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Effects of the geometric configuration on cyclone performance

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ABSTRACT

A cyclone's performance can be optimized by changing its configuration, which is a very challenging task that depends on critical performance indicators. In this work, a comprehensive overview of the effects of a cyclone's longitudinal and radial dimensional ratios (including a/D_c, b/D_c, D_e/D_c, S/D_c, h/D_c, H/D_c, B/D_c) on its cutoff size, pressure drop, as well as the steepness of the sampling curve, was briefly reviewed. In addition, systematic experimental examinations were conducted to investigate different effects of geometric configurations on cyclone performance, and the optimal ranges for the geometric dimensional ratios were proposed. The results were analyzed according to four cyclone geometric components: the overall cyclone body, the cyclone contraction cone, the vortex finder (V.F.), and the inlet, and were compared to the observations reported in the literature. It was found that the effect of the overall cyclone body height (H) is closely related to the natural vortex length (L_v). The optimal H/D_c value based on the compromise between small dimensionless cutoff size ($\widetilde{d_{50}}$) and dimensionless pressure drop (ΔH) is around 5.5–7.0, which is slightly larger than the traditional Stairmand design. A cyclone with a short and wide cone would have a steeper cutoff curve and larger optimal H/D_c value than one with a long and sharp cone. Although a cyclone with cone results in higher collection efficiency, the slope of the efficiency curve is less steep than one without cone. On the other hand, both the collection efficiency and sharpness of the collection curve of a cyclone could be improved by reducing the outlet diameter and using an inlet with higher aspect ratio. The $\widetilde{d_{50}}$ can be double and ΔH can be reduce 70% by varying the D_e/D_c from 0.28 to 0.71, while the effect of the inlet aspect ratio (a/b) is relatively insignificant.

1. Introduction

A cyclone is a particle collector that utilizes centrifugal force to capture particles with high inertia. Due to the low cost associated with manufacturing, operating, and maintenance, as well as their reliability under a wide range of operational conditions, large-scale cyclones are commonly used in industry for air pollution control or collecting particulate products. On the other hand, small-scale cyclones are generally used for particle sampling under ambient and working environments. For example, the Very Sharp-Cut Cyclone (VSCC) was designed and applied in the US EPA approved PM2.5 Federal Reference Method (FRM) sampling systems.

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Nomenclature

a	inlet height (m)
b	inlet width (m)
D_c	cyclone body diameter (m)
H	cyclone total height (m)
H_{max}	maximum-efficiency cyclone height (m)
h	cyclone body height (m)
h_c	cyclone cone height ($=H-h$) (m)
B	cone bottom diameter (m)
S	vortex finder (V.F.) length (m)
D_e	outlet diameter (m)
L	total length below V.F., ($=H-S$) (m)
L_v	natural vortex length (m)
θ	cone angle (rad)
A_i	inlet area (mm^2)
A_e	outlet area (mm^2)
d_{16}	diameter at 16% penetration (m)
d_{50}	diameter at 50% penetration, cutoff size (m)
d_{84}	diameter at 84% penetration (m)
$\widetilde{d_{50}}$	dimensionless cutoff size (dimensionless)
ρ_g	gas density (kg m^{-3})
V_i	average inlet gas velocity (m s^{-1})
ΔP	pressure drop (Pa)
ΔH	dimensionless pressure drop (dimensionless)
C_c	Cunningham correction (dimensionless)
Eu	Euler number (dimensionless)
Re	Reynolds number (dimensionless)
Re_{ann}	Reynolds number using the value of $(D_c-D_e)/2$ as the characteristic length (dimensionless)
Fr	Froude number (dimensionless)

To design new cyclones, Computational Fluid Dynamics (CFD) has recently been used to characterize the flow field and particle trajectory (Cortes & Gil, 2007; Gimbun, Chuah, Choong, & Fakhru'l-Razi, 2005; Griffiths & Boysan, 1996; Hiraiwa, Oshitari, Fukui, Yamamoto, & Yoshida, 2013; Kępa, 2010; Yang, Sun, & Gao, 2013). However, the accurate prediction and optimization of the performance of cyclones with a new geometry is a very challenging and complex task. The number of dimensions required to determine the geometric configuration of a conventional tangential flow cyclone with a rectangular inlet is as many as eight (including inlet height, a; inlet width, b, cyclone body diameter, D_c; cyclone body, height, h; cyclone cone height, h_c; cone bottom diameter, B; vortex finder length, S; outlet diameter, D_e). The complex 3-D vortex turbulence flows and unclear particle–turbulence interaction involved in cyclones are difficult to simulate numerically and verify experimentally (Hsiao, Chen, Greenberg, & Street, 2011). Therefore, most cyclone designers rely on reported semi-empirical/empirical analytical models and knowledge of the effects of geometric configurations on cyclone performance. A brief review of these effects is summarized below.

The effect of the radial dimensions, such as D_c and D_e, of tangential flow cyclones, was studied by Kim and Lee, who reported that decreasing D_e would enhance the cyclone collection efficiency significantly (Kim & Lee, 1990). Kenny and Gussman claimed that geometric factors other than D_c could play an important role in cyclone performance. They indicated that the cyclone performance of short or small-coned cyclones ($H<3D_c$) tends to be controlled by the outlet and inlet designs, while the performance of long or wide-coned cyclones tends to be dominated by the cone dimensions (Kenny & Gussman, 2000). Xiang, Park, and Lee explored the effect of cone dimensions on the particle collection efficiency by varying the cone bottom diameter (B). Their results demonstrated that the cyclone collection efficiency increases significantly as B decreases until it is equal to D_e, while the corresponding change in pressure drop is insignificant (Xiang, Park, & Lee, 2001). Leith and Mehta compared 6 cyclone designs and found that high efficiency cyclones tend to have a smaller inlet area ($a\times b/D_c^2$) and a small D_e/D_c value compared to high throughput designs (Leith & Mehta, 1973). Iozia and Leith suggested that although the inlet area has a major effect on efficiency, the inlet height to width ratio (a/b) does not significantly affect the collection efficiency of the cyclone (Iozia & Leith, 1990). For the longitudinal sizes of the cyclone, results obtained by Iozia and Leith showed no consistent difference between the efficiencies of the short ($h/D_c=0.5$) and the long ($h/D_c=2.5$) cyclones, but the pressure drop of the long cyclone was somewhat lower than that of the short cyclone (Iozia & Leith, 1990). Büttner found that the cutoff size (d_{50}) was independent of the cyclone height for excessive heights. However, if the cyclone height decreased to less than a critical value, the d_{50} decreased to another critical height (Büttner, 1988). This critical height is closely related to the maximum-efficiency cyclone height, and Yang et al. suggested that the natural vortex length plays a major role in determining this value (Yang et al., 2013). Zhu and Lee examined the effects of h and S on the particle collection efficiency, and concluded that the difference between the body height and V.F. length ($h-S$) is critical in determining the efficiency. They found the optimal value of $(h-S)/D_c$ to be around 1.0. The pressure drop decreased substantially as h lengthened or as S shortened (Zhu & Lee, 1999), which is similar to Iozia and Leith's findings. However, Lidén and Gudmundsson showed that d_{50} is independent of the distance ($H-S$) for $D_e/D_c\geq 0.25$, based on combining their experimental results and an extensive review of reported data (Lidén & Gudmundsson, 1997) (including works by Bürkholz for $D_e/D_c=0.33$ and $(H-S)/D_c=0.33$–6 (Burkholz, 1985); Mothes and Löffler for $D_e/D_c=0.38$ and $(H-S)/D_c=0.95$–2.9 (Mothes & Löffler, 1988); Büttner for $D_e/D_c=0.43$ and $(H-S)/D_c=2.1$–19.3 (Büttner, 1988); and Iozia and Leith for $D_e/D_c=0.5$ and $(H-S)/D_c=2.5$–4.5 (Iozia & Leith, 1990)).

The results of these studies on different geometric effects are valuable for designing and optimizing tangential flow cyclones. However, in these studies, the effects of each geometric cyclone dimension were either only partially investigated or lacked a conclusive result. In addition, most of these studies investigated the cyclone performance based on either d_{50} or the pressure drop. Few studies reported the effects on the steepness of the cyclone sampling curve. Therefore, the aim of this study is to provide a comprehensive understanding of the effects of a cyclone's longitudinal and radial dimensions on d_{50} and the pressure drop, as well