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Experimental Analysis of Dual Inlet Cyclone Separator

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ABSTRACT

Cyclone separators are suitable to remove particles in extreme conditions with high pressure and temperature during the gas-solid separation process. The important performance of cyclone separators is determined by the separation efficiency and pressure drop. The inlet parameters including the number of inlets, inlet geometry and inlet gas velocity affects the performance of cyclone separators. In this paper, the experimental investigation has been conducted to determine the effects of dual inlet to the separation efficiency of cyclone separators. The cyclone separator was fabricated using the acrylic materials to accommodate the flow observation and trajectories inside the chamber. The experiments were conducted at 9, 11 and 13 m/s of inlet velocity using three particle sizes at 277.5, 42.5 and 625 μm . Results showed that as the particle sizes increases, the separation efficiency also increases up to 94.5% for 625 μm particles. The findings indicate that the dual inlet cyclone separators increases the performance of cyclone separators especially to remove fly ash in the biomass processing plant and other gas-solid process.

Keywords:

Cyclone separator, separation efficiency, inlet geometry

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1. Introduction

Cyclone separators are widely used in many processes [1-2] either to recover solids or powder from the process stream or removing particles from gases before releasing them to the atmosphere. It is a process to continuously collecting any dust generated by the process. Cyclone separator or also known as dust separator is a separation system that can be said as dry scrubber uses the principle of inertia to remove particle from gasses [3]. Cyclone separator used a system that enhance the quality of air released form the industrial process [4-5]. They are often used as an air pollution control device to enhance air quality.

The performance of the cyclone separator is usually being related to the pressure drop, separation efficiency of particulate matter and the design of the cyclone separators [6-9]. The particle

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size and the flow condition in the cyclone has always been in related with the swirl and turbulence in the separation process. The turbulence drives the solid particles to swirl [10-12] inside the cyclone and end up in the exit stream [13]. The physical properties such as the inlet velocity of the fluid and viscosity also affect the separation efficiency of a cyclone separator [14]. In terms of cyclone separators geometry, the design also plays role in the separation efficiency such as an increase of cylinder length reduces the pressure drop and increases the separation efficiency [15]. A study revealed that vortex length can be useful in predicting separation efficiency, particularly in brief cyclones. The cyclone vortex may not reach the cone apex in protracted cyclones. The collecting efficiency improves with increasing cyclone length until a specific value is reached, at which point it begins to decline [16].

There is also a model available to predict grade efficiency and parametric study to minimize the process variations [17]. Further efforts have been conducted to model the prediction efficiency of cyclone separators [18-21]. Computational method was also adopted to simulate the physical inside the cyclone [22-23]. Various inlet parameters had been investigated intensively by researchers [24-26] including the inlet geometry and the number of inlets of the cyclone separators. Another findings [27] indicate that higher separation efficiency of dual inlets compared to single inlet [28-29]. Besides that, three and four inlets had also been investigated and shows higher separation efficiency but the results of pressure drop varies between the researchers. In actual application, three and four inlets of cyclone separators are complex and difficult to fabricate [30-31]. It is observed that the dual inlet of cyclone separators need to be investigated further since the performance are largely affected by the geometry of the cyclone.

In this paper, the effects of dual inlet on the performance of separation efficiency were investigated experimentally. Secondary inlet was one of the alternative ways to improve the cyclone performance, separation efficiency and further increases the productivity. The flow inside the cyclone chamber is one of the main factors that needs to be emphasized during the investigation of cyclone.

2. Methodology

2.1 Cyclone separator design

Cyclone separators are available in a range of shape and configurations. The reversed flow cyclone, which features a cone under a cylindrical body with tangential entrance is the most widely used. Stairmand high efficiency cyclone separator dimensionless ratio has been used as the main reference on designing the lab-scale dual inlet cyclone separator (Table 1 and Table 2).

Table 1
Stairmand High Efficiency ratio

Item	Dimension	Ratio
1	$H_c/D_c = K_H$	0.5
2	$B_c/D_c = K_B$	0.2
3	$S_c/D_c = K_S$	0.5
4	$H_i/D_c = K_i$	0.5
5	$L_c/D_c = K_L$	1.5
6	$Z_c/D_c = K_Z$	2.5
7	$D_s/D_c = K_S$	0.375

2.2 Optimum Design of Cyclone Separators

For an accurate optimal design of a cyclone, it is critical to employ a dependable pressure drop equation for an accurate and effective cyclone design. Several formulae have been proposed over the years to forecast cyclone efficiency and pressure drop. Key parameter is one of the main considerations to achieve an optimal design. The two major costs involved in running a number of parallel cyclone separators are fixed cost and operating costs. The fixed costs decrease as the number of cyclones grows. However, the pressure drop will be increasing as well as increasing the pumping costs. To reduce or increase the pressure drop in a cyclone separator, the cyclone shell or the diameter of the output pipe can be modified. Because each of these qualities has opposing effects on the cyclone's total expenses, the parameters must be chosen optimally [32].

Dynamic Programming Method of optimizations used to find a design with reduced pressure drop and denudation rate, with minimum change in collection efficiency. Dynamic Programming Method is an optimization technique that can be used to optimize process stages or continuous function that can be approximated by staged process. Dynamic Programming method has its unique property of arriving at an overall optimal plan for sub-sections of the problem. The best plans for sub-sections are employed in further evaluations, and all non-optimal plans are ignored [33].

Dynamic programming is not always compatible with other optimization technique like Lagrange multipliers or linear and non-linear programming. Instead, it is linked to the calculus of variations, which produces an optimum function rather than an ideal state point as a consequence. The challenge is solved using dynamic programming, which divides the entire journey into segment and treats the continuous function as a sequence of steps or stages. The finite-step approach to dynamic programming is an approximation of the calculus-of-variation method in such an application [32].

2.3 Stairmand High Efficiency Cyclone

A Stairmand high efficiency cyclone is a tangential inlet type and cylinder-on-cone type model of cyclone separator. Stairmand high efficiency cyclone can be considered as the most optimized cyclone of its type and most new cyclone models are still built based on Stairmand high efficiency cyclone parameters [15].

A dimensionless ratio of Stairmand high efficiency cyclone can used to identify and obtained the parameters of Stairmand high efficiency cyclone. A Stairmand high efficiency cyclone have a small inlet area and the exit area. The gas exit duct length (L_v) is less in Stairmand high efficiency cyclone because of the inlet height (a) is also less. To avoid the gas short-circuiting the cyclone by travelling directly from the entrance to the outlet without producing a vortex, the exit duct length is always longer than the inlet height. Standard general-purpose design appears to strike a balance between efficiency and throughput [15].

The dimension of these cyclones is shown in Figure 1 and Table 1. The structural diameter for the dual inlet cyclone separator includes cylinder diameter, which is 200 mm, both inlet height with 100 mm, both inlet width 40 mm, and the vortex finder diameter of 100 mm. The extension of the vortex finder inside the cyclone is 100 mm.

Table 3

Stairmand High Efficiency dimensionless ratio [15]

Source	D	a/D	b/D	D_e/D	L_v/D	H/D	H_c/D	D_c/D
Stairmand (1951) High Efficiency	1	0.5	0.2	0.5	0.5	1.5	2.5	0.375

If each of the eight dimensions illustrated is known, the geometry of a cyclone may be characterized. However, it is frequently easier to represent dimensions in dimensionless form, such as a multiple of diameter (D). The cyclone's dimensions are then determined using the ratio given. This allows for a comparison of the geometric similarities of many cyclones based on their dimension ratio, rather than using absolute magnitude to compare the cyclones [34].

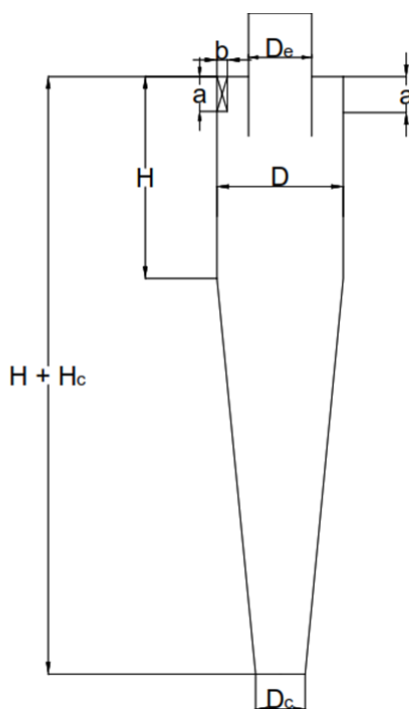


Fig. 1. Schematic of cyclone separator structure

Table 2

Dimensions of the dual inlet cyclone

Geometry Parametric	Symbol	Dimension (mm)	Dimensionless Ratio
Cylinder diameter	D	200	1
Inlet height	a	100	0.5
Inlet width	b	40	0.2
Vortex finder diameter	D_e	100	0.5
Extension of vortex finder inside cyclone	L_v	100	0.5
Cylinder height	H	300	1.5
Cone height	H_c	500	2.5
Cone tip diameter	D_c	75	0.375

The main objective of material selection for the lab-scale dual inlet cyclone separator is it must be a durable material with outstanding strength, stiffness, and optical clarity. Poly (methyl methacrylate) or known as PMMA with 5-millimetre thickness is the most suitable material for the

lab-scale dual inlet cyclone since it is easy to be fabricated. With the transparent features of the acrylic and durability of Perspex, it matches the objective to observe the flow and separation process inside the new lab scale dual inlet cyclone separation chamber with suitable and durable material. Acrylic is well known as a plastic material with high strength, high stiffness, easily to be fabricated and easy to solvent bond using chloroform glue that is suitable to be use for Acrylic and Perspex.

2.2 Experimental Setup

UPVC pipe will be used from blower to a tee connector and flexible ducting used to connect Y tee connector to the cyclone inlets. To control the velocity of the blower, voltage regulator was used to control the voltage of the blower. The velocity then will be obtained using pitot tube that will be installed at the piping of the system to observe the velocity and pressure entering the cyclone separator system.

Data of the cyclone's performance will be collected experimentally. In the testing and commissioning phase. Particle will be injected through the system to analyze the particle collection efficiency; and the pressure drop in the new dual-inlet cyclone separators system. Data from the experiment will be analyzed to study the capability of the secondary tangential inlet. The inlet, outlet, can be obtained using:

$$U_{ce} = \frac{Q}{K_B K_H D_C^2} \quad (1)$$

$$U_{ci} = \frac{4Q}{K_i^2 \pi D_C^2} \quad (2)$$

$$d_c = 2.846 \sqrt{\frac{u_{cri} \mu_c K_i D_C}{\Delta \rho u_{ci}^2}} \quad (3)$$

$$C_f = 2.5 \cdot 10^{-3} + \frac{144}{Re_c} \quad (4)$$

$$C_e = 1 - \left(0.680 - 0.151 \frac{K_i^2}{K_B K_H} \right) K_B^{\frac{1}{3}} \quad (5)$$

$$\Delta P_C = \xi_C \frac{1}{2} \rho_C u_{ci}^2 \quad (6)$$

From the inlet and outlet velocity the cyclone cut-off diameter, d_c and pressure drop, ΔP can be obtained. Where: Q is the volumetric flowrate, m^3/s ; K_B , K_H , K_i – design ratio; D_C is the cyclone cylindrical body diameter; ξ_C is the total pressure drop coefficient of cyclone; ρ_C is cyclone pressure drop, kPa.

The dual inlet cyclone separator efficiency can be obtained through testing and commissioning process when the efficiency can be obtained with the mass (g) amount of particle injected and particle collected on the collection tank of the lab-scale dual inlet cyclone separator.

$$\eta_C = \frac{M_c}{M_i} \times 100\% \quad (7)$$

The experiment using the quartz sand as the solid particle for separation with a density of 1600 kg/m^3 . The average size of the quartz sand particles is $625 \mu\text{m}$, $427.5 \mu\text{m}$, and $277.5 \mu\text{m}$, respectively.

The experimental setup is illustrated in Figure 2. The air blower was employed to press air into the main piping system to the inlet of the dual inlet cyclone. Then from the blower, the air was measured by the pitot tube that connected to the digital airflow meter which was entered the dual inlet cyclone separator. The air flow was adjusted through the voltage regulator that connected with the blower to control the velocity which is 9 m/s, 11 m/s, and 13 m/s. The pressure drop during the experiment was read by the U-tube that connected to the digital manometer.

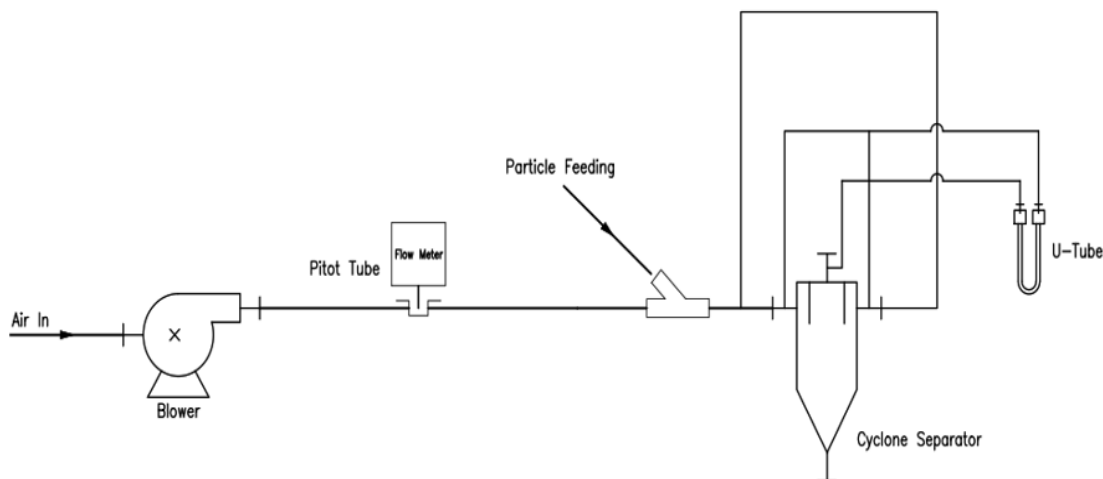


Fig. 2. Schematic diagram of dual inlet cyclone separator

3. Results and Discussion

The performance evaluation was based on the testing and commissioning process. All of the data collected from the testing and commissioning process were observed and noted down for cyclone performance analysis. Density and viscosity of air was based on the temperature. The density and viscosity in this system used based on normal density and viscosity. The particle injected into the system was sand, the injection process using portable sandblasting gun results in particle injected continuously into the system. With the continuously injection process, the flow trajectories and separation process can be observed directly in the cyclone cylindrical body without any delay. Air with density of 1.225 kg/m and viscosity of 1.802×10^{-5} kg/mS.

Table 4

Experimental data

Item	Parameter Name	Variable Value	Unit or Dimension
1	Volumetric Flowrate	0.0552	m ³ /s
2	Velocity	11	m/s
3	Particle Bulk Density	1,600	kg/m ³
4	Particle Injected	300	g
5	Particle Separated	270	g

3.1 Cyclone Performance Analysis

The performance evaluation of the cyclone separator was done theoretically using calculation method and done experimentally in testing and commissioning process. For the testing and commissioning, the cyclone separator system injected with sand particle with the average size of 625

micron. 300 grams of particle injected into the system and 270 grams of particle separated in the cyclone outlet or collection chamber. Geometrical dimension analysis of the lab-scale dual inlet cyclone separator was calculated using the Stairmand high efficiency cyclone dimensionless ratio. Velocity data entering the system was collected using pitot tube and the velocity at inlet and outlet can be calculated using Eqn. 1 and Eqn. 2.



Fig. 3. Weight of particle injected (left) and particle collected on collection tank (right) for the testing and commissioning experiment

From equation 1 to 7 the cyclone performance data can be achieved and calculated. Table 5 shows the lab-scale dual inlet cyclone separator performance data based on the testing and commissioning process. The cyclone performance data was obtained from both theoretically and through the testing and commissioning experiment. Cyclone separator velocity plays a crucial role on separation efficiency. High gas velocity will lead to increasing the amount of particle crashing the wall inside the cyclone chamber and it will increase the separation efficiency of the cyclone separator. The inlet and outlet velocity of the new cyclone separator can be seen influenced by the cyclone geometry itself. From the result below we can see that the outlet velocity dropped extremely.

Table 5
 Cyclone Performance Data

Item	Parameter Name	Variable Value	Unit or Dimension
1	Inlet Velocity	13.8	m/s
2	Outlet Velocity	7.0318	m/s
3	Cut-off Diameter	3	μm
4	Friction Coefficient	0.0031	Dimensionless
5	Contraction Coefficient	0.8231	Dimensionless
6	Pressure Drop	507	kPa
7	Cyclone Separation Efficiency	90	%

3.2 Dimensional Analysis

To achieve equivalent condition for actual size of the lab-scale dual inlet cyclone separator, dimensional analysis or similitude analysis had been performed in order to achieve the actual velocity

at inlet and outlet for the actual size of the cyclone separator. From previous chapter, the equation to determine the velocity for the actual size of cyclone can be seen on Reynolds Numbers (Re) equation.

$$Re = \frac{\rho U_i D_e}{\mu} \tag{8}$$

$$Re_{prototype} = Re_{actual} \tag{9}$$

$$U_{actual} = U_{prototype} \left(\frac{\rho_{actual}}{\rho_{pro}} \right) \left(\frac{D_{pro}}{D_{actual}} \right) \left(\frac{\mu_{pro}}{\mu_{actual}} \right) \tag{10}$$

The lab-scale dual inlet cyclone separator was scaled down into 1:2 ratio. The density and viscosity of air is assumed to be the same in the actual biomass processing industry. There is a secondary inlet that cool down the air before entering the cyclone separator inlet.

Table 6
 Cyclone Performance Data

Cyclone Size	Inlet Velocity	Outlet Velocity	Unit or Dimension
Scaled Down	13.8	7.032	m/s
Actual	27.6	14.06	m/s

This study will relate the relationship between the separation efficiency of the particle in the dual cyclone separator with different size of particle and different inlet velocity. The particle that used during the study are three average particle sizes of silica sand which is 625 μm, 427.5 μm, and 277.5 μm respectively with 200 g of the mass during the particle is injected. The inlet velocity are 9 m/s, 11 m/s, and 13 m/s. The separation efficiency is calculated by determine the amount of the particle injected and the particle that have successfully collected.

3.3 Separation efficiency

In Table 7 are recorded the values obtained by calculating the separation efficiency for experiment that have been executed for three average particle size dimensions which is 625 μm, 427 μm, and 277.5 μm, respectively. Both three experiments repeated for different velocity which is 9 m/s, 11 m/s, and 13 m/s.

Table 7
 Separation efficiency of dual inlet cyclone for 9 m/s, 11 m/s and 13 m/s

Average Particle Size (μm)	Separation Efficiency (%) for 9 m/s	Separation Efficiency (%) for 11 m/s	Separation Efficiency (%) for 13 m/s
625	84.5	92.5	94.5
427.5	77	87	90
277.5	70	83	89.5

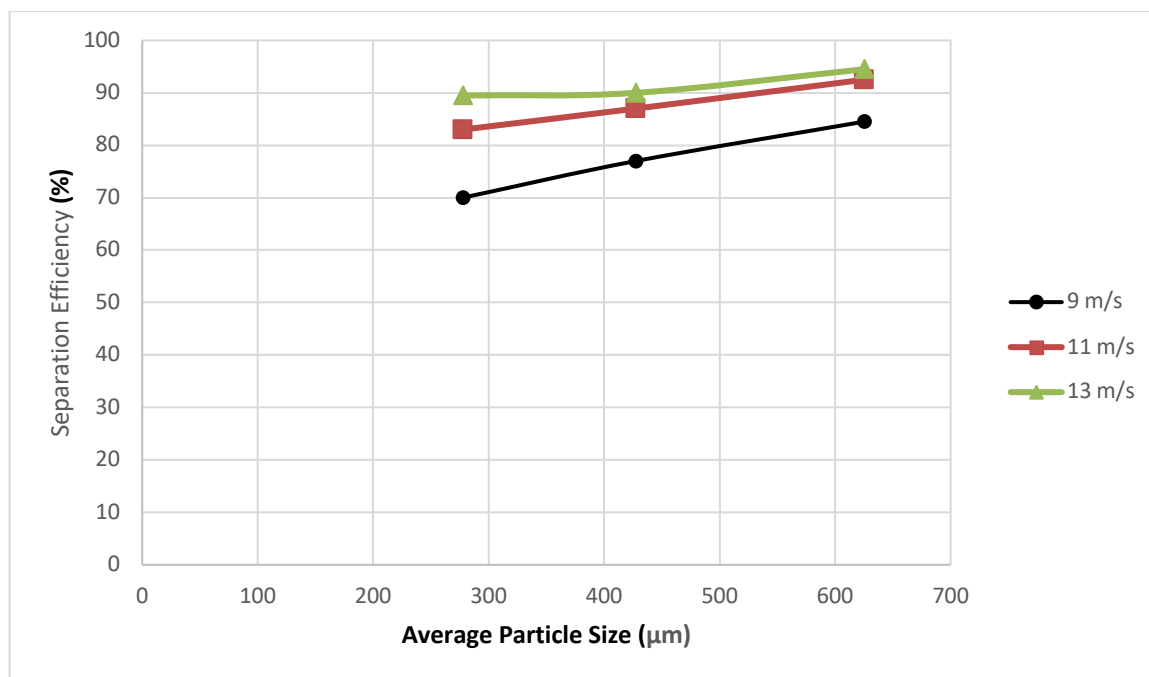


Fig. 4. Variation of average particle size and separation efficiency

Figure 4 shows the separation efficiency at different particle sizes with different velocity at 9, 11 and 13 m/s. The lowest separation efficiency achieved at 9 m/s air velocity with 277.5 µm average particle sizes. The maximum separation efficiency achieved is 89.5 at 13 m/s air velocity. Results show that separation efficiency increases as the particle sizes increases. This prove that the high separation efficiency cyclone separator depends on the size of the particles and the inlet velocity.

The separation ability of the cyclone separators are found to be related to inlet velocity. Besides that, the rebound velocity of particles is also significant. At low inlet velocity, the rebound speed of articles thrown to the wall is low, and few particles rebound into swirl escape. As the velocity increases, the separation increases as the influence of rebound particles also greatly improved [35].

4. Conclusions

In conclusion, this project managed to obtain high separation efficiency of the dual inlet cyclone separator from various particle size are achieved successfully. The dual inlet cyclone separator exceeds 80% of the separation efficiency from the various average particle size from 277.5 µm to 625 µm. This shows that the dual inlet cyclone separator able to separate the particles from the air with a positive result in terms of separation efficiency.

The highest separation efficiency in the experimental of the dual inlet cyclone separator is 92.5% with the particle size 625 µm. For the particle size of 427.5 µm, it obtained 87% of separation efficiency while the particle size of 277.5 µm it obtained 83% of separation efficiency. This shows that the higher the average particle size, the higher the separation efficiency. When the average particle size is bigger, the easier for the solid particle to thrown to the wall of the cyclone separator and it will lose energy and fall moving under the collection tank. With the help of the downward spiral of the air flow inside the dual inlet cyclone separator, bigger solid particle will be easier be separated due to the circulation effect.

The velocity also plays a crucial role to obtain a high efficiency cyclone separator. For the dual inlet cyclone to obtain the high separation efficiency, the velocity for this experimental are 9 m/s, 11 m/s, and 13 m/s. This can be observed as the velocity acquired able to achieve a high separation efficiency for the dual inlet cyclone separator which is exceed 80%. The higher the gas inlet velocity, the efficiency will be more accurate. However, if the velocity is too high, it would decrease the separation efficiency because of the increased in turbulence or particles.

Besides that, pressure drop will affect the separation efficiency and the energy efficiency. The pressure drop is occurred because of the wall friction, area changes, and the dissipation in the vortex finder. Excessive pressure drop will cause in poor cyclone separator performance for separation efficiency and excessive energy consumption. From this study, the larger the average size of particle, the higher separation efficiency and the energy used in the system.

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