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Selection of an Appropriate Particulate Matter (PM) Separation Device for a Proposed Waste Incineration Plant

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Abstract

Purpose: Waste incineration facilities are the most widely used Waste to Energy (WtE) technology employed in developed economies in the disposal and management of Municipal Solid Waste (MSW). A major drawback of waste incineration facilities is the enormous volume of toxic emissions emitted from these facilities. Particulate Matter (PM) is a complex combination of either solid or liquid particulates produced from the combustion of MSW that are suspended in the air. These particles which are carcinogenic are therefore required to be separated from the emissions from the waste incineration plants prior to its emission into the atmosphere.

Materials and Methods: The cyclone, fabric filter, and Electrostatic Precipitators are typical PM separation devices that are employed in conventional coal-fired power generation plants. The adoption of these devices in waste incineration plants therefore require studies to select an appropriate one for use. In this study various models of the waste incineration plants were simulated using the Aspen Plus software aim at selecting an appropriate PM separation device for use in a proposed waste incineration plant in Ghana.

Findings: The study concluded that the fabric filter and the ESP are the optimum PM separation devices, achieving an overall separation efficiency of 99.54% and 99.45 % respectively for all particle sizes. The fabric filter was therefore, adopted for use in the proposed waste incineration plant.

Implications to Theory, Practice and Policy: It is recommended, however, that a techno-economic analysis is performed on the use of the fabric filter and ESP in the proposed waste incineration facility.

Keywords: *Waste Energy, Municipal Solid Waste, Particulate Matter, Cyclone, Fabric Filter, Electrostatic Precipitators*

1.0 INTRODUCTION

According to a report from the World Bank (Kaza *et. al.,* 2018), the global annual generation of Municipal Solid Waste (MSW) is approximately 2.01 billion tonnes, and this is projected to rise to around 3.4 billion tonnes by 2050. The World Energy Resource Council (World Energy Council, 2016) has also projected that Africa's per capita urban MSW generation (measured in kg/day) is currently 0.65 and is expected to steadily increase to about 0.85 by 2025. This increase in waste generation is attributed to factors like population growth, industrialisation, improved living standards, and urbanisation (Solheimslid *et. al.*, 2015; Ni *et. al*., 2006; Patwa *et. al.*, 2020; Han *et. al*., 2018).

While waste incineration has proven advantageous in industriliazed nations, reducing MSW mass by up to 75 % and volume by up to 95 % (The Worldbank, 1999) and contributing to electricity generation, there are associated drawbacks. The combustion of MSW in incineration plants can lead to the generation of toxic gases. The composition of these gases depends on the specific fuel being burned. Combustion processes come with the release of huge volume of exhaust gases, and waste incineration plants are no exception. The pollution from the emission of flue gases from waste incinerators has been a major setback of the waste incineration technology, therefore, it is very important to employ mechanisms that can mitigate the effects of these emissions from waste incinerators. Emission control strategies employed in waste incineration plants are generally grouped into two, thus operational, and Air Pollution Controls (APCs) systems. Operational controls (also referred to as combustion controls) are usually employed in modern waste incineration plants to increase the plants performance in respect to its efficiency and at the end reduce the formation of certain emissions that would have been generated by the plant. APCs (also referred to as post combustion controls) on the other hand are employed in modern waste incineration plant to treat the emissions before they are released into the atmosphere. To meet stringent emission limits set out by environmental protection agencies in developed nations, both control strategies are an integral part of modern waste incineration facilities.

Operational controls (also referred to as combustion controls) are employed on modern waste incinerators to limit the conventional and trace contaminants that would be produced during the combustion process. These controls are to compensate for the natural variability in the quality of MSW as fuel and controls factors that govern the rate of chemical reactions. There are basically three conditions that must be fulfilled to aid in the reduction of organic emissions, and these are; complete mixing of the fuel (which in this case is MSW) and air, maintaining sufficiently high temperatures in the combustion chamber in the presence of sufficient oxygen, and the prevention of the formation of low temperature pathways (what is referred to as quench zones) that may allow partially reacted solids or gases to exit from the combustion chamber. This current research work forms part of a research investigation with a broader aim of proposing the optimal integration of WtE in Ghana and focuses on the selection of an appropriate particulate matter separation device that can be employed in the proposed waste incineration facility for optimum performance.

2.0 LITERATURE REVIEW

Air Pollution Controls (APCs) are designed to clean by products from combustion of the MSW emanating from the combustion chambers of the incinerators and boilers to acceptable levels set out by environmental protection controlling agencies. The various elements comprising the APCs systems are integrated to create a cohesive and efficient overall system designed to treat pollutants within the flue gases. Flue gases or the by-products from the combustion of MSW consists of:

i. Gaseous products of combustion mainly carbon dioxide hydrogen chloride, oxides of nitrogen, sulphur dioxide, and others depending on the composition of the MSW.
ii. Vapour forms of organics and as well as that of metals, and
iii. Solid Particulate Matter (PM), also referred to as fly ashes.

Particulate Matter (PM) is a complex combination of either solid or liquid particulates produced from combustion processes that are suspended in the air. In waste incineration plants this solid particulate matter must be removed from the flue gas stream before it exits the stack into the environment. There are basically three types of PM separation devices that are employed in the separation of PM from flue gases emanating from waste incineration plants. These are the cyclone, fabric filter, and electrostatic precipitator.

Cyclone

The cyclone (also referred to as cyclone separators, cyclone collectors, inertial separators, or centrifugal separators), is a type of PM separation device which is operated by using inertial and centrifugal forces induced by cyclone to create a double vortex on the gas stream to remove heavy particles in the gas. Cyclones may be used in single or in multiples. Cyclones are used to control PM which are primarily greater than 10 μm in aerodynamic diameter. There are, however, high efficiency cyclones design which can effectively remove PM between 2.5 μm to 10 μm in aerodynamic diameter. Although, the collection efficiency of cyclones is affected directly by the cyclone's design and particulate size, but generally, its collection efficiency increases with increase in the following; Inlet duct velocity, cyclone's body length, particle size and/or its density, number of gas revolutions in the cyclone, the ratio of cyclone body diameter to gas exit diameter, dust loading, and the smoothness of the inner walls of the cyclone employed. An increase in the following factors, however, will cause a decrease in the cyclone's removal efficiency; gas viscosity, body diameter, gas exit diameter, gas inlet duct area, and gas density.

There are three designs of the cyclone PM removal device, namely, conventional, high-efficiency, and high-throughput. Figure 1 shows a diagram of a cyclone PM removal device.

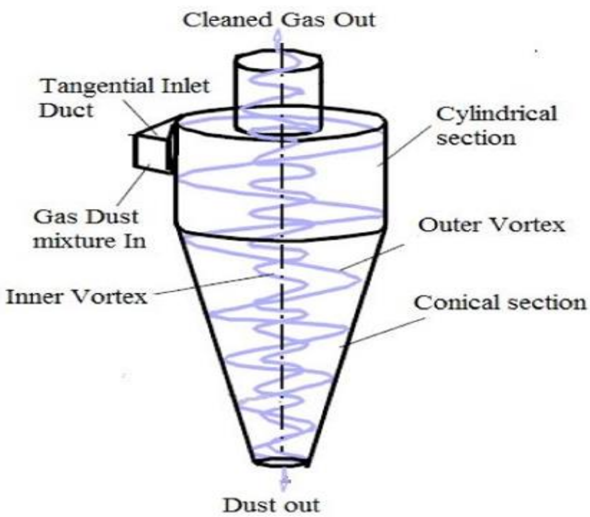

Figure 1: Diagrams of a Cyclone PM Removal Device

Source: Gawali et. al., 2014

The separation (or control) efficiency for a conventional single cyclone is estimated to be between 70 to 90 % for PM_{20}, 30 to 90 % for PM_{10} and 0 to 40 % for $PM_{2.5}$. High efficiency single cyclones are designed purposely to achieve higher control efficiencies for smaller particles than that in the single conventional cyclones. Cooper (1994) estimated that high efficiency single cyclone can achieved efficiencies up to 90 % in control of PM_5 with efficiencies higher than 90 % when removing particles greater than 5µm. The separation efficiency for high throughput is estimated to between 80 to 99 percent for PM_{20}, 10 to 40 % for PM_{10}, 0 to 10 % for $PM_{2.5}$. Vatavuk (1990) reported that high throughput PM cyclones is only guaranteed for PM sizes of 20µm. EPA (1998) reported removal efficiencies of between 80 to 95 % for 5µm can be achieved with the use of multicyclone.

Fabric Filter

A fabric filter, commonly known as a baghouse, functions as a device for separating particulate matter (PM) by employing fabric filtration to extract particles from a polluted gas stream and deposit them onto the fabric material. The process of filtration primarily occurs when the gas stream containing particles is directed through the fabric material, typically a porous and solid medium, which captures the particles within the gas. The filter's effectiveness in removing fine particles is attributed to the build-up of dust rather than solely relying on the properties of the fabric itself. Figure 2 shows a diagram of a typical fabric filter PM removal device.

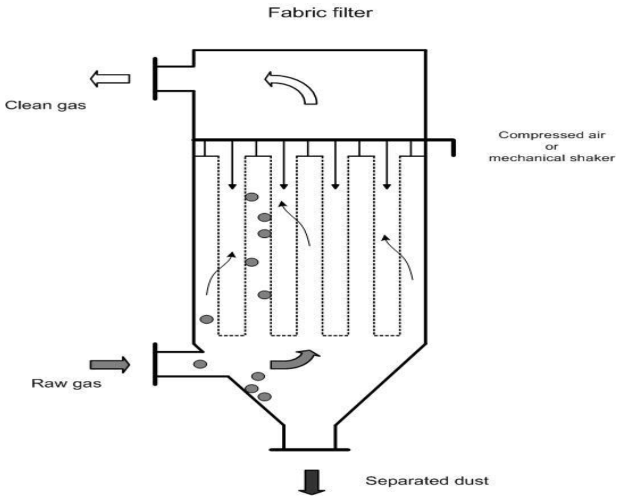

Figure 2: A Fabric Filter PM Removal Device

Source: Emis, 2020

According to the Environmental Protection Agency (EPA) in 1998, fabric filters are reported to achieve collection efficiencies exceeding 99 %. Essentially, there are three main types of fabric filters in use: the shaker baghouse, reverse air baghouse, and pulse jet baghouse. In sizing and operating a baghouse, two fundamental parameters are typically considered: the air-to-cloth (A/C) ratio and the pressure drop across the filters. Other factors that significantly influence the performance of baghouses include the particle size distribution, the composition of the fly ash, the temperature, moisture levels, and the dew point of the flue gas (Miller, 2010).

Electrostatic Precipitator

An Electrostatic Precipitator (ESP) is a PM separation device which removes particles from a gas stream by using electrical energy to charge particles (either negatively or positively). The charge particles are then removed by the collector material either as dry material (in dry ESPs) or washed from the surface with the use of water (in wet ESPs). ESPs are reported to be capable of achieving collection efficiencies above 99 % (Zukeran *et. al*., 1999). Figure 3 is a diagram which illustrates the operation of an ESP particulate matter separation device.

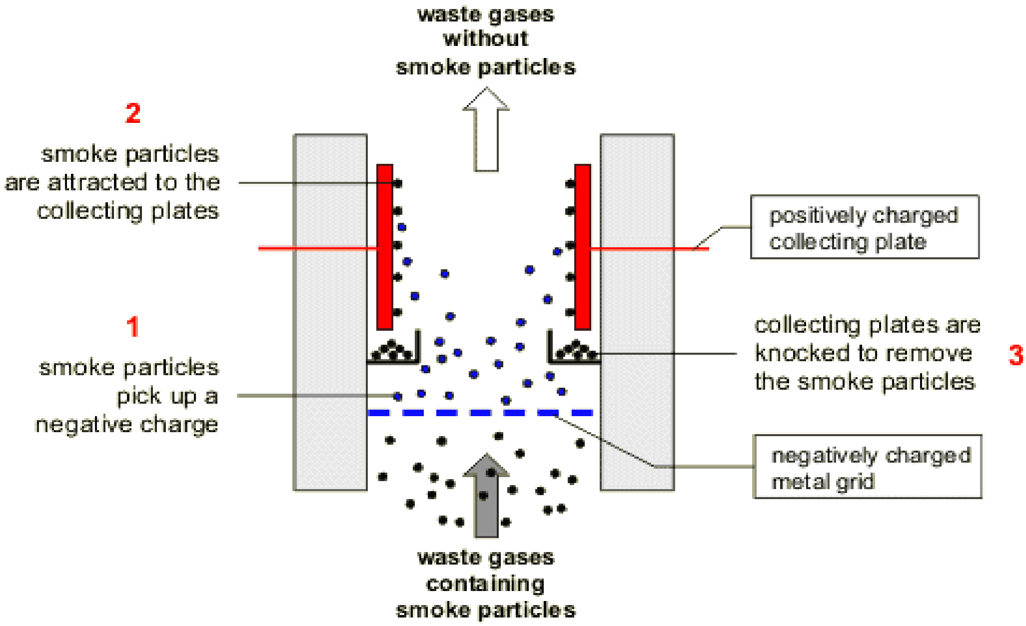

Figure 3: A Diagram of an ESP PM Removal Device

Source: Enviraj, 2018

There are four main components that are used in ESPs to function. These are the gas distribution plates, discharge electrodes, collection surface (which can be a plate or a pipe), and the rappers. The gas distribution plates comprise multiple perforated plates and serve to ensure proper flow distribution of the flue gas stream upon entry into the device. The discharge electrodes are typically divided into two or more fields arranged in series, powered by a Transformer Rectifier (T-R) set power supply. The collection plate or pipes provide the surfaces where charged particulate matter is attracted. The rappers play the role of dislodging the collected particulate matter from the collection surfaces.

ESPs are generally categorized as either dry or wet. The primary distinction lies in how the collector plates or pipes are cleaned. In dry ESPs, cleaning is achieved through mechanical impulses or vibrations that dislodge the loosely collected particulate matter (also known as rapping). Conversely, in wet ESPs, cleaning is accomplished by rinsing the collector plates or pipes with water.

3.0 MATERIALS AND METHODS

Various models of the proposed waste incineration plant were modelled and simulated using the Aspen Plus® software. The integrated system is divided into four subsystems that were simulated using Aspen Plus®. The four subsystem models simulated in this study are described as follows;

Firstly, the waste incineration plant model is simulated to determine the temperature of the flue gases that exits the waste incinerator, the volume of emissions (volumetric flow rate of flue gases exiting the incinerator), as well as flow rates of the various constituents of the flue gas. The waste incineration plant model is the same model that was used in the particulate matter (PM) separation assessment.

Block Flowchart of the Proposed Waste Incineration Plant

The integrated system block flow chart for the proposed waste incineration plant used in this research is depicted in Figure 4. MSW are first fed into the incinerator/boiler, where sufficient air is added to aid in complete oxidation of the MSW. After combustion of the MSW in the incinerator/boiler, the flue gas (which carries with it a high energy and particulate matter) and ash are produced. While ash is collected at the bottom, the flue gas stream exits into a Heat Recovery Steam Generator (HRSG). After heat exchange with high pressure water to produce high pressure steam, the flue gas is cooled down further (to 160℃) before entering a particulate matter (PM) separation device. At this stage, PM is separated from the flue gas stream using either a cyclone, filter bag, electrostatic precipitator PM separation device or a combination of them. The flue gas stream then goes into the wet Flue Gas Desulphurization (FGD) device, where water and aqueous calcium carbonate ($CaCO_3$) are added to clean out acidic gases. The flue gas stream is further cleaned before its release to the environment through a stack. The produced wastewater after acid gas cleaning, on the other hand, is sent to the MD system for treatment prior to reuse or disposal into the environment. The wastewater that goes into the MD system is treated, and produces a cleaned water (Permeate), and the captured solids and the remains in the concentrate (Ret) can be returned to the MD system for further cleaning or disposed.

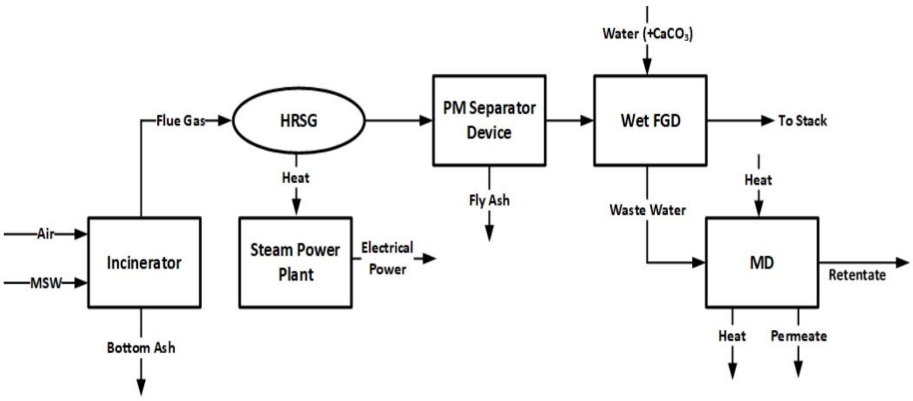

Figure 4: Block Flowchart of the Waste Incineration Plant Used for the Study

Source: Yakah et. al., 2022

Model of the Waste Incineration Plant

In the waste incineration plant, the wet MSW (WET-MSW) is sent into a vessel (DRY-REAC), where hot air (HOTAIR) is mixed with WET-MSW. A calculator block is defined in Aspen plus to control the drying process in another vessel (DRY-FLSH) and the by-products from this vessel are a dry MSW (DRY-MSW) and an exhaust vapour (EXHAUST), which is discharged into the atmosphere.

DRY-MSW is now ready to be combusted. As its composition can vary based on the source and regional factors (e.g., topography, seasons, food habits…), it has been defined as non-conventional in the model. Consequently, for successful simulation of combustion process, DRY-MSW first needs to be defined based on its content. Therefore, an extra vessel (DECOMP) is included in the flowsheet where DRY-MSW is broken down into its various elemental constituents (Q-DECOMPOST). Q-DECOMPOST is then sent into the combustion chamber (BURN), where sufficient air (ATM-AIR) is added to have a complete oxidation of the MSW. Energy is recovered from the flue gases (CPROD-H) from the combustion process in the heat exchanger (HRSG) for the generation of superheated steam (HPSTEAM) which turns a steam turbine (ST-TURB) for the generation of electrical power (WT-TURB). After the recovery of heat energy from CPROD-H, there is a drop in temperature in the flue gas (CPROD-C) before entering particulate matter (PM) separation devices. In the model depicted in Figure 5, all three types (cyclone, bag filter and the electrostatic precipitator (ESP)) of PM removal devices are incorporated. The flue gas stream after the PM separation (ESP-GAS) then goes into the wet scrubbing system for cleaning of acidic gases. Figure 5 is a diagram of a waste incineration Aspen Plus® model flowsheet.

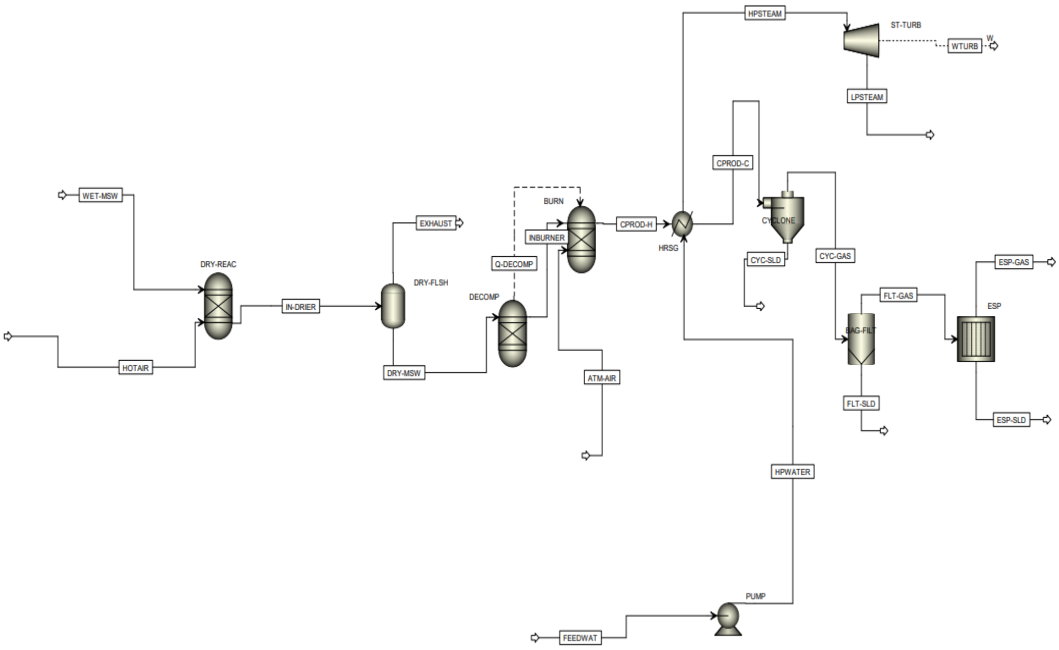

Figure 5: Waste Incineration Plant Aspen Plus® Model Used for the Study

The operating parameters of the various streams and blocks used in the model are specified before simulation. The streams in the model that were specified are (i) WET-MSW, (ii) HOTAIR, (iii) DRY-MSW, (iv) ATMAIR. In addition, the proximate and ultimate analysis of the DRY-MSW is provided in the Proxanal, Ultanal, and Sulfanal sections in the model.

The operating parameters of the blocks that were specified before simulations are (i) BURN, (ii) DECOMP, (iii) DRYFLASH, and (iv) DRY REACTOR. Table 1 list the operating parameters of the streams that are used in the simulation of the waste incineration model, Table 2 lists the proxanal, ultanal, and sulfanal of the MSW used in the simulation, and Table 3 lists operating parameters of the various blocks that are used in the simulation of the waste incineration plant model.

Table 1: Parameters of the Streams Used in the Simulation of the Waste Incineration Plant Model

Stream	Pressure (bar)	Temperature (℃)	Mass Flow Rate (kg/h)	Heat of Combustion (kJ/kg)
WET-MSW	1.01	-	5000	-
HOTAIR	1.01	200.0	1000	-
ATMAIR	1.01	25.0	1000	-
DRY-MSW	1.01	25.0	10 000	7200

Table 2: Proximate and Ultimate Analysis of the MSW Used in the Simulating the Waste Incineration Plant Model

Proxanal		**Ultanal**		**Sulfanal**	
Element	**Value (%)**	**Element**	**Value (%)**	**Element**	**Value (%)**
FC	40.1	Ash	8.4	Pyritic	0.5
VM	51.5	Carbon	67.9	Sulphate	0.1
Ash	8.4	Hydrogen	4.8	Organic	0.7
Moisture	50.0	Nitrogen	1.1		
		Chlorine	0.1		
		Sulphur	1.3		
		Oxygen	16.4		

Table 3: Parameters for the Various Blocks that Were Used for the Simulation of the Waste Incineration Plant Model

Block	Pressure (bar)	Temperature (℃)	Heat Duty (kJ/kg)
BURN	1.01	-	-
DECOMP	1.01	25.0	-
DRY-FLSH	1.01	-	0.0
DRY-REAC	1.01	-	0.0

Particulate Matter (PM) Separation

In performing the technical assessment of PM separation, the same model for waste incineration was used, however, with different arrangement of the PM devices. The devices were incorporated in the model for the assessment as follows, (1) cyclone only (2) fabric filter only (3) ESP only (4) Cyclone and ESP (5) Fabric filter and ESP and (6) Cyclone, fabric filter and ESP. The particles size ranges that were used in the study are 0.0 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.5 µm, 7.5 – 15.0 µm, 15.0 – 26.0 µm.

The flue gases are usually cooled before PM separation, this is usually done to control the production of certain unwanted gases that are produced during combustion of the MSW. A parametric analysis was therefore, performed to assess the effect of cooling of the flue gases on the separation efficiencies of the PM separation devices. The temperature was lowered from 440 ℃ to 240 ℃, and subsequently from 240 ℃ to 120 ℃ during the parametric analysis.

4.0 FINDINGS

Table 4 presents the results from the PM separation assessment. It can be observed from the table that, when only cyclone PM separation device was incorporated, the separation efficiencies for the particle size intervals from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 25 %, 43 %, 59 %, 74 %, and 85 % respectively, with an overall separation efficiency of 69.44 %. It can also be observed from Table 4 that when only the fabric filter was incorporated, the separation efficiencies for the particle size intervals from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 99.03 %, 99.31 %, 99.73 %, 100.00 % and 100.00 % respectively, and an overall separation efficiency of 99.48 %. When only the ESP was incorporated, the separation efficiencies for particle size interval from of 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 96.71 %, 99.99 %, 100.00 %, 100.00 % and 100.00 % respectively, with an overall separation efficiency of 99.54 %.

It can also be observed that when cyclone and ESP was incorporated, the separation efficiencies for the particle size interval from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 97.55 %, 99.99 %, 100.00 %, 100.00 %, and 100.00 % respectively, with an overall separation efficiency of 99.45 %. When fabric filter and ESP was incorporated, the separation efficiencies for the particle size interval from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 98.23 %, 99.99 %, 100.00 %, 100.00 %, and 100.00 % respectively, with an overall separation efficiency of 99.41 %.

When the cyclone, fabric filter and ESP were all incorporated, the separation efficiencies for the particle size interval from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 98.76 %, 99.99 %, 100.00 %, 100.00 %, and 100.00 % respectively, with an overall separation efficiency of 99.49 %. It is therefore evident that the fabric filter and ESP particulate matter separation devices can achieve an overall separation efficiency above 99 % for all particle sizes, which makes the two the best separation devices that should be employed in the waste incineration facilities proposed for used in Ghana. However, the fabric filter separation device is adopted for used because the operation of the fabric filter device does not necessarily consume energy relative to the ESP where electricity is required to charge the particles before separation.

Table 4: Results for the Separation Efficiencies of the Various PM Separation Devices Incorporated into the Waste Incinerator

Particle Size interval	Separation Efficiency					
	Cyclone only	**Fabric Filter only**	**ESP only**	**Cyclone and ESP**	**Fabric Filter and ESP**	**All three**
0.00 – 1.25 µm	0.2496	0.9903	0.9671	0.9755	0.9823	0.9876
1.25 – 3.75 µm	0.4349	0.9931	0.9999	0.9999	0.9999	0.9999
3.75 – 7.50 µm	0.5854	0.9973	1.0000	1.0000	1.0000	1.0000
7.50 – 15.00 µm	0.7428	1.00	1.0000	1.0000	1.0000	1.0000
15.00 – 26.00 µm	0.8527	1.00	1.0000	1.0000	1.0000	1.0000
Overall separation efficiency	0.6944	0.9948	0.9954	0.9945	0.9941	0.9949

The flue gas stream temperature is cooled before PM separation. A parametric analysis was therefore performed, to assess how the cooling of the flue gas stream affects the separation efficiency of the incorporated PM separation device(s). The result of the parametric analysis of the cyclone PM separation device incorporated is presented in Figure 5.

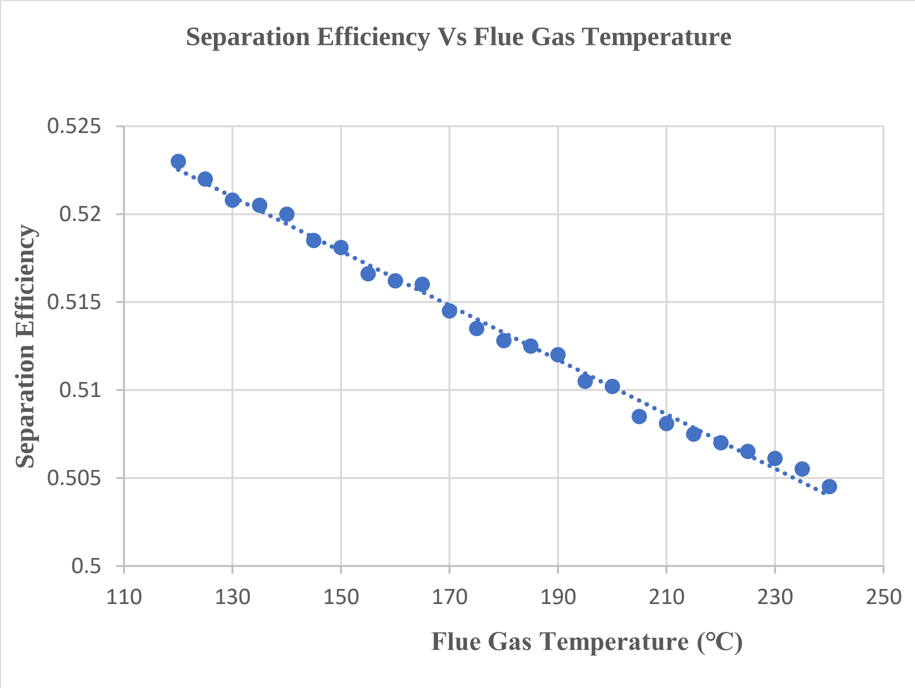

Figure 5: PM Separation Efficiency Vs Temperature of Flue Gas for the Cyclone

It can be observed from Figure 5, that the separation efficiency of the cyclone PM separation device increases with decreasing temperature of the flue gas stream. This can be attributed to the fact that since the cyclone relies on centrifugal forces to separate the particles, it is able to separate larger particles, (that is when the temperature of the flue gas is cooled, the particle sizes or densities increases), however, at higher temperature of the flue gas the particles are smaller and it, therefore, reduces its separation efficiency. However, it was observed that, in the case of using fabric filter and ESP separation devices, the temperature of the flue gases that does not have a significant effect on their separation efficiencies. This can be attributed to the fact the separation efficiency in either the fabric filter or ESP does not depend heavily on the particle's size and/density.

5.0 CONCLUSIONS ANS RECOMMENDATIONS

Conclusions

This research has shown that particulate matter separation devices can substantially minimize the amount of particulate matter that would have been emitted into the atmosphere when using waste incineration facilities. This research has confirmed that the use of ESP and fabric filter can separate particulate matter emitted from waste incineration plants, achieving overall separation efficiencies of 99.45 % and 99.54 % respectively. The fabric filter separation is proposed for adoption in the proposed waste incineration plant to be employed in Ghana, this is attributed to the fact that the ESP although also proved to be effective, however, the operation of the ESP has energy demand which would reduce the net electricity generation from the waste incineration plant.

Additionally, the study also considered combining the various separation devices. It can be concluded that although the overall separation efficiency for the combination was not better than when they were used separately, but in the combination of the ESP and fabric filter there was an improvement in the separation efficiency for particle sizes between 0.00 – 1.25 µm compared to employing ESP only, but the fabric filter only performed better than when it was combined with the ESP. It can therefore be concluded after this study that the fabric filter would perform efficiently when employed in the proposed waste incineration plant for use in Ghana.

Although the incorporation of PM separation devices into waste incineration has become integral part of waste incineration facilities, this increases the cost of the plant. It is therefore paramount to ensure the adoption of an appropriate type which can efficiently separate particulate matter from the flue gases emanating from the combustion of the MSW in waste incineration facilities and is cost effective. It is therefore, recommended that a techno-economic analysis of the ESP and fabric filter particulate matter separation devices are performed in the proposed waste incineration plant.

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Conflicts of Interest

The authors declare no conflict of interest.

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