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Experimental Study on the Relation between the Energy Efficiency and Pressure Drop of Dual Inlet Cyclone Separator in Processing Indoor Farming Biomass Waste

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ABSTRACT

The cyclone separator is a device commonly used to separate particles from air, gas, or liquid streams. The addition of a secondary inlet is aimed at enhancing separation efficiency and productivity. This study aimed to investigate the relationship between energy efficiency and pressure drop in dual inlet cyclone separators. The cyclone separator was intended to be used in processing biomass waste from indoor farming. The experiment was conducted by varying the input velocity of the system and injecting sand particles into the cyclone separator. The results showed that energy efficiency is positively correlated with average particle size and negatively correlated with pressure drop and velocity. The highest energy efficiency was observed when using particles with a size of 624μm and an input velocity of 9 m/s. These findings suggest that optimizing particle size can lead to reduced energy usage and operational costs while minimizing environmental pollution. The present study provides a comprehensive understanding of the relationship between energy usage and efficiency in a cyclone separator, which can help industries improve their performance.

1. Introduction

Cyclone separators are widely used in various industries for separating solid particles from gases or liquids. The effectiveness of the cyclone separator in removing particulate matter depends on several factors, including its design, dimensions, particle size, and operating conditions. Two crucial parameters that significantly affect the performance of cyclone separators are energy efficiency and pressure drop.

Energy efficiency is a measure of the amount of energy required to operate the cyclone separator effectively. A high energy-efficient cyclone separator can reduce the energy consumption of the

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process and lower the overall operating costs. According to a study by Zhang *et al.,* [1], improving the energy efficiency of cyclone separators is crucial to enhance the sustainability of the process.

Pressure drop is the difference in pressure between the inlet and outlet of the cyclone separator. A low-pressure drop cyclone separator can reduce the energy consumption of the process and improve overall efficiency. However, a high-pressure drop can lead to increased energy consumption and reduced performance of the cyclone separator. According to a study by Xiong *et al.,* [2], pressure drop is a crucial parameter affecting cyclone separators' separation efficiency.

Several studies have investigated the relationship between energy efficiency, pressure drop, and separation efficiency of cyclone separators. For example, Zhang *et al.,* [3] conducted an experimental study to evaluate the effects of various parameters, including energy efficiency and pressure drop, on the separation efficiency of a cyclone separator. The results showed that optimizing these parameters could significantly improve the performance of the cyclone separator.

The design parameters of cyclone separators include dimensions, inlet velocity, particle size, and vortex finder length. The diameter of the cyclone separator and the length of the cone are crucial parameters that affect the separation efficiency. A smaller diameter and a longer cone length can increase the centrifugal force, leading to more effective separation [4]. Inlet velocity is another important parameter that influences the performance of cyclone separators. High inlet velocities can increase the centrifugal force and enhance the separation efficiency, but they also increase the pressure drop [5]. The particle size is also a significant factor that affects the separation efficiency. Smaller particles require higher centrifugal forces for effective separation, which can be achieved by increasing the inlet velocity or reducing the diameter of the cyclone separator [6]. The vortex finder length is another design parameter that influences the separation efficiency. A longer vortex finder can reduce the bypass of particles and improve the separation efficiency [7].

Numerous factors affect the performance of cyclone separators, including particle density, shape, and concentration, as well as the viscosity and temperature of the fluid [8]. The particle density is a crucial factor that affects the separation efficiency, as it determines the gravitational and centrifugal forces acting on the particles. The shape of the particles also influences the separation efficiency, as irregularly shaped particles can be more difficult to separate than spherical particles. The concentration of particles is another factor that affects the performance of cyclone separators, as higher concentrations can lead to blockage and reduced separation efficiency. The viscosity and temperature of the fluid also influence the performance of cyclone separators. Higher viscosities can reduce the separation efficiency, while higher temperatures can increase the pressure drop [9].

The optimization of cyclone separators to improve their performance has been investigated in several studies. Demir [10] studied the effect of pressure drop on the separation efficiency of cyclone separators and proposed a new model to predict the pressure drop. Other studies have focused on the effect of different design parameters, such as cone length, inlet velocity, and vortex finder length, on the performance of cyclone separators [4,5,7].

In addition to the studies mentioned, several other papers have investigated the relationship between pressure drop, energy efficiency, and separation efficiency of cyclone separators. Ji *et al.,* [11] conducted experiments and simulations to investigate the effect of inlet velocity and particle size on the performance of a cyclone separator. They found that an increase in inlet velocity led to higher separation efficiency but also increased pressure drop and reduced energy efficiency. They also observed that the effect of particle size on the performance of the separator was more significant at lower inlet velocities. Brar *et al.,* [12] studied the effect of cone length and inlet velocity on the performance of a cyclone separator. increasing the cone length by up to 6.5 times the cyclone diameter shows nearly a 29% reduction in the pressure loss and about an 11% increase in collection efficiency. They also observed that increasing the inlet velocity led to higher separation efficiency but also increased pressure drop and reduced energy efficiency and that the effect of inlet velocity was more significant for shorter cones. Raoufi *et al.,* [13] investigated the effect of vortex finder length on the performance of a cyclone separator. They found that increasing the vortex finder length led to higher separation efficiency but also increased pressure drop and reduced energy efficiency. They also observed that the effect of vortex finder length on the performance of the separator was more significant at higher inlet velocities. Fatahian's *et al.,* [14] results demonstrate that using a convergent vortex finder improves the square cyclone's separation efficiency while producing an increase in pressure drop.

Movafaghian's *et al.,* [15] investigation looked at the advantages of using two intake cyclones rather than one to improve the hydrodynamics of the flow. According to their findings, a cyclone with two inlets performs better than a traditional cyclone. To ascertain the impact of the dual intake on the separation effectiveness of reversed flow cyclone separators, Baharuddin *et al.,* [16] undertook an experimental investigation. Three particle sizes were used in the experiments: 277.5, 42.5, and 625 µm at inlet velocities of 9, 11, and 13m/s. The primary source for designing the lab-scale dual inlet cyclone separator was Stairmand's high-efficiency cyclone separator dimensionless ratio. With a particle size of 625 µm, the experimental dual inlet cyclone separator has the highest separation efficiency at 92.5%. It achieved 87% separation efficiency for 18 particles with a diameter of 427.5 µm and 83% separation efficiency for those with a diameter of 277.5µm. This demonstrates that separation efficiency increases as average particle size increases.

Although dual inlet cyclones were studied by Malahayati *et al.,* [18], focusing on particle separation efficiency for different inlet velocities of 9, 11, and 13m/s, the energy efficiency and pressure drop were not investigated by the authors. In the present study, the study was extended via numerical study with the same experimental parameters to observe the relation between energy efficiency and pressure drop in dual inlet cyclones. This type of cyclone separator is intended to be used in processing biomass waste from indoor farming, particularly the dried roots which have the potential to be used as bio-composite. By improving the cyclone's energy efficiency and reducing pressure drop, industries can reduce operational costs as well as minimize environmental pollution.

1.2 Research Question

The study on the dual inlet cyclone separator intended to observe the effect of inlet velocities and particle sizes on the cyclone's separation and energy efficiency. Hence, our main research question is; how do different air inlet velocities carrying different sizes of particles will affect the performance of a dual inlet cyclone in terms of separation efficiency and energy efficiency?

1.3 Research Objectives

In this experimental study, we aim to investigate the effects of energy efficiency and pressure drop on the separation efficiency of a cyclone separator. We will vary the operating conditions and cyclone design to determine the optimal parameters for achieving high separation efficiency and low energy consumption. The results of this study will contribute to the development of more efficient and sustainable cyclone separators for industrial applications. Hence, our studies objectives are as follows

i. To investigate the effect of particle size on the energy efficiency of a lab-scale dual inlet cyclone, by varying the average particle size and measuring the flow rate and pressure drop across the system.

ii. To determine the optimal inlet velocity for maximizing energy efficiency in a dual inlet cyclone, by comparing the separation efficiency and pressure drop at inlet velocities of 9m/s, 11m/s, and 13m/s.

2. Methodology

There are various shapes and configurations of cyclone separators. The most commonly used type is the reversed flow cyclone, which has a cylindrical body with a cone underneath and a tangential entrance. The design of the Stairmand high-efficiency cyclone separator, which has a dimensionless ratio, has been used as a reference for designing lab-scale dual inlet cyclone separators (refer to Figure 1 and Table 1).

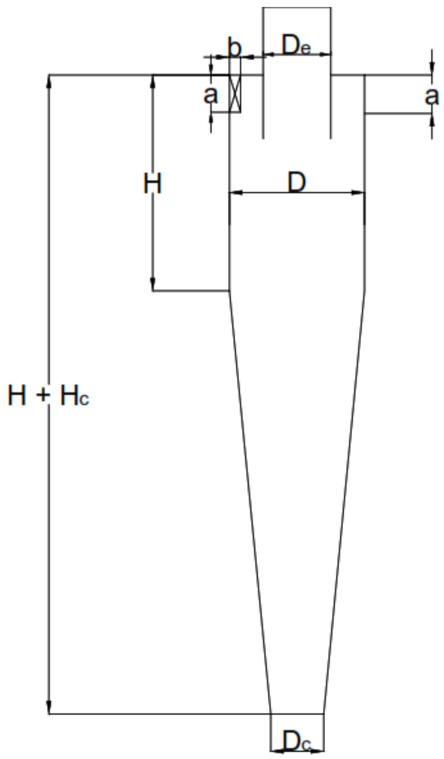

Fig. 1. Schematic of cyclone separator structure

Table 1
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 Stairmand cyclone separator was developed by Stairmand [17] in the 1950s. It is a type of centrifugal separator that is widely used in industries for the separation of particles from gas streams. The Stairmand cyclone has a simple design consisting of a cylindrical vessel with a conical bottom and a tangential inlet near the top. When the gas stream is introduced tangentially, it creates a vortex within the vessel, which causes the heavier particles to migrate toward the wall of the vessel and eventually settle into the conical bottom [18].

Several studies have shown that the Stairmand cyclone can achieve separation efficiencies of up to 99% for particles with a diameter of 5 microns or greater [19]. The separation efficiency depends on various factors such as the inlet velocity, particle size, and cyclone dimensions.

One of the advantages of the Stairmand cyclone separator is its compact size, which makes it suitable for applications where space is limited. It is also relatively low-cost and easy to maintain compared to other particle separation technologies such as bag filters or electrostatic precipitators [20].

The geometry and dimension of the dual inlet cyclone separator are shown in Table 1, respectively. The dual inlet cyclone separator is the lab scale of 1:2 from the actual so that the actual dual inlet cyclone separator can be based on the results from it to obtain similar results of the separation efficiency. The structural diameter for the dual inlet cyclone separator includes cylinder diameter, which is 200 mm, both inlet heights of 100 mm, both inlet widths of 40 mm, and the vortex finder diameter of 100 mm. The extension of the vortex finder inside the cyclone is 100 mm.

2.1 Particle Properties

The performance of a cyclone separator is strongly influenced by the properties of the particles being separated. In this experiment, the solid particle used for separation is quartz sand, which has a density of 1600 kg/m^3. The quartz sand particles have an average size of 625 µm, 427.5 µm, and 277.5 µm, respectively.

Particle size is an important parameter that affects the separation efficiency of cyclone separators. Larger particles tend to be more difficult to separate due to their higher inertia, while smaller particles are more easily carried away by the fluid flow [21]. In this experiment, the range of particle sizes used allows for a comprehensive investigation of the effect of particle size on the separation efficiency of the cyclone separator.

In addition to particle size, the density of the particles is also an important factor that affects the performance of the cyclone separator. The density difference between the solid particles and the fluid flow is what drives the particles to the outer wall of the cyclone and ultimately separates them from the fluid flow. Therefore, particles with a higher density are easier to separate than those with a lower density [22]. The use of quartz sand in this experiment also allows for a comparison of the separation efficiency of the cyclone separator with previous studies that have used similar particles. For example, Padhi *et al.,* [22] used quartz sand with an average particle size of 300 µm to investigate the effect of particle concentration on the separation efficiency of a cyclone separator. Their results showed that the separation efficiency decreased as the particle concentration increased, which highlights the importance of particle properties in cyclone separator performance. Therefore, by using quartz sand particles with different sizes and densities, this experiment aims to investigate the effects of particle properties on the separation efficiency of the cyclone separator.

2.2 Experimental Method

The experimental setup, as shown in Figure 2, consisted of an air blower that forced air into the main piping system leading to the inlet of the dual inlet cyclone separator. The airflow was measured using a pitot tube connected to a digital airflow meter before entering the cyclone. To control the air velocity, a voltage regulator was connected to the blower, allowing for three different velocities to be tested: 9 m/s, 11 m/s, and 13 m/s. During the experiment, the pressure drop was recorded using a U-tube that was connected to a digital manometer. This allowed for accurate measurement of the pressure drop across the cyclone separator, a crucial parameter in assessing the energy efficiency of the system.

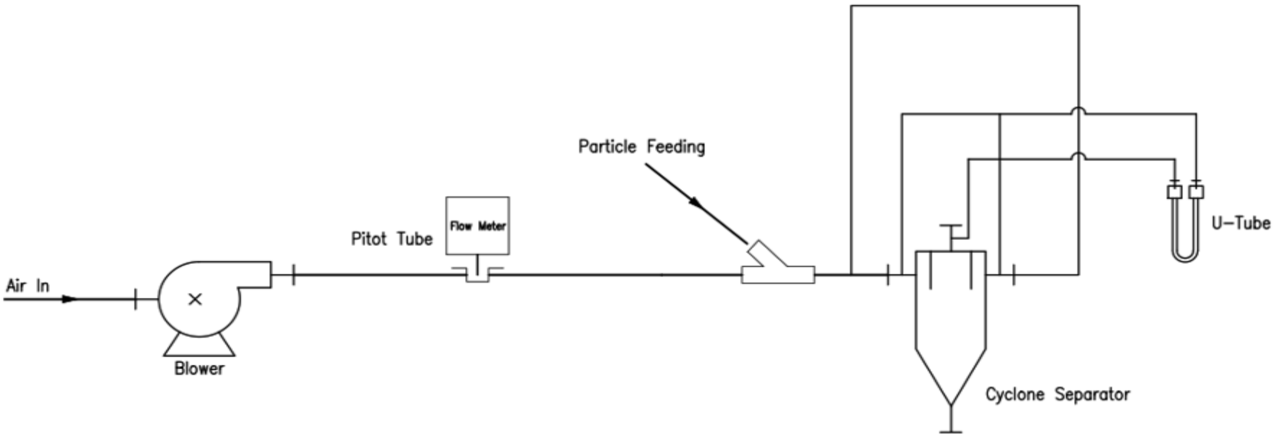

Fig. 2. Schematic diagram of dual inlet cyclone separator

The experimental setup shown in Figure 3 consists of a 3-inch UPVC pipe that is 4 feet long, connected to a blower flange output. The pipe is synchronized with UPVC fittings, sockets, and joints, which are made of the same material as the pipe, as specified in the methodology. To connect the blower pipe to the inlet of the cyclone separator, a socket was fabricated by deforming a 3-inch pipe using heat. The socket was deformed into a cyclone inlet rectangle with an inlet size of 40mm × 100mm. A flexible 4-inch exhaust ducting was used to connect the blower pipe to both inlets of the dual inlet cyclone separator. This setup is designed to study the performance of the cyclone separator in separating particles from the air stream. The use of UPVC fittings, socket, and joint ensures that the material properties are consistent throughout the setup, which is important for accurate experimental results.

Fig. 3. Experimental setup

2.3 Energy Efficiency

To calculate the Potential Energy Recovered, we can use the following formula

The cross-sectional area of the pipe is calculated using Eq. (1).

$$A = \frac{\pi}{4} d^2 \tag{1}$$

The flow rate of the pipe is calculated using Eq. (2).

$$Flow\ Rate, Q = V \times A \tag{2}$$

where
V = Velocity
A = Cross-sectional Area

The energy required for the dual inlet cyclone separator is calculated using the Eq. (3).

$$W = Q \times \Delta P \tag{3}$$

where
W= Energy Required
Q = Flow rate of the Pipe

The proposed energy efficiency criteria of a cyclone separator is

Energy Efficiency = $(\frac{\text{Potential Energy Recovered}}{\text{Input Energy } (Q \times \Delta P)})$ x 100%

where

i. Potential Energy Recovered is the amount of energy that is recovered from the separated material or particles. This is usually calculated based on the mass of the separated material and its specific heat capacity.
ii. Input Energy is the total amount of energy that is required to operate the cyclone separator, including the energy required to power the fan or blower that drives the airflow, as well as any other energy inputs such as electricity or fuel.

Potential Energy Recovered = $(\frac{\text{Mass of Separated Material x Specific Heat Capacity x Temperature Change}}{\text{Time}})$

where

i. Mass of Separated Material is the mass of the material or particles that are separated by the cyclone separator.
ii. Specific Heat Capacity is the amount of energy required to raise the temperature of the separated material by one degree Celsius.

iii. Temperature Change is the difference in temperature between the incoming material and the separated material.
iv. Time is the duration of the separation process.
v. Once we have calculated the Potential Energy Recovered and the Input Energy, we can plug these values into the first formula to determine the Energy Efficiency of the cyclone separator.

2.4 Pressure Drop

For the dual inlet cyclone separator to be able to separate the particle, it required a blower to supply the air to flow into the inlet. Throughout the process, it will generate a pressure drop which is one of the important aspects of the performance of the dual inlet cyclone separator. The pressure drop will mainly be caused by the friction of the fluid or the air and the wall along with the internal vortex flow. The pressure drop can be determined by using the digital manometer as in Figure 4 along with U-tube. One of the connections from the U-tube will be connected to the inlet of the dual inlet cyclone separator and another connection will be connected to the outlet.

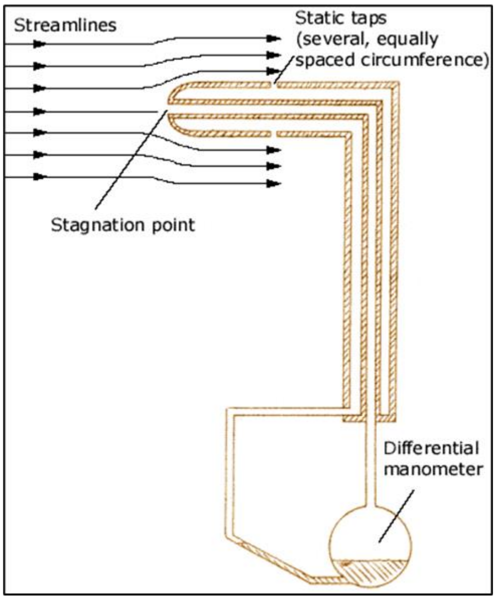

Fig. 4. Working mechanism of pitot tube

Here are the steps to measure the pressure drop

i. Install the pressure gauge or manometer: Install the pressure gauge or manometer at a suitable location on the cyclone separator, preferably on the inlet and outlet sides of the cyclone.
ii. Close the inlet and outlet valves: Close the inlet and outlet valves of the cyclone separator to isolate it from the system.
iii. Turn on the blower: Turn on the blower or fan that drives the airflow through the cyclone separator.
iv. Record the readings: Record the readings on the pressure gauge or manometer. The pressure drop can be calculated by subtracting the outlet pressure from the inlet pressure.
v. Open the outlet valve: Open the outlet valve of the cyclone separator to release the trapped air or gas.

vi. Repeat the measurement: Repeat the measurement process several times to obtain accurate readings.
vii. It is important to note that the pressure drop of a cyclone separator can be affected by various factors such as the size and shape of the cyclone, the velocity of the inlet gas, and the amount and size of the particles being separated.

3. Results and Discussion

The evaluation of the cyclone's performance was conducted through testing and commissioning. Throughout this process, all relevant data was gathered and recorded to enable an analysis of the cyclone's performance. The density and viscosity of air were determined based on the temperature of the system, and normal density and viscosity values were used in calculations. The sand was chosen as the particle for injection into the system, which was achieved through the use of a portable sandblasting gun. This injection process allowed for a continuous flow of particles into the system, providing the opportunity to observe the flow trajectories and separation process directly within the cylindrical body of the cyclone without any delay. The air density in the system was determined to be 1.225 kg/m, with a viscosity of 1.802 ×10-5 kg/ms.

The pressure drop was determined by using U-tubes in conjunction with a digital manometer. At a velocity of 11 m/s, the resulting pressure drop is 470 N/m^2. The energy efficiency is then evaluated as the percentage of separation efficiency per kW of energy usage. Additionally, a flow rate of 0.02 m^3/s is obtained. Figure 4 illustrates how the U-tube can be connected to the digital manometer to obtain the pressure drop. Finally, the amount of energy required by the dual inlet cyclone separator is calculated.

The experiment data in Table 2, shows the relationship between input velocity, average particle size, pressure drop, energy usage, separation efficiency, and energy efficiency in a cyclone separator.

Table 2
Pressure drop and the energy efficiency

Velocity (m/s)	Pressure Drop (N/m^2)	Average Particle Size (µm)	Energy Efficiency
13	663	625	0.0141
		427.5	0.0134
		277.5	0.0132
11	470	625	0.0229
		427.5	0.0216
		277.5	0.0206
9	268	625	0.0449
		427.5	0.0409
		277.5	0.0372

At an input velocity of 13 m/s, the pressure drop is 663 N/m^2, and the energy used is 67.228 watts. The highest energy efficiency of 94.5% is achieved at an average particle size of 625 µm, which corresponds to the best separation efficiency. However, as the average particle size decreases, the energy efficiency drops, meaning that the same amount of energy is used to separate fewer particles. For example, at an average particle size of 427.5 µm, a separation efficiency of 90% can be achieved while still using the same energy of 67.228 watts. The lowest energy efficiency of 0.207 is observed at an average particle size of 277.5 µm.

At an input velocity of 11 m/s, the pressure drop is 470 N/m^2, and the energy used is 40.326 watts. Here, the energy efficiency increases with an increase in average particle size, with values of

0.0229, 0.0216, and 0.0206 observed for average particle sizes of 625 µm, 427.5 µm, and 277.5 µm, respectively.

Similarly, at an input velocity of 9 m/s, the pressure drop is 268 N/m^2, and the energy used is 18.8136 watts. Here, the energy efficiency also increases with an increase in average particle size, with values of 0.0449, 0.0409, and 0.0372 observed for average particle sizes of 625 µm, 427.5 µm, and 277.5 µm, respectively.

The data presented in Figure 5 demonstrates that energy efficiency is positively correlated with average particle size, indicating that larger particles lead to optimized energy usage. Conversely, energy efficiency decreases as pressure drop and velocity increase, as depicted in the graph. Notably, the energy efficiency is at its minimum when the input velocity is 13 m/s, whereas the separation efficiency is at its peak. Additionally, the highest energy efficiency is recorded when using particles with a size of 624 µm and an input velocity of 9 m/s.

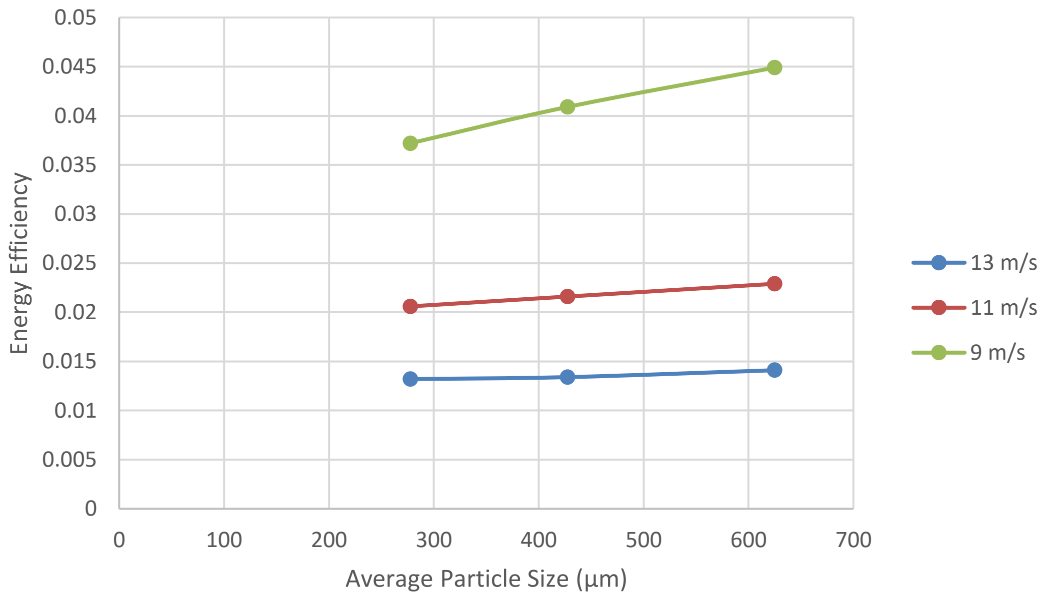

Fig. 5. Effect of average particle size and energy efficiency

While the previous study by Baharuddin *et al.,* [16], examined the separation efficiency of a cyclone separator based on particle size and velocity, the present study provides additional insights into the relationship between energy usage and efficiency. By including energy efficiency as a parameter, the new study offers a more comprehensive understanding of how to optimize the performance of a cyclone separator. It has been found that larger particle sizes lead to optimized energy usage, and energy efficiency decreases with an increase in pressure drop and velocity. Furthermore, it has been demonstrated that the energy efficiency is lowest at an input velocity of 13 m/s, whereas the separation efficiency is highest. These findings are critical for industries that rely on cyclone separators, as optimizing energy usage can lead to significant cost savings and reduce the environmental impact of the process. Therefore, the new study's focus on energy efficiency is particularly important and provides valuable insights for improving the performance of cyclone separators.

Overall, the results suggest that the cyclone separator's performance can be optimized by adjusting the input velocity, average particle size, and other parameters to achieve the desired separation efficiency while minimizing energy usage.

4. Conclusion

Cyclone separators are used to remove solid particles from gases or liquids in various industries. The effectiveness of cyclone separators depends on their design, dimensions, particle size, and operating conditions. Energy efficiency and pressure drop are two critical parameters that significantly affect the performance of cyclone separators. Energy efficiency is a measure of the energy required to operate the cyclone separator effectively, while pressure drop is the difference in pressure between the inlet and outlet of the separator. A high-energy-efficient cyclone separator can reduce energy consumption and operating costs, while a low-pressure drop separator can improve efficiency. Particle density, shape, concentration, fluid viscosity, and temperature are other factors affecting performance. Several studies have investigated the optimization of cyclone separators to improve their performance, including the effect of different design parameters, inlet velocity, vortex finder length, and cone length.

This paper establishes a correlation between particle size, energy efficiency, and pressure drop in cyclones. The goal was to enhance the cyclones' energy efficiency and decrease pressure drop to achieve better separation efficiency, which leads to higher product quality and lower environmental pollution in industries. The findings are followings

i. The highest energy efficiency of 94.5% is achieved at an average particle size of 625 µm, which corresponds to the best separation efficiency.
ii. Energy efficiency increases with an increase in average particle size, with values of 0.0229, 0.0216, and 0.0206 observed for average particle sizes of 625 µm, 427.5 µm, and 277.5 µm, respectively, at an input velocity of 11 m/s.
iii. Energy efficiency also increases with an increase in average particle size, with values of 0.0449, 0.0409, and 0.0372 observed for average particle sizes of 625 µm, 427.5 µm, and 277.5 µm, respectively, at an input velocity of 9 m/s.
iv. The lowest energy efficiency of 0.207 is observed at an average particle size of 277.5 µm, at an input velocity of 13 m/s.
v. Energy efficiency decreases with an increase in pressure drop and velocity.
vi. Energy usage is optimized for larger particle sizes.

Adjusting input velocity, average particle size, and other parameters can optimize the cyclone separator's performance to achieve the desired separation efficiency while minimizing energy usage.

The upcoming research on the dual inlet cyclone separator can be improved by addressing several issues. To improve data accuracy, more parameters can be included, and the graph can be made more varied to facilitate comparison. The following recommendations are suggested for better results

i. Vary the velocity for each average particle size by testing at two or three different velocities, as different velocities can result in different pressure drops.
ii. Use pipes with similar sizes for all connections to avoid pressure losses caused by varying pipe sizes.
iii. Vary the types of particles used to explore the relationship between particle density and separation efficiency.

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