Full Length Research Paper

The effects of vortex finder on the pressure drop in cyclone separators

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In this study, three cylinder-shaped vortex finders with diameters of 80, 120 and 160 mm were designed and manufactured to find out the pressure drop of the cyclones by experimentally investigating the effects of gas inlet velocity, the vortex finder diameter and length on the cyclone performance at different gas concentration. As a result of this experimental analysis, a critical diameter of vortex finder is obtained as 120 mm. Furthermore, analyzing the experimental findings with a statistical regression method indicated that there was a linear relationship between length of vortex finder and pressure loss. Then, according to the analysis results, relevance values were obtained as 98.87, 98.37 and 97.59% for these vortex finders (with diameters of 80, 120 and 160 mm), respectively.

Key words: Cyclone, vortex finder, pressure drop.

INTRODUCTION

Cyclones are devices that employ a centrifugal force generated by a spinning gas stream to separate particles from the carrier gas (Gimbun et al., 2005). Cyclone separators operate under the action of centrifugal forces. Fluid mixture enters the cyclone and makes a swirl motion and, due to centrifugal forces, the dense phase of the mixture gains a relative motion in the radial direction and is separated from main flow (Avci and Karagoz, 2003). In this design, particle-laden gas enters the cyclone at the top of the cylinder and makes several revolutions due to the shape of the entry forming a vortex with a high tangential velocity which accelerates particles outward to the wall for collection. Below the bottom of the gas exit tube, the spinning gas gradually migrates inward, to a "central core" axially along the cylinder centerline, and from there up, finally out exit tube (Zhu and Lee, 1999). Their simple design, low capital cost and nearly maintenance-free operation make them ideal for use as pre-cleaners for more expensive final control devices such as baghouses or electrostatic precipitators. Cyclones are particularly well suited for high temperature and pressure conditions because of their rugged design and flexible components materials. Cyclone collection efficiencies can reach 99 % for particles bigger than 5 μm,

and can be operated very high dust loading. Cyclones are used for the removal of large particles for both air pollution control and process use (Silva et al.,2003). Application in extreme condition includes the removing of coal dust in power plant, and the use as a spray dryer or gasification reactor (Gimbun, 2005).

Engineers are generally interested in two parameters in order to carry out an assessment of the design and performance of a cyclone. These parameters are the collection efficiency of particle and pressure drop through the cyclone (Dirgo and Leith, 1985). An accurate predicttion of cyclone pressure drop is very important because it relates directly to operating costs. Higher inlet velocities give higher collection efficiencies for a given cyclone, but this also increases the pressure drop across the cyclone. Therefore, a trade off must be made between higher collection efficiency and low pressure drop across the cyclone (Griffiths and Boysan, 1996).

The vortex finder size is an especially important dimension, which significantly affects the cyclone performance as its size plays a critical role in defining the flow field inside the cyclone, including the pattern of the outer and inner spiral flows. The vortex finder affected the collection efficiency and pressure drop of cyclones, and proposed an energy-effective cyclone design (Lim et al., 2003).

The purpose of this study is to help in understanding of the pressure drop of cyclones by experimentally exploring

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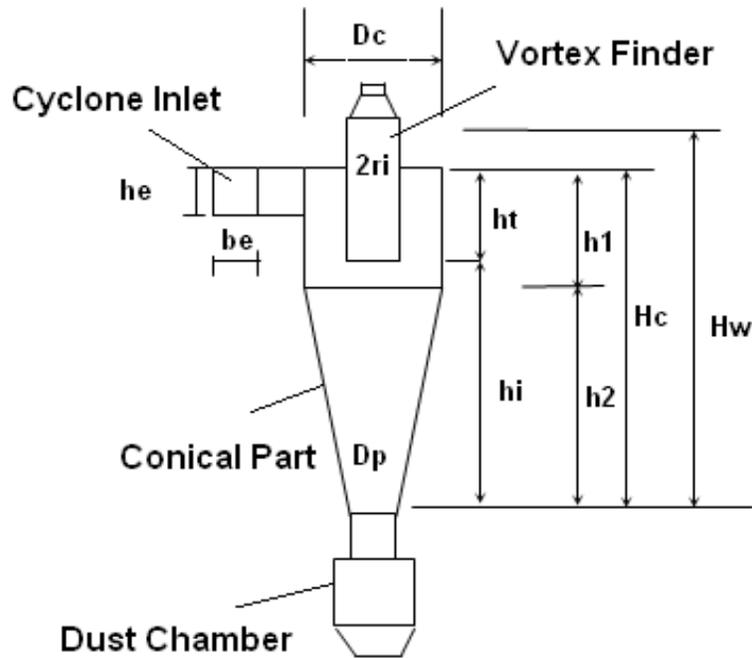
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Figure 1. Reverse flow cyclone.

Table 1. Dimensions of the Tests Cyclone.

Sizes (m)			
Dc	0.340	h1	0.272
Dw	0.126	h2	0.374
Dp	0.068	h3	0.05
Hc	0.647	be	0.075
ht	0.0961	hi	0.550

the effects of gas inlet velocity, the vortex finder diameter and length, at different gas concentration, on the cyclone performance. The pressure drop of cyclones with 3 different vortex finders diameters have been evaluated and compared. This study focused on the effects of the vortex finder diameter on the pressure drop as little work has been performed on cyclones in relation to this dimension.

EXPERIMENT

Cyclone geometry

There are a number of different forms of cyclone but the reverse flow cyclone represented in Figure 1 is the most co mmon design used in the industry. The cyclone consists of four main parts: the inlet, the separation chamber, the dust chamber and the vortex finder. Tangential inlets are preferred for the separation of solid particles from gases (Atmeyer et al., 2004). Cyclone dimension used in this simulation are as shown in Table 1. Cyclone tests were performed on the system as shown in Figure 2.

Definition and composition of the pressure drop

Generally, the pressure drop over a cyclone is the difference of static pressure between the inlet and outlet, which can be written as:

$$\Delta P = P_{si} - P_{so}$$

The static pressure at the inlet cross-section is uniformly distributed because there is no swirling motion. It can be easily measured with a pressure tapping in the wall. But the static pressure at the outlet wall is quite different from its cross- sectional average due to the strong swirling flow. The dynamic pressure stored in the swirling motion can be significant. The determination of the static pressure downstream of a cyclone, hence the pressure drop, becomes more complicated and difficult (Chen and Shi, 2006).

The total pressure drop consists of four partial pressure drops (Equation 1) pressure drop due to gas expansion at the separators entrance; (Equation 2) pressure drop due to wall friction within the separator; (Equation 3) pressure drop due to swirling motion of the gas (Equation 4); pressure drop due to gas flow through the outlet pipe (Zhao,2004).
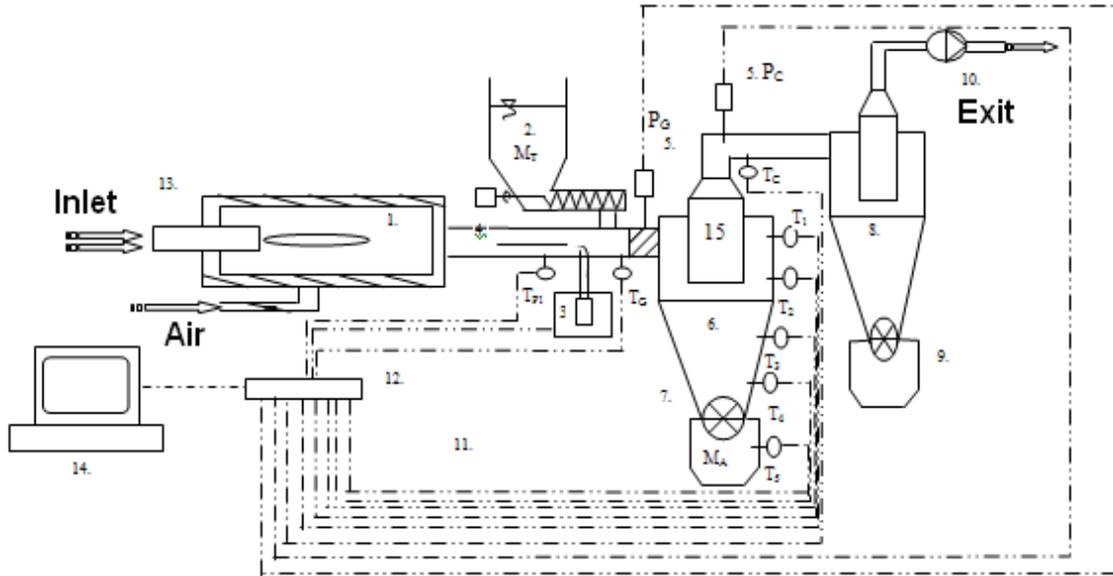
1. Combustion chamber
2. Dust Loading Unit
3. Pitot Tube
4. Pipe
5. Pressure Transmitter
6. Preheat Cyclone
7. Rotary Palette
8. Cyclone
9. Cyclone Dustbin
10. Ventilator
11. Analog Inlet Signals
12. Gather Data Card
13. Brulor
14. Computer and Scada Programme
15. Vortex finder

Figure 2. Schematic diagram of experimental set-up.

Pressure drop due to gas expansion at the separator entrance

Pressure drop due to gas expansion at the separator inlet was determined as follows:

$$\Delta P_{in} = \xi_{in}(\frac{1}{2}\rho_g v_{in}) \tag{1}$$

This pressure drop was calculated for the case of uniform flow from the right pipe to the limited space, and was expressed as:

$$\bar{v}_{\theta ev} = \frac{1}{(R_w - r_e)}\int_{re}^{Rw} v_\theta dr \quad \xi_{in} = \left[1 - \frac{ab}{(R_w - r_e)H}\right]^2 \tag{2}$$

Pressure drop due to wall friction within the separator

Pressure drop due to wall friction within the separator can be described under static equilibrium in the cyclone separators:

$$\Delta P_{fr}\left[\frac{1}{4}\pi(D^2 - d_e^2)\right] = c_1\left[\bar{\tau}_{\theta ev}(\pi DL)\right] \tag{3}$$

c_1 is a swirling flow correction factor related to the uniform flow at the wall in the cyclone separator. According to Stepherd and

Lapple's method:

$$c_1 = \frac{\pi D}{a} \tag{4}$$

$\bar{\tau}_{\theta ev}$ is the mean shear stress of the gas in the external vortex, and can be calculated in terms of Fanning's equation as:

$$\bar{\tau}_{\theta ev} = f(\frac{1}{2}\rho_g \bar{v}_{\theta ev}).\pi DL \tag{5}$$

where $f = 0.0055$.

$\bar{v}_{\theta w}$ is the mean tangential velocity in the external vortex, and can be obtained from:

$$\bar{v}_{\theta ev} = \frac{1}{(R_w - r_e)}\int_{re}^{Rw} v_\theta dr \tag{6}$$

Combining the above equations gives:

$$\Delta P_{fr} = \frac{(\pi D/a)(\pi DL)f}{1/4\pi(D^2 - d_e^2)}\left[\frac{1}{(R_w - r_e)v_{in}}\int_{re}^{Rw} v_\theta dr\right]^2 (\frac{1}{2}\rho_g v_{in}^2) \tag{7}$$

Pressure drop due to swirling motion of the gas

From the Navier-Stokes equation in cylindrical coordinates, the relationship between pressure and 3D velocity can be simplified by neglecting the axial effects:

$$\frac{dp}{dr} = \frac{\rho_g v_\theta^2}{r} \tag{8}$$

According to Mothes and Loffler (1988) the circumferential flow pattern or velocity profile including the wall roughness is expressed as follows:

$$v_\theta = \frac{v_{\theta w}}{(r/R_w)\left[1 + P(1 - r/R_w)\right]} \tag{9}$$

$$v_{\theta w} = \frac{v_d}{\xi . h^*}\left(\sqrt{\frac{1}{4} + \xi . h^* \frac{v_{\theta w}^*}{v_d}} - \frac{1}{2}\right) \tag{10}$$

$$v_{\theta w}^* = v_d \frac{\pi R_w^2}{ab\left[-0.204(b/R_w) + 0.889\right]} \tag{11}$$

$$v_d = \frac{Q}{\pi R_w^2} \tag{12}$$

$$h^* = \frac{a}{R_w^2}\left[\frac{2\pi - \arccos(b/R_w - 1)}{2\pi}\right] + \frac{h}{R_w} \tag{13}$$

$$P = \frac{v_{\theta w}}{v_d}\left(\zeta + \frac{\zeta}{\sin \varepsilon}\right) \tag{14}$$

$$Q = (ab)v_{in} \tag{15}$$

Where $\zeta = 0.0065 - 0.0075$

Although the expression for v_θ looks complicated, the result agrees very well with the typical velocity profile based on the power-law correlation of Alexander (1949). The advantage of this expression is that it presents a quantitative value of the tangential velocity at the edge of the core, $v_{\theta w}^*$, which has sometimes been assumed equal to the inlet velocity.

Combining and transforming the above equations gives:

$$\Delta_{Pvf} = \left[\int_{re}^{Rw} \frac{2(v_{\theta w}/v_d)^2 (ab/\pi R_w^2)}{r(r/R_w)^2(1 + P - P_r/R_w)^2} dr\right]\left(\frac{1}{2}\rho_g v_{in}^2\right) \tag{16}$$

Pressure drop due to gas flow through the outlet pipe

This pressure drop includes the local pressure drop and the friction pressure drop within outlet pipe.

$$\Delta p_{out} = \Delta p_{ol} + \Delta p_{of} \tag{17}$$

The local pressure drop was handled as gas flow contraction loss from the cyclone body to the outlet pipe:

$$\xi_{ol} = \frac{1}{2}\left(\frac{ab}{\pi r_e^2}\right)^2\left[1 - \left(\frac{r_e}{Rw}\right)^2\right]\left(\frac{1}{2}\rho_g v_{in}^2\right) \tag{18}$$

Because of the strong swirling flow in the outlet pipe, this pressure drop was calculated in an analogous way to the pressure drop due to wall frictions within the separator:

$$\Delta p_{ol}\left(\frac{1}{4}\pi d_e^2\right) = c_2'\left[\overline{\tau}_{\theta iv}.\pi d_e(s + \Delta s)\right] \tag{19}$$

$$c_2' = \frac{\pi d_e}{d_e} \tag{20}$$

$$\overline{\tau}_{\theta iv} = f\left(\frac{1}{2}\rho_g \overline{v}_{\theta iv}^2\right) \tag{21}$$

Where $\overline{\tau}_{\theta iv}$ is the mean shear stress of gas in the internal vortex, and $\overline{v}_{\theta iv}$ is the mean tangential velocity in the internal vortex, and can be obtained by assuming it to be equal to the tangential velocity at $r = r_e$:

$$\overline{v}_{\theta iv} = \frac{v_{\theta w}}{(r_e/R_w)(1 + P - \Pr_e/R_w)} \tag{22}$$

Combining and transforming the above equations yields:

$$\xi_{of} = \frac{\pi^2(S + \Delta S)f}{1/4\pi d_e}\left[\frac{v_{\theta w}/v_d}{(r_e/R_w)(1 + P - \Pr_e/R_w)}\frac{ab}{\pi R_w^2}\right]^2 \tag{23}$$

Total pressure drop

Su mming up, the equation for total pressure drop can be expressed as:

$$\Delta p = \Delta p_{in} + \Delta p_{fr} + \Delta p_{vf} + \Delta p_{out} \tag{24}$$

The pressure drop across a cyclone is co mmonly expressed as the number of gas inlet velocity heads ξ, named the pressure drop coefficient (PDC), which is just a function of the cyclone geometrical dimensions. It is accordingly defined as:
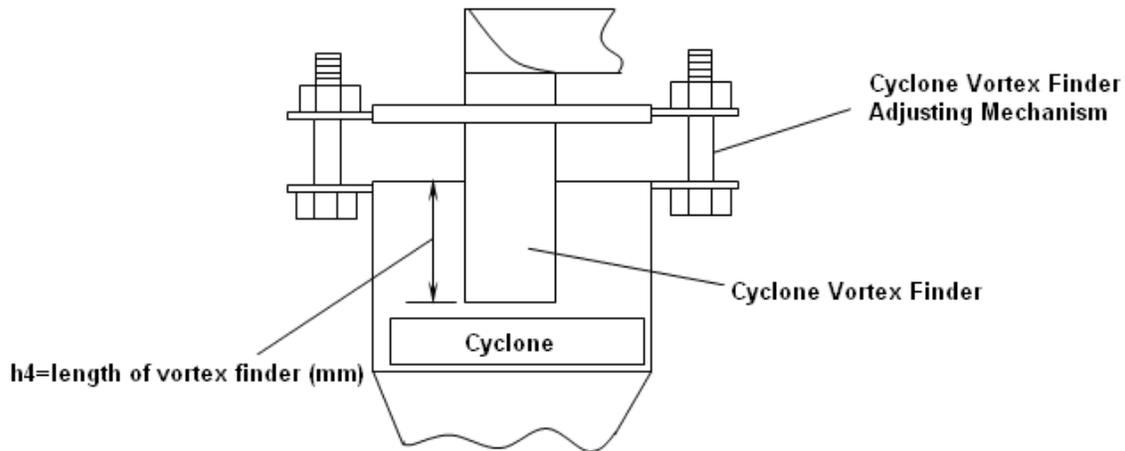
$$\xi = \frac{\Delta p}{1/2\rho_g v_{in}^2} \tag{25}$$

Figure 3. Cyclone vortex finder adjusting mechanism

Test procedure

In the experiment (Figure 2), chimney gas of 1100°C is produced with a diesel oil burner (1). Cyclone inlet flow is measured with a pitot tube. The necessary gas flow is adapted by tuning the cycle number of the exiting ventilator. Desired amount of far is supplied into the system by a loading unit (2) before the entrance of the testing cyclone (6) and after regime is established, the measures are recorded. These measuring results recorded as analog signals are evaluated at Data collecting and Controlling System which is conducted by a PC. In the experiment, the temperature is measured at seven different places beginning from the entrance up to the existence as TG, 1, 2, 3, 4, 5, C with the help of a thermocouple. Moreover, pressures at the entrance and existence of cyclones are measured and their difference is calculated as pressure drop (Ari, 2000).

In the experiments, pressure decrease, change at vent depth of cyclone vortex finder, cyclone entrance velocity, entrance temperature and entrance concentration are chosen as varying parameters and pressure drop are investigating according to these parameters.

The mechanism designed for investigation of the powder suppression efficiency and pressure drop according to cyclone vortex finder insert depth are shown in Figure3. The depth of vortex finder insert depth, here is denoted as h4 and varies from 10 up to 220 mm in length. Experimental program consists of 3 main groups.

First, cyclone, vortex finder diameter of which is changed, is adapted to experiment set-up. For finding the pressure drop and powder suppression efficiencies according to change in depth of vent of the vortex finder, ventilator cycle is stabilized as the flow velocity would be 12.44 m/s for each vent length and regime of the system is waited for. Then, 0.566 kg/ m³ farin is loaded to system. After loading, the decrease of the system entrance temperature to a constant value is waited for. After that process, other test data, cyclone entrance temperature, flow measure temperature, cyclone temperature of conic section, cyclone temperature of cylindrical section, storing temperature of farin, cyclone entrance and existing temperatures are recorded by taking the correct values from Control Unit. Stopping the test, farin, which is and preheated raw material of cement (limestone kalker+clay) and taken from cyclone powder reservoir, is carefully collected and weighed out.

At second group of tests, cyclone characteristics for changing velocities are measured which is increased from 9.5 m/s up to 10.18 m/s. Here, the powder concentration is fixed.

At third and final group of tests, tests are repeated for increasing behavior of particle concentration.

At each experiments with particles and without particles, measured values are recorded (Ficici, 2006).

RESULTS AND DISCUSSION

Dependencies at pressure drop according to length of vortex finder, inlet velocity and concentration for three different types of vortex finders with different vortex finder diameters are investigated at the experiments. These diameters are taken as 80,120 and 160 mm.

Effects of length of vortex finder

The cyclone pressure drops for the different vortex finder are compared at different length of vortex finder in Figure4 and Fig5. Figure 5 shows that pressure drop increases as vortex finder length increases. This situation is observed for all cyclones. Under these conditions there is, however, poor separation of coarse particles. The main reason is that large quantities of coarse particles bypass the separation process via the short circuit flow under the top cover and report to the overflow. Extension of the vortex finder, however, shortens the natural vortex in the cyclone body and reduces the opportunity of the fine particles to separate from the vortex. This has been confirmed for cyclones (Fuping et al., 2006; Martinez et al., 2008).

In these experiments, pressure drop measured between entrance and exit points of cyclone are displayed graphically. According to these results, an increase at pressure drops is determined depending on the diameters of vortex finder. When we increase the diameter of vortex finder to 120 mm in the test cyclone with a diameter of 80 mm, this pressure drop is increased while a further decrease in diameter to 160 mm causes the pressure drop to approach to the measured values of the case with 80 mm diameter. This situation tells us that up to a critical diameter of vortex finder, pressure drop shows
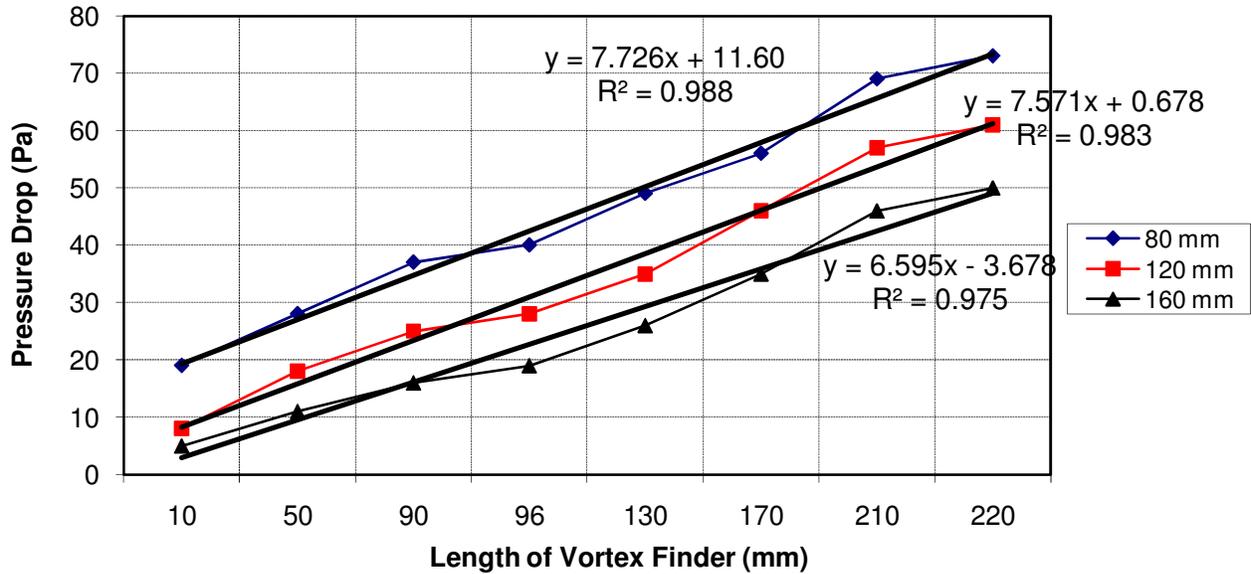
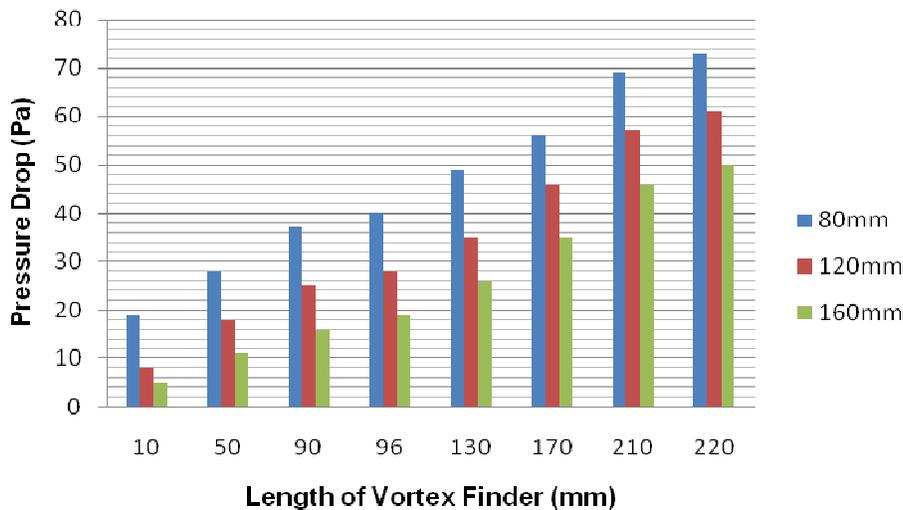**Figure 4.** The effect of length of vortex finder on pressure drop.

Figure 5. Effect of length of vortex finder on pressure drop.

shows a climbing behavior and for further increasing diameters after that absolute diameter value (120 mm), a sinking behavior is observed. This finding is verified in other studies of literature (lim et al., 2003; Cullivan et al., 2004).

In addition, experimental results were also analyzed with statistical regression method. As a result of analyzing the experimental results with such a statistical method, it was observed that there was a linear relationship between length of vortex finder and pressure loss. According to the analysis results, relevance values were obtained as 98.87, 98.37 and 97.59% for lengths of vortex finder considered as 80, 120 and 160 mm,

respectively. Table 2 shows the using regression equations.

Effects of inlet velocity

Measurement of the cyclone pressure drop was carried out for average inlet velocity ranging from 4.62 to 14.16 m/s by Bohnet (Bohnet, 1995) and from 5.1 to 25 m/s by Griffiths and Boysan (1996). In this study, measurement of the cyclone pressure drop was carried out for inlet velocity ranging from 9.56 to 10.18 m/s. The cyclone pressure drops for the different vortex finder are compar-

Table 2. Static analysis of length of vortex finder

Regression	R^2	F	Sigf	β_0	β_1
80 mm	0.9887	1184.11	0.00	7.7262	11.607
120 mm	0.9837	1124.90	0.00	7.5714	0.6786
160 mm	0.9759	1555.20	0.00	6.5952	3.6786
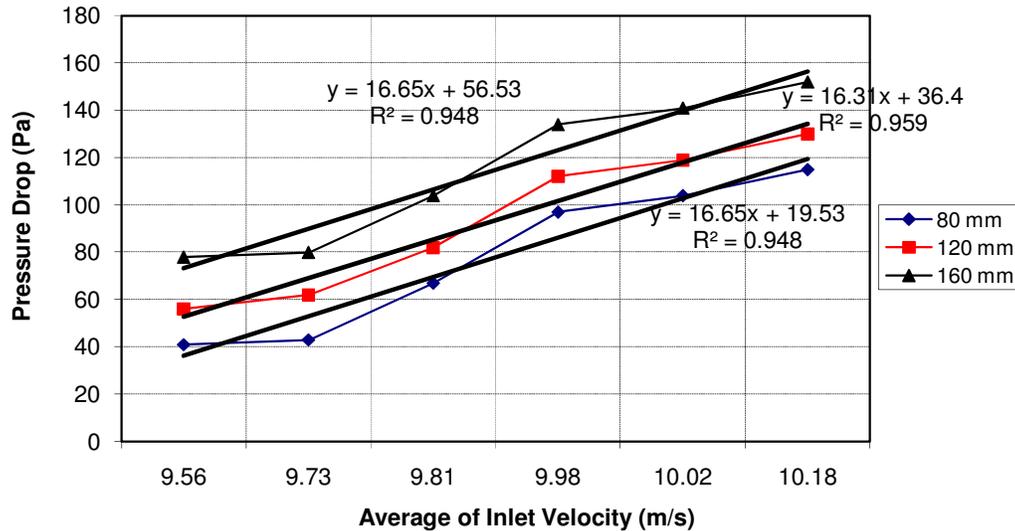
**Figure 6.** Pressure drops of the cyclone separator with different vortex finder diameter.
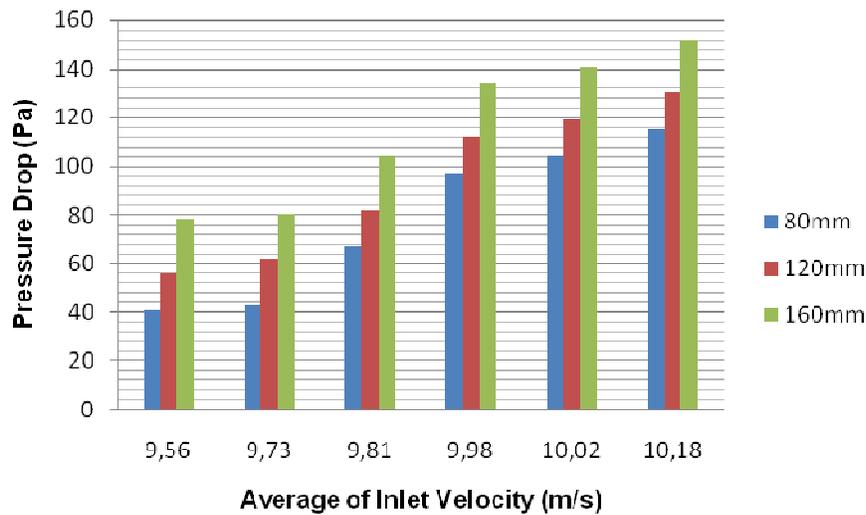
Figure 7. Effect of average inlet velocity on pressure drop.

ed at different inlet velocities in Figures 6 and 7. These Figures show that the cyclone pressure drop is increased with the all vortex finder diameter. At a low inlet velocity, the pressure drop increases slowly, and at a higher inlet velocity, the pressure drop increases greatly (Gimbun et al., 2005).

Additionally, in this experiment when the velocity of gas with particles is increased, pressure drops at each cyclone with three vortex finder diameters differ from each other. With this fact, it is observed that the difference of this pressure drop is decreasing when diameter of vortex finder value is changed from 80 to 120 mm. A

Table 3. Static analysis of inlet velocity

Regression	R^2	F	Sigf	β_0	β_1
80 mm	0.9482	74.44	0.01	16.657	56.533
120 mm	0.9593	54.80	0.02	16.314	36.400
160 mm	0.9482	54.80	0.02	16.657	19.533
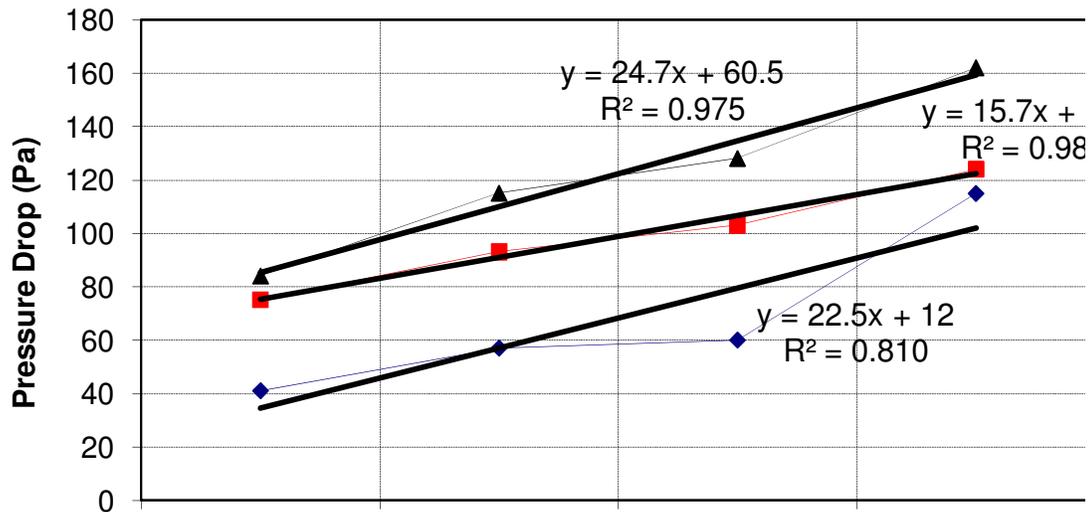
Figure 8. The effect of inlet farin concentration on pressure drop.

Table 4. Static analysis of inlet farin concentration

Regression	R^2	F	Sigf	β_0	β_1
80 mm	0.8106	74.44	0,096	16.657	56.533
120 mm	0.9838	54.80	0,007	16.314	36.400
160 mm	0.975	54.80	0,011	16.657	19.533

further increase up to 160 mm, again these differences of losses become lower. The increase of entrance velocity is very much related with cycle number of swirl. Since the swirl cycle number will be much for smaller diameters of vortex finder, pressure drop is higher than losses at greater diameters. The conclusion presented in this study is consistent with the literature (Fuping and Yanpeng, 2009). In addition, According to the regression analysis results, relevance values were obtained as 94.82, 95.93 and 94.82 % for length of vortex finder considered as 80, 120 and 160 mm, respectively. Table 3 shows the using regression equations.

Effects of inlet farin concentration

The cyclone pressure drops for the different vortex finder are compared at different inlet farin concentration in Figures 8 and 9. In this study, experiments are carried on with cyclone concentrations are varied between 0.19 kg/m^3–0.55 kg/m^3. As the farin concentration is increased, the pressure drop, as expected, also increases. This finding has been observed by many researchers (Kim and Lee, 1990; Saltzman and Hochstrasser, 1983; Dirgo and Leith, 1985; Dirgo and Leith, 1985; Moore and Mcfarland, 1993).

Furthermore, Pressure loss is highest at cyclone with 160 mm diameter. The reason is that, number of swirls is less at this diameter. Thus, higher pressure loss is seen at 160 mm. Table 4 shows that relevant values were obtained as 81.06, 98.38, and 97.5% for length of vortex finder considered as 80, 120 and 160 mm, respectively.

Conclusions

As a result of this experimental research and data from it, a critical diameter of vortex finder is obtained. This is
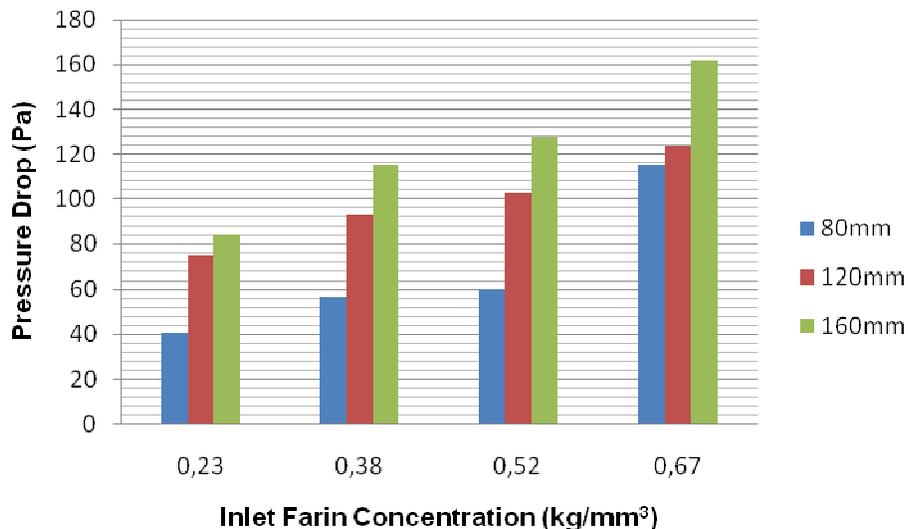
Figure 9. Effect of inlet farin concentration on pressure drop.

determined as 120 mm. A desired result has not been obtained according to cyclone collection efficiency despite the fact that further increase in diameter lowered the pressure drops. That means that pressure drop can be lowered with increasing diameter, however efficiency of collection is lost then. In this research, the theoretical argument of critical vortex finder is experimentally proved.

ACKNOWLEDGEMENT

NOMENCLATURE

a	[m]	inlet height
b	[m]	inlet width
B	[m]	particle outlet diameter
c	[-]	swirling flow correction factor
D	[m]	cyclone body diameter
d_e	[m]	gas outlet diameter
h	[m]	cyclone cylinder height
H	[m]	cyclone height
L	[m]	natural length of cyclone
p	[Pa]	pressure
P	[-]	parameter of momentum exchange between gas at the wall
Q	[m³/s]	volumetric gas flow rate
r	[m]	radial dimension
R_w	[m]	cyclone body radius
r_e	[m]	vortex finder radius
S	[m]	gas outlet duct deep length
ΔS	[m]	gas outlet duct extend length

Greek symbols

e	[rad]	the cone slope
ρ_g	[kg/m³]	gas density
t	[Pa]	shear stress
u	[m/s]	gas velocity
ξ	[-]	the pressure drop coefficient
ζ	[-]	the wall friction coefficient

Subscripts

d	cyclone body
g	gas
e	near the exit or vortex finder
fr	friction
in	cyclone inlet
iv	internal vortex
ol	outlet local loss
of	outlet friction loss
out	cyclone outlet
vf	vortex flow
θ	tangential coordinate directions
r	radial coordinate directions
w	near the wall

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