Design and Testing of a Prototype Cyclone Separation System for Woodwaste Combustion

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ABSTRACT

The reduction of fine particulate emissions from woodwaste fuel-driven-boilers is one of the most challenging problems associated with the exhaust pollution control. A most common and cheaper air pollution control equipment is a cyclone separator (CS) but they have limitations for fine particulates. This paper presents an improved cyclone separation system for controlling particulate matters (PM) through an aggregation chamber (AC) located upstream of the CS. A spray of water (mists) is simultaneously and continuously jet to the stream of dust-laden flue gases thus enhancing the size of fine particles. The mixing of mists and flue gases in the AC can lead to the build-up and growth of clusters with sizes easily captured in CS by inertial methods. An extensive matrix has been used to test three sampling locations and three nozzle orientations over three flue gas velocities. A total of 28 samples have been collected and its particle size distribution and the elemental composition are all investigated using Scanning Electron Microscopy and Energy Dispersive X-ray spectroscopy (SEM-EDX). Results showed that sampling locations have little significant to the aggregation of particles when damper is fully open. The gradient of the growth of particles is almost equivalent for the three nozzle orientations. The highest particle size obtained is 381.23 microns at 24.4 m/s flue gas velocity and counter flow orientation. A model based on aggregation is used to predict the particle diameter after spraying mists. Predicted values of particle diameter agreed well with measured values. Sampling tests indicate that flue gases treated with mists have successfully reduced a significant amount of fine particulates that could have been emitted to atmosphere.

Keywords: *fine particulates, cyclone separator, particle size distribution, aggregation chamber, flue gas*

INTRODUCTION

Woodwaste is a renewable fuel source belonging to the family of biomass fuels. Some popular biomass fuels are woodwaste, rice husk, and saw dust. These fuels are reactive and as a result, combustion is not a major issue. The product of combustion of these biomass fuels, which is the source of air pollution, is the main concern particularly on how to effectively mitigate this pollution. In 2004, the Philippine Congress recognized the need to implement stricter measures to grant permits to construct structures that emits pollution. These statutory regulations hamper the wood processing industries, all the more for the small-scale industries that particularly used woodwaste fuel for its boilers. Most of these woodwaste fuel-driven-boilers emit particulate matter with relatively large and broad particle size distributions which according to the law must be installed with an air pollution control devices (APCDs).

Over the years, many attempts have been made to improve the performance of APCDs in capturing fine particles. Innovations have been made to enhance the efficiency of these devices though all of the devices have limitations for the fine particulate matters. Some of the methods are still being used. Some are being revived due to the introduction of new technologies. The use of separation technology, such as cyclone separators, has been identified as a means of reducing expenses associated with production operations. A cyclone separator is a device that separates particles from a gas stream using centrifugal force. There are various types of cyclone designs that have been proposed. However, the reverse-flow cyclone is the type most commonly used for industrial gas cleaning. The basic flow pattern has been visually studied with different techniques by Shepherd and Lapple (1939) and Stairmand (1951). Their description of the cyclone flow includes an outer downward directed vortex and an inner upward directed vortex at the center. Cyclone separators, compared to the conventional APCDs, are simple, compact, low-cost, low-weight, and are easy to maintain and install. These advantages have been the major driving force in promoting the use of cyclone separators in many applications.

Smaller particles can aggregate to form larger, heavier groups, which together have enough mass to be captured in the CS. The technique is to aggregate them into larger particles before entering the CS. Particles may be soluble in water. A word that can describe this phenomenon is hygroscopicity which defines as the tendency for a particle to take up water. This can be done by contacting the individual particles with drops of water (mists). Most fine particles will adhere to a liquid drop if they contact it. In the aggregation process, the particle surface is wetted and the particles will stick together and then forms the bigger size particles.

Weber et al. (2001) developed the original particle-into-liquid sampler (PILS), which grows particles in saturated water vapor, thereby creating droplets sufficiently large to be collected by inertial impaction and then chemically analyzed. The PILS was developed for measurement of water-soluble aerosol components. It operates by increasing the size of particles through condensational growth in a saturated water vapor environment to sizes easily captured by inertial methods. Like the PILS, the steam-jet aerosol collector (Khlystov et al., 1995) was designed for aerosol measurement. Rapid mixing of the hot saturated flow with the cooler aerosol flow creates the supersaturated atmosphere needed for particle activation and growth. Further analysis techniques have also been applied to collection of grown droplets in a system called the condensational-growth and impaction system wherein an aerosol sample flow is saturated with water vapor that further condenses on the particles in a laminar flow tube (Sierau et al., 2002). The techniques introduced by Weber, Khlystov, and Sierau have limitations wherein cooler ambient aerosol was used instead of hotter flue gases. This process can lead to significant uncertainties particularly when dealing with flue gases whose temperature is high.

This study focused on the development and testing of a simple, cost and energy efficient method of effectively capturing particulate matters. The principal objective of this study was to optimize the design of a cyclone separation system and to evaluate its performance for the effective control of fine particulate matters. To capture these fine particles, a mechanism was needed in order to increase the size of particles from fine to sizes which are easily captured by inertial impaction. This perception was studied and achieved by spraying mists at aggregation chamber (AC) located upstream of the cyclone separator. Specifically, the cyclone separation system was done to: (1) determine the particle size distribution (i.e., the equivalent diameter of PM) and the elemental composition of the particles extracted from the three sampling ports of the AC using Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM-EDX), (2) calculate the efficiency of cyclone separation system, and (3) calculate the pressure drop of the cyclone separator.

EXPERIMENTAL SET-UP

The general layout of the system is shown schematically in Figure 1. A furnace of 60 cm in diameter and height of 60 cm was used as the miniaturized source of air pollution for woodwaste combustion. Fuel was fed in the furnace manually. A hood of 60 cm round base and vertical height of 30 cm was placed above the furnace to capture flue gases which was drawn by an exhaust blower. Through a 90° elbow and a 120-cm length pipe of diameters 10 cm, the hood was connected to the first cyclone separator.

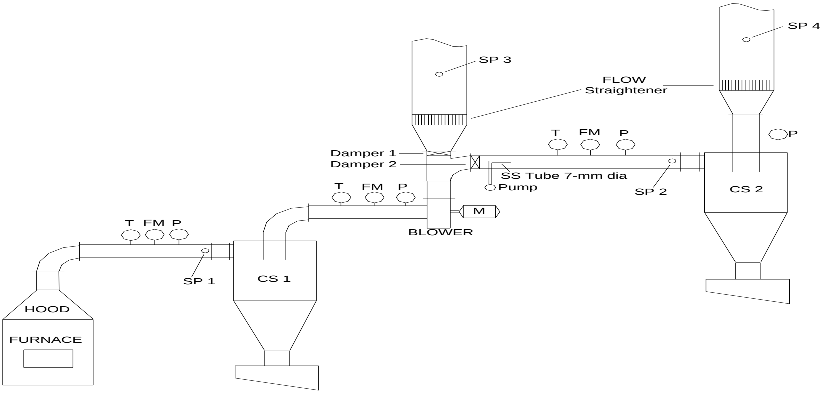


Figure 1: Experimental set-up

A transition duct was placed to allow the entrance geometry to the first cyclone separator from the round pipe to rectangular cross-section. The location of the sampling port should be hydrodynamically long enough to allow the flow field to normalize free from flow disturbance. In theory, the distance must be 8 to 10 times its diameter. At 100 cm downstream of the 90^o elbow, a 4-cm diameter sampling port (SP 1) was mounted by the side of the round duct in which sample particles could be extracted to a soot filter. An external vacuum pump unit attached to the bottom of filter box of the sample train drew the filtered gas stream.

A blower with a rated capacity of 0.13 cubic meters per second was used to drive the exhaust flue gas through the flow measurement section toward the first cyclone. The first cyclone was used to collect coarse particles. The fine particulates, which are the unfiltered fraction of the total flow from the first cyclone, were carried by the hot flue gas and passed down to a 15-cm ID steel pipe which was drawn by this blower. This stream passed through this blower to a 10-cm ID steel pipe aggregation chamber (AC). PM sample could be extracted in AC while damper 1 was closed.

The aggregation chamber (Figure 2) was a round pipe of 10-cm diameter and 150-cm long. The chamber-length could be extended up to 180-cm to accommodate additional two sampling ports. Hence, there were three sampling ports in which samples could be extracted of varying lengths. The flue gas stream going to this chamber would be mixed with water from peristaltic pump. The experimental set-up included a water supply circuit. The water discharged from the supply tank goes to the nozzle at the test section inlet. At 120 cm downstream from entrance of AC, a 4-cm diameter sampling port (SP 2a) was mounted by the side of the round pipe in which sample particles could be extracted to a soot filter. Two more sampling ports were mounted at locations 150 cm and 180 cm for sampling port 2b (SP 2b) and sampling port 2c (SP 2c), respectively. An external vacuum pump unit attached to the bottom of filter box of the sample train drew the filtered gas stream.

Figure 2: Aggregation Chamber

The flow rate of the flue gas could be adjusted with a damper located at the discharge section of the blower. A standard wye pipe was connected at the discharge section of the blower where its two exits were being controlled by dampers. Damper 1 would be totally closed when extracting sample particles at sampling ports 2 and 4. Damper 2 would be totally closed when extracting sample particles at sampling port 3.

A hot flue gas was practically generated for this experiment. This would fix the physical properties of the flue gas. The only variables that could be changed during the conduct of the experiments were the gas velocities and the residence time of coalescing process. The gas velocities were controlled by adjusting the damper of the blower to fully open, two-thirds opening, and one-thirds opening. The residence time of coalescing process would depend on the distance travelled by the coalescing particulate and mists.

A transition duct was placed to allow the entrance geometry to the second cyclone separator from the round pipe to rectangular cross-section. The second cyclone separator was used to measure the collection efficiency of the cyclone separation system. Using EPA Method 5, a sample probe was inserted at sampling port 4 (SP 4) wherein mass concentration of PM could be extracted while damper 1 was closed.

DETERMINATION OF PM EMISSIONS

PM mass concentrations in treated gas were determined by isokinetic sampling using EPA Method 5 – sampling method for stationary sources. In this method, PM was collected on 82-mm glass microfiber filter. The PM laden filter and PM mass collected from the probe washed by acetone was put into a desiccator for at least 24 hours to obtain a moisture free sample. The total PM mass was determined by gravimetric method. The PM mass concentration was obtained by dividing the total mass with the total sample volume corrected to standard conditions (1 atm, 293^{o}K). Isokinetic testing requires a thorough understanding of the first five test methods. Method 5 provides the general sampling train operation procedure but Methods 1 through 4 prescribe techniques reinforcing the sampling activities associated with method 5. Table 1 outline methods of the basic protocols for determining particulate concentrations and mass emission rates.

Table 1: Methods for determining PM concentrations and mass emission rates

Method	Description
Method 1	Determination of sampling location and traverse points
Method 2	Determination of stack gas velocity and volumetric flowrates
Method 3	Determination of dry molecular weight and percent excess air
Method 4	Determination of moisture content
Method 5	Determination of PM emissions

RESULTS AND DISCUSSION

An extensive test matrix has been used. Three sampling test locations (XP1, XP2, and XP3) and three nozzle orientations (concurrent, cross, and counter-flow) have been tested over three different flue gas velocities (Vel_1, Vel_2, and Vel_3). Experiments have been conducted with constant spraying of mists (water) over a combination of different operating parameters. A total of 28 experiments have been conducted.

Table 2 shows the list and ranges of operating and design parameters that is used in this investigation. The samples obtained on Petri discs were analyzed by Scanning Electron Microscopy (SEM) equipped with Energy Dispersive X-ray (EDX) technique. The sampling of PM was performed at three different locations identified as XP1, XP2, and XP3. The sampling period lasted for 30 minutes per sample.

Table 2: List and ranges of operating and design parameters

Carrier Gas	Flue Gas
Flue Gas Velocity	8.6 m/s (Vel_1) 16.5 m/s (Vel_2) 24.4 m/s (Vel_3)
Flue Gas Temperature	115°C
Mist Liquid	Water
Water Injection Temperature	22°C
Flow Direction	Concurrent Flow Cross Flow Counter Flow
Nozzle	Fixed Geometry Nozzle
Nozzle Diameter	1 mm
Nozzle Droplet Size Distribution	39.4 μm at 276 kPa
Mists Velocity	4 m/s
Aggregation Chamber Internal Diameter	10 cm
Aggregation Chamber Sampling Locations (measured from entrance of AC)	120 cm (XP1) 150 cm (XP2) 180 cm (XP3)

Figure 3 shows images of samples acquired using SEM-EDX at magnification of x100 and x800. This is sample #1 in which particles has not been treated with mists. The result estimates an average diameter of 8.34 μm.

It indicates that without mist sprayed on the flue gases, particles obtained are in the range of 1.5 μm to 16.99 μm and the particles are approximately evenly distributed.

The flow configuration consists of flue gases flowing in one direction and a mists issuing from a nozzle of 1-mm diameter into a concurrent, cross, and counter – flowing orientations. The sampling of PM was performed at three different locations identified as XP1, XP2, and XP3. The two streams met at the entrance of aggregation chamber and mix via entrainment resulting to the reduction of relative velocity between the flue gas and the much slower mists velocity.

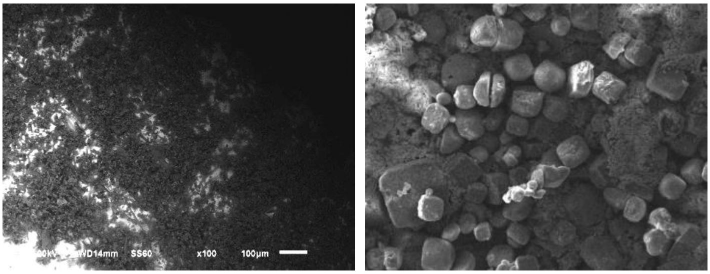
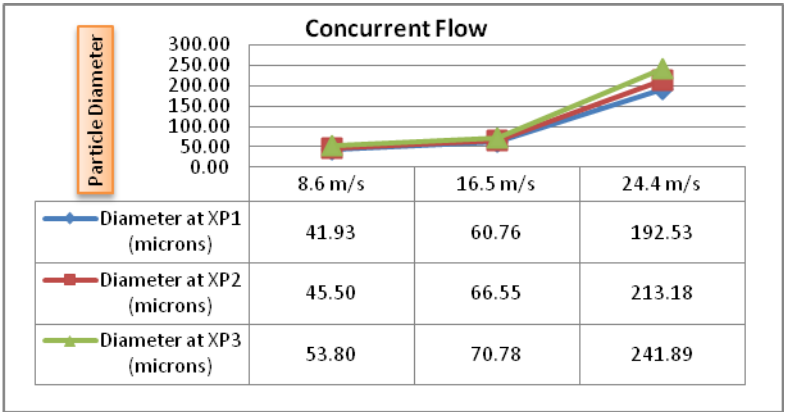


Figure 3: SEM images without mists at x100 and x800 magnification

A graph in Figure 4 will show the particle diameters for concurrent flow of varying flue gas velocities at three different AC locations. It can be seen that as the AC length increase particle size also increase. There is a little significant increase of particle size when damper opening is between one-thirds and two-thirds at XP1 and XP2. It can be seen from the graph that there is an abrupt increase of particle size when damper opening is between two-thirds and fully-open at sampling locations.

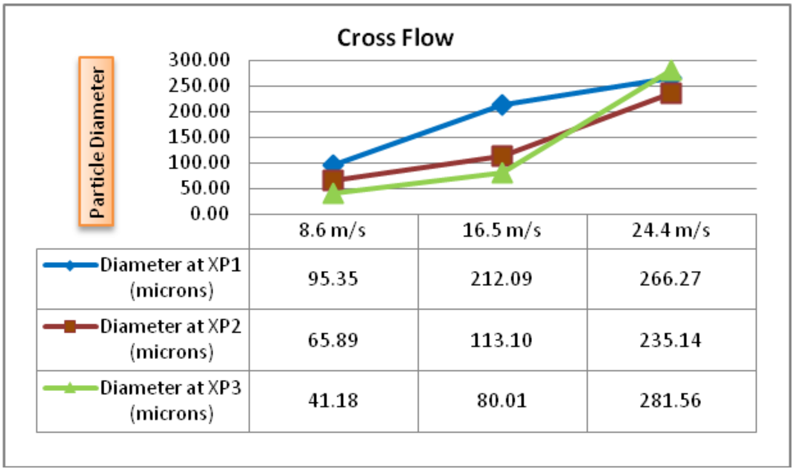


	8.6 m/s	16.5 m/s	24.4 m/s
Diameter at XP1 (microns)	41.93	60.76	192.53
Diameter at XP2 (microns)	45.50	66.55	213.18
Diameter at XP3 (microns)	53.80	70.78	241.89

Figure 4: Particle Diameters of Concurrent Flow at Three Locations

It means that Vel_3 should be the minimum flue gas velocity in order to produce large particle size considering pump operating conditions and nozzle design as constants. However, at XP3, a fully-open damper can produce the highest particle diameter of 241.89 microns. For concurrent flow, the sampling locations have little significant to the growth of particles corresponding Vel_1 and Vel_2. However, it is obvious that at Vel_3, there is a significant difference of the growth of particles based on the sampling locations.

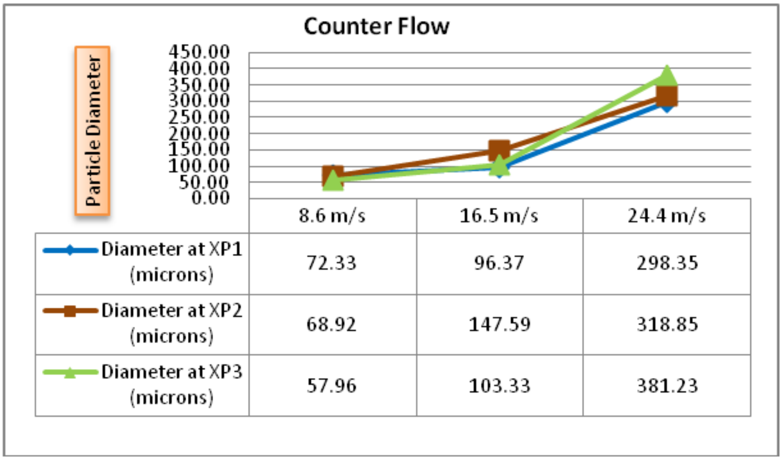
A graph in Figure 5 will show the particle diameters for cross flow of varying flue gas velocities at three different AC locations. This is the case where particles are collected as they collide with droplets sprayed from nozzle at right angles to flue gas flow. It can be seen that as the AC length increases particle size also increase. However, at XP3, a fully-open damper can produce a particle diameter of 281.56 microns which is higher by 16.4 % as compared to concurrent flow at the same condition.



	8.6 m/s	16.5 m/s	24.4 m/s
Diameter at XP1 (microns)	95.35	212.09	266.27
Diameter at XP2 (microns)	65.89	113.10	235.14
Diameter at XP3 (microns)	41.18	80.01	281.56

Figure 5: Particle Diameters of Cross Flow at Three Locations

A graph in Figure 6 will show the particle diameters for counter flow of varying flue gas velocities at three different AC sampling locations. The particle diameter profile of counter flow is generally similar to the particle diameter profile of concurrent flow shown in Figure 4. It is interesting to note that profile size is generally dominated at XP2. However, at XP3, a fully-open damper can produce the highest particle diameter of 381.23 microns with an increase of 57.6 % compared to concurrent flow and 35.4% increase compared to cross flow.



	8.6 m/s	16.5 m/s	24.4 m/s
Diameter at XP1 (microns)	72.33	96.37	298.35
Diameter at XP2 (microns)	68.92	147.59	318.85
Diameter at XP3 (microns)	57.96	103.33	381.23

Figure 6: Particle Diameters of Counter Flow at Three Locations

Figure 7 shows the effect of carrier gas velocity to the growth of particles. It is evident that in any flow orientation, increase in growth particle is achieved when the carrier gas velocity is at 24.4 m/s, i.e., when damper is fully-opened.

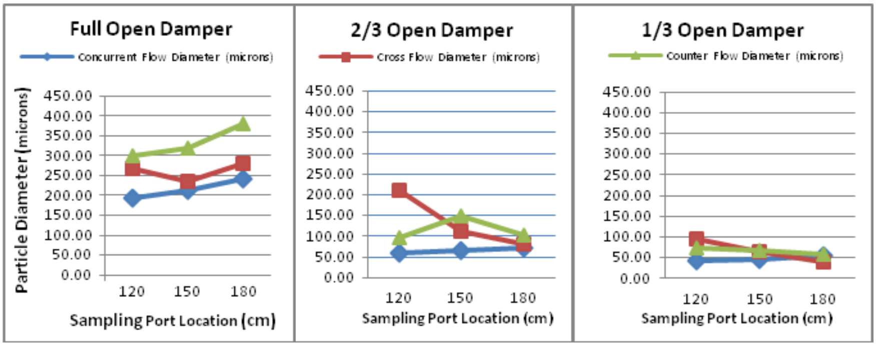


Figure 7: Particle Diameters Based on Carries Gas Velocity

At this velocity, counter flow is consistently producing high growth rate of particles in any three locations, being the highest is at XP3. It is interesting to note that cross flow dominates in the two-thirds and one-thirds damper openings at XP1. It can be observed that lowering the flue gas velocity equivalent to one-thirds and two-thirds of damper opening will cause a drop in particle diameters at location further downstream from XP1. This is probably because at slower velocity, the grown particles can no longer follow the carrier gas stream. Thus, there is a tendency for that grown particles to fall at the bottom of the pipes. This reveals that particles can no longer reach the locations XP2 and XP3 because of slower velocity. As a result, only fine particles are collected when samples were extracted at locations XP2 and XP3.

In this study, measurement of particle concentrations was done using the sampling train. Samples were extracted both upstream, m_u, and downstream, m_d, of the cyclone separator. Mass of PM collected upstream of the system without mist was 201.56 mg. Mass of PM collected downstream of the system with mist was 156.48 mg. The efficiency was computed and found to be 22.4%. It means that 45.08 mg of PM were collected in the cyclone separator.

Another test was made when samples were taken at sampling port (SP 4) located 2.75 meters above the outlet pipe of the cyclone. Mass of PM collected without mist was 508 mg and mass of PM collected with mist was 90 mg. The mass with mist was only 17.7% of the mass without mist. It means that the system was successfully reduced the fine particulates that could have been emitted to the atmosphere by 82.3%. It can be observed that there is a significant improvement in its performance when mist was applied to the cyclonic separation system.

The pressure drop across the cyclone is directly related to the fan power required to operate a cyclonic device. It is expressed as the number of inlet velocity heads, ΔH. The value ΔH is constant for a cyclone design, i.e., cyclone dimension ratios, while ΔP varies with operating conditions. Using the empirical model developed by Dirgo (1988) and Ramachandan et al. (1991), the cyclone dimensions will give result of ΔH =6.786. The predicted pressure drop through the prototype cyclone is 1.760 kPa (13.18 mm Hg).

The cyclone inlet velocity was determined by measuring the velocity pressure upstream of the cyclone prior to particles being fed into the system. The inlet velocity was measured using a Pitot tube that is attached to an inclined manometer. The manometer reads 1.46 inch H_2O which is equivalent to a velocity of 24.4 m/s. The exit velocity was measured using the sampling train and found to have a velocity equivalent to 10.3 m/s. The observed pressure drop through the prototype cyclone is 1.054 kPa (7.896 mm Hg).

The experimentally observed pressure drop was lower than that predicted by the empirical formula. This pressure drop was only 60% of the pressure drop predicted using empirical model. The deviation is probably due to the measurement of the exit pressure which was actually taken at sampling port (SP 4) located 2.75 meters above the outlet pipe of the cyclone. Another factor is the size of the stack where SP 4 is attached has a diameter of 30.5-cm while the outlet pipe of the cyclone is 10-cm diameter.

CONCLUSION AND RECOMMENDATIONS

The characterization of the samples indicates that there was an aggregation of particles and mists. Fine particles can grow inside the aggregation chamber due to their hygroscopic properties. Water droplets (mists) were used to form aggregates of fine particles. The injection of mists has shown growth of particle size diameter. Without aggregation agent, i.e., mist, the mean diameter is the smallest. After the injection of mist, particles grew from 8.34 µm to a larger extent. The result also showed that particle size increased with increasing flue gas velocity; the greater flow of aggregation, growth rate is faster. The combination is best when flow is counter, flue gas velocity is 24.4 m/s, and extraction of sample is done at location 180-cm downstream from aggregation chamber.

The significance of this study is quantification of the overall cyclone separation system efficiency. Cyclone separator is just a part of the whole system. The system had successfully reduced the fine particulates that could have been emitted to the atmosphere by 82.3%. Cyclone efficiency was greatly improved when mist was applied.

The actual pressure drop was lower than that predicted by the empirical formula. This pressure drop was only 60% of the pressure drop predicted using empirical model. This will reduce the operating cost of the system.

For further research, it is suggested that a transparent aggregation chamber may be installed in order to examine and monitor the behavior of mixing between particles and mist while proceeding with the experiments.

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