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ABSTRACT

The objective of this study is to develop a particle collector by using a micro gas cyclone with a body diameter of 10 mm. Design and performance of a cyclone separator is determined by collection efficiency and pressure drop. The behavior of a rectangular inlet-type cyclone for relatively high solid loading rates is reported in this study. For different solid loading flow rates varying from 11.7 to 16.7 liter per min, pressure drop and collection coefficient were evaluated through simulation and experimental work. The experimental part of this study was conducted using Snifter MA+ device. Since the Snifter MA+ is designed to handle flows which are approximated by laminar conditions and the flow regime within the cyclone is mostly turbulent, in order to achieve a suitable performance, the flow in the cyclone should be controlled to be close to laminar conditions. Given these circumstances, the highest cyclone efficiency was recorded for the lowest flow rate and in turbulent condition. The obtained efficiency shows that the cyclone has a reliable performance. As flow rate decreases, pressure drop reduces as well. In order to investigate the pressure drop behavior, velocity and flow trajectories for different flow rates, SOLIDWORKS software, which is applied for drawing and also for simulation was utilized to simulate the model. The simulation results show that by increasing the flow rate, pressure drop also increases.

Keywords: cyclone separator, PM2.5, pressure drop, overall collection efficiency, and dust collection.
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Introduction

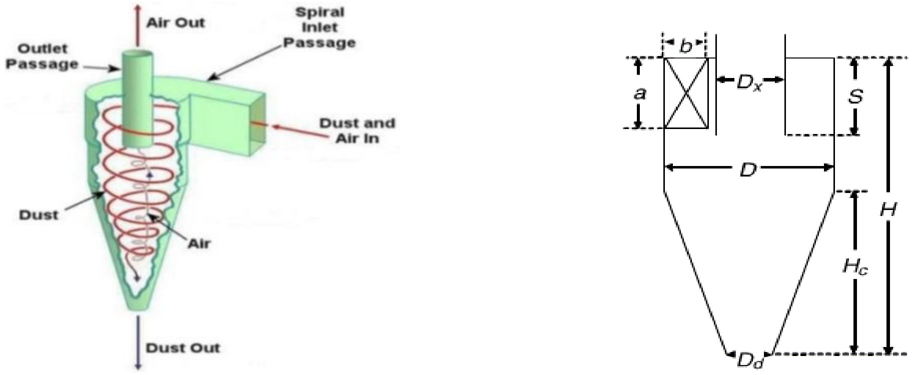
Firstly, the transition from traditional society to modern society is an issue that Particulate matter (PM) is considered to be the most harmful pollutant in the air. It consists of carcinogenic compounds such as PAH (polynuclear aromatic hydrocarbons), nitro-PAH, and sulfates, which can easily enter the human respiratory system (Kittelson, 1998; Oh et al., 2002). Cyclone is introduced as one of the oldest equipment to collect the particulate matter. Since the late 19th century, the cyclone's popularity as an efficient and cost-effective device to separate solids from an air flow is still considerable (Hoffmann and Stein, 2002). Over the years, researches developed various models that apply experimental data in relevant to the geometry and operating conditions of specific cyclone designs. These models are considered to estimate cyclone collection efficiency. Leith (1984) summarized some of these models. His study included models by Stairmand (1951), Barth (1956), Lapple (1951) and Leith and Licht (1972). Ogawa (1984) reviewed and studied as well a number of predictive models including Lapple and Shepherd (1940), Barth (1956) and Stairmand (1951) (Kegg, 2008). Their simple design, easily fabricable, low capital cost, maintenance and energy consumption are their primary advantages (Qiu, Deng and Kim, 2012, Haig, Hursthouse, Mcilwaina and Sykes, 2015). Swirl and turbulence are the two competing phenomena in the separation process: the swirl induces a centrifugal force on the solids phase which is the driving force behind the separation. On the other hands, they employ centrifugal force due to the spinning gas stream to separate the particular matter from the carrier gas (Krishna, Rao and Singh, 2006). It is because of its high particle loading capacity and relatively low pressure drop. Turbulence disperses the solid particles and enhances the probability that particles get caught in the exit stream. Both phenomena are related to the particle size, and the flow conditions in the cyclone (Hoekstra, Derksen, Akker, 1999). Classification of cyclone separators is according to their body shape, inlet configuration, and inlet/outlet flow direction. Most common cyclone separators are revered flow type that consists of inlet, cylindrical and conical parts (Kim, Jahan and Kabir, 2013). Although a cyclone separator has been extensively and effectively applied for gas-particle separation in different fields like aerosol/particle science technology, pulp and paper plants, cement plants, steel mills, petroleum coke plants, metallurgical plants, sawmills and other kinds of facilities that process dust, but it has still separation performance issues. It refers to complexity of the flow mixture within the cyclone (Cortés and Gil, 2007; Duquenne, Coulais, Bau and Simon, 2017; Ganegama and Leung, 2016; Hiraiwa, Oshitari, Fukui, Yamamoto and Yoshida, 2013; Mazyan, Ahmadi, Ahmed and Hoorfar, 2017; Siadaty, Kheradmand and Ghadiri, 2017). It is because of three dimensionalities of the flow, the interaction between particles and fluid and walls, fluid and particle properties, design parameters, and operating conditions. Many studies carried out through theoretical, experimental and lately computational fluid dynamic (CFD) simulations to find out the cyclone separators performance. The most important performance variables of cyclone separators are collection efficiency and pressure drop. The reported studies mostly deal with the collection efficiency rather than pressure drop (Karagoz and Avci, 2007). To improve the efficiency of a cyclone, the effect of particle solid loading rate is considered for any type of cyclone design (Utell and Frampton, 2000; WHO, 2013). In this study, it is aimed to develop and to evaluate a PM collector by using a micro gas cyclone with a body diameter of 10mm. This research study is accomplished through two parts and the following steps. The first part is including simulation of the model by using SOLIDWORKS software to determine acceptable pressure drop and see the flow behavior within the cyclone for three different flow rates varying from 11 L/min to 16.7 L/min. Through the second part and an experimental work, by using the Snifter MA+ device, effect of different solid loading flow rates on overall collection efficiencies is being investigated.

Methodology

Design of Prototype Mini Cyclone

As is shown in Figure 1, a cyclone consists of two main parts; an upper cylindrical a lower conical part. In a cyclone separator, the dirty flue gas is fed into the body of the cyclone and creates a spiral vortex (Figure 1b). As the lighter components of the gas have less inertia, therefore it is easier for them to be influenced by the vortex and move upward. And larger components of particulate matter due to their greater inertia respect to lighter particles are not easily influenced by the vortex. Since following the high-speed spiral motion for the larger particles is difficult, the particles hit the inside walls of the container and fall down into a dust collection chamber. The cleaned flue gas escapes out at the top of the cyclone (Wolfson, 2012; Patil, 2015). Lapple model is chosen to design a cyclone for this study. With respect to the cyclone body diameter of 10 millimeters, other parameters are defined. The geometric parameters of cyclone are given in Table 1.

Figure 1. *Sketch of a Reverse- Flow, Cylinder –on-cone with a Tangential Inlet (Mills, 2015)*



a) b)

The geometry of cyclone is determined by eight following dimensions. Body diameter (BD), is the diameter of the cylindrical section. The total height of the cyclone (from roof to dust exit) is introduced by (H). (D_x) is the diameter of the vortex finder. (H_c) is the height of the conical section. Height and width of the inlet are (a) and (b) respectively. (D_d) is the diameter of the dust exit. And (S) is the length of the vortex finder (Extending from the outlet into the body). The geometric parameters of studied cyclone separator are given in Table 1.

Table 1. *Cyclone Dimensions for Lapple Model and Study Model*

Parameters	Model 1: Lapple	Study model (mm)
Body Diameter (BD)	1	10
Vortex Finder Diameter (Dx)	0.5	5
Length of Body ($L1$)	2	20
Length of Cone (Hc)	2	20
Width of inlet (b)	0.25	2.4
Height of inlet (a)	0.5	5
Dust exit Diameter (D_d)	0.25	2.5
Length of Vortex (S)	0.625	6.2

Simulation

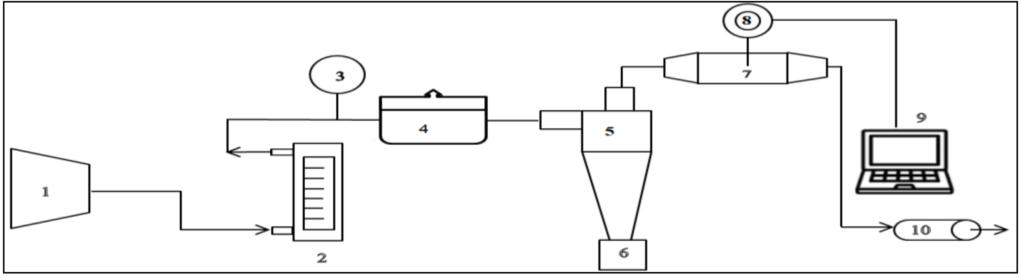
The simulation is performed by using SOLIDWORKS software. The effect of the different solid loading rates on the flow field pattern has been investigated computationally. SOLIDWORKS simulation is able to test and validate designs for a variety of design variables. It can reduce time by saving time and effort in searching for the optimum design. SOLIDWORKS Simulation provides simulation solutions for linear and nonlinear static, frequency, buckling, thermal, fatigue, pressure vessel, drop test, linear and nonlinear dynamics, and optimization analyses (SOLIDWORKS Help, 2018). It is utilized to investigate the pressure drop, velocity behavior and flow trajectories for different flow rates. So for this purpose, two boundary conditions are defined; a velocity inlet boundary condition is assumed at the cyclone inlet and pressure gradient at the gas outlet is defined at atmospheric pressure.

Experimental Work

To better understand the cyclone performance and flow behavior, an experimental system is prepared at a laboratory condition as shown in Figure 2. The experimental work is repeated for three flow rates conditions, 11.67 and

13.33 and 16.67 (L/min). As it was mentioned before, the cyclone of study has a cylindrical body of 10 mm in diameter with a rectangular type of inlet. Air and solid are mixed in the inlet duct and flow into the cyclone tangentially.

Figure 2. (1) *Air Compressor* (2) *Flow Meter* (3) *Manometer* (4) *Dust Feeder* (5) *Gas Cyclone* (6) *Dust Collector* (7) *Gas Outlet* (8) *Snifter MA+* (9) *Dust Tool Software* (10) *Dust Outlet*



An air compressor is applied to force the air into the gas cyclone separator and a flow meter controls the air flow rate. A vibrated dust feeder is producing dust particles that are fed into the cyclone inlet**.** Snifter MA+ is utilized for monitoring dust level in gasses, offers accurate results with minimum maintenance. It is attached to the gas outlet of the cyclone. This small electric device provides the signal that is proportional to the dust level and is monitored by the electronics. Consequently, the generated signals are represented as graphs and through DustTool software. The obtained data is then used to determine the collection efficiency. For this purpose, the data is measured twice (in two steps). The first time is when the cyclone is not in the system, the obtained data is assumed as initial concentration and the second time is when the cyclone is in the system and it is used to collect the dust particles. This concentration is defined as outlet concentration.

Collection Efficiency

The capacity of a cyclone to collect particles is measured by its efficiency (η). It is influenced by the particles size and the input velocity of the gas into the cyclone (Paraschiv and Paraschiv, 2016). Collection efficiency is calculated as the mass or concentration fraction of the feed solids that are captured by the cyclone. Feed, captured (or collected or underflow) and overflow (or emitted or lost) are three particle functions that are defined in the cyclone. The mass flow rates of the three particle functions are represented by the symbols Mf, Mc and Me, respectively. The solids mass balance over the cyclone is defined as the following equation:

$$Mf = Mc + Me \quad (1)$$

And the overall efficiency is calculated through the following equation (2) (Hoffmann and Stein, 2002):

$$\eta = \frac{Mc}{Mf} = 1 - \frac{Me}{Mf} \qquad (2)$$

It can be also rewritten as concentration description, so the new equation is represented as the following formula:

$$\eta = \frac{Cc}{Cf} = 1 - \frac{Ce}{Cf} \qquad (3)$$

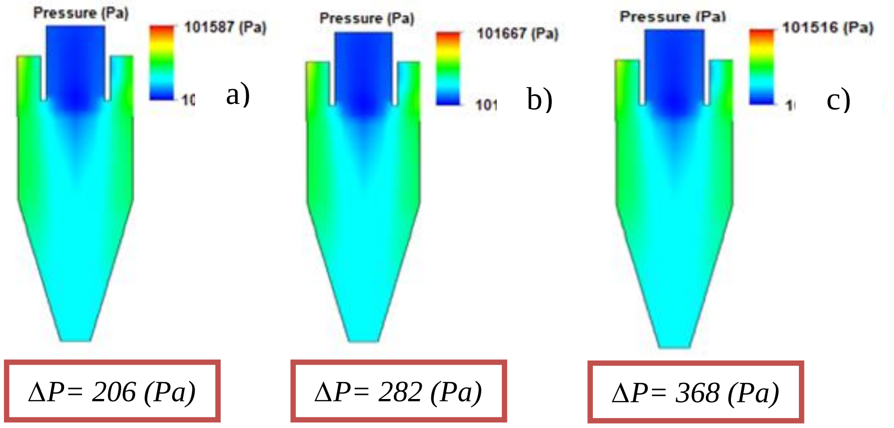
Therefore Cc , Cf and Ce represent the concentration of captured (or collected or underflow), feed and overflow (or emitted or lost) fractions. With obtained values from Snifter MA+ and using the above equations, the overall efficiency is determined.

Results

Simulation Results

One of the important performance variables to design a cyclone is the pressure drop, because it is directly proportional to the required energy (Wang, 2004). The total pressure drop over a cyclone is the sum of losses at the inlet, outlet and within the cyclone (Pandya, 2010). There are Neuromas models such as Shepherd and Lapple (1939), Stairmand (1949, 1951), First (1950) and Barth (1956) that have been developed for cyclone pressure drop determination. The derived pressure drop equations that are considered for either empirical models or involve variables and dimensionless parameters not easily evaluated for practical applications. Cyclone pressure drop depends on various parameters such as cyclone design and its operating parameters such as inlet velocity (Wang, 2004). A good method that can be considered to determine the pressure drop is simulation. In this study for the investigation of pressure drop, velocity behavior and flow trajectories for different flow rates, SOLIDWORKS software is utilized to simulate the model. Figures 3 to 5 show the pressure, velocity contours and flow trajectories for evaluated gas flow rate of 11.67, 13.33 and 16.67 (l/min) respectively.

Figure 3. *Contour of Pressure Obtained for Flow Rates of* a) *11.67* b) *13.33 and* c) *16.67(l/min)*



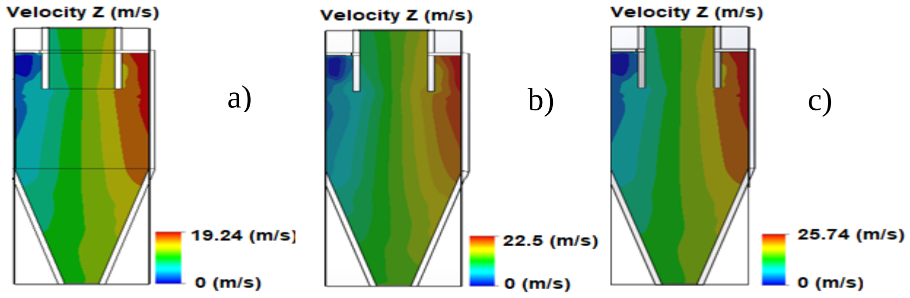
ΔP= 206 (Pa)

ΔP= 282 (Pa)

ΔP= 368 (Pa)

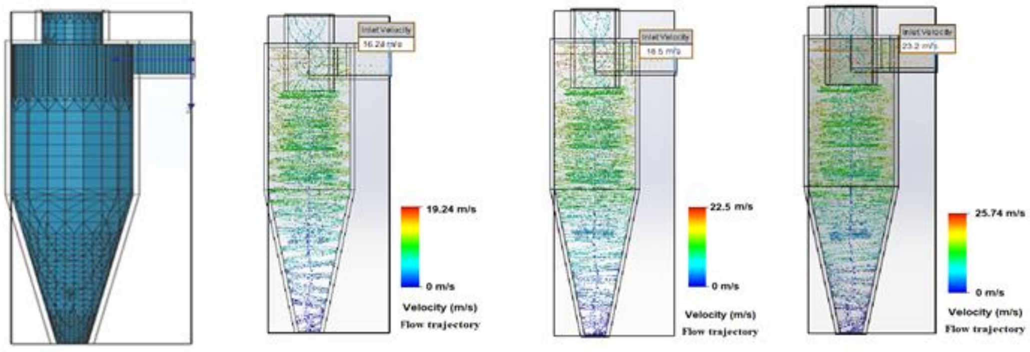
The velocity field in a cyclone has three dimensions at x, y and z axes as radial, axial and tangential velocities. Among the mentioned velocities, tangential velocity has the highest value, It increases to the maximum value at the boundary ($r = D_o/2$) of the outer vortex and inner vortex. In the inner vortex the tangential velocity decreases as the rotational radius decreases (Peng et al., 2002; Hamdya et al., 2017).

Figure 4. *Contour of Velocity Obtained for Flow Rates of* a) *11.67* b) *13.33 and* c) *16.67 (l/min)*



The solid particle movement is caused due to the mass particle and the encountered turbulence of the particle along its trajectory (Wang, Zhang and Wand, 2006). The sample particle trajectories that obtained by gas and particle flow are evaluated for different gas flow rates of 11.67, 13.33 and 16.67 (l/min) at different time steps and are illustrated in the Figure 5.

Figure 5. *Contour of Flow Trajectory Obtained for Flow Rates of* b) *11.67* c) *13.33 and* d) *16.67(l/min)*



a) b) c) d)

Experimental Results

In this study, the experiments are repeated for three different flow rates of 11.67, 13.3 and 16.67 (l/min). Snifter mA+ uses inductive electrical technology that the interaction of particles with the sensor rod causes a small electrical charge to pass between the particulate and sensor. The generated signal by the small electric charge that is represented as a graph is proportional to the dust level even if particles accumulate on the sensor. Since the Snifter MA+ is working at the laminar flow and the flow regime within the cyclone is mostly turbulent, in order to achieve a good performance, the flow in the cyclone is controlled to be close to the laminar conditions. Figures 6 to 8 show the obtained graphs for these mentioned flow rates. Temperature and humidity at the test time are reported between 39 to 40°C and 85-90 respectively. The obtained overall efficiencies for these flow rates are represented in Figure 9 (a), and Figure 9 (b) shows the collected dust in the dust collector chamber.

Figure 6. *Flow Trend at Flow Rate of 16.67 (l/min)*

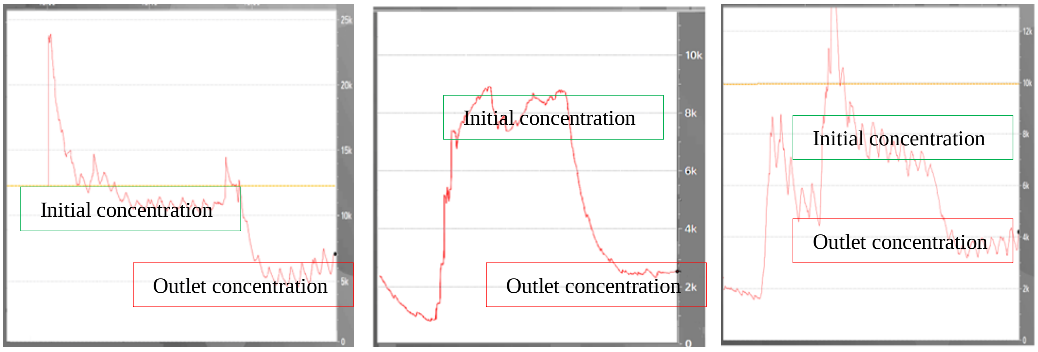


Figure 7. *Flow Trend at Flow Rate of 13.33 (l/min)*

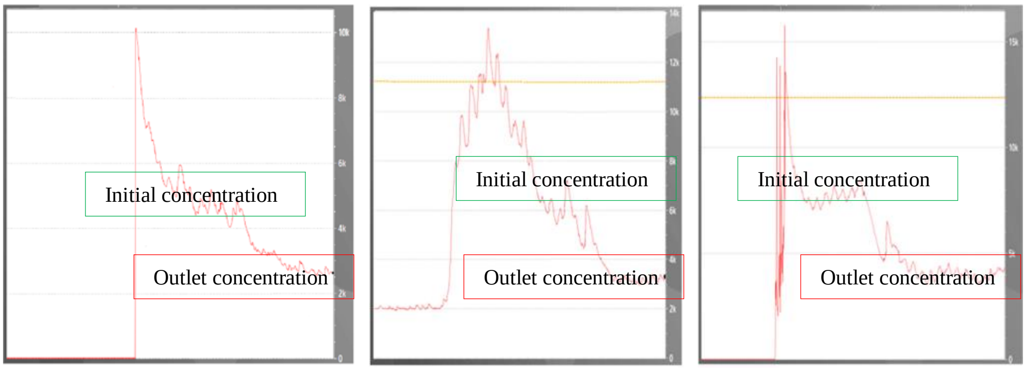


Figure 8. *Flow Trend at Flow Rate of 11.67 (l/min)*

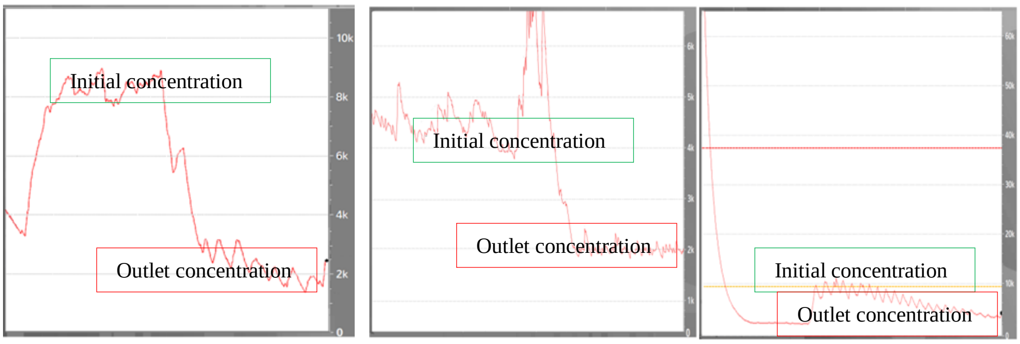
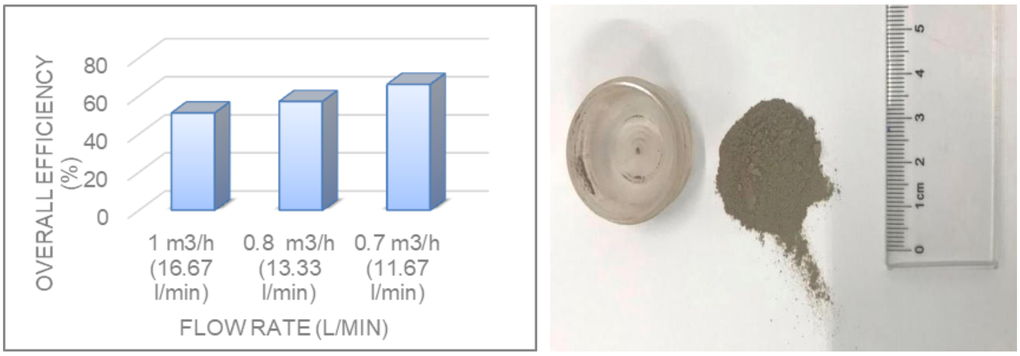


Figure 9. a) *Obtained Overall Efficiencies for the Flow Rates of 11.67, 13.3 and 16.67 (l/min)* b) *Collected Particles by the Cyclone in the Dust Collector Chamber*



a) b)

In addition, the obtained value of pressure drop for each flow rate through a manometer is reported 200 to 400 (Pa).

Discussion

Simulation Results

Pressure Drop

Figure 3 represents that the pressure has the highest value at the wall. Its value decreases radially from the wall to the center and a negative pressure zone appears in the center (Hoffmann and Stein 2002; Wang, Zhang and Wand, 2006). The pressure gradient is the largest along the radial direction, as there is a highly amplified forced vortex. The centrifugal force caused by high-speed rotation of the gas flow is effective to generate a lower or sometimes negative pressure in the center (Shi, Wei and Chen, 2013). In addition by increasing the flow rate, there is also an increase in pressure drop. These values for three flow rates are obtained 206, 283 and 369 Pa respectively.

Velocity Behavior

As mentioned earlier, the velocity field in a cyclone comprises three components: radial, axial and tangential velocities (Peng et al., 2002) and tangential velocity has the highest value among them. Figure 4 shows the variation of tangential velocity at different flow rates. For each flow rate, the value of this velocity equals to zero at the center and increases radially and reaches to maximum value then decreases partially because of the friction of the walls. Tangential velocity increases by increasing the cyclone inlet velocity and also by increasing the radial distance between the inlet and the center core of the cyclone (Hamdya et al., 2017).

Flow Trajectory

Figure 5 shows the flow trajectories of particles inside the cyclone. The main trajectory of the solid particles is near the wall region. The particles with large diameters are collected in the dust collector and the small particles with higher probability escape through the gas outlet.

Experimental Results

It is said that the overall collection efficiency increases with the increment of solid loading. Swirling and centrifugal force are intensified by the increase of the inlet velocity; therefore the number of collected particles will be greater (Sakura and Leung, 2015). Based on the Snifter MA+ function that is working at laminar flow, increasing the inlet velocity causes the adverse effect. In addition due to the micro size of the cyclone, the flow regime within the cyclone is mostly turbulent. Therefore controlling the flow condition close to laminar regime gives the higher efficiency. The generated graphs by DustTool software that are proportional to the dust level at different flow rates are illustrated through the Figures 6 to 8. The green rectangular border on the graph shows the trend of dust behavior when the cyclone is not in the system and is assumed as initial concentration. Red border represents the trend of dust behavior when the cyclone is in the system and it is collecting the dust. It should be mentioned that the part of the graph, which has no significant fluctuation is chosen for efficiency calculation. This section indicates that during this period the dust particles concentration is almost stable. Figure 9 illustrates the obtained overall efficiencies for each flow rates. The approximate overall efficiencies for each flow rates were obtained 51% ±1, 57 ±1 and 66 ± 1 respectively. These results show that decreasing the inlet velocity near to laminar flow yields higher efficiency. Although keep decreasing the flow rate to reach a laminar condition inside the cyclone should give greater efficiency but lowering the flow rate cause to have an accumulation of dust inside the pipes. In this condition, there is no flow of mixed gas to reach the inlet of cyclone. The read values for pressure drops throughout a manometer at these flow rates indicate that there are no significant differences between the values and obtained results from the simulation part.

Conclusions

- Simulation and experimental results represent, as the flow rate increases the pressure drop also increases. No significant differences were observed between the simulation and experimental data.
- The generated graph is proportional to the dust level at different flow rates.
- Since the Snifter MA+ is working at the laminar flow and the flow regime inside the cyclone is mostly turbulent, in order to achieve a good performance, the flow in the cyclone is controlled to be close to laminar conditions.
- Although it is said by increasing the flow rate overall efficiency is also increasing but due to the performance of Snifter MA+ that is working at laminar flow, lower flow rate yields better efficiency.
- These obtained efficiencies are also affected by high humidity due to presence of water droplets in tubes.
- The obtained pressure values by simulation and experimental study are not significant.
- Regarding the obtained results, it can be suggested to use this micro cyclone in indoor places for small particles collection.

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