Aerosol and Air Quality Research, 14: 1003–1016, 2014

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2013.04.0129

An Experimental Study on Performance Improvement of the Stairmand Cyclone Design

Chia-Wei Hsu[1], Sheng-Hsiu Huang[1], Chih-Wei Lin[1], Ta-Chih Hsiao[2], Wen-Yinn Lin[3], Chih-Chieh Chen[1*]

[1] *National Taiwan University, Taipei, Taiwan*
[2] *National Central University, Jhongli City, Taoyuan County, Taiwan*
[3] *National Taipei University of Technology, Taipei, Taiwan*

ABSTRACT

The cyclone is widely used as air cleaning device. Many studies have been made on how to enhance its particle collection efficiency or reduce the airflow resistance, but usually the alteration of only one dimension is discussed, and only the collection efficiency or the airflow resistance is considered. Some studies have compared the 50% cut-off size under the same airflow resistance, or compared the airflow resistance under the same 50% cut-off size to obtain the optimal configuration. Yet steps like this take long time to complete, which makes it difficult to compare the cyclone efficiency comprehensively.

This work adopts the cyclone quality factor as the performance index, and the cyclone designed by Stairmand is adopted as the basic configuration in the present study. With the cyclone body diameter (D) fixed, we vary the cyclone length (H), inlet height (a) and width (b), cyclone length without the cone (h_b), cone height (h_c), cone bottom diameter (B), and vortex finder length (S). The results show that each of these design parameters has a different impact on the cyclone performance.

Based on the cyclone quality factor, equivalent to the filter quality factor, it is found that the H and S of the Stairmand cyclone are already the optimal conformations. The cyclone performance could be further improved, if further changes could be made to the other conformations, for example, narrowing down the inlet (adjusting a/b from 13/5 to 20/3.2), reducing the cone bottom diameter (adjusting B from 9 mm to 4 mm) and decreasing the vortex finder diameter (adjusting D_e from 13 mm to 8 mm), The cyclone quality factor appears to be a function of the volumetric flow rate. Results demonstrate that while the air flow is fixed at 15 L/min, the newly improved cyclone could perform 12 times better than the Stairmand cyclone, according to the cyclone quality factor.

Keyword: Cyclone quality factor; Cyclone design; Cyclone performance.

INTRODUCTION

The cyclone has long been used as air cleaning device by collecting large particles with higher centrifugal force within the vortex. It has many advantages, including a simple yet strong structure, as well as high resistance to both temperature and as pressure. It also has higher loading capacity for particles than the impactor, making it suitable to high concentrations of dust and for long-term sampling. Large cyclones are commonly used in industrial dust removal, while small ones are mostly used in atmospheric or workplace dust sampling.

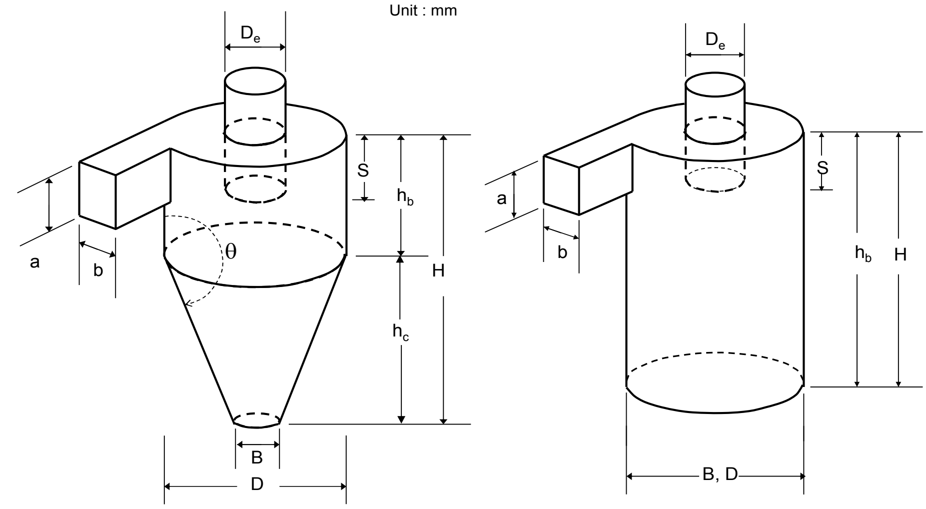
The structure of the traditional cyclone includes a square inlet, a circular outlet, a cylindrical main body (diameter D) and a conical bottom. The conventional cyclone is described by nine different aspects: cyclone body height (H), angle of the stem and cone base (θ), inlet width (b) and height (a), cyclone cylinder length without the cone (h_b), cone height (h_c), cone bottom diameter (B), vortex finder length (S), and vortex finder diameter (D_e),shown in Fig. 1. Airflow inside the cyclone is divided into two spiraling flows, with the outer flow swirling toward the bottom, while the core flow rises from the bottom and is discharged through the outlet. Though the development of the cyclone began in the 1940s (Zhu and Lee, 1999), and its relevant empirical or semi-empirical simulations have been widely used in research, a complete model for the flow field has not been fully developed. It is therefore still difficult to accurately simulate cyclone performance (Dietz, 1981; Iozia and Leith, 1989; Trefz and Muschelknautz, 1993; Muschelknautz and Greif, 1996; Avci and Karagoz 2003; Karagoz and Avci, 2005; Swamee *et al*., 2009; Elsayed and Lacor 2010). Thus, using experimental methods to accurately assess cyclone performance is necessary.

Currently, there are many studies focusing on changing

[*] Corresponding author.
E-mail address: ccchen@ntu.edu.tw

D	a	b	S	D_e	h_b	h_c	H	B
25	13	5	13	13	38	62	100	9

Unit : mm



(a) With cone (b) Without cone

Fig. 1. Geometry and dimensions of Stairmand cyclone design.

the cyclone configuration to assess its particle sampling characteristics. These are conducted by changing various parameters to enhance the collection efficiency of the cyclone or to reduce the amount of pressure drop, where a 50% cut-off size is often used as the reference for assessing collection efficiency. Some studies even consider pressure drop as reference for energy loss. Several studies have shown that changing H does not significantly affect the 50% cut-off size of the cyclone (Iozia and Leith, 1990), though others suggest that this could be untrue (Büttner, 1988; Zhu and Lee, 1999). Zhu and Lee (1999) make changes to five different types of h_b and demonstrate that h_b affects the particle collection efficiency of the cyclone. When h_b/D is between 1 and 2, the cyclone is at the minimum 50% cut-off size, the pressure drop decreases as h_b increases. Though the effect of h_b on collection efficiency and pressure drop has been described in previous studies, using both airflow resistance and penetration efficiency as the indicators has not been done in a systematic way, so there is still no clear suggestion for the optimal specification for h_b.

According to a study by Stern *et al.* (1955), the cone is not required for the cyclone. Yet other studies have shown that a cone can improve the tangential velocity of airflow, thereby increasing the inertial force of particles and leading to higher particle collection efficiency (Gupta, 1984; Zhu and Lee, 1999; Avci and Karagoz, 2003). On the contrary, Bryant (1983) claims that if swirling air inside the cyclone makes contact with the bottom, the particles collected there could be stirred up again. A cone shape can therefore affect the particle collection efficiency in two different ways (Bryant *et al.*, 1983). Having experimented with three different values for B, Xiang *et al.* (2001) indicate that a smaller cross-sectional area for the cone will result in a larger tangential velocity and greater inertial force, and thereby increasing the airflow resistance and particle collection efficiency.

Many studies have shown that D_e has a significant impact on the cyclone's particle collection efficiency. For example, when D_e decreases, particle collection efficiency increases (Saltzman and Hochstrasser, 1983; Iozia and Leith, 1990; Kim and Lee, 1990; Moore and McFarland, 1993). Kim and Lee (1990) make changes to four different types of D_e and suggest that changing D_e will affect both the inner and the outer flow of the vortex. Lim *et al.* (2004) use three types of D_e with different shapes for their experiment and find that different specifications for D_e or different shapes can have a significant effect on the particle collection efficiency. Zhu and Lee (1999) make changes to S with three different lengths, and find that when the ratio of S to D is close to 1, the cyclone has the smallest 50% cut-off size. They also discover that the cyclone performance is superior when $(h_b - S)/D = 1$. The decrease in pressure drop shows that the longer the h_b or the shorter the S, the smaller the pressure drop in the cyclone will become (Zhu and Lee, 1999).

Several studies attempt to define the optimal cyclone configuration by changing the collection efficiency and pressure drop between various conformation parameters (Kim and Lee, 1990; Xiang *et al.*, 2001; Lim *et al.*, 2004). However, due to the lack of objective evidence, the optimization process remains incomplete. A single indicator alone, neither the 50% cut-off size nor the airflow resistance, can be regarded as optimal. Though many studies have taken both indicators into consideration, so far there are few studies on using a single indicator to assess both collection efficiency and airflow resistance are limited.

Therefore, an indicator must consider both particle collection efficiency and pressure drop to objectively and fully assess cyclone performance. The filter quality factor, which considers both filtration efficiency and air resistance and is commonly used in the filter industry, can be directly applied to judge cyclone performance (Hinds, 1999). The cyclone (performance) quality factor, q_c, is shown in the following equation,

$$q_c = \frac{\ln(\frac{1}{P})}{\Delta p} \quad (1)$$

where P represents aerosol penetration through the cyclone, and Δp represents the cyclone pressure drop. For each specific cyclone design, q_c is a function of flow rate and particle size. Therefore, cyclone quality must be compared only under identical air flow and particle size.

This study selects the cyclone configuration designed by Stairmand in 1951 as its basis and applies the cyclone quality factor to evaluate the cyclone performance. The objectives are to identify the most influential operating parameters and to improve the cyclone performance from the perspective of cyclone quality factor.

EXPERIMENTAL MATERIALS AND METHODS

The experimental apparatus shown in Fig. 2 is a closed positive pressure system, with a connecting tube to the cyclone as the only exit. A syringe pump transports potassium sodium tartrate tetrahydrate solution (PSTT, Wako Pure Chemical Industries, Ltd.) to an ultrasonic atomizing nozzle (Model 8700-60MS and Model 8700-120MS, Sono-Tek Inc., Ponghkeepsie, NY, USA.). Via the sonication, the solution is split into tiny droplets, diluted and dried as challenge aerosol. The particles then pass through a radioactive source (10 mCi Am 241) to be neutralized to the Boltzmann charge equilibrium, then enter the test chamber. The mode of the challenge particle is between 2–6 µm, with GSD around 1.5 and number concentration about 300–400 #/cm^3.

The aerosol number concentration and size distribution upstream and downstream of the cyclone are measured using an Aerodynamic Particle Sizer (APS, Model 3321, TSI Inc., St. Paul, MN), to obtain the collection efficiency as a function of particle size. The APS is calibrated against monodisperse PSL particles. The performance testing of the cyclones is carried out using positive pressure mode. The upstream aerosol concentration is taken from the connecting tube when the cyclone is detached. The downstream aerosol centration is measured right at the outlet of cyclone. The aspiration flow rate of APS is fixed at 5 L/min for both upstream and downstream measurements. Air flows through cyclone are monitored and controlled by using mass flow controllers (Hasting Instruments, VA), which are calibrated against an electronic bubble meter (Gilibrator, Gilian Instrument Crop., Wayne, NJ). Flow rates ranging from 15 to 60 L/min are applied to study the flow dependency on pressure drop. The effect of each cyclone dimension on the aerosol collection efficiency and the cyclone quality factor is studied while the flow rate is fixed at 30 L/min. Each aerosol penetration measurement is repeated at least five times to assure data quality. The pressure drop across the cyclone is measured on the internal envelope surface of the inlet and outlet tubes of the cyclone, using an inclined manometer (model 400, Dwyer instrument, Inc.)

As shown in the left plot of Fig. 1, this study adopts a cyclone based on the configuration proportions of Stairmand type. The major operating parameters and their values are listed in Table 1, and design values of the Stairmand cyclone are in bold and underlined. The cyclone body diameter, D, of 25 mm is used as the reference. All other dimensions - including cyclone body height (H), cyclone height without cone under cylinder (H = h_b), cone height (h_c) at fixed H, cone height (h_c) at fixed h_b, angle of cone (θ), cone bottom diameter (B), inlet height (a), inlet width (b), vortex finder diameter (D_e), and vortex finder length (S) - are variations on the design of the Stairmand cyclone. The right column lists the test specifications adopted in each test.

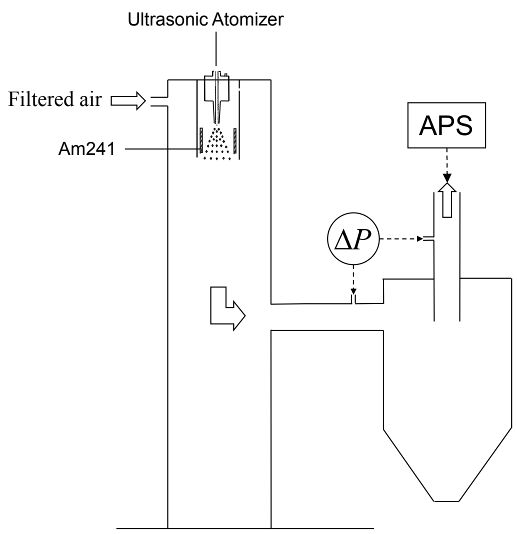


Fig. 2. Schematic diagram of the experimental system set up.

RESULTS AND DISCUSSION

Cyclone Cylinder Length (h_b) with h_c Kept Constant

Fig. 3 shows the effect of cyclone height on the pressure drop across the cyclone (Fig. 3(a)), the aerosol penetration through the cyclone as a function of particle size (Fig. 3(b)), and the filtration quality factor (Fig. 3(c)). To better understand the effect of a change in H, h_c was first fixed to 60 mm, with other conditions set to D = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, De = 13 mm, and B = 9 mm. Note that H is the sum of h_b and h_c. Fig. 3(a) shows the pressure drop as a function of cyclone height, indicating that the airflow resistance of the cyclone increases as the flow increases and as H decreases. This experimental result is similar to the trends found in many other studies (Iozia and Leith, 1990; Ramachandran *et al.*, 1991; Zhu and Lee 1999), which is related to natural vortex length. Natural vortex length is the distance between the turning point - where the outer air flow within the cyclone turns toward the exit after running its natural course - and the entrance location of the vortex finder. A longer natural vortex length indicates that airflow can reach positions closer to the bottom (Alexander, 1949). In other words, when H is less than the natural vortex length, a shorter H will force the air flow into the cone of the cyclone, so the opportunity for friction between the air flow and the bottom of the cyclone will also increase (Ramachandran *et al.*, 1991; Zhu and Lee, 1999; Surmen *et al.*, 2011).

Table 1. Dimensions and operating conditions of the cyclones tested.

Dimensions and operating conditions	Values	Fig. No.
Cyclone length with cone under cylinder , H (mm)	90, **100**, 140, 160, 180, 210, 250, 280, 310,390	3
Cyclone length without cone under cylinder , H = h_b (mm)	30, 40, 80, 100, 140, 160, 180, 210, 250, 280, 310, 390	4
Cone height at fixed h_b, h_c (mm)	20, 40, 60, 80, 100	5
Cone heights at fixed H, h_c (mm)	0, 20, 40, **60**, 80	6
Cone height at fixed h_b and q, h_c (mm)	20, 35, 50, 65, 80	7
Cone bottom diameter, B (mm)	4, **9**, 12.5, 16, 25	8
Inlet height : fixed the a/b = 2.6, the opening a × b (mm^2)	46.2, 55.2, 65, 163	9
Inlet height : fixed the a × b = 64 mm^2, the ratio a/b	1.00, 2.05, 2.65, 4.18, 6.67	10
Vortex finder diameter, D_e (mm)	7, 8, 9, 10.8, 12, **13**, 13.7, 16.7	11
Vortex finder Length, S (mm)	0, 6, **15**, 30, 45, 60, 75	12
Flow rates at Figs. 3–12, a, Q (L/min)	15, 30, 45, 60	
Flow rates at Figs. 3–12, b and c, Q (L/min)	30	
Cyclone body diameter, D (mm)	**25**	
Temperature, T (K)	293	

The values in bold and underlined are dimensions of Stairmand cyclone.

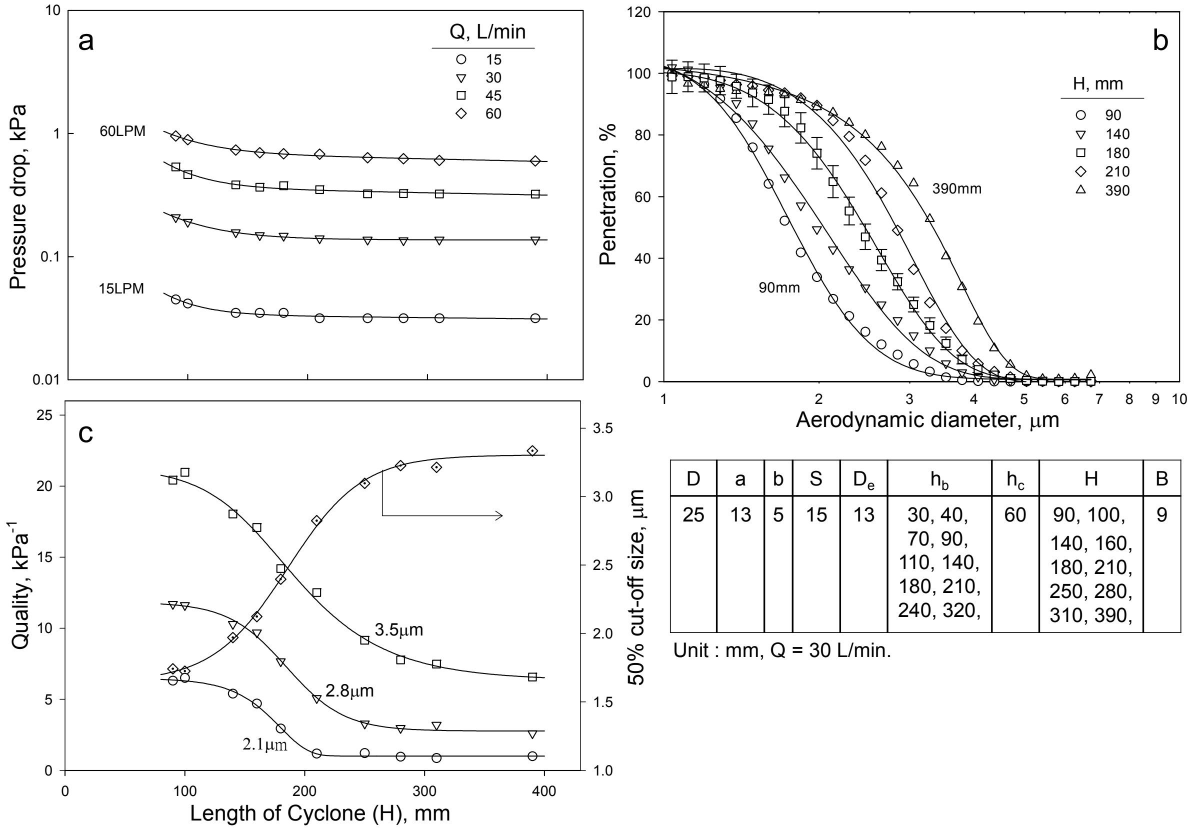


Fig. 3. The effect of cyclone length (h_b) with h_c = 60 mm on the cyclone quality factor. (a) Pressure drop with different H. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of H.

The impact of change in H on aerosol penetration is shown in Fig. 3(b). Aerosol penetration increases with increasing H because more airflow does not reach the bottom of the cyclone, as concluded in Zhu and Lee (1999). The 50% cut-off size of the penetration curve is summarized in Fig. 3(c), showing that when H is less than 240 mm, the 50% cut-off size increases sharply as H increases, and the length of the optimum collection efficiency is about 90 mm. No significant changes occur when H is longer than 240 mm. That means an overextended H will form unutilized space at its bottom where the airflow cannot reach, no longer increasing particle collection efficiency (Büttner, 1988; Iozia and Leith, 1990). This result is also shown in Fig. 3(c) as viewed from the perspective of cyclone quality factor, indicating that, with shorter H, there is higher cyclone quality factor for all particle sizes. In terms of changes to specifications of H in this work, the configuration with the highest cyclone quality factor occurred at an H of 90 mm.

With the h_c of the configuration in this experiment being 60 mm, the minimum obtainable H is 90 mm (with an external entrance height of 25 mm, an h_c of 60 mm, and an interval of 5 mm necessary for cyclone construction). In this situation, observing the cyclone characteristics under an H of less than 90 mm is difficult, and a modification to the basic configuration is needed. By changing the cyclone to one without a conical bottom (flat-bottomed cyclone as shown in the right plot of Fig. 1), the shortest possible H becomes 30 mm (including the entrance height of 25 mm and the interval of 5 mm), in which case, h_b will equal H. Other factors under this condition are as follows: D = B = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, D_e = 13 mm, and h_c = 0 mm since the configuration is not cone-based, showed as Fig. 1(b). The test results of this cyclone without a cone are shown in Fig. 4. Altering the H of the flat-bottomed cyclone results in the same changing trends of the pressure drop and of the 50% cut-off size as those obtained from the cone-attached cyclone.

However, the result also demonstrates that when H is beneath 100 mm, the pressure drop decreases sharply with increasing H, as shown in Fig. 4(a), similar to the behavior of cone-based cyclone shown in Fig. 3(a). This decreasing trend becomes insignificant when H is larger than 100 mm, indicating that extra length of H is not effective. The aerosol penetration increases with increasing H (shown in Fig. 4(b)), similar to the behavior of the regular cone-based cyclone, as shown in Fig. 3(b). The results in this experiment are similar to previous investigations when the scale of the H/D_e is in the same range (Butter, 1988; Iozia and Leith, 1990), where it was claimed that this phenomenon was due to the fluid dynamics. The larger height resulted in lower energy swirl, while the shorter height created higher energy swirls. According to Fig. 4(c), the cyclone quality is optimal with an H of 40 to 100 mm. This is because an excessively short H will cause the cyclone quality factor to decline, probably due to the increased airflow resistance.

The results from Figs. 3 and 4 are compared to verify the effect of the cone on cyclone quality factor. Fig. 4(c) shows that, in a flat-bottomed cyclone, the optimum cyclone quality factor is approximately 8.8 kPa^{-1} for a particle size of 2.8 µm. For the cone-attached cyclone in Fig. 3, the optimum quality factor for 2.8 µm particles is approximately 12 kPa^{-1}. This implies that a conical bottom can considerably improve the cyclone performance. Therefore, cyclones with a cone should be more effective.

Cone Height (h_c)

Few studies have discussed the impact of h_c on cyclone performance. To better understand the effect of a cone on cyclone performance, in this work, h_c is varied, while h_b remains fixed. Notice that H will change as a result of the changes in h_c, while other conditions are set as follows: D = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, D_e = 13 mm, h_b = 40 mm, and B = 9 mm. The pressure drop curve as a function of cone height in Fig. 5(a) shows that the pressure

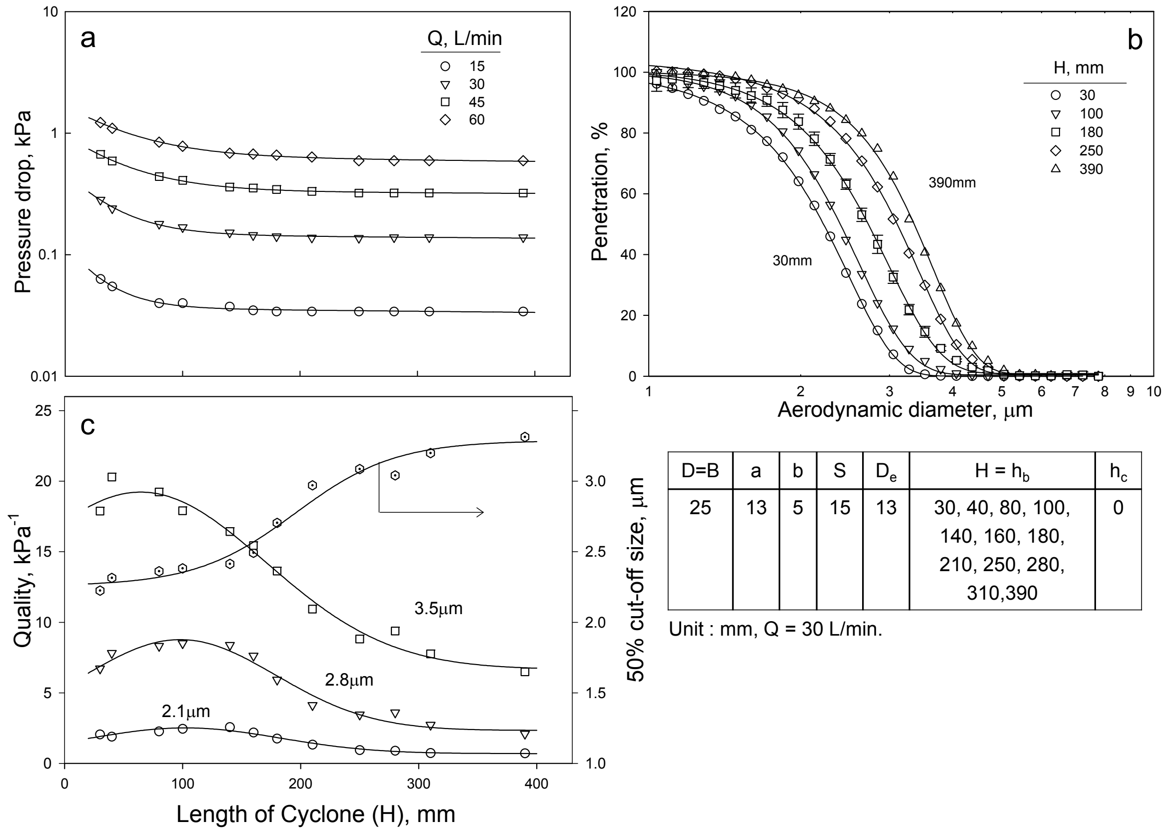


Fig. 4. The effect of cyclone length (h_b) with h_c = 0 on the cyclone quality factor. (a) Pressure drop with different H. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of H.

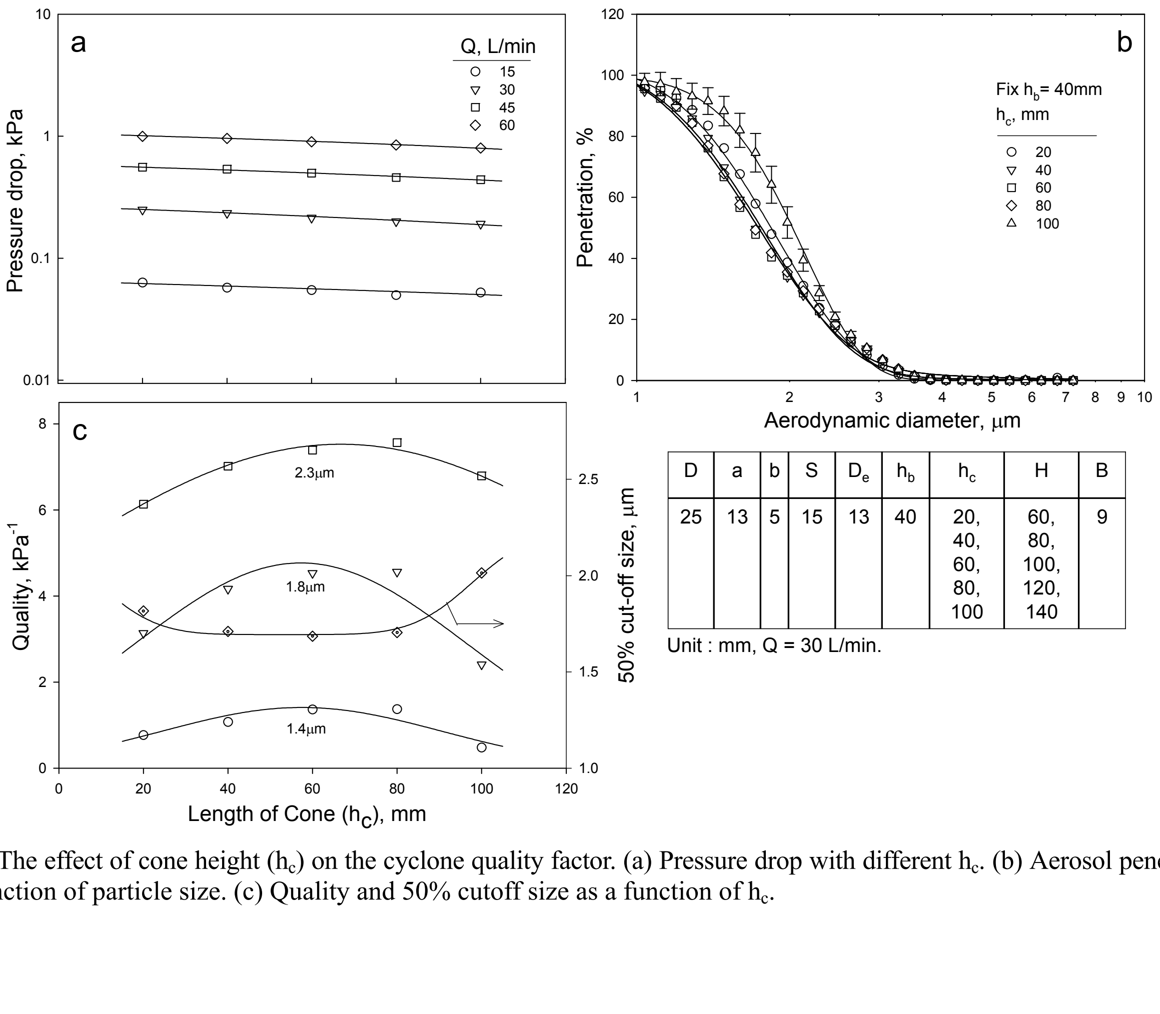
drop decreases slightly with increasing h_c. With a smaller θ as a result of the shorter cone, the airflow tends to have more friction on the wall, while the short cone forcing the airflow to turn earlier for the exit will also increase the friction. On the other hand, a larger h_c will provide more interior space and thereby reduces the airflow resistance of the turning airflow as well as the proportion of air reaching the cone wall, which then leads to overall lower airflow resistance.

A different h_c value forms a particle penetration curve, as shown in Fig. 5(b), with its 50% cut-off size recorded in Fig. 5(c). The figure shows that the minimum 50% cut-off size occurs at an h_c of 60 mm. An h_c shorter than this will cause the airflow to have fewer spirals in the interior, which reduces the particle collection. This result is similar to that of Zhu and Lee (1999), who show that an excessively short H can cause an increase in the 50% cut-off size. On the other hand, when h_c is longer than 60 mm, the cross-sectional area becomes larger with a larger θ and less air can reach the cone bottom as H increases, hence the lower collection efficiency (Zhu and Lee, 1999). Fig. 5(c) demonstrates that the cyclone quality factor is optimal when h_c is at 60 mm. If h_c is less than 60 mm, the cyclone quality factor decreases due to larger airflow resistance and lower filtration efficiency. If it is longer, the unutilized space will still reduce the particle collection efficiency despite of the smaller airflow resistance. Therefore, while the cone could make significant contribution to the collection efficiency, its excessive length may hinder it.

To further understand the effect of the proportion of h_c to H on cyclone performance, the experiment is carried out by fixing H at 110 mm and modifying h_c, in which case h_b will change accordingly. The other conditions are set as follows: D = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, De = 13 mm, and B = 9 mm. Fig. 6(a) shows that the pressure drop increases with h_c. The increase in h_c allows the airflow to enter the cone earlier, which then increases the friction between the airflow and the inner wall of cone. Thus, a higher h_c leads to higher airflow resistance.

Fig. 6(b) shows the penetration curve of particles, and the results of its 50% cut-off size are listed in Fig. 6(c). The results show that the minimum 50% cut-off size occurs at an h_c of 80 mm. Though h_c at this height will cause greater airflow resistance, the airflow entering the cone nevertheless has higher tangential velocity, which is helpful for particle collection at the inner wall (Gupta, 1984). With both factors considered, an h_c of 80 mm (the largest) results in the optimal cyclone quality factor. It can be implied that when H is fixed, a higher proportion of, h_c will enhance the cyclone performance.

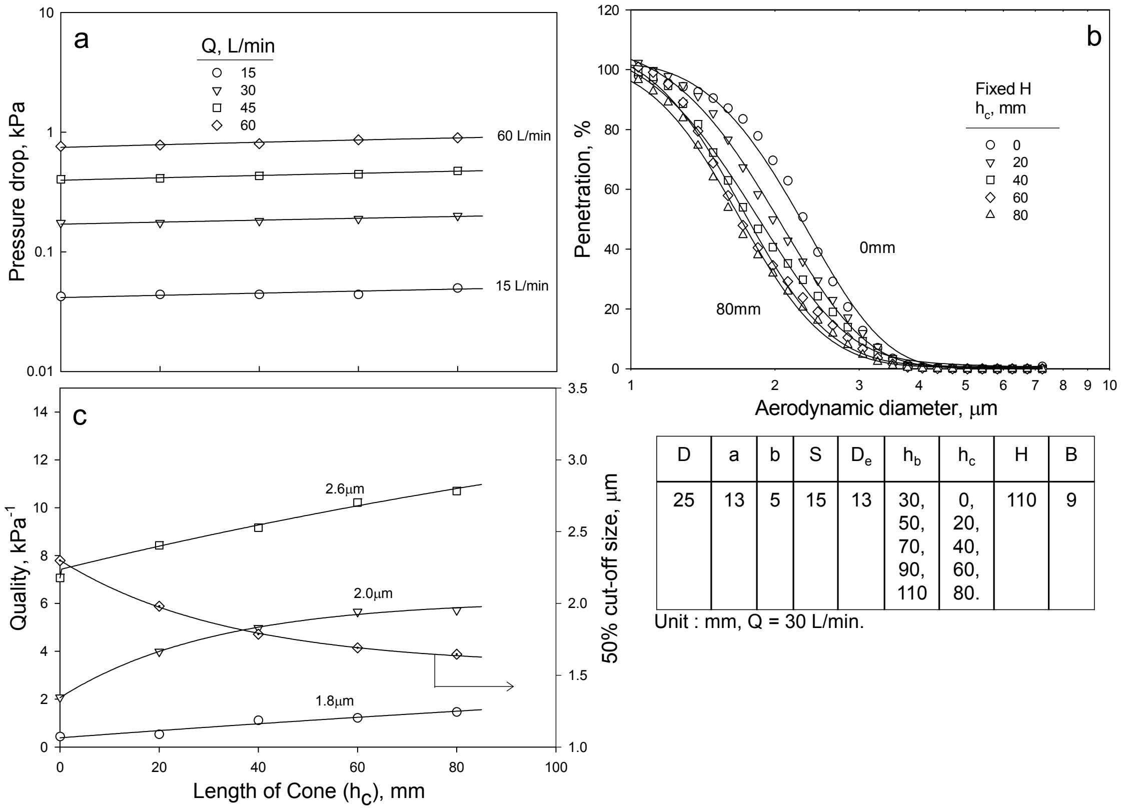
While changing the two parameters above-- fixing h_b while changing h_c, and fixing H while changing h_c -- θ is altered accordingly, In Fig. 7, θ is fixed while only the cone height, h_c, is changed so as to monitor the effect of different h_c with the same θ on cyclone performance, with H and B changing with h_c accordingly. Other conditions include D = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, D_e



D	a	b	S	D_e	h_b	h_c	H	B
25	13	5	15	13	40	20, 40, 60, 80, 100	60, 80, 100, 120, 140	9

Unit : mm, Q = 30 L/min.

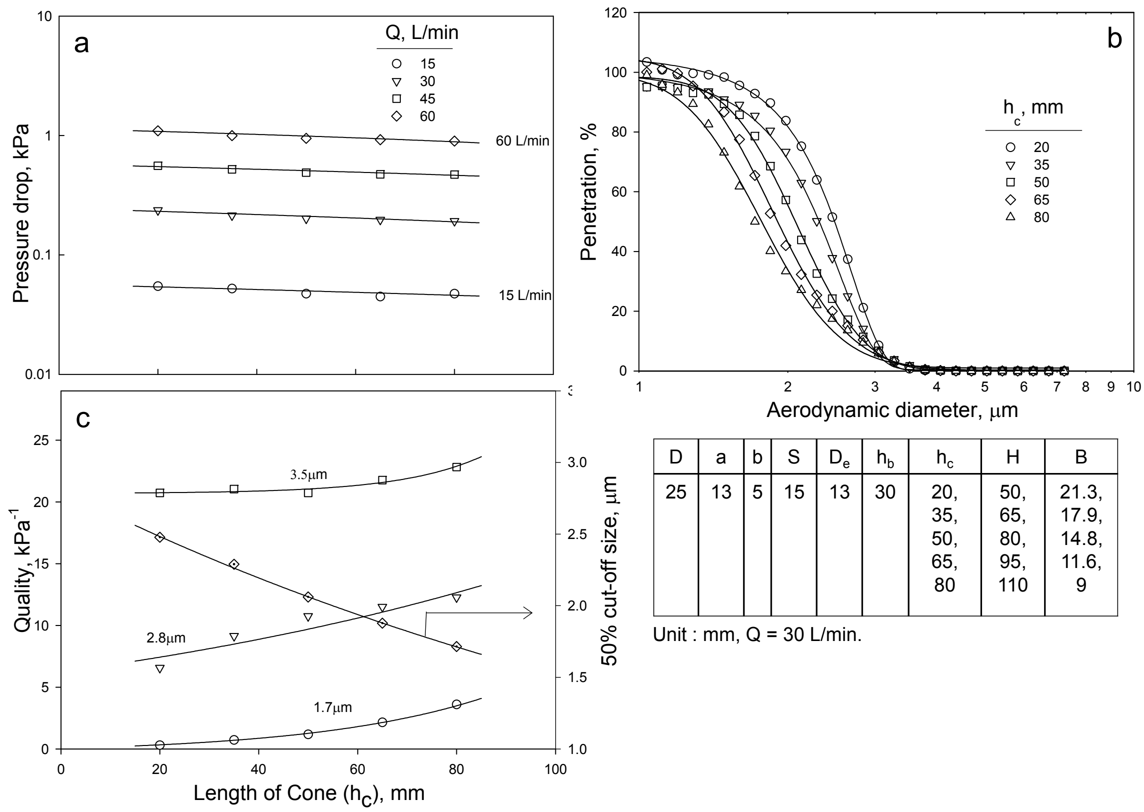
Fig. 5. The effect of cone height (h_c) on the cyclone quality factor. (a) Pressure drop with different h_c. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of h_c.



D	a	b	S	D_e	h_b	h_c	H	B
25	13	5	15	13	30, 50, 70, 90, 110	0, 20, 40, 60, 80.	110	9

Unit : mm, Q = 30 L/min.

Fig. 6. The effect of body height (h_c) on the cyclone quality factor. (a) Pressure drop with different h_c. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of h_c.



D	a	b	S	D_e	h_b	h_c	H	B
25	13	5	15	13	30	20, 35, 50, 65, 80	50, 65, 80, 95, 110	21.3, 17.9, 14.8, 11.6, 9

Unit : mm, Q = 30 L/min.

Fig. 7. The effect of cone height (h_c) on the cyclone quality factor. (a) Pressure drop with different h_c. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of h_c.

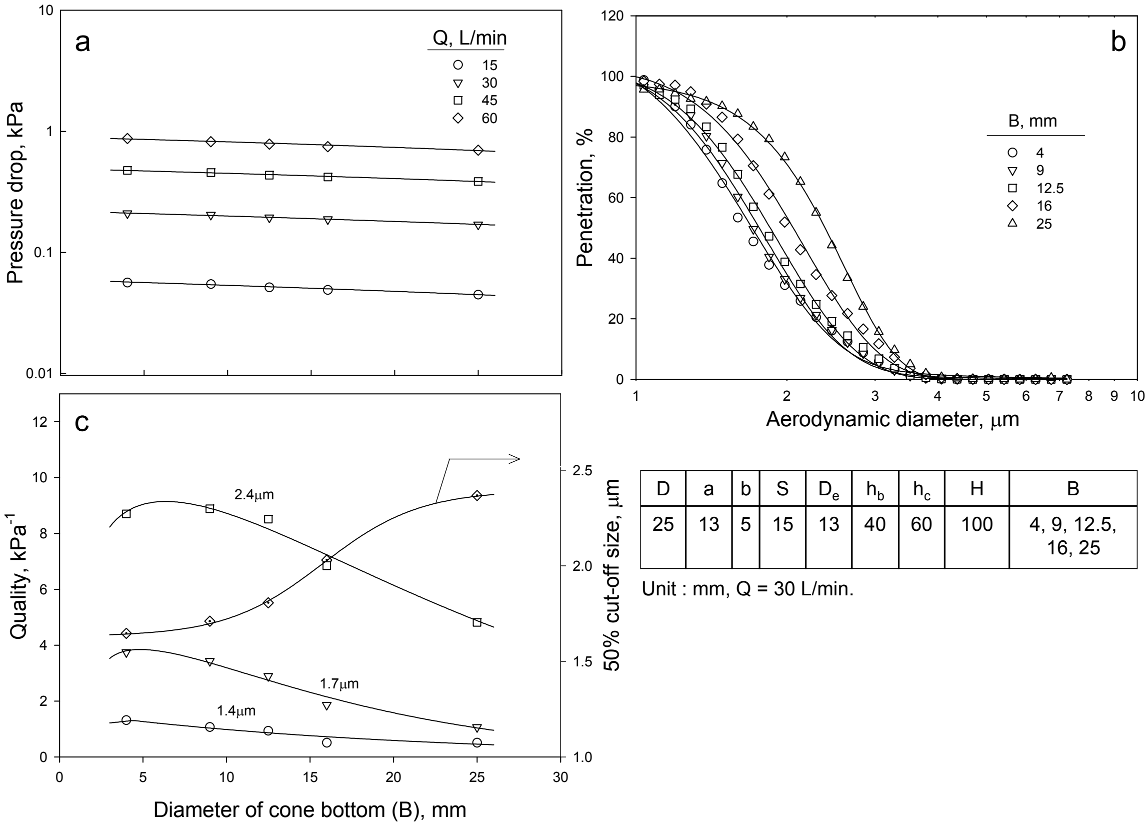
= 13 mm, and h_b = 30 mm. Fig. 7(a) features the pressure drop as a function of cone height. It shows that longer h_c will have smaller airflow resistance. This occurs because an increase in h_c will lead to a decrease in the friction between the airflow and the inner wall of the cone bottom, and the increase of the internal space will reduce the airflow friction. The aerosol penetration decreases with increasing cone height, as shown in Fig. 7(b), and the 50% cut-off size of these aerosol penetration curves is displayed in Fig. 7(c). It suggests that longer h_c results in smaller 50% cut-off size, indicating that the collection efficiency is enhanced due to a decrease in the cross-sectional area (Gupta, 1984). Considering both airflow resistance and collection efficiency, Fig. 7(c) shows that longer h_c leads to higher cyclone quality factor. These results indicate that when H-S approximates to the natural vortex length, the cone bottom contributes significantly to the cyclone quality factor. Raising the proportion of h_c in H of the Stairmand configuration therefore will help improve the cyclone performance.

Cone Bottom Diameter (B)

This part of experiment changes B to investigate its effect on the cyclone performance, as shown in Fig. 8, with other conditions set as D = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, D_e = 13 mm, h_b = 40 mm, h_c = 60 mm, and H = 100 mm. Fig. 8(a) shows that smaller B leads to higher pressure drop, which corresponds to the results in Xiang *et al.* (2001). Their study showed that as long as B is larger than D_e, a reduction in B will increase the collection efficiency without increasing the pressure drop, but when B is smaller than De, a reduction in B will increase the pressure drop without a corresponding increase in collection efficiency (Xiang *et al.*, 2001). However, in our experiments, D_e does not show an apparent correlation with B.

Fig. 8(b) shows the particle penetration curves under different B, and Fig. 8(c) displays the 50% cut-off size. These figures indicate that as B decreases, the 50% cut-off size becomes smaller, as also concluded in Xiang *et al.*'s study (2001). They indicate that, because the particles in the core of the flow can have more contact with the inner wall with smaller cross-sectional area, the particle collection efficiency increases as the cross-sectional area reduces (Xiang *et al.*, 2001).

The influence of different B values on cyclone quality factor is shown in Fig. 8(c), which suggests that when B is at 5 mm, the cyclone quality factor is optimal. Though reducing the cross-sectional area raises the airflow resistance, the collection efficiency nevertheless increases. This disagrees with the study of Xiang *et al.* (2011), which makes only a rough comparison between the collection efficiency and the pressure drop. They claim that reducing B can increase the cyclone collection efficiency without increasing the pressure drop significantly, when B is not smaller than D_e. According to our experiment, however, when B of the Stairmand configuration is in the rage of 4 to 9 mm, the cyclone performs best.



D	a	b	S	D_e	h_b	h_c	H	B
25	13	5	15	13	40	60	100	4, 9, 12.5, 16, 25

Fig. 8. The effect of cone bottoms (B) on the cyclone quality factor. (a) Pressure drop with different B. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of B.

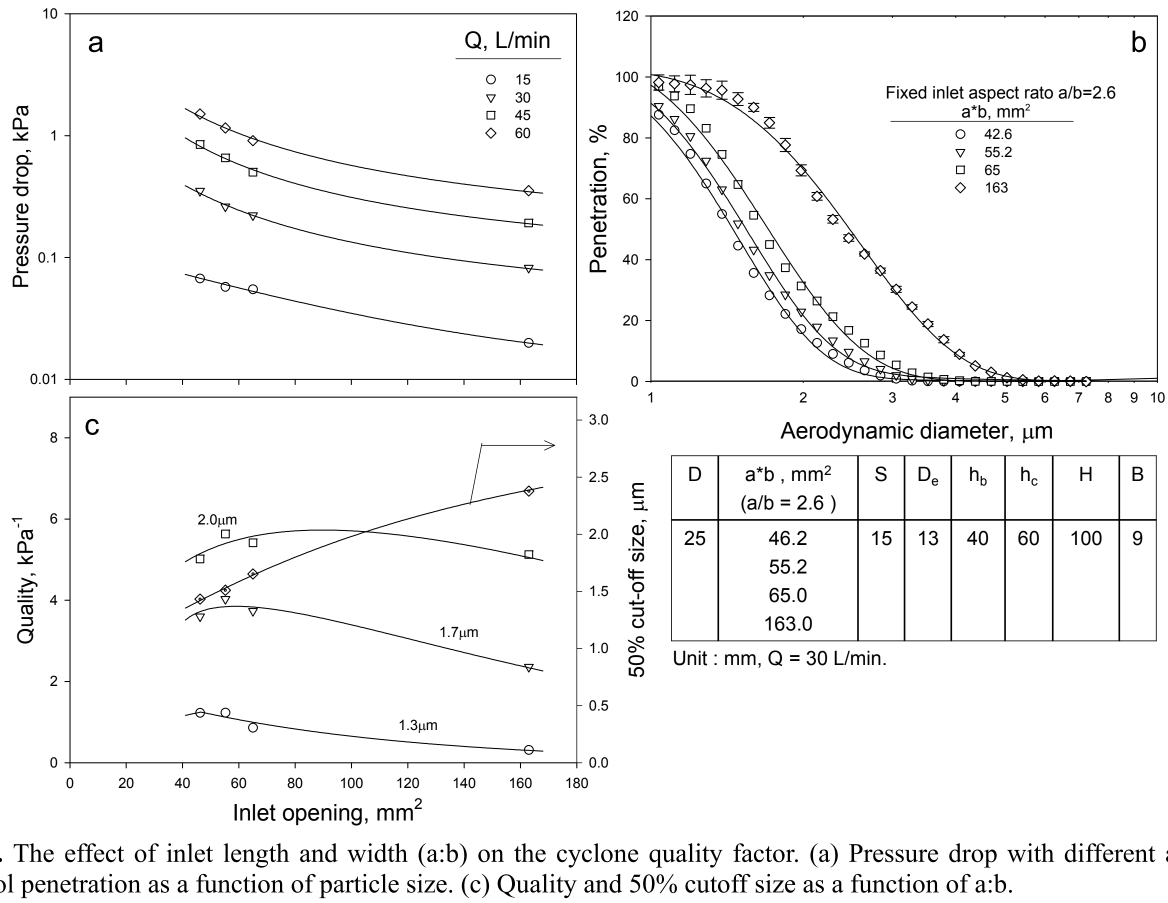
Inlet Area (a × b)

To understand the influence of the inlet area on the cyclone quality, this experiment fixes the inlet aspect ratio at 2.6:1, with other conditions set as follows: D = 25 mm, S = 15 mm, De = 13 mm, h_b = 40 mm, h_c = 60 mm, H = 100 mm, and B = 9 mm. The results are displayed in Fig. 9. Fig. 9(a) features the pressure drop. Though the volume of the flow remains the same, smaller inlet will lead to higher airflow resistance since the flow velocity rises as the inlet size decreases. Fig. 9(b) shows the penetration curves, and Fig. 9(c) records the 50% cut-off size and cyclone quality factor. The figures suggest that smaller inlet results in a smaller 50% cut-off size. Because the higher velocity caused by the smaller inlet will raise the inertial force of the particles, the particles will collide with the inner wall more often and hence be collected. This result agrees with many other studies (Dirgo and Leith, 1985; Iozia and Leith, 1990; Kim and Lee, 1990). For example, Iozia and Leith (1990) claims that the inlet area affects the inlet velocity, which then changes the tangential velocity and has a significant influence on the collection efficiency and airflow resistance; Hoffmann *et al.* (1995) also suggests that higher inlet velocity can increase the natural vortex length and thereby promote the collection efficiency. The overall cyclone quality factor of this experiment is shown in Fig. 9(c). Although the smallest inlet (11 × 4.2 mm^2) has the highest collection efficiency, the cyclone quality declines due to the increasing airflow resistance causing growing energy loss. The optimal inlet area therefore lies between 46.2 and 55.2 mm^2, depending on particle size. However, this optimal inlet area is for the particular Stairmand cyclone tested in this work. The optimal inlet area is likely to correlate to the overall size of the cyclone, for example, D and/or H, and needs to be studied further.

Inlet Aspect Ratio (a:b)

Different inlet area will influence the inlet velocity as well as the tangential velocity. Therefore, in this experiment, the inlet area will be fixed while its aspect ratio (a:b) varies from 1.0 (8.0:8.0) to 6.5 (20:3.2). These five sets of inlet should lead to the same tangential velocity, under which we may understand the influence of inlet configuration on the cyclone quality. Other conditions are set as follows: D =25 mm, S = 15 mm, D_e = 13 mm, h_b = 40 mm, h_c = 60 mm, H = 100 mm, and B = 9 mm. The results are shown in Fig. 10.

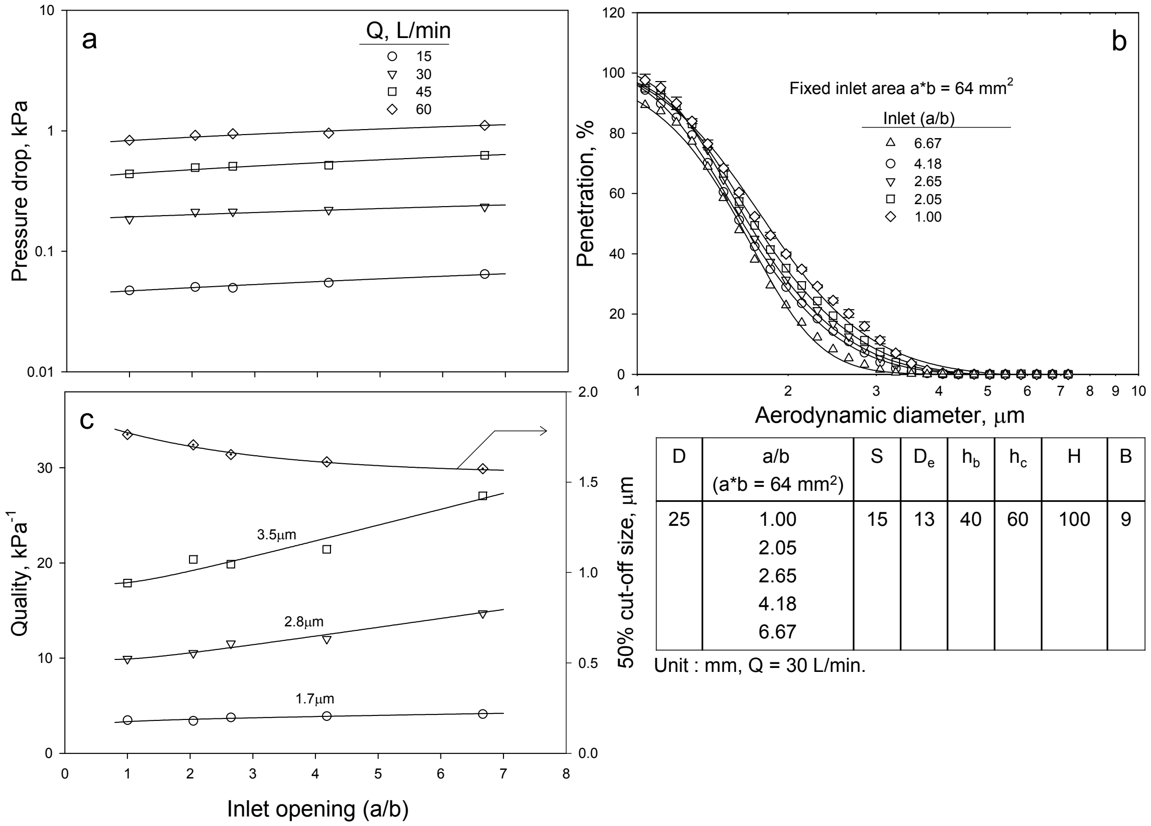
Fig. 10(a) shows that as the aspect ratio of a to b grows, the airflow resistance increases. Larger inlet height (a) indicates that the airflow will have more friction with the inner wall, thus raising the airflow resistance. Fig. 10(b) shows the penetration curves, and Fig. 10(c) displays their 50% cut off sizes. They suggest that, under the same inlet area, larger inlet height leads to smaller 50% cut-off size since the airflow tends to have higher chance colliding with the inner wall through a narrower inlet, and hence be more efficiently collected. This result is supported by Lim *et al.* (2003) who verify that the proximity of the airflow to



D	a*b , mm² (a/b = 2.6)	S	D_e	h_b	h_c	H	B
25	46.2 55.2 65.0 163.0	15	13	40	60	100	9

Unit : mm, Q = 30 L/min.

Fig. 9. The effect of inlet length and width (a:b) on the cyclone quality factor. (a) Pressure drop with different a:b. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of a:b.



D	a/b (a*b = 64 mm²)	S	D_e	h_b	h_c	H	B
25	1.00 2.05 2.65 4.18 6.67	15	13	40	60	100	9

Fig. 10. The effect of inlet length and width (a:b) on the cyclone quality factor. (a) Pressure drop with different a:b. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of a:b.

the wall has significant impact on the collection efficiency. From Fig. 10(c), we may also conclude that higher aspect ratio of a to b results in higher cyclone performance. This result agrees with the tendency described by Iozia and Leith (1990), but is different from the aspect ratio of 2.6 (a:b = 13:5) suggested by Stairmand. Based on our experiment, we suggest that increasing the inlet aspect ratio will further improve the performance of Stairmand cyclone. Similar to the optimal inlet area, the optimal inlet aspect ratio might be correlated to other sizes of the cyclone, such as h_b and/or S. Searching for the ultimate optimal inlet aspect ratio can be complex, and will take more experiments to clarify.

Vortex Finder Diameter (D_e)

To understand how D_e will affect the cyclone quality factor, this experiment varies D_e from 7 to 16.7 mm while other conditions set as follows: D = 25 mm, a = 13 mm, b = 5 mm, S = 15 mm, h_b = 40 mm, h_c = 60 mm, H = 100 mm, and B = 9 mm, as shown in Fig. 11. The results indicate that whatever the volumetric flow rate, smaller D_e results in larger airflow resistance, as suggested in Fig. 11(a). This tendency is slightly different from Kim and Lee's description, which suggests that a D_e/D between 0.5 and 0.6 leads to the smallest pressure drop (Kim and Lee, 1990). From Fig. 11(a), it can be expected that when D_e approximates to D, the pressure drop will rise considerably because of the increasing air velocity. Therefore, an optimal D_e based on pressure drop should exist. Yet the complete curves cannot be shown because the coverage of the parameters is physically limited. Nevertheless, the overall tendency of this experiment still agrees with other studies (Bryant *et al.*, 1983; Iozia and Leith 1990). For example, Ficici *et al.* (2010) claim that smaller D_e will increase the number of turns of the airflow and therefore raise the airflow resistance.

Fig. 10(b) shows the penetration curves, and Fig. 10(c) displays their 50% cut-off size. These figures suggest that smaller D_e leads to smaller 50% cut-off size. Many studies also suggest that reducing D_e can enhance the collection efficiency (Saltzman and Hochstrasser 1983; Iozia and Leith 1990; Kim and Lee 1990; Moore and McFarland 1993; Lim *et al.*, 2004). Among them, Moore and McFarland (1993) indicate that with smaller D_e, the air will remain concentrated to the cone bottom before being discharged. The flow velocity rises since a vortex finder with a smaller diameter has a smaller cross-section, which also contributes to the collection efficiency.

Furthermore, Kim and Lee (1990) claim that changing D_e will alter the outer and inner flow of the vortex simultaneously, which then affect the collection efficiency. Smaller D_e generates an outer sinking flow and a core rising flow which is thinner and longer, this then prolongs the course of the aerosol flow within the cyclone and increases its chance of entering the cone and thus be collected. The relationship between D_e and the natural vortex length is also worth investigating (Alexander, 1949). Many studies have shown that smaller D_e results in longer natural vortex

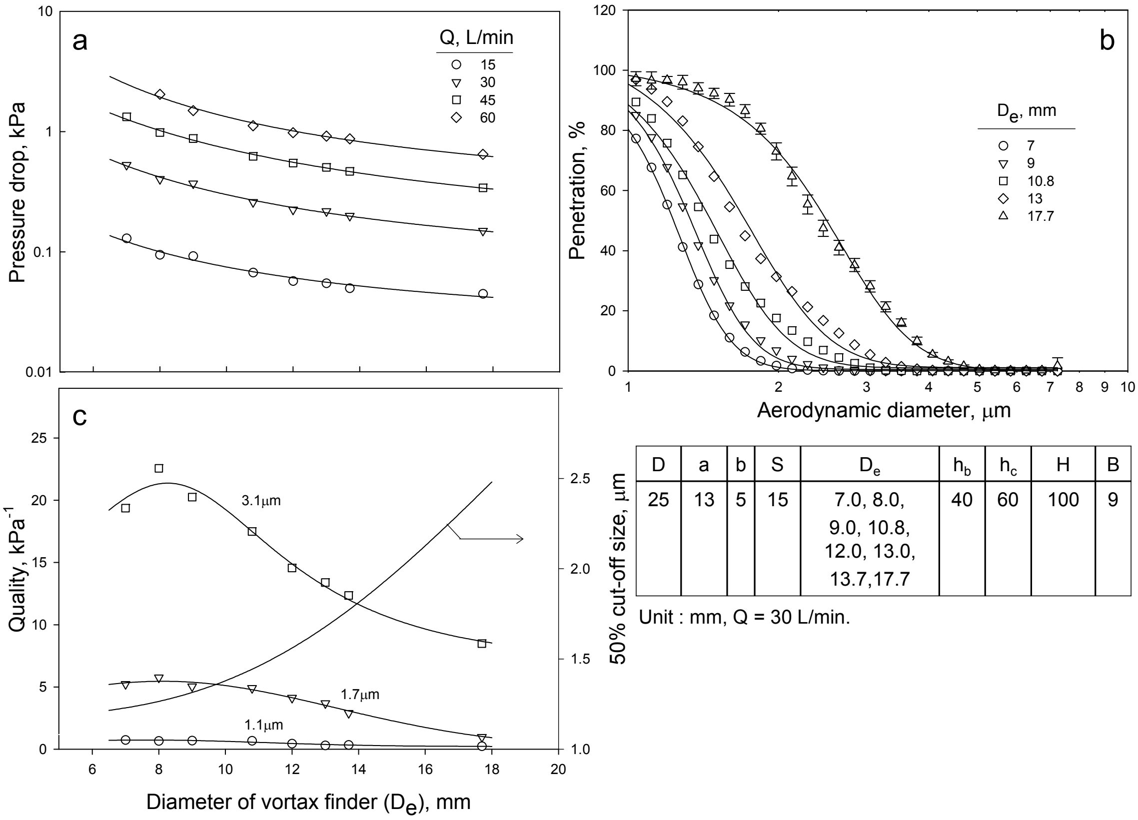


Fig. 11. The effect of vortex finder diameter (D_e) on the cyclone quality factor. (a) Pressure drop with different D_e. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of D_e.

length, which then enhances particle collection and raises the airflow resistance (Bryant *et al.*, 1983; Ji *et al.*, 1990; Avci and Karagoz, 2003). Nevertheless, when D_e is excessively small, the airflow resistance increases even though the collection efficiency increases. Based on our experiments, the optimal cyclone quality is achieved with a D_e of 8 mm. This result differs from the D_e = 13 mm suggested by Stairmand, indicating that further changes to the current D_e could improve its performance.

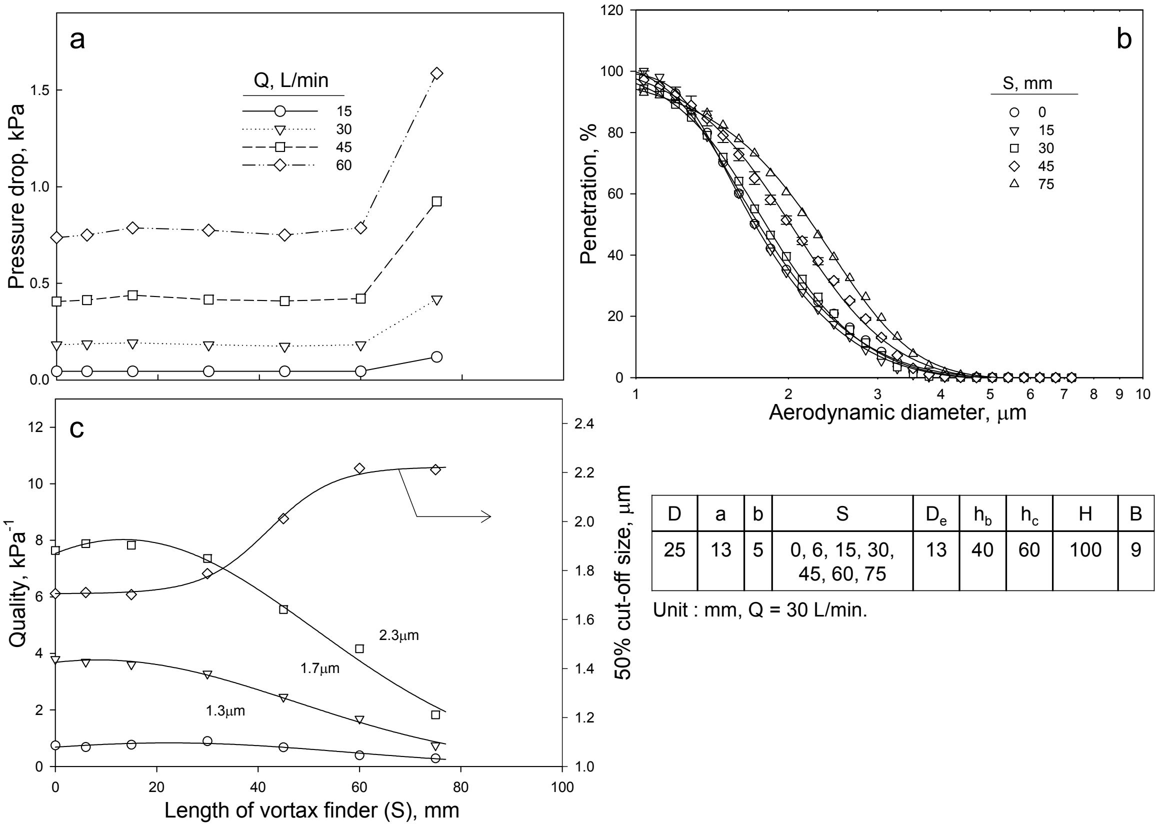
Vortex Finder Length (S)

To understand how S affects the cyclone quality factor (as shown in Fig. 12), this experiment varies S from 0 to 75 mm, with other conditions set as follows: D = 25 mm, a = 13 mm, b = 5 mm, D_e = 13 mm, h_b = 40 mm, h_c = 60 mm, H = 100 mm, and B = 9 mm. Fig. 12(a) shows the pressure drop as a function of S. An ambiguous turning point occurs when S is at 15 mm, after which the airflow resistance begins to decrease as S decreases. This happens because when S is shorter than a (inlet height), some of the air entering the inlet will head for the outlet and be directly discharged, which then lowers the volume of air reaching the bottom and causes the pressure drop to decline. When S is between 15 and 60 mm, the pressure drop appears to be less dependent on S. According to the simulation formula of the natural vortex proposed by Ji *et al.* (1990), the turning point where the outer flow of the vortex turns to the core flow will not be altered despite the changes of S. Therefore, when H is slightly smaller than the natural vortex length, the outer flow of the vortex should be able to reach the cone bottom even without the guidance of S (Ji *et al.*, 1990). Yet, as S is prolonged excessively, as in this experiment when S exceeds 60 mm, air flow becomes overly pressed to the bottom, and increases the airflow resistance, as shown in Fig. 12(a).

Fig. 12(b) shows the aerosol penetration curves as a function of S under 30 L/min, and Fig. 12(c) displays their 50% cut-off sizes. The figures show that the smallest 50% cut-off size happens at an S of 15 mm, because the flow may be discharged directly from the outlet when the S is shorter than this height. However, this effect is insignificant. When S is between 15 and 75 mm, the collection efficiency drops as S increases since longer S will decrease the natural vortex length and raise the 50% cut-off size. This finding somehow contradicts the physical law, because even if a longer S decreases the natural vortex length, the distance travelled by the particles down to the turn of the vortex will still be the same. However, this result corresponds to the tendency found in Zhu and Lee (1999), which demonstrates that when S/D equals to 1, there would be the minimum 50% cut-off size. It can be concluded that the cyclone quality factor is optimal when S is about 15 mm, a result close to the 13mm proposed by Stairmand.

Comparison of High-Performance Cyclones and the Stairmand Cyclone

Combining the optimal configurations from the above-



D	a	b	S	D_e	h_b	h_c	H	B
25	13	5	0, 6, 15, 30, 45, 60, 75	13	40	60	100	9

Unit : mm, Q = 30 L/min.

Fig. 12. The effect of vortex finder length (S) on the cyclone quality factor. (a) Pressure drop with different S. (b) Aerosol penetration as a function of particle size. (c) Quality and 50% cutoff size as a function of S.

mentioned experiments, a high-performance cyclone is made in order to compare its' performance with a Stairmand cyclone, as shown in Fig. 13. We first vary the volumetric flow rate to compare the performance of these two cyclones. When the flow rate is at 45 L/min and the particle diameter at 0.7 µm, the cyclone quality factor of the high-quality cyclone is 4 times higher than the Stairmand configuration; when the flow rate is at 30 L/min and the particle diameter at 1.2 µm, the cyclone quality factor is 5 times higher than the Stairmand cyclone; when the flow rate is at 15 L/min and the particle diameter at 1.8 µm, the cyclone quality factor is 12 times higher. We may conclude that the cyclone performance will be significantly enhanced if appropriate modifications can be made to its configuration.

CONCLUSIONS AND RECOMMENDATIONS

In this experiment, we conduct tests on several parameters of the cyclone based on the basic Stairmand configuration. The major findings are as follows:

(1) Cyclone quality factor is an appropriate indicator for the cyclone performance. For example, through this index, it can be implied that a cyclone with cone bottom is superior in performance than the one without it.

(2) The cone bottom has significant impact on cyclone performance, as the decreasing cross-sectional area of the cone enhances the particle collection efficiency. Higher proportion of h_c in H will lead to higher cyclone quality factor. The performance of the Stairmand cyclone can be improved if the h_c increases from 60 mm to 70 mm, and the cone bottom diameter (B) decreases from 9 mm to 4 mm.

(3) The optimal length of the cyclone (H) will be influenced by the natural vortex length. An overly extended H results in unutilized space, while an overly short H raises the airflow resistance and lowers the cyclone quality factor. The optimal H of the Stairmand cyclone is around 100 mm, indicating that H/D should equal to 4.

(4) An exceedingly large or small inlet may both lower the cyclone quality factor. An exceedingly large inlet will reduce the inlet velocity, decreasing the collection efficiency and thereby lowering the cyclone quality factor. An exceedingly small inlet will raise the airflow resistance and hence also lower the cyclone quality factor. After the optimal inlet area has been set, changing the inlet aspect ratio of the Stairmand cyclone from a:b = 13:5 to 20:3.2 will considerably improve its performance.

(5) The vortex finder length (S) and vortex finder diameter (D_e) also affect the cyclone quality factor. An overly short S cannot guide the airflow while an overly long one will reduce the natural vortex length and lessen the collection efficiency. The size of D_e also influences the natural vortex length. Both factors considered, an optimal D_e of the Stairmand should be reduced to 8 mm from the originally proposed 13 mm.

	Dimensions, mm									ΔP, kPa		
Symbol	D	a	b	S	D_e	h_b	h_c	H	B	15 L/min	30 L/min	45 L/min
High quality type	25	20	3.2	15	8	30	70	100	4	0.10	0.46	1.13
Stairmand type	25	13	5	15	13	38	62	100	9	0.05	0.18	0.45

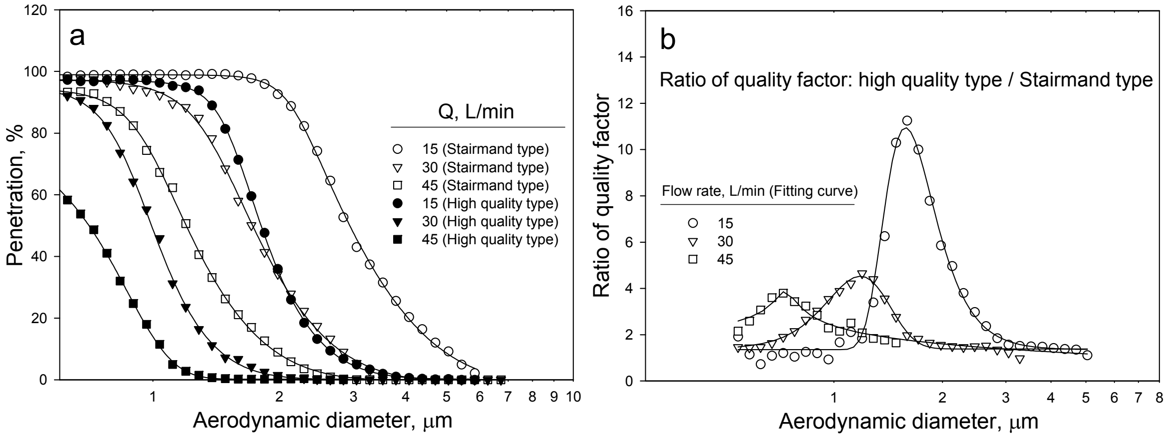


Fig. 13. Comparison of high quality cyclone with Stairmand cyclone.

(6) The cyclone quality factor is a function of air flow. When the flow rate is at 30 L/min, the cyclone quality factor could be 5 times higher than the original one; when the flow rate is at 15 L/min, the cyclone quality factor could be even 12 times higher. Despite this difference, the significant effect of the configuration modification on the cyclone performance is evident, and worth further study.

(7) The cyclone structure is simple. Yet the alterations of configurations in the cyclone affect one another, which make it complicated to fully understand the impact of every configuration on the particle collection efficiency, pressure drop, and the combined cyclone quality factor. This could explain that while many studies have been made on the simulation formula, its application is still limited. This experiment intends to adopt cyclone quality factor as the main indicator, analyzing the correlation between the configurations, collection efficiency, and airflow resistance. It is expected that this experiment could contribute to the future design of a higher quality cyclone, and provide practical information for the development of the empirical or semi-empirical simulation formula. The complicated interactions among parameters operated in this work call for further clarification in the future experiments and model developments.

REFERENCES

Alexander, R.M. (1949). Fundamentals of Cyclone Design and Operation, Proceedings of the Australian Institute of Mining and Metallurgy, 152: 203–228.

Avci, A. and Karagoz, I. (2003). Effects of Flow and Geometrical Parameters on the Collection Efficiency in Cyclone Separators. *J. Aerosol Sci.* 34:937–955.

Bryant, H.S., Silverman, R.W. and Zenz, F.A. (1983). How Dust in Gas Affects Cyclone Pressure Drop. *Hydrocarbon Process.* 62: 87–90.

Büttner, H. (1988). Size Separation of Particles from Aerosol Samples Using Impactors and Cyclones. *Part. Part. Syst. Char.* 5:87–93.

Dietz, P.W. (1981). Collection Efficiency of Cyclone Separators. *AlChE J.* 27: 888–892.

Dirgo, J. and Leith, D. (1985). Cyclone Collection Efficiency: Comparison of Experimental Results with Theoretical Predictions. *Aerosol Sci. Technol.* 4: 401–415.

Elsayed, K. and Lacor, C. (2010). Application of Response Surface Methodology for Modeling and Optimization of the Cyclone Separator for Minimum Pressure Drop, Proceeding of Fifth European Conference on Computational Fluid Dynamics, p. 14–17.

Ficici, F., Ari, V. and Kapsiz, M. (2010). The Effects of Vortex Finder on the Pressure Drop in Cyclone Separators. *Int. J. Phys. Sci.* 5: 804–813.

Gautam, M. and Sreenath, A. (1997). Performance of a Respirable Multi-inlet Cyclone sampler. *J. Aerosol Sci.* 28: 1265–1281.

Gerrard, A.M. and Liddle, C.J. (1976). The Optimal Choice of Multiple Cyclones. *Powder Technol.* 13: 251–254.

Gupta, A.K. (1984). *Swirl Flows*, Taylor & Francis.

Hinds, W.C. (1999). *Aerosol Technology Properties, Behavior, and Measurement of Airborne Particles* -2nd (Ed, Wiley-Interscience.

Hoffmann, A.C., De Jonge, R., Arends, H. and Hanrats, C. (1995). Evidence of the 'Natural Vortex Length' and Its Effect on the Separation Efficiency of Gas Cyclones. *Filtr. Sep.* 32: 799–804.

Iozia, D.L. and Leith, D. (1989). Effect of Cyclone Dimensions on Gas Flow Pattern and Collection Efficiency. *Aerosol Sci. Technol.* 10: 491–500.

Iozia, D.L. and Leith, D. (1990). The Logistic Function and Cyclone Fractional Efficiency. *Aerosol Sci. Technol.*

12:598–606.
Ji, Z., Wu, X. and Shi, M. (1990). Experimental Research on the Natural Turning Length of the Cyclone, Fil Tech Europa' 91 2: 583–589.
Karagoz, I. and Avci, A. (2005). Modelling of the Pressure Drop in Tangential Inlet Cyclone Separators. *Aerosol Sci. Technol.* 39: 857–865.
Kim, J.C. and Lee, K.W. (1990). Experimental Study of Particle Collection by Small Cyclones. *Aerosol Sci. Technol.* 12: 1003–1015.
Lim, K.S., Kwon, S.B. and Lee, K.W. (2003). Characteristics of the Collection Efficiency for a Double Inlet Cyclone with Clean Air. *J. Aerosol Sci.* 34: 1085–1095.
Lim, K.S., Kim, H.S. and Lee, K.W. (2004). Characteristics of the Collection Efficiency for a Cyclone with Different Vortex Finder Shapes. *J. Aerosol Sci.* 35:743–754.
Mainza, A., Powell, M.S. and Knopjes, B. (2004). Differential Classification of Dense Material in a Three-product Cyclone. *Miner. Eng.* 17: 573–579.
Martínez-Benet, J.M. and Casal, J. (1984). Optimization of Parallel Cyclones. *Powder Technol.* 38: 217–221.
Moore, M.E. and McFarland, A.R. (1993). Performance Modeling of Single-inlet Aerosol Sampling Cyclones. *Environ. Sci. Technol.* 27: 1842–1848.
Muschelknautz, E. and Greif, V. (1996). Cyclones and Other Gas—Solids Separators, In *Circulating Fluidized Beds*, Grace, J.R., Avidan, A.A. and Knowlton, T.M. (Eds.), Springer, p. 181–213.
Ramachandran, G., Leith, D., Dirgo, J. and Feldman, H. (1991). Cyclone Optimization Based on a New Empirical Model for Pressure Drop. *Aerosol Sci. Technol.* 15:135–148.
Saltzman, B.E. and Hochstrasser, J.M. (1983). Design and Performance of Miniature Cyclones for Respirable Aerosol Sampling. *Environ. Sci. Technol.* 17: 418–424.
Stern, A.C., Caplan, K.J. and Bush, P.D. (1955). Cyclone Dust Collectors.
Surmen, A., Avci, A. and Karamangil, M. I. (2011). Prediction of the Maximum-efficiency Cyclone Length for a Cyclone with a Tangential Entry. *Powder Technol.* 207: 1–8.
Swamee, P.K., Aggarwal, N. and Bhobhiya, K. (2009). Optimum Design of Cyclone Separator. *AlChE J.* 55: 2279–2283.
Trefz, M. and Muschelknautz, E. (1993). Extended Cyclone Theory for Gas Flows with High Solids Concentrations. *Chem. Eng. Technol.* 16: 153–160.
Xiang, R., Park, S.H. and Lee, K.W. (2001). Effects of Cone Dimension on Cyclone Performance. *J. Aerosol Sci.* 32: 549–561.
Zhu, Y. and Lee, K.W. (1999). Experimental Study on Small Cyclones Operating at High Flowrates. *J. Aerosol Sci.* 30: 1303–1315.
Zhu, Y., Kim, M.C., Lee, K.W., Park, Y.O. and Kuhlman, M.R. (2001). Design and Performance Evaluation of a Novel Double Cyclone. *Aerosol Sci. Technol.* 34: 373–380.

Received for review, April 18, 2013
Accepted, August 30, 2013