a practical model for cyclone pressure drop that accounts for the parameters h_b, h_c, and S. The results from this study will enable one to make good estimations for cyclone pressure drop without the need for using complicated models such as CFD.

2. Materials and methods

2.1. Experimental setup

A lab-scale experimental setup similar to that reported in Shepherd and Lapple [16] was used. The experimental setup was composed of three main parts: The air blower, the inlet channel and the cyclone separator. The capacity of the air blower was 1500 m^3/h. The inlet channel was of circular cross-section with an inner diameter of 194 mm, and included a flow-control valve (FCV) and an orifice meter (ISO 5167-2: 2003) equipped with a Honeywell DPTM1000D digital differential pressure transmitter to monitor and control the gas flowrate into the cyclone separator. The gas flowrate is calculated by the pressure drop at the orifice according to the procedure given in ISO standard 5167-2: 2003. The uncertainty of discharge coefficient for the orifice was defined as lower than 0.7% in the standard. The accuracy of the digital differential pressure transmitter was reported as 0.2% in technical specifications of the device. The inlet velocities were calculated as ratios of flowrate to cross-sectional area of inlet opening.

Static pressures were taken at a number of pressure taps on cyclone wall. The vortex finder tube was extended outside of the cyclone and a pressure tap was placed near the exit of the tube. The locations of pressure taps are shown in Fig. 1. Since the cyclone discharged directly to the atmosphere for all runs, the pressure drops through the cyclone was measured as the static pressures at *P1*. For convenience, the differential pressures between *P1* and *P5* were also measured, which was almost equal to the static pressure at *P1*. This proves that the fluctuations in static pressure due to swirling motion in vortex finder were eliminated.

The experimental setup was designed to allow a wide range of cyclones with various dimensions and geometry. Fig. 1 shows geometry of cyclone separators used. Based on literature data, Stairmand high efficiency design is one of the cyclone designs offering the highest particulate collection efficiency. Modifications were based on this design. 162 cyclones of various geometries were used. All of the cyclones were of tangential inlet. Table 1 summarizes dimensions of cyclone parts and their mode of use in experiments.

2.2. Model development

In literature, it is customary to express the pressure drop in cyclone separators in terms of inlet velocity head as follows:

$$\Delta P = \frac{1}{2}\rho_G V_i^2 N_H. \tag{1}$$

Here, ΔP is cyclone pressure drop, ρ_G is gas density, V_i is inlet velocity, and N_H is number of velocity heads, and it is a pressure drop parameter to account for all of pressure drop components in terms of inlet velocity heads. Over years, a great number of models have been proposed including Shepherd and Lapple [16], Alexander [17], Stairmand [18], First [19], Barth [20], Casal and Martinez [21], and Chen and Shi [5]. Some of these models, the former one for instance, only accounted for the pressure drop components at the inlet and outlet sections, while some others included the effects of body and conical heights as well as vortex finder height. Still others incorporated gas viscosity and friction factor into the model. Table 2 shows a summary of models for the number of velocity heads.

Most of the current texts report Shepherd and Lapple [16] formulation for total number of inlet velocity heads. Unfortunately, Shepherd and Lapple's model does not consider the influence of body height (h_b), conical height (h_c), and vortex finder height (S). In contrast, those models in which these dimensions are included, like Chen and Shi's [5] model, are somewhat complicated and inappropriate for practical use. Although First's [19] model relates the pressure drop with these dimensions and seems to be easy-to-use, Leith and Mehta [30] reported that the results from this model are weakly correlated with measured data.

Cortes and Gil [6] reported that the main contributors to the clean pressure drop in a cyclone separator are (*1*) losses at the inlet, (*2*) losses due to friction inside the cyclone, and (*3*) losses at the outlet. Although the second and the third are the dominant pressure drop components in cyclones, a great number of researchers omitted the second component in their models. Cortes and Gil [6] reported that increasing body height and conical height increases the pressure drop component due to