KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

DESIGN, CONSTRUCTION AND TESTING OF A FLUE GAS FILTER SYSTEM FOR SMALL SCALE INCINERATORS

By

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CERTIFICATION

I hereby declare that this submission is my own work towards the Master of Science degree in Mechanical Engineering at the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana under the supervision of the undersigned and that to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the university, except where due acknowledgement has been made in the text.

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ABSTRACT

Increased public awareness posed by global warming has led to greater concern over the impact of anthropogenic emissions from incinerators. This lead to the development of alternative air pollution control systems such as wet scrubber systems, gravity separators, centrifugal collectors, fabric filters and electrostatic precipitators (ESP). This thesis is aimed at designing, construction and testing of a relatively simple, efficient and practical unit suitable for incinerator exhaust gas cleaning. A low energy orifice wet scrubber was constructed and tested with an existing small scale domestic waste incinerator. The inlet and outlet temperatures of the scrubber were recorded with pyrometers and the chimney outlet measured with infrared thermometer. Smoke samples were passed through filter papers separately at the scrubber inlet and outlet to capture the smoke particles. The particles were observed under microscope at the KNUST Physics laboratory and the results analyzed. The smoke emissions from the incinerator exhaust during the testing of the incinerator were compared to the Ringelmann smoke chart and the smoke density before and after the filter installation determined. The scrubber was able to reduce the smoke density from 21.34 % to 17 %. The test result on particle distribution showed that the scrubber could not collect particle matter (PM) less than 5 µm and particle collection efficiency for PM greater than 30 µm was more than 80 percent. Mean particle size diameter at scrubber inlet and outlet were 73.4 µm and 23.8 µm respectively.

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ACRONYMS

AWMA …………….. Air and Waste Management Association

ESP ……………. Electrostatic precipitators

EPA ……………. Environmental Protection Agency

EPD ……………. Environmental Protection Department

PM ……………. Particulate Matter

MSW ……………. Municipal Solid Waste

WHO ……………. World Health Organisation

NOMENCLATURE

D - Diameter of scrubber

A_S - Cross sectional area of scrubber shell

Q_g - Exhaust gas flow rate

U_g - Flue gas velocity

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background of the project

Incineration process allows complete oxidation of solid wastes, liquids or gases at elevated temperatures. Several communities have adopted diverse ways of waste disposal, for instance burial, disposing in landfill location and hasty disposal in gutters and bushes. These waste dumping systems have been established to be unsafe and not hygienic.

Disposing municipal solid waste (MSW) has become a serious problem in present societies, though, some measures have been adopted to avoid, recycle, reuse and reduce these wastes. Improved and environmentally accepted options for waste disposal include incineration with air pollution control (Quina et al, 2011).

Nevertheless, Ghana, like many other countries is diverting from the precarious and unsafe ways of waste disposal to hygienic waste incineration with energy recuperation which is intended at reducing volumes of waste with little pollution and producing energy as well. A number of incinerators have been constructed in Ghana for domestic waste treatment but all are without air pollution control devices. For instance, the Ghana Education Trust Fund in 2007 to 2008 constructed incinerators in all Girls Senior High Schools in Ghana purposely for sanitary towels disposal but all were without air pollution control devices.

In order to attain the required standards of emission for current incinerators, the use of different air pollution control equipment is important. Such values cannot be achieved by small-scale incinerators which have no particulate control equipment. According to the World Health Organisation, appropriate design and proper incinerator operation should attain necessary temperature, residence time and other conditions to eliminate pathogens and reduce emissions.

Incineration has the aim of taking care of and disposing of waste as well as reducing incinerator emissions and hazards. Small-scale incineration is viewed as an intermediary way of disposal for health-care and domestic waste and hence the need for incinerator flue gas treatment.

1.2 Statement of the Problem

The use of small-scale incinerators appears to be very extensive nowadays and it is preferred to the unhygienic ways of disposing waste in unsecured pits, landfills and uncontrolled burning. The main problems related with uncontrolled burning are the huge volume of gaseous emissions which may cause environmental health risks and the harmful smoke and air pollution residues that remain after incineration.

Incinerator operators are usually exposed to various risk levels of toxins irrespective of their use of standard protective clothing. People living around incinerators are also exposed to some level of emissions. Any method of disposing waste which creates more toxins than the waste put in it is considered an unwise and unsustainable disposal method (GAIA, 2008). Incinerators in general cannot meet the requisite emission standards without the use of emission controls (Bateman, 2004).

High black smoke emission levels are produced by small scale domestic and medical incinerators found in Ghana. There is therefore the need to design and construct air pollution control devices for incinerators to clean exhaust flue gas of small scale incinerators. This will guarantee the use of small scale incinerators as sustainable, environment and operator friendly and hygienic.

1.3 Objectives of the thesis

The main objective of the thesis is to design an air pollution control device suitable for exhaust gas cleaning of small scale incinerators in Ghana for the reduction of black smoke emissions. The specific objectives are:

1. To rehabilitate the existing small scale incinerator at the KNUST mechanical engineering workshop for use as a case study.
2. To design and construct at the KNUST mechanical engineering workshop, a relatively simple, efficient, and a small air pollution control device suitable for gas cleaning of small-scale incinerators
3. To test the air pollution control device to ascertain its performance with regard to black smoke emission reduction.

1.4 Significance of the thesis

The purpose of this thesis is to design, construct and test a filter system suitable for flue gas cleaning of small-scale incinerators in order to reduce black smoke emissions. The thesis also seeks to sensitize people about the need for best practices for incinerator design and construction as well as the inclusion of air pollution control devices in locally manufactured small-scale incinerators to lower emissions to acceptable standards.

1.5 Methodology

Incineration and air pollution control methods would be reviewed. The areas of interest includes the understanding of the various types of air pollution control devices commonly used with regard to small scale incinerators with emphasis on their design and collection efficiencies. The KNUST library, KNUST Journals, books and the internet as well as field surveys would be used.

The proposed scrubber would be constructed at KNUST mechanical engineering workshop. The Ringelmann smoke chart would be used to analyze the flue gas from the stack and the smoke density of the flue gas without scrubbing determined and compared to that with scrubbing.

Flue gas samples at inlet and outlet of the scrubber would be analyzed under a microscope at the KNUST Physics department to determine particle size distribution and the particle collection efficiency.

1.6 Limitation of the study

The study was limited to black smoke emission of small scale domestic incineration. Although scrubbers could remove some gaseous pollutants, their effectiveness with respect to this scrubber was not studied. Factors such as liquid droplets, atomization analysis were not considered in the study.

1.7 Assumption

It was assumed during the testing that the domestic waste used during incineration without scrubbing and that with scrubbing were of the same composition.

1.8 Thesis Organization

The thesis is organized into five chapters. The first chapter is an introduction to the thesis topic. The chapter includes the background of the project, the problem statement, the aims and objectives as well as the significance of the project and the limitations of the project.

Chapter two gives a literature review on incinerators and pollution control devices. This chapter discusses waste classification, the common types of incinerators, incinerator emissions and their control, emission limits as well as various air pollution control devices. Some designed air pollution control systems are also discussed.

The third chapter contains information on the methodology the thesis has used to come up with the proposed scrubber. It includes the design criteria, design requirements, materials selection for construction of the proposed air pollution control device.

The fourth chapter gives the results and discussions regarding the testing of the air pollution control device.

The fifth chapter gives the conclusion and recommendation of the project.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter covers literature review of the study. It includes incineration and incinerator types, waste classification, flue gas emission control, as well as various kinds of air pollution control devices.

2.1 Incinerators and Incineration

Incineration process translates waste into ashes, flue gases and heat (Akhtar et al, 2013). The inorganic constituents of the wastes make up the ash. It is essential that the flue gases are cleaned of gas and particle contaminant before going into the atmosphere.

Incineration process seeks to minimize waste volume and its toxicity and is thus a practical management plan globally used for taking care of the growing combustible municipal solid waste (MSW), which is difficult to be recycled (Akhtar et al, 2013). According to Akhtar et al, (2013), municipal solid waste incineration decrease waste volume (by about 90 %), the mass of the original waste (by about 75 %) of MSW and gives energy but it cannot be regarded as the ultimate way out of treating municipal solid waste.

To attain complete combustion, i.e. change all the HC to CO_2 and water, enough space, time, turbulence and high temperature sufficient to ignite the waste are very essential.

According to Theodore and Buonicore (1988), the "three T's" of combustion; time, temperature, and turbulence, oversee the speed and entirety of the combustion reaction.

According to Jenkins et al (1998), universal equation combustion of wastes in air, can be represented by the form:

$$C_{x1}H_{x2}O_{x3}N_{x4}S_{x5}Cl_{x6}Si_{x7}K_{x8}Ca_{x9}Mg_{x10}Na_{x11}P_{x12}Fe_{x13}Al_{x14}Ti_{x15} + n_1\,H_2O + n_2\,(1+e)\,(O_2 + 3.76N_2) \rightarrow n_3CO_2 + n_4\,H_2O + n_5\,O_2 + n_6\,N_2 + n_7\,CO + n_8\,CH_4 + n_9\,NO + n_{10}\,NO_2 + n_{11}\,SO_2 + n_{12}\,HCl + n_{13}\,KCl + n_{14}\,K_2SO_4 + n_{15}\,C + \ldots\ldots..$$

If the incinerated waste material is represented by a formula like $C_uH_vO_wN_xS_y$, then the combustion equation may be simplified and represented by:

$$C_uH_vO_wN_xS_y + (u+v/4 - w/2 + y)\,O_2 \rightarrow u\,CO_2 + v/2\,H_2O + x/2\,N_2 + y\,SO_2$$

Table 2.1 Classification of wastes

TYPE	DESCRIPTION	APPROXIMATE COMPOSITION % BY WEIGHT	MOSTURE CONTENT %	INCOMBUSTIBLE SOLIDS %	BTU VALUE/LB OF REFUSE AS FIRED
Trash	Highly Combustible waste; paper, wood, cardboard, cartons including up to 10% treated papers, plastics or rubber scraps; commercial and industrial sources	Trash 100	10	5	8500
Rubbish	Combustible waste paper, cartons, rags, wood scrap, combustible floor sweepings, domestic, industrial and commercial sources	Rubbish 80 Garbage 20	25	10	6500
Refuse	Rubbish and garbage	Rubbish 50 Garbage 50	50	7	4300
Garbage	Animal and vegetable waste	Garbage 65 Rubbish 35	70	5	2500
Animal solid and organic waste	Carcass, organs, solid organic waste; from hospitals, laboratories, abattoirs, animal pounds and similar sources	Animal and human tissues 100	85	5	1000
Gaseous liquids or semi-liquid wastes	Industrial process wastes such as tar, paints, solvent and sludge	Variable	Dependent on predominant components	Varies according to wastes	Varies according to wastes
Semisolid and solid wastes	Industrial process waste such as rubber, plastic and wood	Variable	Dependent on predominant components	Varies according to wastes	Varies according to wastes

Source: U.S Army and Air Force, 2003

Table 2.2 Ultimate analysis of a typical general solid waste

Waste content	Typical %
Moisture	35
Carbon	20
Oxygen	18
Hydrogen	2.5
Nitrogen	0.6
Sulphur	0.06
Noncombustible‟s	23.84

Source: U.S EPA (1982), „‟Control Techniques for Particulate Emissions for Stationary Sources.

2.1.1 Advantages of incinerators

Incinerators are equipment that are able to withstand heat and are designed to efficiently decrease waste volumes (U.S Army and Air Force, 2003). The following are some of the advantages of using incineration technique of waste disposal.

- Incineration reduces land filling required for municipal solid waste disposal.
- Incineration also reduces waste volume by 90 percent and weight by 70 percent.
- Incineration gives a likely recovery of energy (electricity or heat).
- High temperature incinerators can destroy pathogens and toxic organic contaminants.

- Incineration requires minimum land as compared to land filling.

2.1.2 Disadvantages of Incineration

The following are some of the disadvantages for using incineration technique of waste disposal.

- Incineration creates hazardous waste that requires safe disposal.
- Incineration creates slag (bottom ashes).
- Incineration creates vast volume of flue gases which may be hazardous.
- Incineration requires high investment, operating and maintenance costs.
- Incineration has negative public opinion because they pollute the atmosphere.

2.2 Types of Incinerators

There are various kinds of incinerators. They can be big or small. Based on daily incineration capacities, incinerators may be grouped as follows:

a. Municipal incinerators
b. Industrial and Commercial incinerators

2.2.1 Municipal incinerators.

Incinerators may be either big or small, with a daily waste burning rate of 50 tons. The two major types of municipal incinerators are as follows:

a. Rectangular incinerators.

Rectangular incinerator is the most common type of municipal incinerators. It has a multiple chamber units that are either water cooled or made with refractories and also has a combustion chamber as well as a mixing compartment where secondary air is added for complete combustion. Usually, it has a settling compartment after the mixing compartment. Primary air is supplied beneath the fire grate while ash is taken out from pits beneath the chambers.

J. K. Nsiah, a former senior lecturer at KNUST has been designing some rectangular incinerators (Figure 2.1) known as Nsiah Incinerator RCT series for medical waste and domestic waste disposal using local materials but all are without air pollution control device. Gas burners and forced draft fans are attached to the incinerators to attain the desired temperature for complete combustion.

Figure 2.1 An Nsiah RCT5 rectangular incinerator at St Francis College of Education

at Hohoe

Source: Nsiah incinerator series, Design and construction Manual, 2012

b. Vertical circular incinerators.

In vertical circular incinerators (Figure 2.2), waste is regularly introduced into the combustion zone from the top. The grates have of a revolving cone located in the center enclosed by a fixed section with a dumping section around it. It has arms coupled to the revolving cone which stir up the waste and brings the ash to the outside. Primary air is supplied below the grate.

Figure 2.2 An Nsiah CT5 circular domestic incinerator at Ada Foah in the Greater Accra Region, showing black smoke emission

Source: Nsiah incinerator series, Design and construction manual, 2012

2.2.2 Industrial and commercial incinerators.

Industrial and commercial incinerators capacities usually vary between half and 50 tons per day. They can be categorized into six types. These are:

1. Single Chamber incinerators
2. Multiple Chamber incinerators
3. Conical incinerators
4. Trench incinerators
5. Controlled air incinerators
6. Fluidized bed incinerators

They are usually operated erratically. The most common types are the single and multiple chamber incinerators.

a. Single chamber incinerators.

Single chamber incinerators have combustion compartment made of refractories and an ash pit which is separated by a grate. It has a supplementary fuel burner usually located below the grate and has no mixing compartment. They are normally operated on natural draft. Emissions from single chamber are high because of incomplete combustion (U.S Army and Air Force, 2003)

b. Multiple chamber incinerators.

Multiple chamber incinerators (Figure 2.3) normally have primary and secondary combustion chambers and a mixing compartment. The primary chamber is comparable to a single chamber unit incinerator. Primary air is added beneath the grate and through over fire air ports. Secondary air is added in the mixing compartment whilst complete combustion is achieved in the secondary combustion compartment. They are usually natural draft.

Figure 2.3 An imported multiple chamber incinerator for Allterian Services Group (ATS) at Newmont Ghana Gold, Kenyasi Mines Plant Site.

Source: Nsiah Incinerator Series, Design and construction manual, 2008

2.3 Incinerator Emissions

Incineration is contributing factor to global air pollution. The pollutants (detailed in Table 2.3) are ash, sulphur oxides (SO_2), chlorides, nitrogen oxides (NO_2), carbon monoxide and hydrocarbons (U.S Army and Air Force, 2003). Generally, present pollution code requirements cannot be achieved by incinerators without air pollution control devices (Batterman, 2004).

Figure 2.4 An Nsiah CT5 incinerator at Old Tafo Government Hospital in Kumasi showing black smoke emissions.

Source: Field survey (picture taken in July, 2015

Table 2.3: Emission factors for refuse incinerators with control[a]

Incinerator type	Particulate lb/ton	SO_2 lb/ton	CO lb/ton	CH_4 lb/ton	NO_2 lb/ton
Municipal					
Multi-chamber, uncontrolled	30	2.5	35	1.5	3
With settling chamber & spray sys.	14	2.5	35	1.5	3
Industrial/Commercial					
Multi-chamber	7	2.5[f]	10	3	3
Single chamber	15	2.5[f]	20	15	2
Wood	13	0.1[g]	N[h]	N	4
Rubber tires	138	N	N	N	N
Municipal refuse	37	2.5[f]	N	N	N
Controlled air	1.4	1.5	Neg	Neg	10
Flue-fed single chamber	30	0.5	20	15	3
Flue fed (modified)	6	0.5	10	3	10
Domestic single chamber					
Without primary burner	35	0.5	300	100	1
With primary burner	7	0.5	Neg	2	2
Pathological	8	Neg	Neg	Neg	3

a - Average factors given based on EPA procedures f - Based on municipal incinerator data g - Based on data for wood combustion in conical burners

N - Not available

Source: U.S Army and Air Force, 2003

Table 2.4 Incinerator pollutants and their environmental effects

Pollutant	Health and Environmental Effects
Acid Gases	
Sulphur dioxide	Aggravates symptoms of heart and lung disease, including coughs and colds, asthma, bronchitis, and emphysema. Toxic to plants. Can erode statues and corrode metals. Precursor to acid rain.
Nitrogen oxides	High concentrations can be fatal; at lower levels, can increase susceptibility to viral infections such as influenza, and irritate the lungs, and cause bronchitis and pneumonia. Toxic to plants. Precursor to acid rain.
Organics	
Dioxins and furans	A proven human carcinogen according to the World Health Organisation International Agency for Research on Cancer. An environmental hormone, dioxin interferes with the body"s endocrine system. Causes reproductive and developmental problems. Linked to high levels of exposure from industrial accidents have resulted in chlordane, altered liver function and skin disorders. Chickoedima disease in birds; linked to breeding failure in herring gulls.
PCBs	In high exposures, can cause chlordane, liver disorders and jaundice.
	May cause birth defects.

Heavy Metals	
Lead	In chronic or acute exposures, children may suffer neurological disorders and women may experience reproductive problems. Probable human carcinogen according to U.S. EPA.
Inorganic mercury	Can cause serious neurological disorders and degenerative kidney problems. Linked to birth defects.
Methyl Mercury	Reproductive toxin. Has been shown to cause tumors in mice at high doses. Also an endocrine-disrupting chemical, impairing normal thyroid functions.
Cadmium	Probable human carcinogen according to U.S. EPA. May cause lung cancer, also linked to kidney disorders.
Chromium	May cause liver and kidney damage and respiratory disorders.
Arsenic	Probable human carcinogen according to U.S. EPA. May cause liver and kidney damage.

Source: www.essentialaction.org

2.4 Emission Limits

Flue gas typically includes nitrogen, carbon dioxide, excess oxygen and water vapour. It also has a small fraction of contaminant such as particulate matter, nitrogen oxide, carbon monoxide and sulphur dioxide (Perry and Green, 1984).

According to the Guidance note of Environmental Protection Department of the US on the best practicable means for incinerators, the entire emissions to atmosphere, apart from steam and water vapour, should be free from persisting mist or fume, colourless and free from droplets. Also emissions from incineration process throughout regular function (together with start-up and shut-down) ought not to emerge to be as dark as or darker than Shade 1 on the Ringelmann Chart when compared correctly with an approved device or the Ringelmann Chart.

Air contaminant released from incinerators must not surpass the concentration restrictions tabulated in Table 2.5 (EPD Guidance notes, 2008).

Table 2.5 Concentration limits for emission from incinerators

Daily average value

Air pollutant	Concentration limits (mg/m^3)
Particulates	10
Gaseous and vapourous organic substance expressed as total organic carbon	10
Hydrogen Chloride (HCL)	10
Hydrogen Flouride (HF)	1
Sulphur dioxide	50
Nitrogen oxides expressed as nitrogen dioxide (NO_2)	200
Carbon monoxide	50

Source: Environmental Protection Department, Air Policy Group, U.S, 2008

2.5 Control of Emissions

Acceptable emission limits cannot only be attained by the use of particulate control devices, but also by the proper design, construction and proper incinerator operation.

Kwakume (2005) designed and constructed a 0.4 m^3, high temperature "Gas boy" medical incinerator as a substitute for placenta pits in hospitals. His design had no air pollution control device but was aimed at controlling emissions by achieving efficient combustion through a fast build up and maintaining high temperature and even distribution of heat to destroy most pathogens at elevated temperatures of about 1200 ^oC using atmospheric burners rated at 158 kJ. His design also aimed at minimizing heat loss through the wall using double layer refractory bricks. Kwakume (2005) concluded that a properly designed incinerator will keep much of the heat for incineration than escape through the walls.

According to the Environmental Protection Department of the U.S, appropriate incinerator furnace design ensures successful destruction of combustible substances in the waste gas. Also, appropriate design and siting of the chimney also helps in reducing emissions from incineration. According to World Health Organisation "Best Practices for Incineration", small scale incinerators must have chimneys higher than 4 m. Also, the velocity of gas leaving the stack must not be lower than 15 m/s at full load condition. The temperature of gas leaving the chimney during incineration should not be lower than 80 ^oC (EPD Guidance notes, 2008).

2.6 Flue Gas Cleaning Equipment for Incinerators

There is quite a number of equipment used for controlling incinerator emissions. The most commonly used devices for controlling particulate emissions include:

- Cyclones
- Wet scrubbers,
- Electrostatic precipitators
- Fabric filters (also known as bag houses)

In several cases, at least two of these devices are used in succession to attain required removal efficiencies. For instance, a cyclone may be employed to collect large particles before a contaminant stream goes into a wet scrubber (AWMA, 2007).

2.6.1 Cyclones

The cyclone is an extensively used kind of particle removal equipment in which contaminant gas goes into a conical chamber tangentially and exit from a central hole. The resultant whirling gas flow cause a tough centrifugal force field in which particles, due to their inertia, break up from the contaminant gas (U.S Army and Air Force, 2003).

Cyclones are most excellent at removing of large particles. They can usually attain efficiencies of 90 % for particulates greater than 20 microns. They are normally employed as pre-cleaners and then other efficient air-filter device such as scrubbers or others may follow the cyclone (http://www.britannica.com/EBchecked/topic/cyclones).

2.6.1.1 Types of Cyclones

Cyclones are commonly classified with respect to their gas inlet design and particle discharge design, removal efficiency and their gas managing capacity, and their array (U.S Army and Air Force, 2003).

a. Conventional cyclone

The conventional cyclone is the most frequently used cyclone. They are employed mainly to remove larger particles when removal efficiency and space necessities are not a main thought. Normally their collection efficiency on 10 μm is 50 to 80 percent.

b. High efficiency cyclone

The high efficiency single cyclone (Figure 2.5) is normally used once greater removal efficiency 80 - 95 percent is a principal concern in cyclone choice. They are generally smaller in diameter than the conventional cyclone and they offer a superior force of separating for similar inlet velocity and a shorter distance for the particle to travel before getting to the cyclone walls.

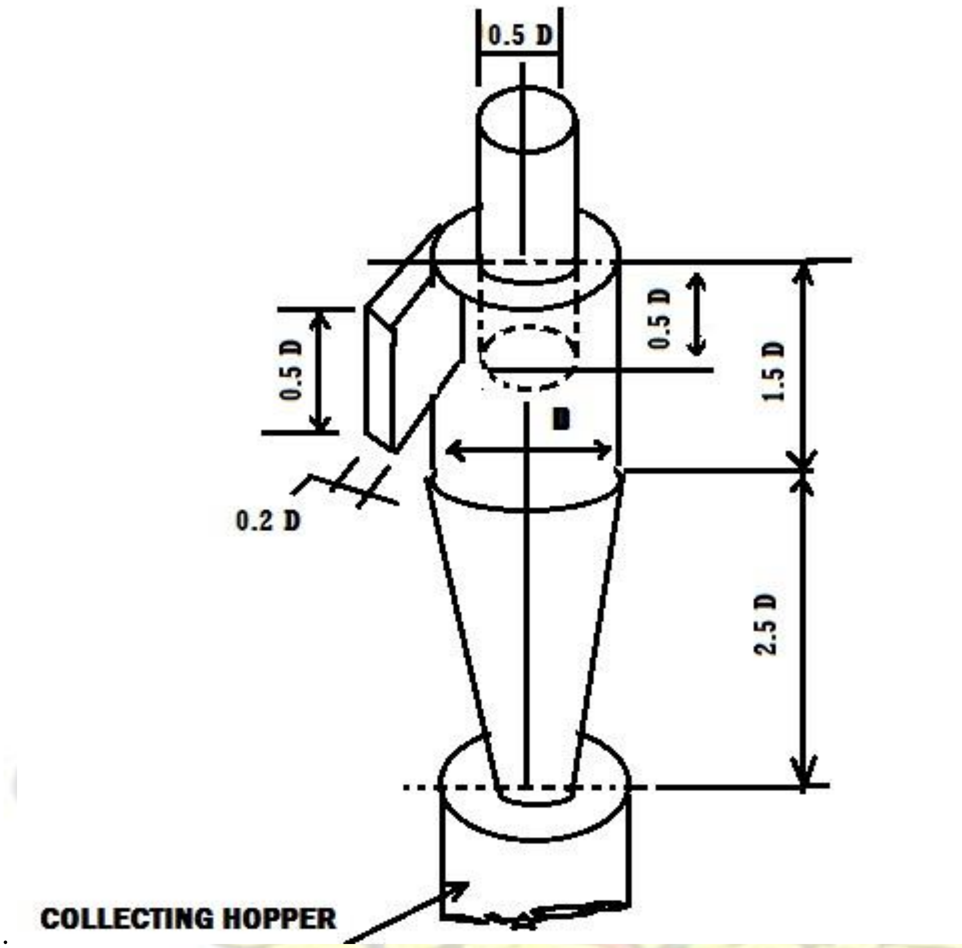

Figure 2.5: High efficiency single cyclone unit (long cone)

Source: U.S Army and Air Force, 2003

c. Multi-cyclones

Multi-cyclone (Figure 2.6) is used in particulate control where high collection efficiencies are desired and large gas volumes are to be handled (U.S Army and Air Force, 2003). They are made up of a combination of several elements arrange with a singular dust hopper, a common inlet and outlet plenums. The function of multi-cyclones may be affected by poor delivery of gas to the various elements, small diameter dust outlet fouling, and air outflow or back flow from the dust hopper into the cyclones (U.S Army and Air Force, 2003).

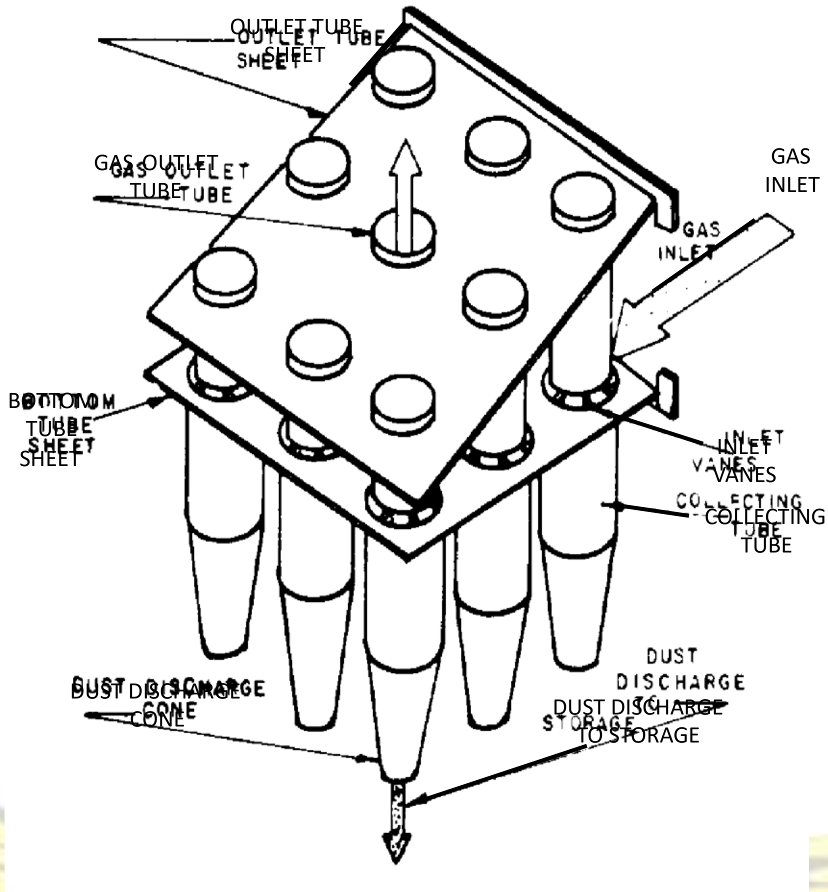

Figure 2.6: High Efficiency Multi-cyclone

Source: U.S Army and Air Force, 2003

2.6.1.2 Cyclone performance

Cyclones are basically used for the collection of particles 50 µm or bigger. Efficiencies over 90 percent for particle sizes of 10 µm or larger is likely to be achieved. Cyclone efficiency rises with particle size diameter as shown in Figure 2.7 as well as gas inlet velocity, with particle density, cone length, and the ratio of body diameter to gas outlet diameter (AWMA, 2007).

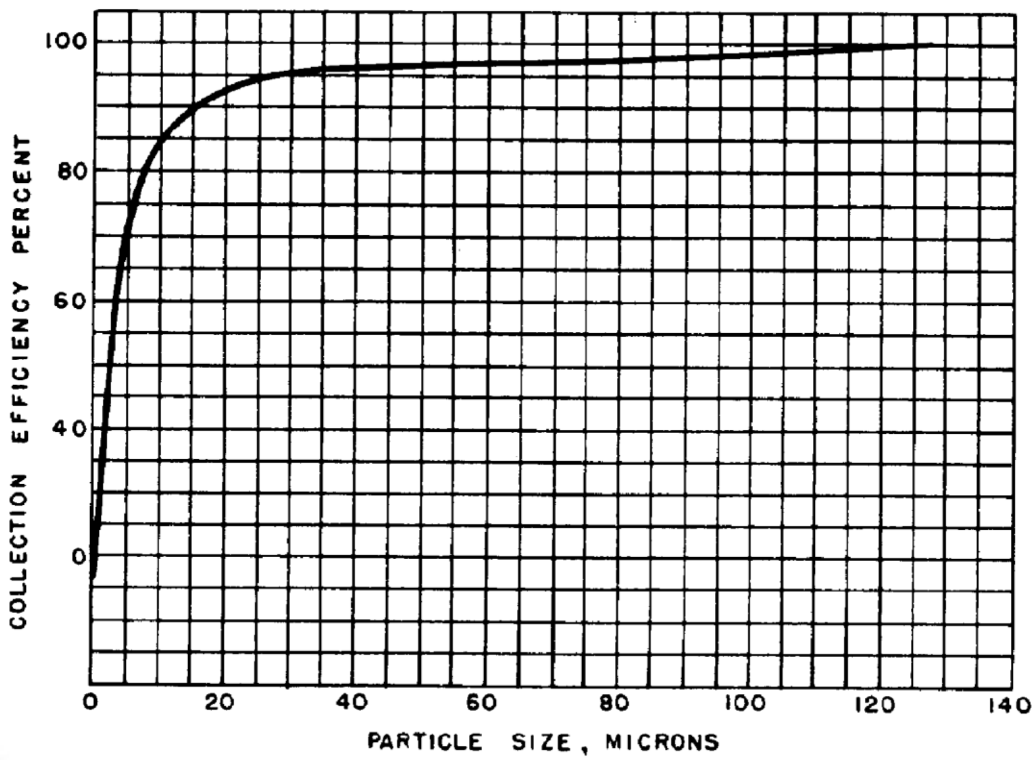

Figure2.7: Size – Efficiency curve for high efficiency cyclone (long cone)

Source: U.S Army and Air Force, 2003

2.6.2 Wet Scrubbers

Scrubbing is a process by which particulates, vapors, and gaseous contaminants are removed from a gas stream by either passing the gas stream through a liquid solution or injecting a liquid into a gas stream (AWMA, 2007). The most frequently used scrubbing liquid is water. A scrubber employs a liquid to collect particles or gaseous pollutants from flue gas. Collection is attained by mass contact between the liquid and gas (U.S Army and Air Force, 2003). Fly ash, hydrogen chloride and sulfur oxides are among incinerator emissions controlled by scrubbing method.

2.6.2.1 Types of Scrubbers

Wet scrubbers can be categorized into two main groups namely, low energy scrubbers and high energy scrubbers.

a. Low energy scrubbers

They are very proficient at gaseous collection than at particle collection. It makes use of a long liquid gas contact time to advance mass transfer of gas and relies on extensive contact surface between the liquid and gas streams to permit removal of particles or gaseous pollutants (U.S Army and Air Force, 2003). Their pressure drops are lower than 12.7 cm (5 in.) of water (Gerald and Beachler, 1998). The four common types of low energy scrubbers are discussed below.

i. Plate-type scrubbers

It is made up of a vertical hollow cylinder which has one or several plates placed transversely in the cylinder. Gas enters at the base of the cylinder, and must go through perforations and other openings or slots in each plate before leaving from the top. Liquid is normally supplied at the top plate, and flows consecutively across every plate as it progresses to the base which is the exit of the liquid. Particle collection is caused by the liquid and gas contact. Plate-type scrubbers can eliminate gaseous pollutants to any preferred concentration on condition that an adequate number of plates are used (U.S Army and Air Force, 2003). They are suitable for particles greater than 1 µm.

ii. Preformed spray scrubbers

A preformed spray scrubber also known as spray tower is a scrubber that removes particulates or gases on liquid droplets and uses spray nozzles for liquid droplet atomization

(U.S Army and Air Force, 2003). The sprays are forced into a chamber duly shaped to carry the gas through the liquid droplets which is atomized. They are intended for less pressure drop and more liquid use. It is an inexpensive process for accomplishing gas absorption because they are simple in design with few internal parts.

Due to the low gas pressure drop, the operating power cost is low. They are very suitable for the collecting of gaseous pollutants with greater liquid solubility. It has higher collection efficiency for particles larger than several microns in diameter (U.S Army and Air Force, 2003).

iii. Orifice scrubbers.

Orifice scrubbers, also known as entrainment scrubbers, utilize a shell that holds a stationary liquid. The contaminant gas stream is directed to move over the scrubbing liquid as it goes through an orifice. With the greater gas velocities noted of orifice scrubber, the liquid from the pool becomes entrained in the gas stream as droplets (Scrubber Manual, 1995). Particulate matter and droplets are then collected from the gas stream by impingement on a succession of baffles that the gas comes across after the orifice. The particulate matter and the collected liquid drains back into the stationary liquid pool below the orifice. Examples of orifice scrubbers are shown in Figures 2.8 and 2.9.

Orifice scrubbers can remove particles greater than 2μm in diameter and has pressure drop varying from 4 to 20 inches, water gauge (US EPA, 1982). Orifice scrubbers typically have low liquid demands, since the same scrubbing liquid can be used for extensive period of time (Cooper and Alley, 1994). They are comparatively simple in design. Orifice scrubbers infrequently drain continually from the base due to the fact that a static pool of scrubbing liquid is required at all times.

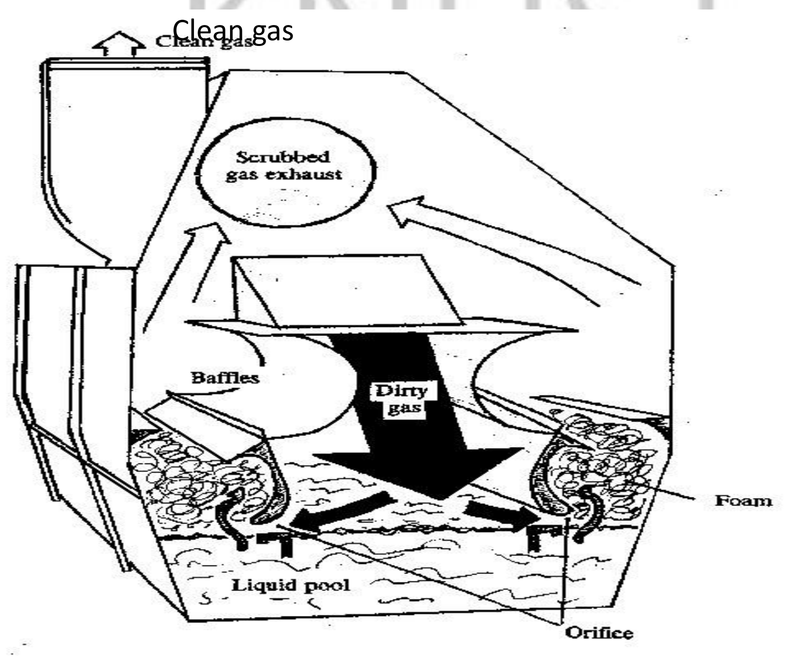

Figure 2.8: Diagram of an Orifice scrubber

Source: Cooper and Alley, 1994

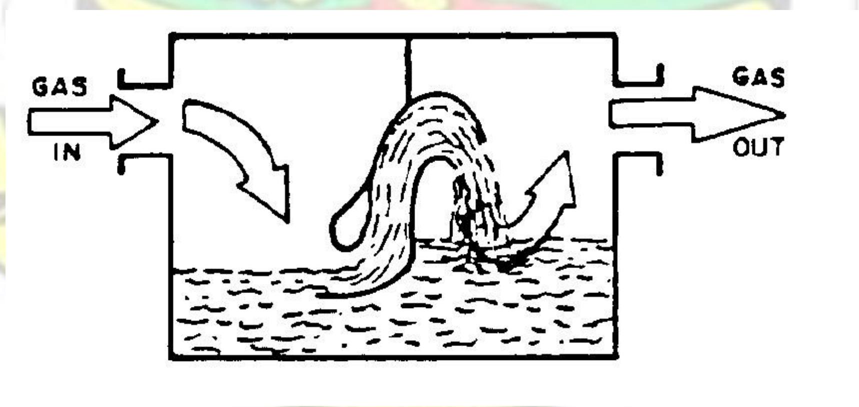

Figure 2.9: Impingement and entrainment scrubber

Source: U.S Army and Air Force, 2003

iv. Impingement plate Scrubber

This type of scrubber (Figure 2.10) consists of a vertical chamber which has plates placed horizontally in a hollow shell with the scrubbing liquid flowing from top to down the tower while the gas stream flows from down to the top of the tower. The contaminant gas and liquid contact take place on the plates. The plates have openings which permit the gas to go through (EPA, 1998).

They are normally designed to give the operator chance to all trays, making them comparatively simple to clean and maintain. Impingement-plate scrubbers are more appropriate for particle removal and can efficiently remove particles larger than 1 μm in diameter, but some particles less than 1 μm in diameter will go through this equipment (EPA, 1998).

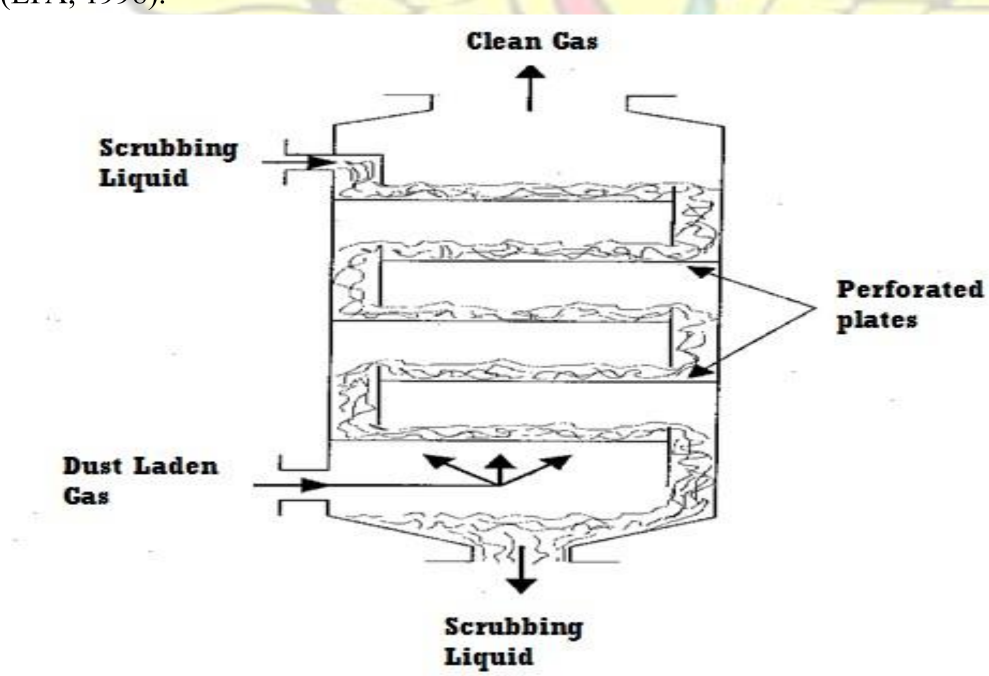

Figure 2.10 Schematic Diagram of an Impingement Plate Tower Scrubber Source: Cooper and Alley, 1994

b. High energy scrubbers.

High energy scrubbers make use of greater gas velocities to promote collection of particulates to sub-micron size. They have pressure drops greater than 38.1 cm (15 in.) of water (Gerald and Beachler, 1998). High energy scrubbers include venturi scrubber, dynamic (wetted fan) and the Ejector venturi with the former been the most common.

i. Venturi scrubbers.

The venturi scrubber (Figure 2.11) uses moving gas stream to atomize and move the liquid droplets. A convergent- divergent nozzle is employed to attain a gas velocity of 60 to 180 m/s that improves liquid atomization and particle collection (U.S Army and Air Force, 2003). In a venturi scrubber, contaminant gas goes into a venturi throat of the scrubber where water and gas achieve greater velocities, creating high turbulence in the water and gas streams, which effect liquid-particle contact. Water is forced into the gas stream either instantly before or at the venturi throat (AWMA, 2007).

Velocity and pressure difference due to the constriction makes numerous small and larger water droplets to form. These droplets collide with the particulates and in effect stick to them. The reduced velocity at the expanded end of the venturi throat permits droplets of water which contains the particles to come together into larger droplets, which then leave the gas stream. Collection efficiency varies by varying gas velocity. The velocity of the gas is adjusted by restricting the area of the venturi throat (U.S Army and Air Force, 2003).

Venturi scrubbers are the most efficient of the wet scrubbers, attaining collection efficiencies greater than 98 % for particles larger than 0.5 micron in diameter and their efficiency depends on the relative velocity between the droplet and particulates (http://www.britannica.com/Ebchecked/topic/625632/venturi-tube).

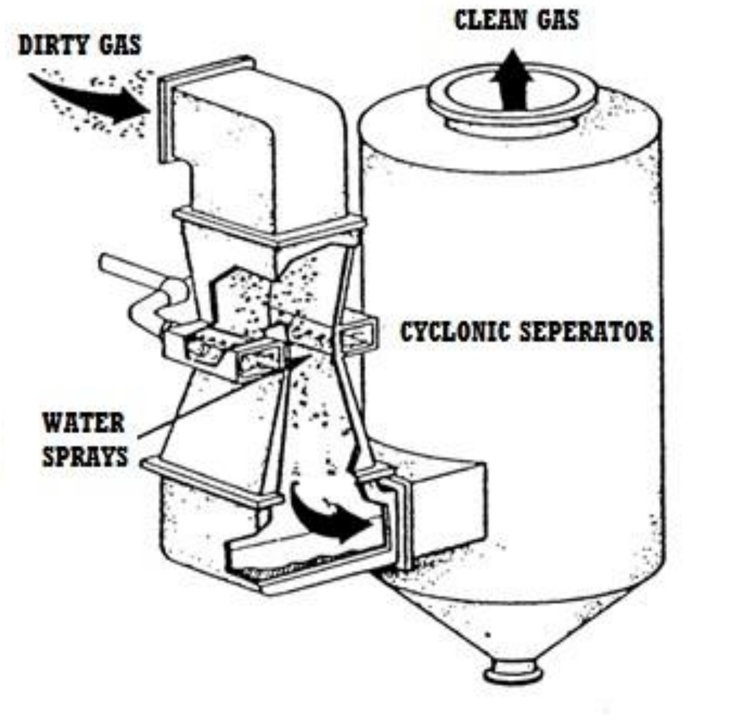

Figure 2.11: Fixed throat venturi scrubber

Source: U.S Army and Air Force, 2003

2.6.2.2 Advantages of Scrubbers

The advantages of choosing wet scrubbers ahead of other particulate control equipment are:

- They have gas absorption ability for collection of dangerous and hazardous gases.
- They can be very efficient in collecting particles, with collection efficiencies of up to 99 percent.

- They are capable of reducing the high exhaust gas temperatures.

2.6.2.3 Disadvantages of Scrubbers

The disadvantages of wet scrubbers include:

- They require energy usage for greater removal efficiency.
- They have huge repair costs.
- It may require exhaust gas reheat to keep plume dispersion.

2.6.3 Electrostatic precipitators (ESP)

It is air pollution control equipment which collects particles from a gas stream. It accomplishes particle collection by utilizing an electric field which passes on a negative or positive charge to the particle and draws the particle to an oppositely charged plate or tube. It then collects the particle from the collection surface to a hopper by shaking or tapping the collection surface (U.S Army and Air Force, 2003). ESPs are comparatively large, low velocity dust collection equipment that collects particles in a manner similar to static electricity in clothing picking up small pieces of lint. Transformers are employed to develop very high voltage drops between collecting plates and charging electrodes. The electric field generated as the gas stream goes through the high voltage field creates a charge on the particles, which is attracted to the collecting plates (AWMA, 2007).

Quina et al (2011) reports that the overall efficiency of ESP is based primarily on the plates and rapper design. Also, the collection zones must be cautiously designed to guarantee the sufficient thickness of laminar boundary layer, so as to avoid reentrainment into the gas stream, the aggregate formed with the collected particles. Usual gas velocities within the precipitation region are at all times below 1 m/s and very often below 0.5 m/s. ESP can be designed to have removal efficiencies of 99.9 % and cannot be used to control SO_2 (U.S Army and Air Force, 2003).

2.6.4 Fabric Filtering System (Bag houses)

Fabric filtration (Figure 2.12) is an efficient technique of dust collection. They can collect acid gases using basic compounds or adsorb some contaminants. They are prepared using a woven or felted material with a cylindrical bag shape or a flat supported envelope. Fabrics used in fabric filtration are made of a number of various materials, selected for the particular application (AWMA, 2007).

During operation, contaminant gas flows through the filters that collect the particulates from the gas stream. Considerable testing has revealed that emission from a fabric filtering system entails particles less than 1 micron in diameter. Collection efficiency for bag houses is 99 % or more (U.S Army and Air Force, 2003).

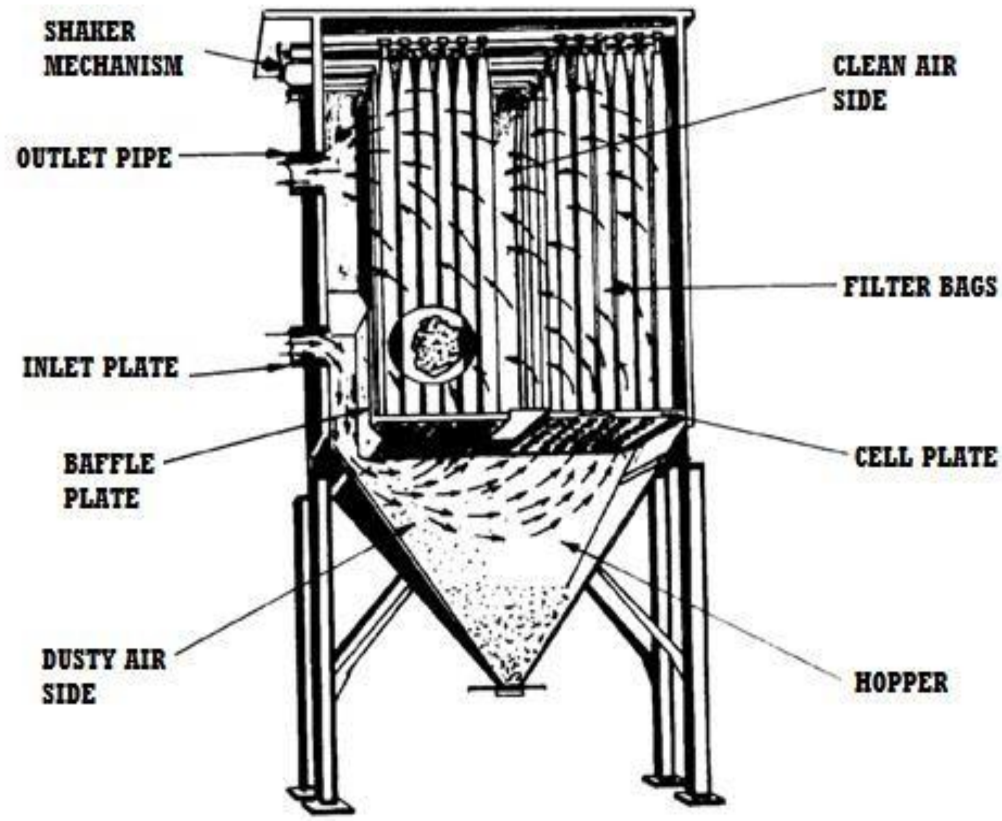

Figure 2.12: Fabric filter system

Source: AWMA, 2007

2.7 Review of some air pollution control device designs

Different pollution control devices have been designed for different purposes. Some have been design for incineration plant flue gas cleaning, industrial air pollution control among others. Below are reviews of some air pollution control device designs.

2.7.1 Performance Evaluation of wet scrubber system for industrial air pollution control.

Danzomo et al (2012) designed a pilot spray tower scrubber method with data from cement industry. According to Danzomo et al (2012), wet scrubbers have significant advantages when compared to other air pollution control devices. They can handle huge volume of gases, can collect dust particle like combustible and explosive dusts, foundry dust cement dusts and can absorb gaseous contaminants, acids, mists, furnace fumes. The design of the pilot spray tower was based on volume flow rate of 29.13 m^3/s, gas density of 0.82 kg/m^3 and dust burden (concentration) of 22 859 $\mu g/m^3$. The scrubber shell had a diameter of 8 m and a height of 16 m. The system focused on the design of a scrubber for the collection of dust particle sizes of 1µm, 5 µm, and 10 µm that are produce from cement production. Liquid to gas ratio of 0.7 to 2.7 ℓ/m^3 proposed by EPA were used to look into the suitable ratio that will give best result for the functioning of the system. It was concluded in the study that the proposed method could be employed in controlling the recommended particle sizes of 5 µm and 10 µm that are released from industrial productions. Maximum removal efficiencies for 5 µm and 10 µm were 99.98 percent and 100 percent respectively at 2.7 ℓ/m^3 and 500 µm droplet sizes, while minimum removal efficiencies for 5 µm and 10 µm were 43.8 percent and 58.728 percent respectively at 0.7 ℓ/m^3 and 200 µm droplet sizes.

2.7.2 Modern flue gas cleaning system for waste incineration plants

A modern flue gas cleaning system was designed by ABB as a total cleaning and Recycling system for gas cleaning of incineration plants, for waste incineration plants to comply with the clean air decree of Europe emission legislation known as the 17^{th} BlmSchV. The design is particularly good when it comes to adsorbing furans and dioxins as well as any leftover mercury remaining after scrubbing. It also gets rid of any hazardous acids, dust and heavy metals that may be present and therefore clean gas values less than detection limits are obtained. The system can simply be retrofitted to older incineration plants.

The scrubber which utilizes a caustic soda solution is a proven ABB design with over 65 modules; 15 of these are part of the waste incineration flue gas cleaning method. The design of the intermediate bottoms and the nozzle lances are among features that makes a critical contribution to the excellent results.

The outcome from a demonstration system in operation in Hobro, Denmark proves the good function of the ABB technology. An assurance value of 70 mg/m^3 was given for the NO_x emissions in the clean gas. This compares with a maximum value of 600 mg/m^3 in the raw gas. Practically, NO_X values of 50 to 60 mg/m^3 are obtained for the clean gas (Jurgen et al, 1996).

2.8 Summary of Literature Review

i. According to Batterman (2004), incinerators in general cannot satisfy present pollution code requirements without particulate control equipment. Emission standards for current incinerators consequently need the use of various air pollution control devices.

ii. Control of emissions cannot only be achieved by the use of particulate control devices, but can also be attained by appropriate design, construction and operation of the incinerator. According to Kwakume (2005) and the Environmental Protection Department of the U.S, appropriate design of incinerator furnace ensures successful destruction of combustible substances in the waste gas. Sufficient and proper control of combustion gas temperature, residence time, and air supply as well as gas turbulence can help accomplish this requirement. Also the appropriate design and siting of the chimney aids in reducing emission from incineration.

iii. Cyclones are not sufficient to achieve strict air quality standards. They are normally employed as pre-cleaners and then other efficient air-filter device such as scrubbers or others may follow the cyclone for further gas cleaning (http://www.britannica.com/EBchecked/topic/cyclones). According to the U.S Army and Air Force (2003), ESPs are not good for SO_2 control. These imply that one particular flue gas cleaning device is not suitable for the emission control of flue gases of incinerators. In several cases, more than one of these pollution control devices is used in succession to obtain preferred collection efficiencies for the contaminants of concern. For instance, a cyclone may be employed to collect large particles before a pollutant stream goes into a wet scrubber for further particle collection (AWMA, 2007).

iv Gerald and Beachler (1998), report that wet scrubbers can attain high collection efficiencies for either particles or gases and, in some instances, can accomplish high collection efficiency for both pollutants in the same system. Nevertheless, in several cases, the best operating conditions for particle collection are the poorest for gas removal. For particulate control, wet scrubbers are evaluated against bag houses and electrostatic precipitators (Gerald and Beachler, 1998).

v. In spite of the extensive literature review, it appears most air pollution control device designs are basically for incineration plants and industrial air pollution control. For small scale incinerator exhaust gas cleaning, the proposed flue gas filter would be an orifice scrubber, because according to Cooper and Alley, 1994, orifice scrubbers have low liquid demands, because the same scrubbing liquid can be used for extensive period of time and are comparatively simple in design.

CHAPTER THREE

DESIGN METHODOLOGY

3.0 Introduction

According to the Environmental Protection Department of the U.S, appropriate design of incinerator furnace guarantees effective destruction of combustible substances in the waste gas. Also, according to the World Health Organisation "Best practices for incineration", small scale incinerators must have chimneys higher than 4 m. There is therefore the need to rehabilitate the model incinerator at KNUST mechanical engineering workshop to meet these standards. Some parts of the dilapidated furnace walls and the stocking door need be reconstructed. The chimney of original diameter 100 mm has to be changed to 150 mm diameter and a height of 4.2 m to enhance the draft. An orifice scrubber was selected as the proposed flue gas filter system, because according to Cooper and Alley (1994), they typically have low liquid requirements, because the scrubbing liquid can be reused for extensive period of time and are comparatively simple in design and usually have little or no moving parts. These advantages of the orifice scrubber satisfy the main objective of this project.

3.1 Design Requirements of the scrubber

The design requirements of the wet scrubber gas filter are to produce a relatively simple, efficient, small and practical unit suitable for gas cleaning. Further significant features are size, capacity, water consumption, maintenance and safety.

The key operating parameters affecting pollutants collection are:

1. Flue gas velocity and gas flow rate
2. Liquid –to-gas ratio

3. Particle size distribution
4. Temperature

3.1.1 Flue gas velocity and gas flow rate

The collection efficiency of various scrubbers is based on the velocity of the stream gas entering the liquid section of the scrubber shell. For particulates, the relative velocity between the scrubbing liquid droplets and particulates is vital to contaminants removal. When a high temperature gas stream goes into the scrubber, the volumetric flow rate reduces as a result (due to the temperature of the scrubbing liquid) the gas is being cooled by the scrubbing liquid. As the system flow rate reduces, the consequential relative velocity may not be enough to collect the required amount of particles and emission will increase (US EPA-ACI Manual, 1985). According to Perry and Green (1985), flue gas flow rate induced by draft of a flue gas stack is given by the equation:

$$Q = CA^{\sqrt{2gH}\left[\frac{Ti - To}{Ti}\right]}$$

Where Q = the flue gas flow rate in m^3/s

A = cross sectional area of chimney in metre square (m^2)

C = discharge co-efficient usually taken as 0.65 to 0.7 g

= acceleration due to gravity (9.81 m/s^2)

T_i = absolute average temperature of gas inside the stack in Kelvin (K)

T_o = absolute outside air temperature in Kelvin (K)
H = stack height in metres (m)

Given discharge co-efficient c = 0.65, stack height (H) = 4.2 m, T_i = 353 K, T_o =

298 K, cross sectional area of chimney (A) = $\pi \frac{d^2}{4}$, diameter of chimney (d) = 0.15m

Therefore flue gas flow rate (Q) = 0.04 m^3/s

The orifice scrubber has a maximum gas flow rate of 1500 ft^3/min (0.7m^3/s) which is ideal for small scale incinerators (Plastic air, 1999).

3.1.2 Liquid –to- Gas Ratio

The liquid-to-gas flow rate is an intended value reflecting the liquid reuse rate (gal/min) for every 1000 ft^3 (28.3 m^3) of gas filtered. Usual values vary from 2 to 40 gallons of liquid per 1000 ft^3 of inlet gas (shown in Table 3.1) and are a function of inlet solids contents, inlet gas temperature and water induction method. High liquid-to- gas ratios are required for high temperature gas streams. When the liquid-to-gas ratio falls below the design value, collection efficiency will reduce.

Table 3.1 Typical Liquid-to-Gas Ratio for Wet scrubbers

Scrubber type	**Liquid-to-Gas Ratio (gal/1000 ft^3)**
Venturi	5 – 8
Cyclonic spray tower	5 – 10
Spray tower	10 – 20
Impingement plate	3 – 5
Packed bed	1 - 4

Source: US EPA Air Pollution Engineering Manual Second AP-40

3.1.3 Particle size distribution

Particulate emission control performance of scrubbers relies on the gas stream particle size distribution. Efficient removal of submicron contaminants confronts the application of all type of controlling devices. Changes in process devices or function can alter the particle size distribution and sequentially, impact collection efficiency (US EPA, 1973). Flue gas samples at the scrubber inlet and outlet would be captured separately on a filter paper and the particles observed under a microscope to determine the particle collection efficiency of the designed scrubber.

3.1.4 Temperature

Wet scrubber inlet and outlet temperatures are key parameters that should be checked when controlling gas streams with high temperature. An increase in temperature could show a malfunction of the cooling device, which will cause a reduction in pollutant collection efficiency and possible damage to the scrubber. According to World Health Organisation "Best Practices for incineration", gas entering pollution control equipment for small scale incinerators must be less than 230 ^{o} C. The prototype orifice scrubber has a maximum inlet temperature of 232 ^{o}C (450 ^{o} F).

3.2 Selection of materials

When selecting materials for scrubber construction, some relevant working parameters must be regarded. Materials for scrubbers essentially depend on conditions of carrier gas velocity, temperature (U.S Army and Air Force 2003). Based on conditions including temperature and abrasion, mild steel of 4mm thickness is the appropriate material for the scrubber construction.

3.3 Criteria for sizing the wet scrubber

According to Daniel and Paula, the waste gas flow rates are very essential factors in designing a scrubber. By knowing the exhaust gas flow rate, and gas velocity, the crosssectional area of the scrubber can be determined by the equation:

$Q_g = A_S \times U_g$ ……………… (1)

Where Q_g = exhaust gas flow rate, A_S= cross-sectional area of the scrubber and U_g = gas velocity.

The factors that affect sizing are gas flow rate, temperature, pressure, gas composition, humidity, contaminant loading and desired outlet conditions. Gas streams entering a wet scrubber may or may not be fully saturated; however, they will leave the scrubber completely saturated. This saturation process causes a change in volume, temperature and density.

On the whole, scrubber diameter is a function of the velocity of saturated gas through the scrubber shell. The saturated volume content can be calculated by knowing the moisture content of a gas stream usually expressed as pounds of water per pounds of dry gas and the inlet temperature. The volume correction chart (shown in Figure 3.1) can be used for a close estimation of the change in gas volume flow rate.

Thus, Inlet volume x correction factor = Outlet volume (saturated)………….. (2).

For wet scrubbers, the maximum capacity is based on shell velocity of 500 ft per minute. The cross-sectional area of the scrubber shell can be calculated using the equation below from which the scrubber diameter can be calculated (SLY Inc, 2009).

$$A_S = \frac{\text{Corrected saturated volume } (ft^3/min)}{500\ (ft/min)} \quad \text{………………………..} (3)$$

$$A_S = \pi \frac{D^2}{4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Where A_S is the shell cross-sectional area in ft^2 and D, is the scrubber shell diameter (ft).

For an inlet volume gas flow rate of 1500 ft^3/min ($0.7 m^3$/s) @ 450 ^{O}F (232 ^{o}C) containing 0.15 H_2O/ dry air, the correction factor is 0.75. From equation 2, the corrected saturated volume is estimated at 1125 ft^3/min. From equation 3, the scrubber cross-sectional area (A_S), is 2.25 ft^2. The scrubber diameter is estimated at approximately 0.5 m using equations 3 and 4. According to Cheremisinoff and Young (1976), usual height to diameter ratio of scrubber shell generally considered is approximately 2:1; hence the scrubber height is estimated at 0.95 m.

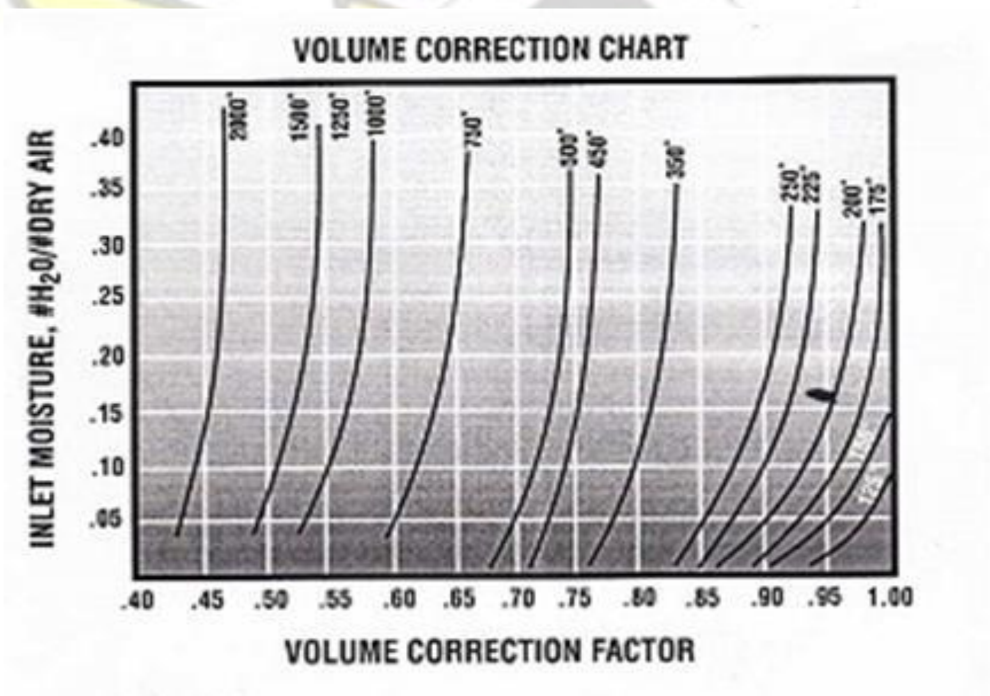

Figure 3.1: Volume correction chart
Source: (SLY Inc, 2009).

3.4 Ringelmann Smoke Chart

The Ringelmann smoke chart provides shades that the density of smoke coming out from a stack may be compared. It is a means for establishing whether emissions of smoke are within permissible limits or standards recognized and expressed with reference to the chart. The chart gives shades of cards 1,2,3,4 on a single sheet which are known as Ringelmann No. 1,2,3,4 respectively. A clear stack is recorded as No. 0 and 100 percent, whiles black smoke is recorded as No. 5 (Rudolf, 1955).

To utilize the chart, it is maintained on a level with the eye; at such a distance from the viewer that the lines on the chart come together into shades of gray, and as almost as possible in line with the stack. The observer glances from the smoke, as it comes out from the stack, to the chart and notes the Ringelmann number most nearly matching with the shade of the smoke and then records this number with the time of observation. To establish average smoke emission over a comparative period of time, such as an hour, observations are normally repeated at one-fourth or one-half minute intervals. For the purpose of this project, the observations would be repeated at every half minute. The readings are then summarized to the total equivalent of No. 1 smoke as a standard. No. 1 smoke being considered as 20 percent dense, the percentage "density" of the smoke for the entire period of observation is obtained by the formula:

$$\text{Smoke density} = \frac{\text{Equivalant number of units of No.1 smoke}}{\text{Number of Observations}} \times 20 \text{ percent}$$

The Ringelmann chart would be used to compare the smoke from the stack of the small scale incinerator at KNUST mechanical engineering workshop.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.0 Introduction

The constructed flue gas orifice scrubber filter was coupled to the model domestic refuse incinerator of capacity about 0.7 m^3 at the KNUST mechanical engineering workshop for testing as shown in Figure 4.2. The smoke from the stack was observed for an hour at an interval of every half minute and compared to the Ringelmann smoke chart. The scrubber inlet and out temperatures as well as the stack temperatures were also recorded. The results obtained have been tabulated and discussed in this chapter. Flue gas sample at scrubber inlet and outlet were trapped on separate pieces of papers and the particulate matter analyzed under microscope and the results analyzed.

4.1 Description and operation of the flue gas filter device

The constructed flue gas filter device (Figure 4.1 and Figure 4.2) was operated on impingement and entrainment scrubbing method. A cylindrical shell of diameter 0.5 m and height 0.95 m was used as the scrubber shell. It was constructed with 4mm mild steel plate. It has a laden gas inlet of diameter 0.1 m and a clean gas outlet of diameter 0.1 m with a clean water inlet and a dirty water outlet at the top and bottom of the scrubber respectively. Scrubbing liquid (water) of 90 liters (20 gallons) is contained in the scrubber shell with an orifice between the liquid and the impingement baffle.

During incineration, the flue gas stream from the combustion chamber, flows through a pipe which opens into the scrubber through the scrubber inlet. Flue gas is directed to move over the surface of the scrubbing liquid. Scrubbing is accomplished when the high velocity particle-laden gas stream passes over the surface of the pool of scrubbing liquid as it enters the orifice to form jet streams. With reasonably high gas velocities, the liquid from the pool becomes entrained in the gas stream as droplets.

Particulate matter and droplets are then taken out of the gas stream by impingement on a baffle that the gas comes across after the orifice. The collected liquid and particle matter drain from the baffle back into the scrubbing liquid. Cleaned gas leaves the filter device through the scrubber outlet located on top of the scrubber and flows through the stack and then to the atmosphere.

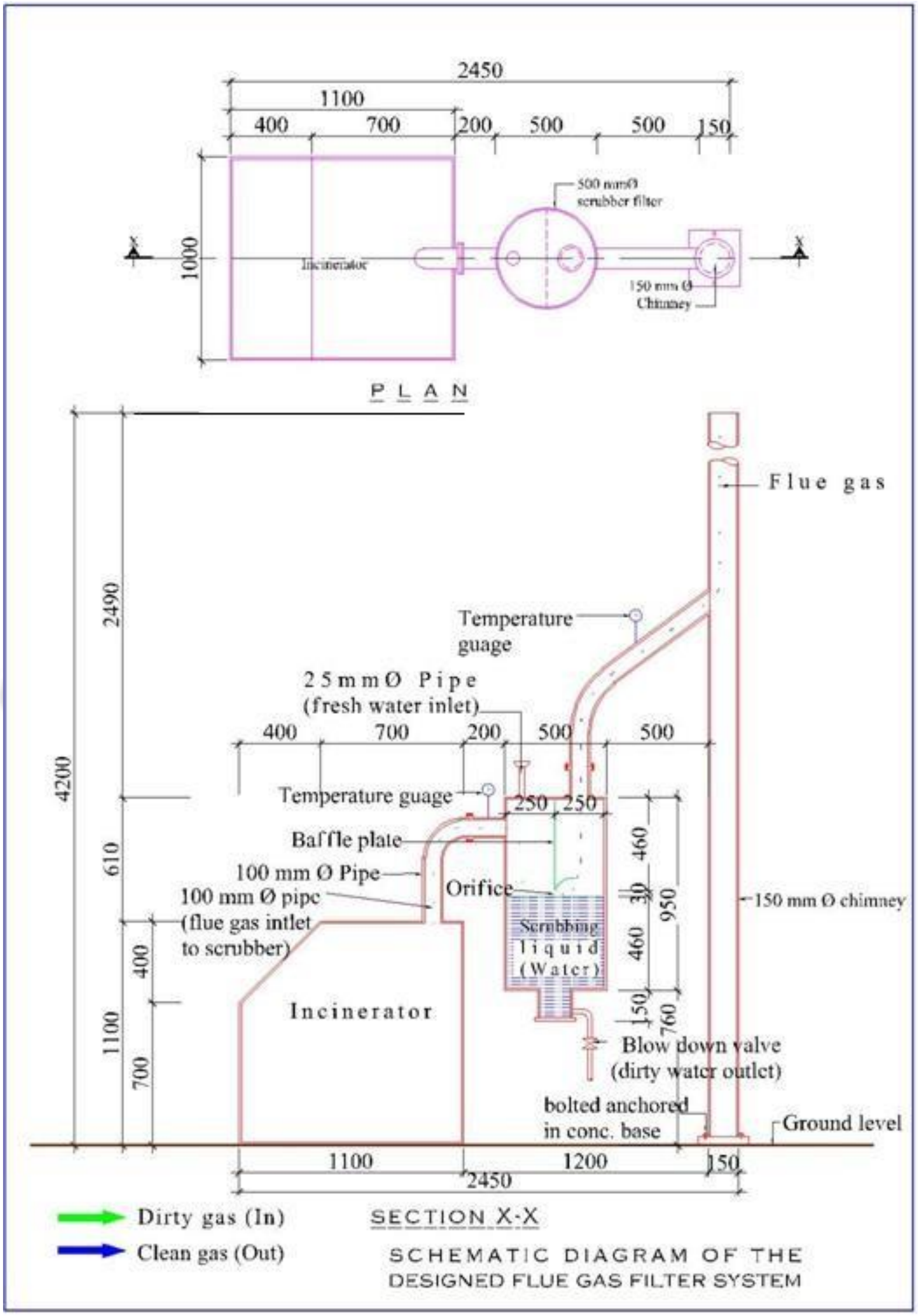

Figure 4.1: Drawing of the prototype orifice scrubber

Figure 4.2 Picture showing test firing of the incinerator

4.2 Test Results on the Ringelmann Chart Reading

The results for the Ringelmann chart readings with and without scrubbing have been recorded in Tables 4.1, 4.2, 4.3, and 4.4.observaions were done every half minutes for an hour given a total of 120 observations for each case.

Table 4.1 Ringelmann Chart Readings (for flue gas without scrubbing)

Time (min)	**0**	**½ min**	**Time (min)**	**0**	**½ (min)**	**Time (min)**	**0**	**½ (min)**	**Time (min)**	**0**	**½ (min)**
1	0	0	16	1	1	31	1	1	46	1	1
2	0	0	17	1	1	32	1	1	47	0	0
3	2	2	18	2	2	33	1	1	48	0	0
4	1	1	19	2	2	34	1	1	49	1	1
5	1	1	20	1	1	35	1	1	50	1	1
6	1	2	21	1	1	36	1	1	51	1	1
7	2	2	22	1	1	37	1	1	52	1	1
8	2	2	23	1	1	38	1	1	53	1	1
9	1	1	24	1	1	39	1	2	54	1	1
10	1	1	25	1	1	40	2	2	55	1	1
11	1	1	26	2	2	41	2	1	56	1	1
12	1	1	27	2	2	42	1	1	57	0	0
13	1	1	28	2	1	43	1	1	58	0	0
14	1	1	29	1	1	44	1	1	59	0	0
15	1	1	30	1	1	45	0	0	60	0	0

Table 4.2 Summary of flue gas readings (without scrubbing)

Ringelmann Smoke No.	Number of observations	Equivalent No. 1 smoke
Unit No.0	12	0
Unit No.1	88	88
Unit No.2	20	40

Table 4.3 Ringelmann Chart Readings (with the flue gas filter connected to the model incinerator)

Time (min)	0	½	Time (min)	0	½ (min)	Time (min)	0	½ (min)	Time (min)	0	½ (min)
1	0	0	16	1	1	31	1	1	46	0	0
2	0	0	17	1	2	32	1	1	47	0	0
3	1	1	18	2	2	33	0	0	48	0	0
4	1	1	19	2	1	34	0	0	49	1	1
5	1	1	20	1	1	35	1	1	50	1	1
6	1	2	21	1	1	36	1	1	51	1	1
7	2	2	22	1	1	37	1	1	52	1	1
8	1	1	23	1	1	38	1	1	53	1	1
9	1	1	24	1	1	39	1	2	54	1	1
10	1	1	25	1	1	40	2	2	55	1	1
11	0	0	26	1	2	41	1	1	56	0	0
12	0	0	27	2	2	42	1	1	57	0	0
13	0	0	28	2	1	43	1	1	58	0	0
14	1	1	29	1	1	44	1	1	59	0	0
15	1	1	30	1	1	45	0	0	60	0	0

Table 4.4 Summary of flue gas readings (with the filter connected)

Ringelmann Smoke No.	Number of observations	Equivalent No. 1 smoke

Unit No.0	32	0
Unit No.1	74	74
Unit No.2	14	28

4.3 Determination of smoke Densities

The smoke densities for the flue gas emissions observed with and without the scrubber were as follows:

4.3.1 Determination of smoke Density (without scrubbing)

Total number of observations = 120

Equivalent number of units of No. 1 smoke = 128

Smoke density $= \frac{\text{Equivalant number of units of No.1 smoke}}{\text{Number of Observations}} \times 20 \text{ percent}$

Smoke density = $\frac{128}{120} \times 20$ percent

Smoke density = 21.34 percent

4.3.2 Determination of smoke Density (when the gas filter was used)

Total number of observations = 120

Equivalent number of units of No. 1 smoke = 102

$$\text{Smoke density} = \frac{\text{Equivalant number of units of No.1 smoke}}{\text{Number of Observations}} \times 20 \text{ percent}$$

$$\text{Smoke density} = \frac{102}{120} \times 20 \text{ percent}$$

Smoke density = 17 percent

4.4 Temperature Readings

The scrubber inlet, outlet and stack temperatures during the test firing the incinerator were recorded at an interval of every five minutes for an hour and the corresponding graph shown in Figure 4.3.

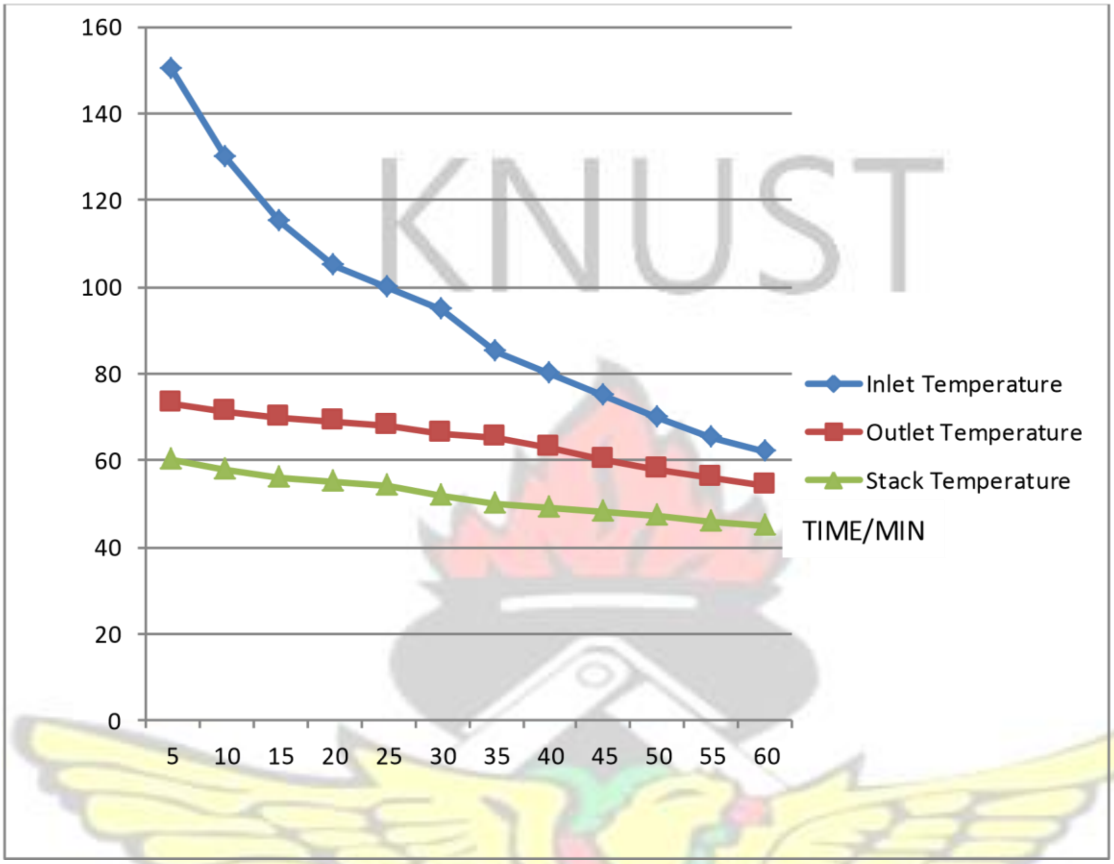

Figure 4.3 Graph of inlet, outlet and stack temperatures against time

4.5 Test Results on the Particle size distribution

Test results on the flue gas at scrubber inlet and outlet are shown in Tables 4.5 and 4.6 and the corresponding size – efficiency curve shown in Figure 4.4.

Table 4.5 Emission factors for different size fractions of particulate matter for the flue gas at scrubber inlet

Particulate matter PM (µm)	Size fraction %
Fine particles (PM < 5)	0
Coarse particles (5 < PM < 20)	5
Large particles (20 < PM < 30)	10
Very large particle (PM > 30)	85
Total suspended particles	100 %

Mean particle size at scrubber inlet 73.4 µm

Table 4.6 Emission factors for different size fractions of particulate matter for the flue gas at scrubber outlet

Particulate matter PM (µm)	Size fraction %
Fine particles (PM < 5)	0
Coarse particles (5 < PM < 20)	5
Large particles (20 < PM < 30)	80
Very large particle (PM > 30)	15
Total suspended particles	100%

Mean particle size for scrubber outlet 23.4 µm

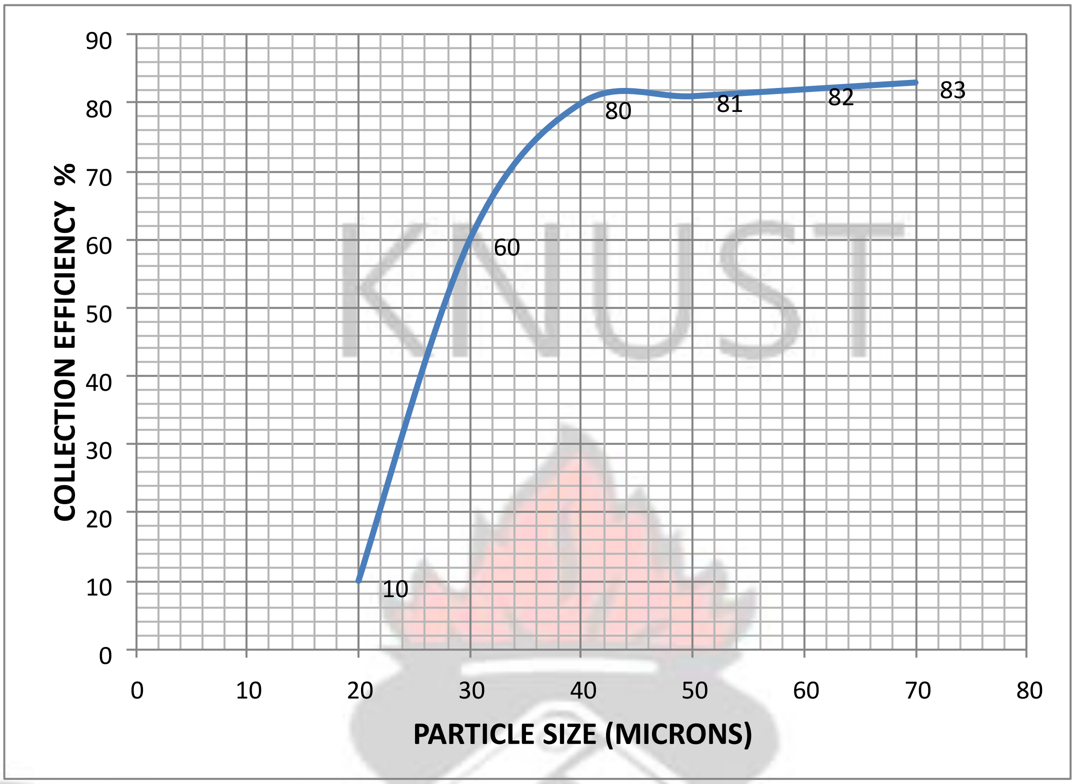

Figure 4.4 Size – Efficiency curve for the prototype orifice scrubber

4.6 Discussion of Results

From the temperature graph (Figure 4.3), it took a maximum of 5 minutes for the inlet, outlet and stack temperatures to rise to their maximum during start up. The temperatures kept on diminishing with increasing firing time till shut down.

According to the Environmental Protection Department of the U.S, the temperature of the exhaust gas leaving the chimney during incineration process must not be less than 80 ºC at full load condition. The maximum stack temperature recorded was 60 ºC and the corresponding inlet gas temperature was 150 ºC. To maintain a stack temperature of 80 ºC and above, it is important to ensure that the scrubber inlet temperature is not more than 230 ^{o}C.

According to the Guidance note of Environmental Protection Department of the US, smoke emission from incineration process during normal operations (together with startup and shut-down) should not appear to be as dark as or darker than Shade 1 on the Ringelmann chart when compared correctly with the Ringelmann chart or an approved device. The smoke emission from the test incineration process (together with start-up and shut-down) did not appear to be as dark as or darker than Shade 1 (20 percent dense) when compared in an appropriate manner with the Ringelmann chart. Thus, the smoke density was 17 percent. This means the smoke was within acceptable emission limits.

The flue gas particulate matter analyzed showed that the scrubber could not collect particulate matter (PM) less than 5 µm. According to US EPA, 1982, orifice scrubbers can effectively collect particles larger than 2 µm in diameter. From the size – efficiency curve (Figure 4.4), the collection efficiency of very large particles, thus PM greater than 30 µm was more 80 percent. Mean particle size diameter at scrubber inlet was 73.4 µm while mean particle size diameter at scrubber outlet was 23.8 µm. This shows that particles involved in the flue gases from the furnace are of sizes 15 µm to 73.4 µm. The scrubber filters particles of sizes greater than 24 µm successfully. The size – efficiency curve for the prototype scrubber can be likened to that of the high efficiency long cyclone with higher collection efficiencies at particle sizes greater than 20 µm in diameter.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The main objective of the thesis was to design, construct and test a simple and efficient flue gas filter for small scale incinerator flue gas cleaning. Following analysis of incinerator application in Ghana, literature studies and theoretical analysis as well as local materials available, the orifice scrubber was selected, designed, constructed and retrofitted to the model incinerator at KNUST mechanical engineering workshop.

The designed scrubber was able to reduce smoke density of flue gas from 21.34 percent to 17 percent, hence satisfying the main objective of the study.

The scrubber could not collect particle matter (PM) less than 5 μm and particle collection efficiency for PM greater than 30 μm was more than 80 percent. Mean particle size diameter at scrubber inlet and outlet were 73.4 μm and 23.8 μm respectively.

5.2 Recommendations

The study was limited to refuse waste incineration. It is recommended therefore that a further study should focus on the scrubber to ascertain its performance on medical and industrial waste.

It is also recommended that a further study should focus on the scrubber‟s performance with varied orifices.

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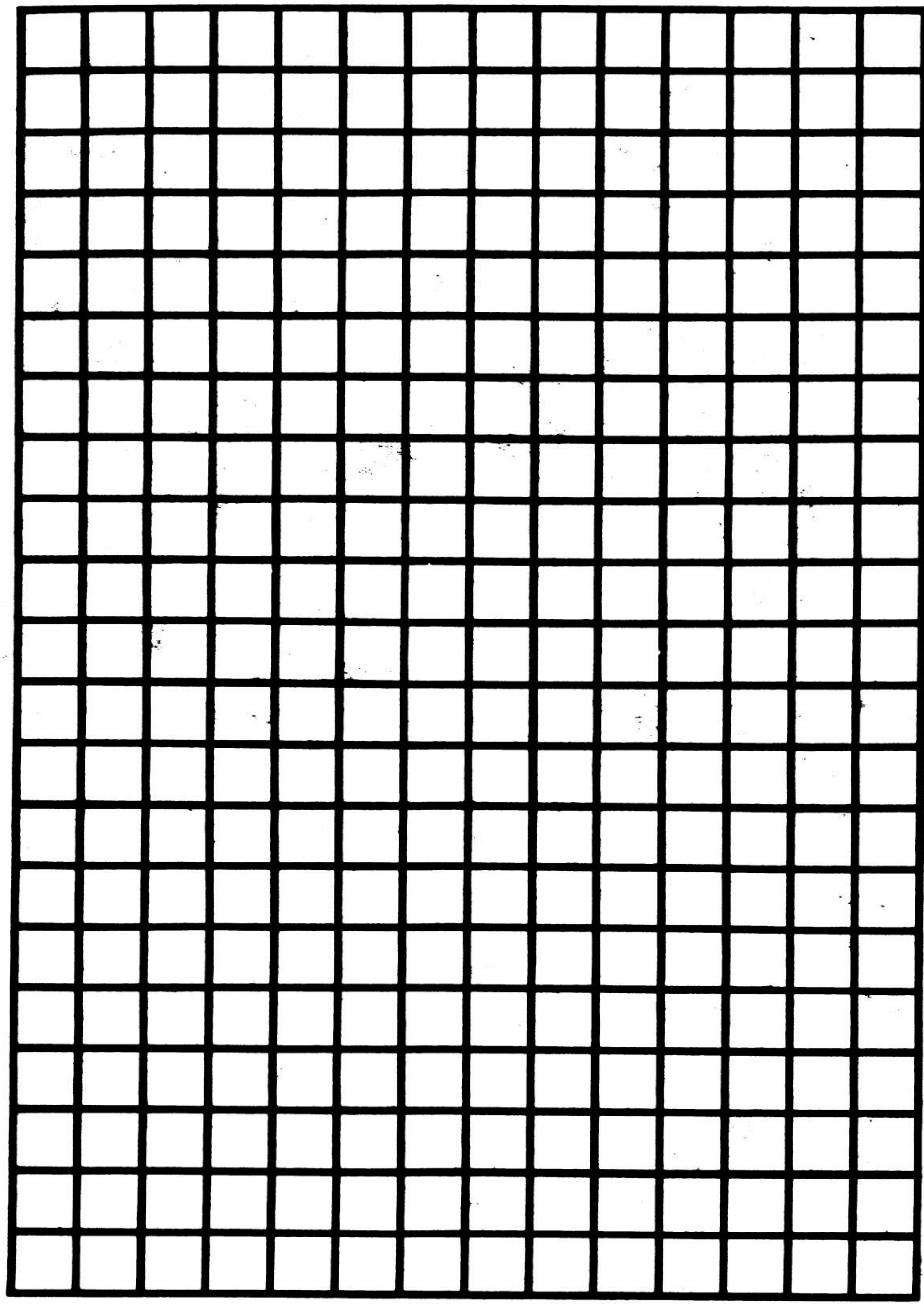
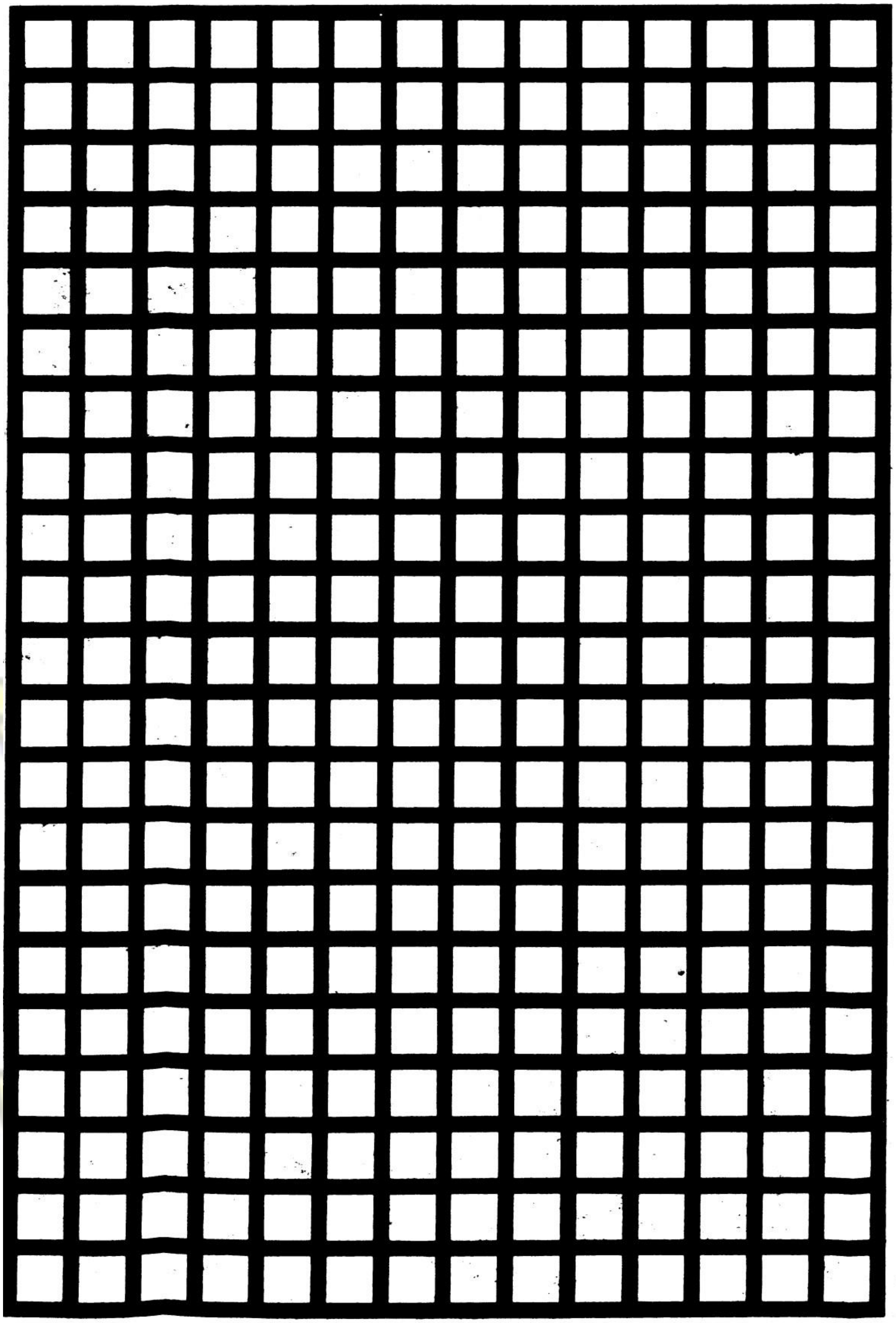
APPENDIX: Ringelmann Smoke Charts

Ringelmann Smoke Chart Shade No. 1



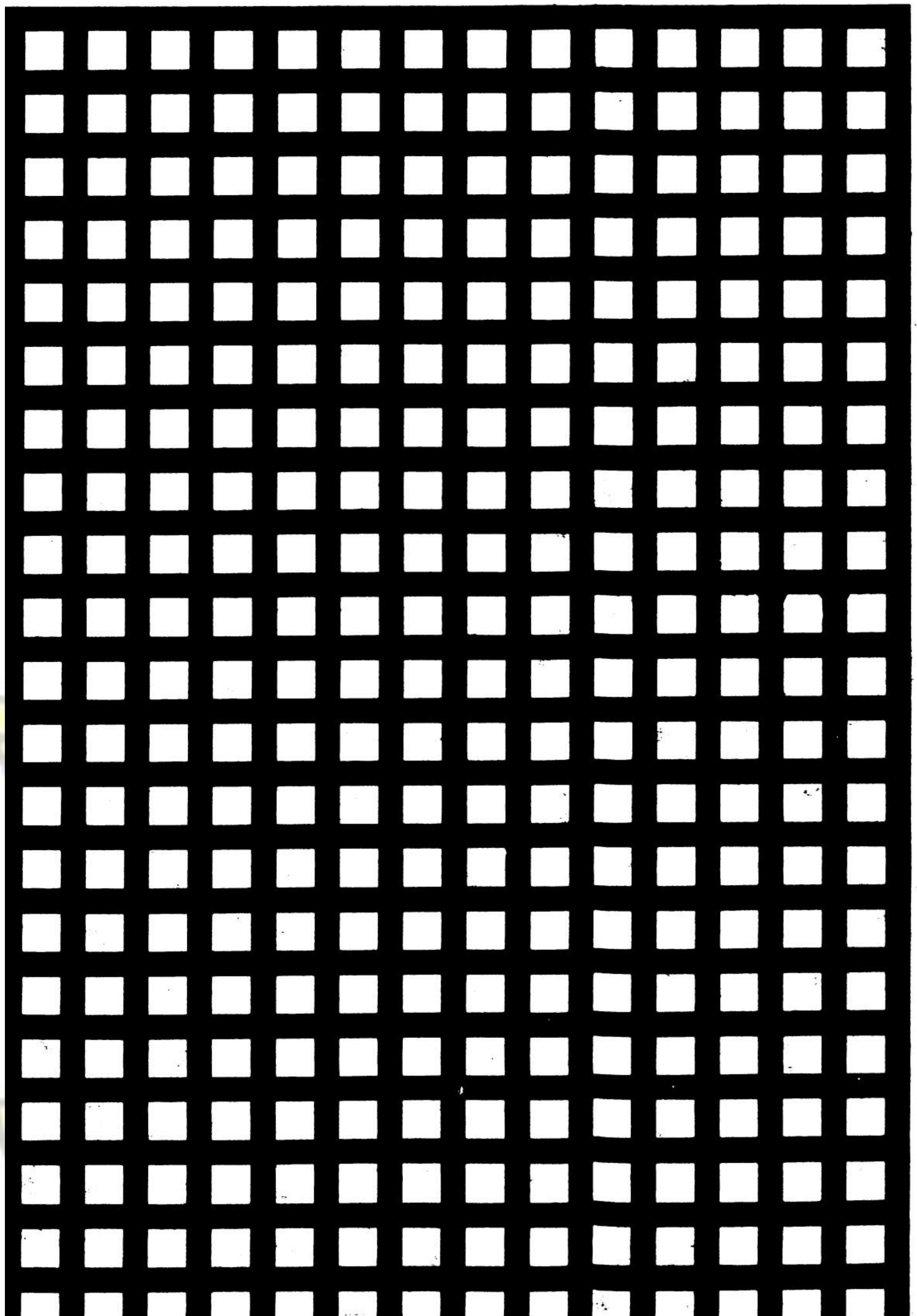
I. EQUIVALENT TO 20 PERCENT BLACK.

Ringelmann smoke chart shade No.2



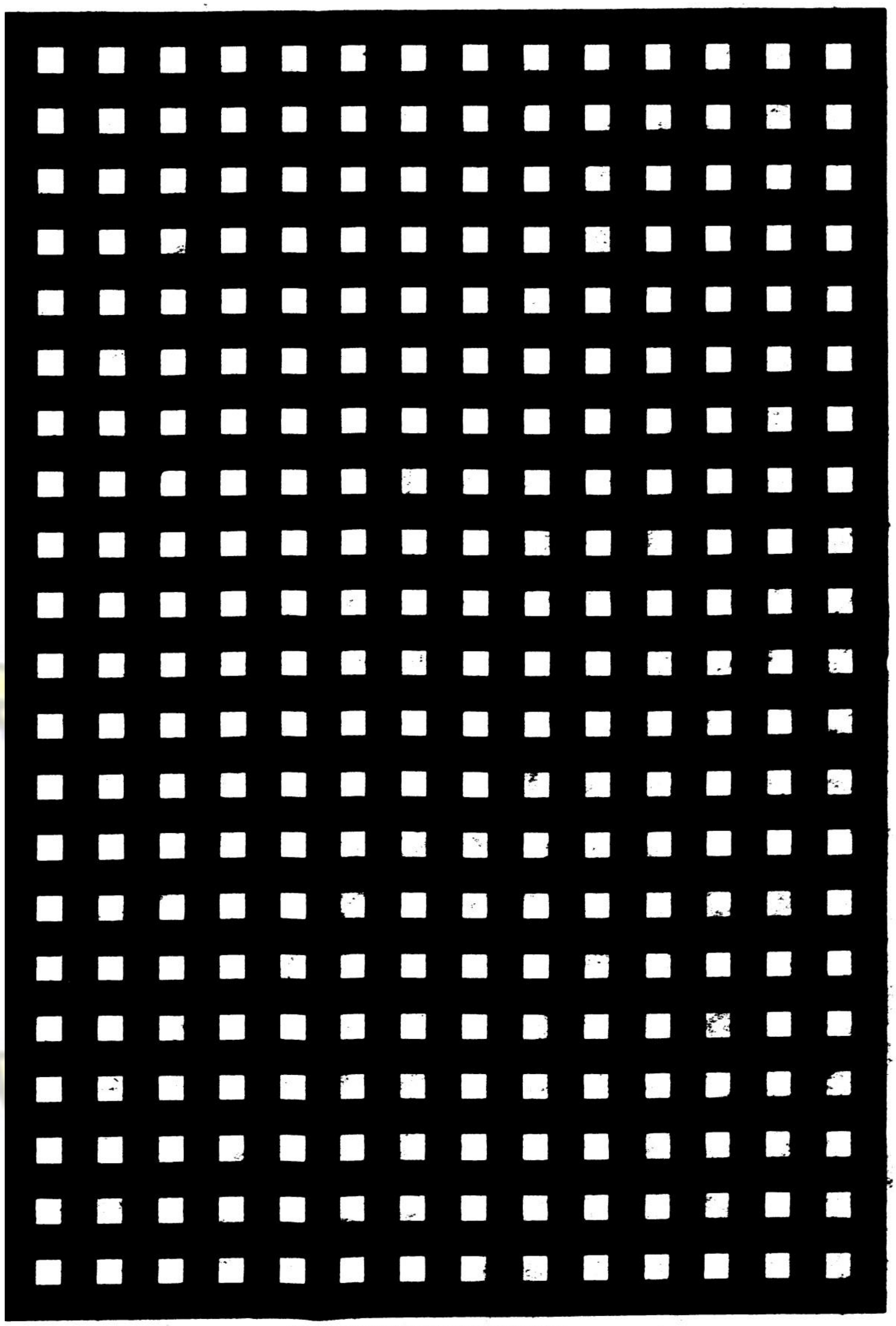
2. EQUIVALENT TO 40 PERCENT BLACK.

Ringelmann smoke chart shade No. 3



3. EQUIVALENT TO 60 PERCENT BLACK.

Ringelmann smoke chart shade No. 4



4. EQUIVALENT TO 80 PERCENT BLACK.