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# Design and Implementation of an Electrostatic Precipitator and Its Cleaning System for Small Scale Combustion

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## ABSTRACT

A simple wire-plate electrostatic precipitator (ESP) was constructed in order to test the efficiency of collecting smoke particles from combustion of rubber-wood that is used as a source of biomass energy. The ESP contains collection cylinder electrode and 2 wire electrodes between cylinder. The maximum input voltage of the Wheatstone bridge circuit using a high-voltage neon transformer was 10.5 kV (DC). The gap between the cylinder and the distance between wires were adjustable. Results from the field test in a furnace indicate that the device could be used for a period of about one hour before cleaning the electrodes was required. The collection efficiency was decreased during the course of wood burning as the dust loading increased. Maximum efficiency was near 80% during the initial period. The distance between the collection plate electrodes had a greater influence on efficiency than the distance between the wire electrodes. The cleaning system used in this experiment was made from a row of PVC pipes to allow water to discharge radially to the cylinder electrodes on both sides. Efficiency was increased after 120. This ESP is suitable for small and medium-sized enterprises (SMEs) to alleviate the release of detrimental chemicals such as PAHs into the atmosphere.

Keywords: Electrostatic Precipitator (ESP), Efficiency, Electrode and Furnace Collection plate.

## 1. INTRODUCTION

Biomass is currently a major source of renewable energy. Wood is an important biomass fuel, and it has been extensively used in direct combustion. But, combustion of firewood leads to pollution in the form of gases and smoke particles, which are composed of various chemical components. Incomplete combustion results in the formation of polycyclic aromatic hydrocarbons (PAHs) and other chemical compositions. PAHs include hundreds of compounds that are carcinogenic, especially those that contain four to six aromatic rings. Factory workers who are exposed to PAHs may develop cancer and experience other negative health effects [1].

In communities where wood heating is common, wood smoke can be responsible for as much as 25% of the airborne particulate matter, 7% of CO in the air. The smoke also contains small quantities of other toxic compounds including nitrogen oxides and chlorinated toxins which can contribute to environmental hazards like smog and acid rains.

Smoke from wood combustion can cause eye, nose and throat irritations as well as headaches, nausea and dizziness; in addition, it can make illnesses like asthma and breathing problems worse [4].

An Electrostatic Precipitator (ESP) is a device that is used to remove and collect the particles from a flue gas by using the force of an induced electrostatic charge from a high voltage power supply unit. This is the most efficient way to solve the pollution problem as a result of wood combustion [3, 4].

A high voltage is applied to the discharge wires to form an electrical field between the wires and the collecting plates, and also ionizes the gas around the discharge wires to supply ions as

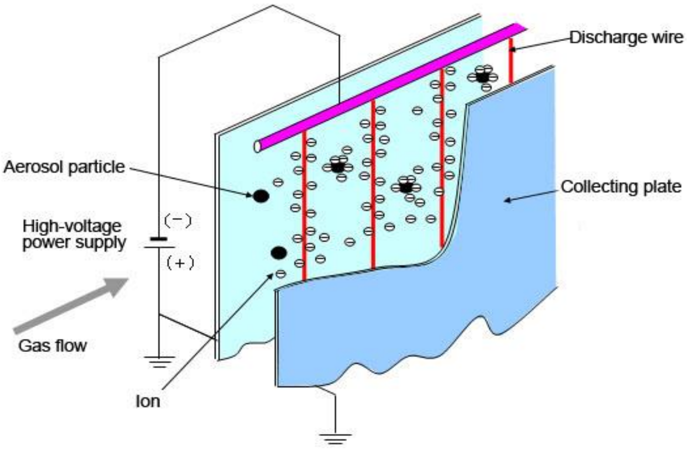

Figure 1: Principle of electrostatic

When gas that contains an aerosol (dust, mist) flows between the collecting plates and the discharge wires, the aerosol particles in the gas are charged by the ions. The Coulomb force caused by the electric field causes the charged particles to be collected on the collecting plates, and the gas is purified. This is the principle of electrostatic precipitation, and Electrostatic Precipitator applies this principle on an industrial scale. Electrostatic precipitators are highly efficient filtration devices that minimally impede the flow of gases through the device, and can easily remove fine particulate matter such as dust and smoke from the air stream. Nowadays these ESPs are gaining importance as to obtain the environmental clearance for setting up of new industrial plants and green environment [1].

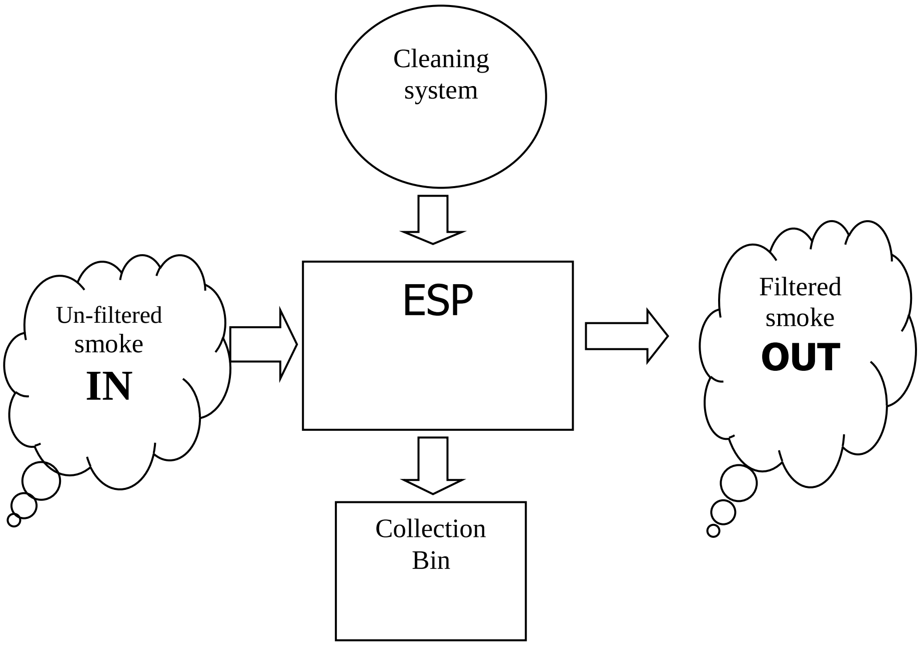

Figure 2: ESP process flow

## 2. EXPERIMENTAL METHODS

The type of ESP used in the present study is a plate-wire. This configuration is selected because it has flat collection electrodes that are easy to clean. This is very important because the emitted gas from wood combustion contains sticky tar that requires regular cleaning.

### *2.1 Design*

As mentioned earlier, an ESP is a device that separates particles in a gas, in this case, air. The air passes through a negatively charged metal rod between a positively charged collection.

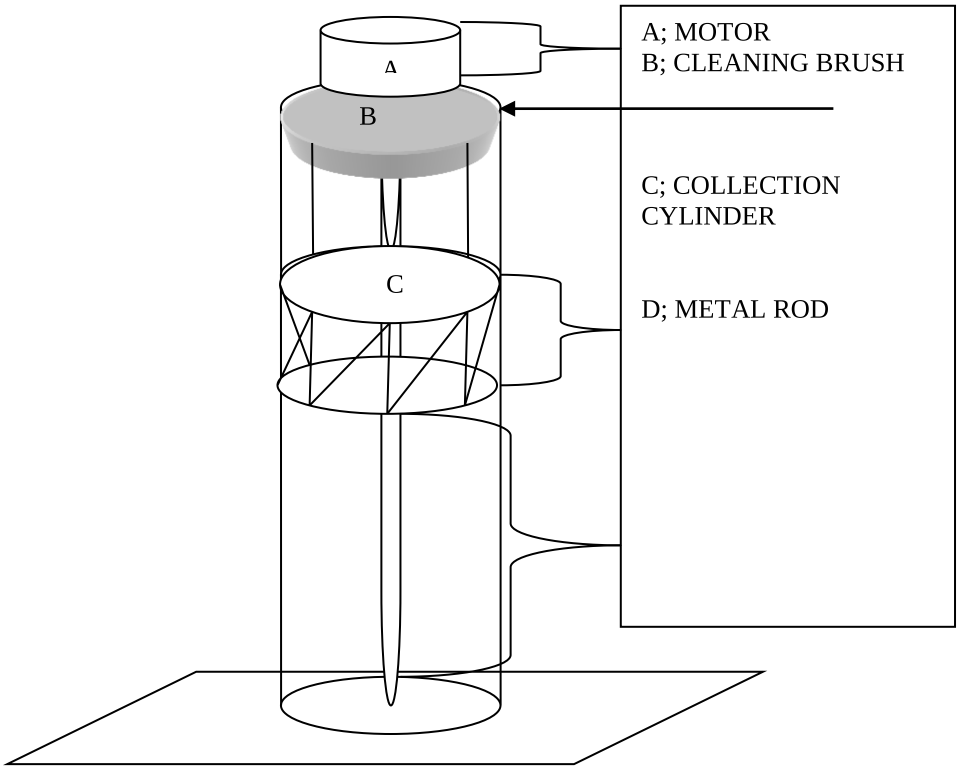

Figure 3: ESP Structure

A 10 kV (DC) from a high-voltage ignition coil through a rectifier circuit is supplied to the plate and wire rod. The high voltage is required to produce a corona discharge which is caused by ionization of the aerosol particles surrounding a conductor. The corona power is a result from the current and voltage applied, current is required for charging the particles and voltage is required to produce an electric field. Particles through an electrode with a high negative charge will be negatively charged (carry negative change) and will be attracted to another electrode with a positive charge.

But, accumulation of the aerosol particles on collection causes a reduction in collection efficiency [5, 6].
A cleaning system was installed to do the following;

- Isolate smoke from the inlet to the ESP
- Cut off the high voltage between the electrodes

- Scrub off the dust from the plates
- Power back the plates of open the isolate to let the smoke back through the ESP.

### *2.2 Negatively charged copper wire rods*

This part of the ESP that ionizes the particles in the air upon being passed through.

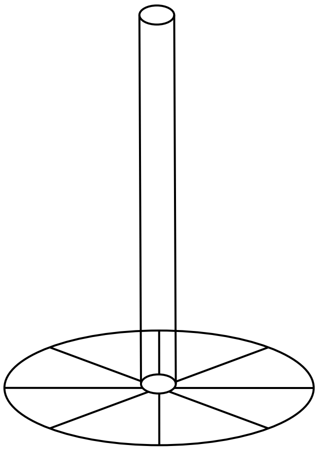

Figure 4: The negatively charged copper rods

We choose copper for its ability to conduct electricity, as well as the cost of the material compared to other strong electric conductors.

### *2.3 Plastic inlet pipe*

The plastic inlets pipe will be circular to allow the passage of smoke through the ESP to the atmosphere, and plastic was an easy choice as we did not want this component to conduct electricity.

### *2.3.1. Positively charged aluminum collection plates*

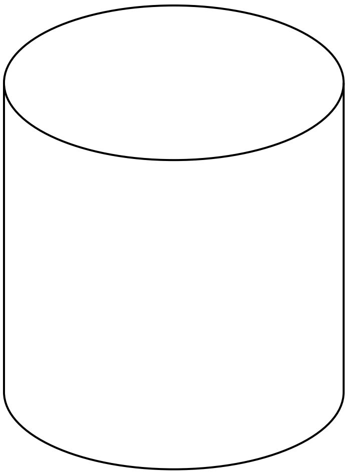

Figure 5: Positively Charged Collection Plate

This plate is positively charged, as the ionized graphite particles pass by, they are attracted to the plate and stick it.

### *2.4 Cleaning system*

This comprises the following a small DC motor, brush, long bolt and a nut. The construction is shown in figure 6 below.

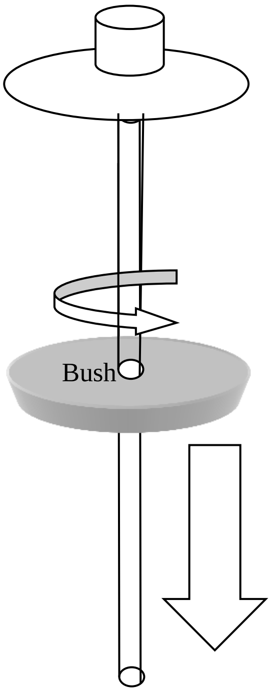

Figure 6: The Construction of the cleaning system

The nut is mounted in the middle of the brush, a bolt is screwed through the brush and the bolt is mounted at a fixed position on top of the ESP. The DC motor shaft is coupled with the bolt by a PVC tube. During the cleaning process, the dc motor rotate the bolt in an anti-clockwise direction for some time, then rotate in a clockwise direction, to return the brush to the wait position [7].

### *2.5 Hopper*

This is a pyramidal shaped container used to direct the cleaned particulate matter that has been collected from the expelled air. Once the graphite is scrubbed off the plates, this hopper will guide the particles to a collection bin. We are going to install this hopper just below the plates so that graphite will pass through to the bin. The collection bin will contain water to dissolve the cleaned particulate matter. This is to prevent the dispersal of the matter.

### *2.6 Power Supply System*

The ESP has two power supplies thus 10kv dc (high voltage power supply), 5v dc and 6v dc as shown in the figure 7 below.

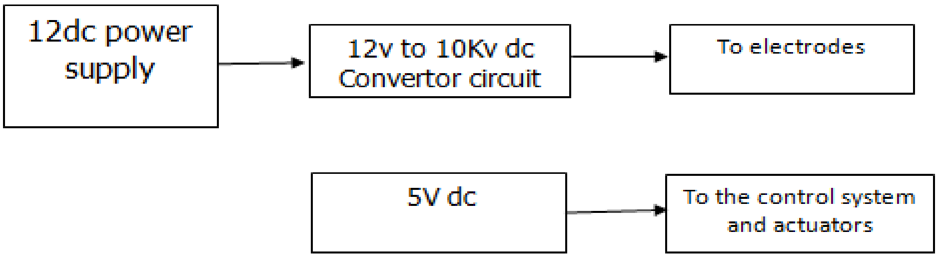

Figure 7: Power supply block diagram

The high voltage is supplied to the collection plates and the wire rod electrodes, 5v to the bush motor and to the control circuit and actuators.

### *2.7 Control Mechanism*

The controller is designed to work in the way that after every 1 minute, the ESP turns off and the electrodes will be cleaned by the brushes. After every a minute delay from the atmega 328 microcontroller, a signal is being given to close the relay circuit so the HV circuit is open and the 5v motor circuit is closed. When this closes, the motor rotates clockwise and moves the brush downwards for a specific time then rotates in the opposite direction to move for that time to bring the motor back to its initial position. The time for the motor to move in one direction is proportional to the distance. he HV circuit is programmed to close after a certain period were the relay opens two seconds after the motor has stopped.

## 3.0 RESULTS AND DISCUSSION

A high-voltage transformer was used to convert the input voltage of 12VAC to 10 kVAC. A simple Wheatstone bridge circuit that rectified the AC current to DC current employed eight high voltage diodes (1N, 1 kV, 4 mA). These diodes were encompassed in an insulating tape with paper to prevent discharge at high voltages. Fifteen diodes were connected in series in each branch to increase the voltage two folds (15 kV) before forming the bridge. The negative polar of the Wheatstone bridge circuit was applied to copper wire electrodes, and the collection plates of the ESP was grounded. Output DC voltage of this full-wave bridge rectifier circuit without capacitor filter showed a waveform rather than the exact direct behaviour, and its rms value was about 13.5 kV corresponding to the previous research study. This output value was used for all experiments [9]. Experimental parameters, including the gaps between collection electrodes (dc) and the distances between wires electrodes (do), varied in the experiment. Prediction of the voltage-current of the designed ESP indicates that the gap between collection electrodes (dc) has greater influence than the distance between wires electrodes (dw). In any case, the onset voltage is far lower than the designed operating voltage (13.5 kV). This ensures the onset of corona discharge at the operating condition. It also shows that the current was increased with the applied voltage. Prediction of the numbers of charges and corona onset values from the designed ESP [10].

### 3.1 The Driver Circuit

This is the driver circuit that powers the ignition coil.

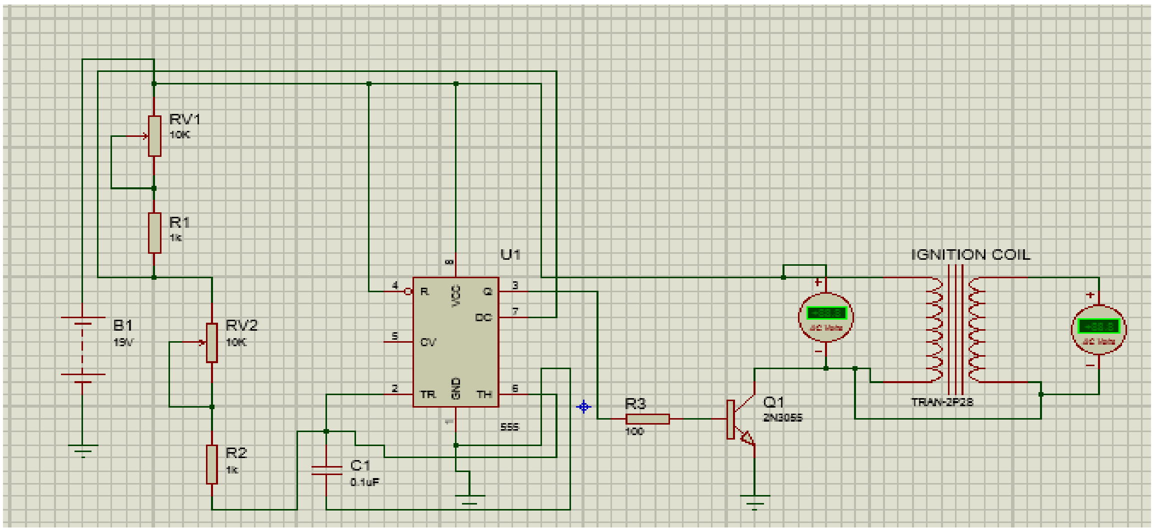

Figure 7: Circuit that powers the ignition coil

Two 10k ohm potentiometers

Two 1k ohm resistors

One 555 timer IC

One 8-dip IC socket

One 100 ohm resistor

One .1uf 12v capacitor

One tip 3055 power transistor and heat sink

12v 6amp DC power supply

### 3.2 Cleaning System

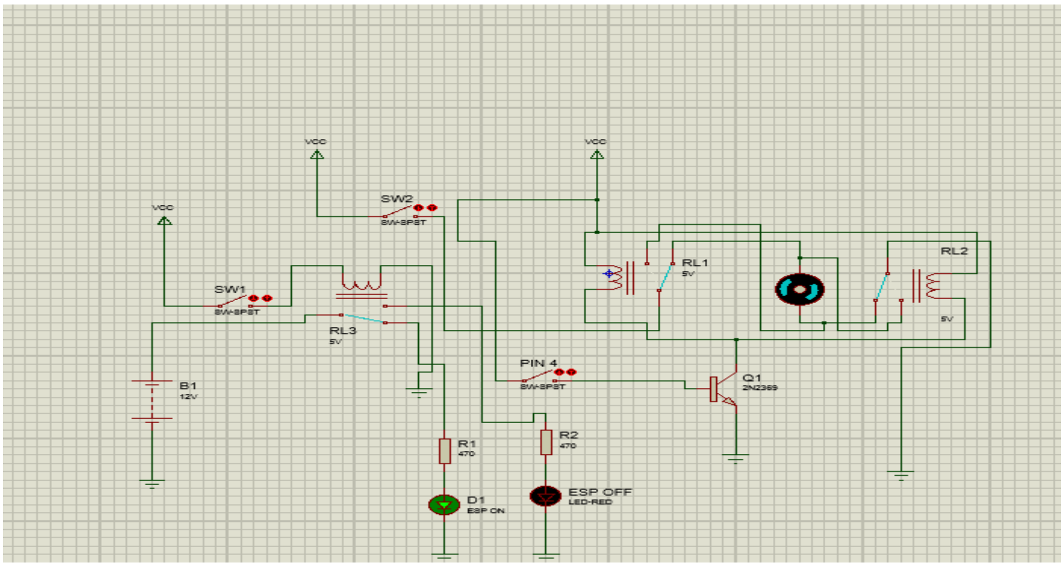

Figure 8: Circuit of the cleaning system

Using an Atmega328, signals are sent to various switches to control the movement of the motor for cleaning. Cleaning occurs after the ESP is turned off by a relay (RL3). The first signal turns the ESP off; the second allows the brush to start moving downwards thus cleaning of the ESP. All the switches have a time delay for which they are supposed to operate. The second switch is turned off to allow the brush to continue moving upwards thereafter turning the circuit for cleaning off. This is so that the ESP can turn back on [8].

### *3.3 Testing of the Project*

To prove the theory behind our ESP, we hooked up our power supply to a small ESP constructed out of a small PVC pipe, aluminium mesh, and aluminium foil. To test this, we hooked up the negative lead to the mesh and the positive lead to the aluminium foil. Once connected, we lit small incense on fire that produced a constant flow of smoke upwards. When the power supply was turned on, the flow of smoke was immediately stopped and the smoke particles began collecting on the aluminium foil.

The experimental setup to determine collection efficiency of the ESP is shown in Fig. 4. The ESP was connected to the wood combustion furnace where 4 kg of rubber-wood was burned. Aerosol sampling was conducted at the upstream and downstream locations of the ESP using HEPA filters. The input voltage for the ESP was 12 VAC, which is equivalent to the output of 10 kVDC. The collection efficiency ( $\eta$ ) can then be calculated from inlet exit c where c inlet and c exit are the mass concentrations of particles at the inlet and exit of the ESP. Sampling flow rates for both lines were controlled at 24 L/min by control valves, orifice meters, and a vacuum cleaner used as a suction pump as shown in Fig. 4. The sampling flow rate corresponds to the average velocity of 0.079 m/s. This is in the range of the actual gas velocity in the ESP, ranging from 0.04 to 0.2 m/s, equivalent to the flow rate of 0.02 to 0.09 m3/s, which covers the designed value. The large variation of the velocity is due to the fact that the flow was natural. The condition of isokinetic sampling was approximately achieved. The variation does not significantly affect the loss or gain of the sampled particles as the MMAD of smoke particles is very low (0.68 microns). The maximum Reynolds number in the ESP was about 1.0 × 104 which indicated that the flow was laminar [8].

The first sampling was performed 15 minutes after the start of wood burning. Samplings lasted 15 minutes each and were taken with 15-minute intervals between each sampling for five hours (10 samplings were collected for each line). The 110-mm-diameter HEPA, or high-efficiency particulate air filters (Cambridge, glass fibre filter), were used in all samplings. The filters were treated in a controlled environment (25°C and 50% RH) for 72 hours before and after the sampling [9].

### *3.4 Efficiency Improvement by Plate Cleaning*

The cleaning system used in this experiment was made from a row of 1/2-inch PVC pipes (thermal conductivity = 0.19 W/m.K dielectric constant = 3.0), as shown in Fig. 8. Each pipe was drilled by 3-mm holes along two rows in order to allow water to discharge to the plate electrodes on both sides. A centrifugal pump (200 L/min, Head 10 m) was used to supply water to the system. Water was introduced from both ends of the pipes once every hour, and each spraying time lasted 15 minutes. The cleaning system was equipped with the case of maximum collection efficiency discussed in the preceding section; the gap between collection plate electrodes was 50 mm, and the distance between wires electrodes was 64 mm. Results from two experiments During the first two hours, the collection efficiency decreased at a slower rate than when no cleaning system was equipped. It dropped from more than 82% at 30 minutes to about 60% after 120 minutes. The efficiency could not be maintained at the initial value because the smoke contained sticky tar, which was attached to the collection electrodes, and it was difficult to remove. However, after 120 minutes, the collection efficiency was raised to about 60% by the water spraying. The reduction of tar resulted from the combustion and the ESP could effectively remove the smoke particles.

Cleaning effectiveness can be seen, which displays the collection electrodes before and after the water spraying. The particle trails at the end of the operation (after 5 hours) when no cleaning system was installed. Most of the particles were attached to the plate in the vicinity of the discharge electrodes resulting from high electrical field strength in the area. The particles were effectively removed by the cleaning mechanism [10].

### *3.5 Results*

Set of calculations represents the efficiency of our first design, and the other represents Design Calculations. In our initial calculations, we were still learning the science behind ESPs and mistakenly used an incorrect variable, the drift velocity of the collection plates instead of the graphite particles. So we have two sets of calculations, both with the correct variables. The first the efficiency of the revised design.

Initial design
Calculating drift velocity of the machined graphite particles:
Derived from the current formula I = nAve
V, drift velocity = I/nAe
I = current, .006 A
n = free electron density for graphite (a semi-conductor), n = 6 x 1016 m3
A = .37 m2
e = elementary charge (electric charge carried by a single proton, or the negation of the electric charge carried by a single electron), 1.6 x 10-19 C
Q = flow rate, .73m3 /s
V =$InAe$
V =.006 $(6*1016\ m3)(.37\ m2)(1.6*10-19\ C)$
= 1.68 m/s

Collection efficiency:
$R = 1 - (-.37\ m2*1.68\ m/s.73\ m3/s)$= .573 = 57.3% collection efficiency
Revised design

V, drift velocity = I/nAe

I = current, .03 A

n = free electron density for graphite (a semi-conductor), n = 6 x 10^16 m^3

A = 1.02 m^2

e = elementary charge (electric charge carried by a single proton, or the negation of the electric charge carried by a single electron), 1.6 x 10-19 C

Q = flow rate, .73 m3/s

V =$InAe$

V =$.03\ (6*1016\ m3)(1.02\ m2)(1.6*10-19\ C)$

= 3.06 m/s

Collection efficiency:

$R = 1-(-1.02\ m2*3.06\ m/s.73\ m3/s)$ = .985 = 98.5% collection efficiency

Tables to show the effect of electrode spacing affect the collection efficiency.

| OPERATION TIME (min) | COLLECTION EFFICIENCY (%) |
|---|---|
| 30 | 75 |
| 60 | 65 |
| 90 | 55 |
| 120 | 50 |
| 150 | 45 |
| 180 | 40 |
| 210 | 40 |
| 240 | 35 |
| 270 | 30 |
| 300 | 15 |

**Table 1: dc=75mm, dw=85mm**

| OPERATION TIME(min) | COLLECTION EFFICIENCY (%) |
|---|---|
| 30 | 80 |
| 60 | 75 |
| 90 | 60 |
| 120 | 55 |
| 150 | 58 |
| 180 | 54 |
| 210 | 40 |
| 240 | 35 |

| | |
|---|---|
| 270 | 30 |
| 300 | 20 |

**Table 2: dc=50mm, dw=85mm**

| OPERATION TIME (min) | COLLECTION EFFICIENCY (%) |
|---|---|
| 30 | 73 |
| 60 | 70 |
| 90 | 75 |
| 120 | 40 |
| 150 | 50 |
| 180 | 39 |
| 210 | 35 |
| 240 | 35 |
| 270 | 18 |
| 300 | 20 |

**Table 3: dc=75mm, dw=64mm**

| OPERATION TIME (min) | COLLECTION EFFICIENCY (%) |
|---|---|
| 30 | 84 |
| 60 | 70 |
| 90 | 60 |
| 120 | 58 |
| 150 | 55 |
| 180 | 50 |
| 210 | 48 |
| 240 | 38 |
| 270 | 35 |
| 300 | 20 |

## 4. CONCLUSION

The maximum collection efficiency of the designed ESP was found to be near 80% during the initial period. The collection efficiency decreased as the dust loading increased. Results show that the gap between the collection plate electrodes has a greater influence on efficiency than the distance between the wire electrodes. In practice, the minimal distance between the collection plate electrodes should be about 50mm for safe and efficient operation. The efficiency was reduced from 80% to 70% when CVT was about 2kg/m, which corresponds to about two hours of operation. The efficiency of the cleaning system increased after 120 minutes. The ESP used in this study is suitable for the small and medium-sized enterprises (SMEs) using wood combustion for production because it is low in cost and the efficiency is sufficient to alleviate emissions of detrimental chemicals like PAHs into the atmosphere.

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