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Optimization of incineration process

Omari, Arthur Mngoma

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OPTIMIZATION OF INCINERATION PROCESS

Arthur Mngoma Omari

A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

Municipal solid waste management has become a challenge in many cities in the developing countries due to the poor methods of waste disposal, which increase the risk of the spread of diseases, leach and increase the demand of land for waste disposal. Characterization study of waste samples from Arusha shows that the combustible fraction is about 87% and biodegradable is 80%. The Thermal gravimetric analyser and Bomb calorimeter show the energy value of about 12.5 MJ/kg and the degradation of about 85%. The study shows that the municipal solid waste disposal method can be thermal, biological or physical. However, thermal method by incineration process is the most preferred and convenient because it destroys pathogens and reduces waste volume in the fastest way. The waste flow analysis of Arusha city shows that the waste has the annual recoverable potential of 128GWh. The case study used an existing incinerator as showed the variation of effluents with operating conditions. The design optimization using computational fluid dynamic techniques to predict the performance of incinerator showed the deviation of input air by 14%, the mass flow rate by 26.5%, the mass fraction of carbon dioxide by 10.4% and slight deviation of nitrogen dioxide and carbon monoxide. The research suggested removing the ash during the incineration process by using a moving grate mechanism to minimize the possibility of formation of NO_X. To feed the incinerator by using mechanical means without direct opening the door, it suggested to incorporating moving grate mechanism. The operating conditions of the incinerator designed should have the optimum values for input air one $A_{1\text{-}1}$ as 0.036 39 kg/s, the input air two $A_{2\text{-}1}$ as 0.030 46 kg/s, the input air three $A_{3\text{-}1}$ as 0.034 09 kg/s, the input fuel value as 19.6 kg/h and the maximum capacity of incinerator as 68 kg/h.

DECLARATION

I, **ARTHUR MNGOMA OMARI** do hereby declare to the Senate of Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Arthur Mngoma Omari _____ _____

Date

The above declaration is confirmed

NAME OF SUPERVISORS

1. **Prof. Karoli Nicholas Njau** _____ _____

   Date

2. **Prof. Peter Lucas Mtui** _____ _____

   Date

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CERTIFICATION

The undersigned certifies that, they have read and hereby recommend for acceptance by the **Nelson Mandela African Institution of Science and Technology** a dissertation titled **"Optimization of the Incineration Process"** in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Sustainable Energy Science and Engineering of the **Nelson Mandela African Institution of Science and Technology.**

Prof. Karoli Nicholas Njau _____ _____

Name and signature of supervisor 1 **Date**

Prof. Peter Lucas Mtui _____ _____

Name and signature of supervisor 2 **Date**

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DEDICATION

This study dedicated to my parents, the late father, Mr. Charles Sembe Luboko Omari and my Mother Agnes Bridget Mamng'ombe.

(God bless you all)

TABLE OF CONTENTS

ABSTRACT i

DECLARATION ii

COPYRIGHT iii

CERTIFICATION iv

ACKNOWLEDGEMENTS v

DEDICATION vi

TABLE OF CONTENTS vii

LIST OF FIGURES xiii

LIST OF ABBREVIATIONS AND SYMBOLS xvii

CHAPTER ONE 1

GENERAL INTRODUCTION AND BACKGROUND 1

1.1. Introduction 1

1.2. Research Problem and Justification of the Study 4

1.3. Research Scope and Objectives 5

1.4. Research Hypotheses 5

1.5. Significance of the Research 6

CHAPTER TWO 8

ENERGY RECOVERY ROUTES FROM MUNICIPAL SOLID WASTE: A CASE STUDY OF ARUSHA – TANZANIA 8

Abstract 8

2.1. Introduction 8

2.2. Material and Methodology 9

2.3. Results and Discussion 12

2.4. Conclusion and Recommendations 17

2.5. Acknowledgements 18

CHAPTER THREE 19

POTENTIAL OF MUNICIPAL SOLID WASTE AS RENEWABLE ENERGY SOURCE: A CASE STUDY OF ARUSHA, TANZANIA 19

Abstract 19

3.1. Introduction 19

3.2. Background Information 19

3.3. Material and Methods 23

3.4. Results and Discussions 24

3.5. Conclusion and Recommendations 30

3.6. Acknowledgements 30

CHAPTER FOUR 31

OPERATING CONDITIONS OF A LOCALLY MADE FIXED-BED INCINERATOR: A CASE STUDY OF BAGAMOYO IN TANZANIA 31

Abstract 31

4.1. Introduction 31

4.2. Materials and Methods 34

4.3. Results and Discussion 40

4.4. Conclusion and Recommendations 52

4.5. Acknowledgements 52

CHAPTER FIVE 53

MASS AND ENERGY BALANCE CALCULATIONS FOR A FIXED BED INCINERATORS, A CASE STUDY OF A LOCALLY DESIGNED INCINERATOR IN TANZANIA 53

Abstract 53

5.1. Introduction 53

5.2. Materials and Methods 58

5.3. Results and Discussion 63

5.4. Conclusion and Recommendations 70

5.5. Acknowledgements 70

CHAPTER SIX 71

COMPUTATIONAL MODELLING OF LOCALLY MADE INCINERATOR FOR MUNICIPAL SOLID WASTE, A CASE STUDY OF BAGAMOYO – TANZANIA 71

Abstract 71

6.1. Introduction 71

6.2. Model Description and Methodology 77

6.3. Results and Discussion 80

6.4. Conclusions and Recommendations 93

6.5. Acknowledgements 94

CHAPTER SEVEN 95

GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS 95

7.1. General Discussion 95

7.2. Studying the Operation Conditions of Incinerator 99

7.3. Energy Balance of the Incinerator 103

7.4. The Simulation Model Results 106

7.5. Conclusion and Recommendations 111

REFERENCES 113

LIST OF TABLES

Table 1: Proximate Analysis, Ultimate Analysis and HHV of Arusha Municipal Solid Waste 13

Table 2: Activation Energy and Pre-Exponential Factor of Municipal Solid Waste 16

Table 3: Waste composition in various countries 26

Table 4: Proximate and Ultimate analysis of Arusha Municipal Solid Waste 29

Table 5: Emission Standards for Waste to Energy Power Plant 38

Table 6: Waste Sample Composition of Municipal Solid Waste 40

Table 7: The Combustibles Fraction of Municipal Solid Waste 41

Table 8: Proximate and Ultimate analysis of Arusha Municipal Solid Waste 42

Table 9: The Operation for One Cycle with Emission from Incinerator 45

Table 10: Flue Gas Emission at Primary Temperature 400℃ 48

Table 11: Flue Gas Emission at Primary Temperature 500℃ 49

Table 12: The Stack Temperature against Excess Air and Efficiency of incinerator with Primary Chamber Temperature 400℃ 50

Table 13: The Stack Temperature against Excess Air and the Efficiency of Incinerator with Primary Chamber Temperature 500℃ 51

Table 14: Auxiliary Equipment of Incinerator 59

Table 15: Proximate, Ultimate Analysis and HHV Studied of Municipal Solid Waste 59

Table 16: Diesel and Air Consumption of Burners 65

Table 17: Mass Balance Summary Analysis of the System 66

Table 18: Parameters due to Flue Gas Released 68

Table 19: Energy Balance Summary 70

Table 20: Chemical Equations Described using Single Step Reactions 80

Table 21: The Comparison between Inputs Experimental and Simulation Parameters..... 81

Table 22: The Comparison between Output Experimental and Simulation Parameters..... 82

Table 23: Validation of Simulation..... 92

Table 24: The Burners Diesel and Air Consumption..... 103

Table 25: The Flue Gas Parameters 104

Table 26: The Comparison Output Between Experimental and Simulation Results..... 107

LIST OF FIGURES

Figure 1: Waste Management Hierarchy 2

Figure 2: Schematic Framework of the Dissertation 7

Figure 3: TG of Municipal Solid Waste 14

Figure 4: DTG Curves of Municipal Solid Waste 15

Figure 5: Determination of Kinetic Parameter of Arusha Municipal Solid Waste.....15

Figure 6: DSC Curves of Arusha Municipal Solid Waste Sites 17

Figure 7: Technology Tree and Methods of Waste Disposal for Energy Recovery.....21

Figure 8: Waste Generated and Collected per Month.....24

Figure 9: Arusha Waste Generation, Monthly Average Fraction Contribution for 2010 – 2012 25

Figure 10: Waste Composition of Arusha, Tanzania.....25

Figure 11: The Pilot Incinerator at Bagamoyo front view 35

Figure 12: The Pilot Incinerator at Bagamoyo Side View 36

Figure 13: The Pilot Incinerator at Bagamoyo Cross Section View.....37

Figure 14: Typical Temperature Distribution in an Incinerator for One Complete Cycle 43

Figure 15: NO_X and CO Emissions from Incinerator for One Complete Cycle.....44

Figure 16: Efficiency, CO_2 and O_2 Emission from Incinerator 44

Figure 17: Flue Gas Emission at Primary Chamber Temperature 400℃. 48

Figure 18: Flue Gas Emission at Primary Chamber Temperature Fixed 500℃. 49

Figure 19: Variation of Efficiency against Excess Air and Oxygen with Primary Chamber Temperature 400℃ 50

Figure 20: Variation of Efficiency against Excess Air and Oxygen with Primary Chamber Temperature at 500℃ 51

Figure 21: Mass Balance of the System 56

Figure 22: Energy Balance of the Incinerator 57

Figure 23: The Fixed Bed Incinerator Layout 58

Figure 24: Wheatstone-bridge Configuration 61

Figure 25: Computational Fluid Dynamic Analysis Process 76

Figure 26: Incinerator Geometry 77

Figure 27: Meshed Incinerator Geometry 78

Figure 28: Contours of Velocity Magnitude (m/s) 82

Figure 29: Contour of Static Temperature (k) 83

Figure 30: Contour of Mass Fraction of O_2 (%) 84

Figure 31: Contour of Mass Fraction of CO (ppm) 85

Figure 32: Contours of Mass Fraction of CO_2 (%) 86

Figure 33: Contours of Mass Fraction of NOx (ppm) 87

Figure 34: Particle Traces Colored by Residence Time(s) 88

Figure 35: Pathlines Colored by Particle ID 89

Figure 36: Particle Traces, Colored by Particle Diameter (m) 90

Figure 37: Temperature Variation with Incinerator Height 91

Figure 38: Average NO_x at Incinerator Exit (ppm) 92

Figure 39: Typical Temperature Distribution in an Incinerator for One Complete Cycle at Bagamoyo 99

Figure 40: Temperature Variation with Incinerator Height.....110

Figure 41: Average NO_x at Incinerator Exit (ppm) 110

LIST OF APPENDICES

Appendix 1: Operating Procedure for Measurements of Emissions from Locally Made Fixed Bed Incinerator, A case study of Bagamoyo Tanzania.....131

Appendix 2: Conference paper 1 - Energy Recovery from Municipal Solid Waste. In the 9th SIDA Regional Collaboration Conference, Entebbe. Uganda 20th -23rd July 2014.....132

Appendix 3: Conference paper 2 Non-Isothermal kinetics of Agriculture, forestry and Municipal solid waste. A Case of Arusha, Kilimanjaro and Mbeya – Tanzania. In the International Conference on Energy, Environment and Climate Change (ICEECC 2015). Mauritius, 8th -9th July 2015.....133

Appendix 4: Conference paper 3 Chemical kinetics of forest and municipal solid waste. A case study of Arusha - Tanzania. In the 4th International Conference on Mechanical and Industrial Engineering. 1st – 2nd September 2016. Arusha International Conference Centre, Arusha, Tanzania.....134

Appendix 5: Conference paper 4 Computational Analysis of a Locally Made Municipal Solid Waste Fixed Bed Incinerator Combustion Chambers. In the fifth International Conference on Mechanical and Industrial Engineering MIE'2018 "Promoting Engineering Innovations for Sustainable Development" 16th - 17th August 2018, the Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha-Tanzania.....135

LIST OF ABBREVIATIONS AND SYMBOLS

LIST OF ABBREVIATIONS

ASTM	American Standard Test and methods
BICO	Bureau for Industrial Cooperation
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
COSTECH	Commission for Science and Technology
DSC	Differential Scanning Calorimetry
DTG	Differential Thermal Gravimetry
HHV	Higher Heating Values
LHV	Lower Heating Value
MSW	Municipal Solid Waste
MUST	Mbeya University of Science and Technology
NM AIST	Nelson Mandela African Institution of Science and Technology
OFA	Over Fire Air
PDE	Partial Differential Equations
PDF	Probability Density Function
QUICK	Quadratic Upstream Interpolation for Convective Kinetics
RANS	Reynolds Average Narvier-Stokes Equation
RNG	Renormalized Group
RSM	Reynolds Stress Model
RTD	Residence Time Distribution
SGS	Sub-Grid Scale
SNCR	Selective Non-Catalytic Reduction
SOFA	Secondary/Over Fire Air
SWM	Solid Waste Management
TBL	Tanzania Breweries Ltd
TEMDO	Tanzania Engineering and Manufacturing Design Organisation.
TGA	Thermal Gravimetric Analysis
UDF	User Define Function
UDSM	University of Dar es Salaam
WMH	Waste Management Hierarchy

LIST OF SYMBOLS

Symbol	Units	Definition
A	s^{-1}	Pre-Exponential Factor
C_p	$kJ\,kg^{-1}K^{-1}$	Specific Heat Capacity at Constant Pressure
C_v	$kJ\,kg^{-1}K^{-1}$	Specific Heat Capacity at Constant Volume
$D_{i,m}$	m^2/s	Diffusion Coefficient for Species *i* in The Mixture
E_k	kJ/m^2s	Activation Energy for K^{th} Reaction
H	kJ	Heat of Reaction
h	kJ/kg	Enthalpy
k	m^2/s^2	Turbulence Kinetic Energy
m_i	kg	Mass of Specie *i*
$\dot{m}$	kg/s	Mass Flow Rate
P	N/m^2	Pressure
Q	kJ/s	Energy Flow Rate
q	kJ/s K	Radiation Heat Flux
T	K	Temperature
t	s	Time
V	m^3	Volume
v	m/s	Velocity
ε	m^3/s^3	Turbulence Dissipation Rate
Γ	m/s	Diffusion Coefficient
μ	kg/ms	Fluid Viscosity
ν	m^2/s	Kinematic Viscosity
ρ	kg/m^3	Density

CHAPTER ONE

GENERAL INTRODUCTION AND BACKGROUND

1.1. Introduction

1.1.1 Background Information

The extensive migration of people to urban centres coincides with many things among them is the increase of the solid waste. It is estimated that the World waste production would reach 27 billion tonnes per year by 2050 (Modak *et al.*, 2010). The waste generation with inadequate waste collection, transportation and disposal system can negatively affect public health, environments and economy.

Effective solid waste management (SWM) is the major problem in many local municipalities. Hence, for a sustainable municipal solid waste management, classification into domestic wastes and non-hazardous industrial wastes or waste management hierarchy is one of the dependable intervention (Sridevi *et al.*, 2012).

1.1.2 Municipal Solid Waste Generation

The definition of municipal solid waste (MSW) depends on individual country, but generally MSW is defined as a household waste, recycling and composting waste dumped by householders, street sweeping, park and garden waste (Tarr, 1996; Igoni *et al.*, 2008). The hazardous wastes from industries that include waste from factories, mills and mining operations are not classified as municipal solid waste (Rattanaoudom, 2005). The hazardous wastes from industries are separate from the non-hazardous waste and their treatment are different as the depend on the activity of the industry (Bagchi, 2004).

1.1.3 Waste Management Hierarchy

Waste management hierarchy (WMH) is the waste management option in which it leads to the maximum production benefit of goods to generate a minimum quantity of waste. The benefit of WMH are such as prevention of the greenhouse gas emission, minimize pollution, conserve raw materials, resources, create employment and developing green technologies.

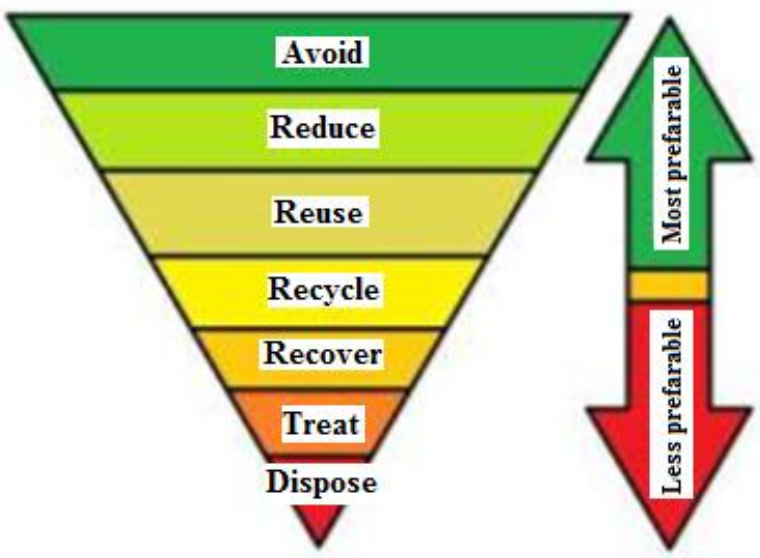

Figure 1: Waste Management Hierarchy (Fodor and Klemeš, 2012)

i) Avoid and Reduce

The Fig. 1 demonstrates the approach in waste management. The waste avoidance and waste reduction are the most viable forms of action in waste management. The waste disposal is the last option. The waste reduction is the method of reducing the waste generated by using goods that can be reused, recycled or repaired. Reduce waste by purchasing only what you need. The reducing minimizes the amount of waste to dump.

ii) Recycling

Recycling is a recovery as well as utilization of secondary material. Recycling is the process of destruct waste into the new raw material and products. The recycling process includes either open loop recycling where a processed material is producing a different product (Van Beukering and Bouman, 2001) the close loop process when the material of the product is recycled into the same product (Schoot Uiterkamp *et al.*, 2011). In the recycling process, the emphasis on collection, processing and marketing is crucial to the success of recycling. The recycling recovers materials and energy. The recycling, composting of organic waste may reduce the amount of waste into the dumpsite and therefore reduce costs (Senzige *et al.*, 2014). Recycling is cheaper than processing a fresh raw material; it saves a lot of energy since the amount of energy used to re-fabricate material is lower than that used to process a new raw material. Utilization of waste resources to new product reduces pollutions by minimizing the amount of fossil fuels used in manufacturing (Schoot Uiterkamp *et al.*, 2011; Chang *et al.*,

2013). Materials that can be recycled from municipal solid provide a cheaper source of raw materials for industries (Henry *et al.*, 2006).

iii) Composting

About 87% of MSW are biodegradable, which converted to valuable compost materials. Composting is a natural way of decomposing biodegradable waste into new soil materials, which used as organic manure. The municipal solid waste is suitable for composting since it has high moisture and organic contents (Ahsan *et al.*, 2014). The manure is used by plants for food (Senzige *et al.*, 2014).

1.1.4 Methods of Waste Disposal

i) Incineration

Incineration is a controlled combustion process for reducing solid, liquid, or gaseous combustible waste to carbon dioxide, water vapour, gaseous and relatively tiny non-combustible particles processed in an environmentally acceptable standard. Benefits of incineration include the reduction of mass and volume of waste and energy recovery from waste (Seo *et al.*, 2004). The utilization of municipal solid waste as source of energy is more favourable as this can replace other source of energy such as fossil fuels (Trvalo and Prostredia, 2005).

The major challenges of municipal solid waste incineration are nature of solid waste materials, the flue gases coming out during incineration, which are of concern on environmental pollution. The possibilities of waste reduction and recycling seem to be not economical. The resource recovery through heat and power generation seems to be more favourable (McKay, 2002).

ii) Landfills

Landfill is a simple, economical and most common method of waste disposal used globally for many years (Rawat and Ramanathan, 2011). The landfill involves the burial of waste to a pit, and they are generally located at a distance from towns to avoid their harmful effects. The wastes in landfills are compacted to minimize their volume, and closed to avoid trespassers. Some landfills have a system for the extraction of gases for energy recovery. Essentially, landfill should not pollute surface and groundwater, this is done by lining the landfill,

compaction of the upper layer and selecting the site which is not subject to flooding (Fodor and Klemeš, 2012).

a) Sanitary Landfills – these landfills designed so that the risk of environmental and human health reduced. The locations of these landfills placed such that the landfills become resistant to hazardous waste and far from the water table and water bodies. Wastes are isolated until they become safe to the environment (Pandey *et al.*, 2016).

b) Controlled Landfills – These are similar to sanitary landfills. They are developed in order to control gas from the landfill for the purpose of energy recovery (Haivadakis *et al.*, 1988).

iii) Open Dumps

This is the common method of waste disposal used in developing countries like Tanzania.

iv) Dump into the Sea

The ocean dump is the dispose of the human waste into the ocean.

v) Fermentation and Biological Digestion

Biological digestion is the process of decomposition of biodegradable waste in the absence of oxygen. The main product is biogas. Biogas is a mixture of 65% methane and 35% carbon dioxide.

1.2. Research Problem and Justification of the Study

There has been some advancement in *waste* disposal methods worldwide, but in Tanzania, the only method used for MSW disposal is open dumping. The inherited problem with such a method is an amount of methane generated due to improper handling. This could lead to environmental problems, such as those associated with greenhouse gas emissions (Taiwo, 2011). Alternatively, another way of MSW disposal is the use of the incinerator, which does not generate methane. Disposal of MSW by incineration can increase resource utilization by generating energy to replace convention fuels. However, MSW incineration can be a challenge as it can pose a pollution problem to the environment.

Incineration of solid waste in Tanzania is practiced only in hospitals (Ntakamulenga, 2012). The process of incineration can produce hazardous pollutant gases due to incomplete combustion. Pollutants in combustion gasses that are considered hazardous include furans, dioxins, acid gases, polycyclic aromatic hydrocarbons among others (Mininni *et al.*, 2007; Domingo and Nadal, 2009). These pollutants decompose in a two stage staved incinerator at a temperature of 850℃ with residence time of about 2s, or at temperature of 1000℃ with residence time of one second (Mtui, 2013).

In order to deal with these pollutants, the operating conditions and geometry of the incinerator must be optimum. The optimization of operating conditions and geometry of designed incinerator is therefore inevitable.

1.3. Research Scope and Objectives

1.3.1 Scope of the Research

The scope of this research was limited to Arusha city municipal solid wastes.

1.3.2 General Objective

To develop an efficient incinerator with minimum pollution through optimization of incineration process.

1.3.3 Specific Objectives

i) Characterization of municipal solid waste
ii) Studying the working conditions of incinerator.
iii) Optimize the operating conditions of incinerators using computational fluid dynamic (CFD) techniques

1.4. Research Hypotheses

i) Municipal solid waste in Arusha has a desirable quality of energy recovery.
ii) Locally manufactured incinerator can optimized to reduce pollutants and increase incineration capability.

1.5. Significance of the Research

1.5.1 Waste Handling and Hygiene

Incineration of municipal solid waste will reduce the volume of waste for final disposal. The incineration disinfected waste and generates non-hazardous products, switching from dumping to incineration minimize the risk of contamination and infection (Kuo *et al.*, 2008).

1.5.2 Energy Recovery

The energy from waste can provide a potential energy recovery, which can be taped to process heat or could be used to run turbines for energy generation (McKendry, 2002b). Optimal design of a high efficiency incinerator and an optimal operating condition will yield the maximum energy from the municipal solid waste. The optimization helps in improving the efficiency by using less fuel for energy production.

1.5.3 Pollution Control

The process will reduce environmental pollution, eliminate the polluting gases and contribute to reduce global warming by using alternative sources of renewable energy in place of fossil fuels (Calabrò, 2009; Udomsri *et al.*, 2011). By improving, the efficiency of the incinerator, the process will also reduce the bottom ash production.

1.5.4 Generate Knowledge Base and Social Well - Being

Incineration of municipal solid waste will contribute to scientific knowledge and societal well-being. The process will create job opportunities in sorting and collecting wastes, and expertise of power during the production of waste to energy. The expected impact to the society is to improve the life standard due to availability of sustainable energy and clean environment.

1.6. Dissertation Format

This dissertation consists of seven chapters. The first chapter discussed the background information, research hypothesis, objectives and justification. The second and the third chapter discussed the study on characterization of municipal solid waste.

The fourth chapter discussed the study of the operating conditions of the incinerator. In this case, the study of locally made hospital incinerator at Bagamoyo Hospital carried out. The

hospital incinerator was used due to unavailability of municipal solid waste incinerator in Tanzania (Ntakamulenga, 2012).

The fifth and sixth chapters the study of the optimization of the incinerator design discussed. In chapter, five the mass and energy balance undertaken, whereas in chapter six is the study of optimization of the incinerator operation conditions using Computational fluid dynamic techniques. Chapter 7 is the conclusion, recommendations and future works of this study. The framework of this dissertation shown schematically in Fig. 2.

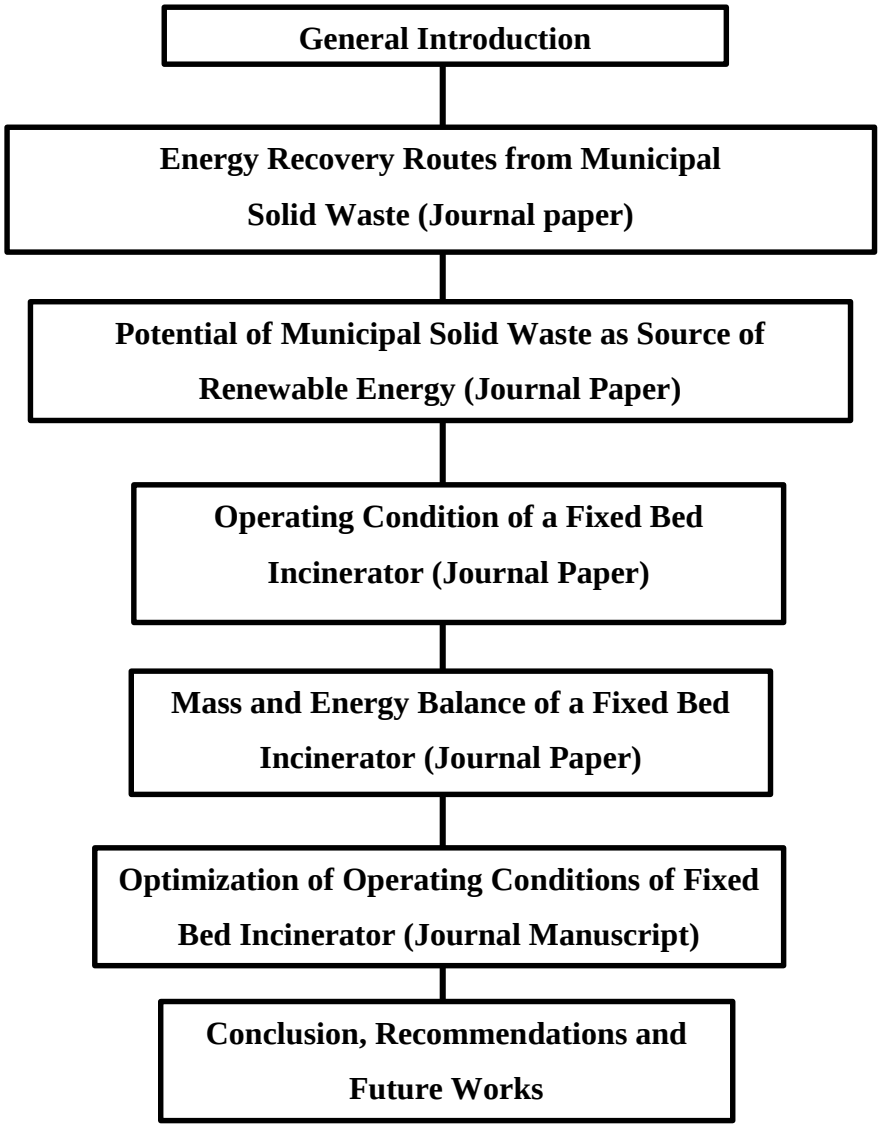

Figure 2: Schematic Framework of the Dissertation

CHAPTER TWO

ENERGY RECOVERY ROUTES FROM MUNICIPAL SOLID WASTE: A CASE STUDY OF ARUSHA – TANZANIA

Abstract

A study of energy recovery from municipal solid waste was undertaken. The energy content of the solid waste is 12MJ/kg. The elemental composition shows that the municipal solid waste contains 50% and 5% of carbon and hydrogen respectively. The energy flow (exothermic and endothermic) and thermal degradation analysis carried out using differential scanning calorimetry and thermo-gravimetric analyser respectively. Experiments performed at heating rates of 10K/min, 20 K/min, 30K/min and 40K/min in the nitrogen atmosphere at a temperature between room temperature and 1273K. The thermal degradation kinetic parameter values of the activation energy (E_a) ranged from 205.9 to 260.6kJ/Mol. It has observed that municipal solid waste is less reactive to combustion as compared to coal and biomass, but its reactivity improved through pre-treating process to reduce noncombustible materials such as oxygen and ash. In addition, pyrolysis and gasification used to convert municipal solid waste to liquid and/or gaseous fuel respectively.

Keywords: Municipal Solid Waste, Thermal behavior, Thermo gravimetric Analysis.

2.1. Introduction

2.1.1. Background Information

Municipal solid waste generation has been on the increase due to population growth, changing lifestyles, technology development and increased consumption of goods. The increase of waste generation may lead to environmental problems if not properly managed (Johari *et al.*, 2012). Urban centers in developing countries are facing a challenge in solid waste management due to population growth and are constrained by the lack of an effective recycling of the biodegradable components into useful materials, poor waste management and waste handling infrastructure (Henry *et al.*, 2006; Kuo *et al.*, 2008).

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Despite having abundant solid waste in developing countries, these countries are facing an energy crisis, which poses a challenge to the economic and social development. Combining waste management with waste energy recovery from municipal solid waste can address the problems of solid waste management and partly the energy crisis. A disposal method using thermal degradation processing could be a better option for the waste management than biogenic methods. This method has advantages, such as substantial reduction in volume and mass. In order to apply the method in a large scale, there are fundamental parameters such as fuel behaviour in thermal degradation, energy contents and its chemical reactions that should be in place so as to assist designers to come up with an appropriate method of waste energy recovery and disposal system (Quina *et al.*, 2008).

In this study, the thermal degradation behaviour of municipal solid waste in a growing urban city of Arusha in Tanzania as a case study is undertaken. This includes determination of its proximate analysis, ultimate analysis higher heating value and kinetics.

2.2. Material and Methodology

2.2.1. Materials

Municipal solid waste from Arusha city used and equipment used for thermal and chemical composition characterization were located in University laboratory.

2.2.2. Methodology

The methodology consists of sampling selection, sorting and laboratory analysis to determine the chemical and physical properties of municipal solid waste of Arusha city. The method of sampling was based on ASTM D5231 namely random truck sampling and quartering (AbdAlqader and Hamad, 2012). In this study, the wastes collected by means of pushcarts and donkey carts, and randomly collected from the different collecting point of Sakina, Kaloleni and Central market within the Arusha City. The wastes sorted and weighted using weighing balance and then separated according to defined classification such as plastics, glass, paper,

food waste and metals. The non-combustible wastes removed from the rest of the wastes. The combustible waste was availed for analysis in accordance to the method developed by (McCauley-Bell *et al.*, 1997; Kalanatarifard and Yang, 2012).

In order to get waste composition accurately an average weight of about 200kg of municipal solid waste taken. The waste then taken as good representative of the total municipal solid waste composition at each collecting points under this study. The samples were subjected to standards test methods of proximate and ultimate analysis in accordance to ASTM D3172 and ASTM D3176 respectively (ASTM, 1989, 2007).

The thermal degradation analysis studied under nitrogen condition using a thermo gravimetric analyzer type NETZSCH STA 409 PC Luxx connected to power unit 230V, 16A. High purity nitrogen, 99.95% used as carrier gas controlled by gas flow meter fed into the thermo gravimetric analyzer with flow rate of 60ml/min and a pressure of 0.5 bars. In the STA 409 PC Luxx, proteus software utilized to acquire, store and analyze the data.

i) Sample Preparation

The samples were shredded into smaller pieces of approximately 30mm size, mixed and in a machine to less than 1mm size in order to increases surface area of the sample that will allow easier penetration of heat (Yusoff *et al.*, 2012). Then a sample of 30±0.1 mg with average particle size less than 1mm was loaded to crucible, subjected into furnace, and heated from 303 to 1273K at heating rates of 10K/min, 20K/min, 30K/min and 40K/min. The heating rate variation changes the peak temperature of the decomposition, as the heating rate increases, the peak temperature also increases (Ledakowicz and Stolarek, 2003). The calculated thermo-gravimetric output from Proteus software obtained as thermal decomposition profile; thermo-gravimetric (TG), differential thermo-gravimetric (DTG) and differential scanning calorimetry (DSC) curves.

Heat release and absorbed by municipal solid waste degradation was determined by using differential scanning calorimetry curves (Sun *et al.*, 2007). The DSC monitors heat effect associated with phase changes transitions and chemical reactions as a function of temperature

(Huffman and Pan, 1990). The heat was determined by calculating the area between the baseline and the curve. The heat can be positive or negative. When the heat is positive the process is endothermic and when the heat is negative the process is exothermic (Tettamanti *et al.*, 1998).

ii) The Kinetic Parameter Determination

The kinetic parameter was determined by using Kissinger's method. This is used as a standard method for studying the thermal degradation of municipal solid waste under non-isothermal condition (Ledakowicz and Stolarek, 2003). The kinetic parameter was determined by using Kissinger's method. This is used as a standard method for studying the thermal degradation of municipal solid waste under non-isothermal condition (Sonobe and Worasuwannarak, 2008).

The rate constant calculated by using Arrhenius equation

$$k = A\exp\left(-E_a/RT\right) \tag{1}$$

$$dx/dt = Af(x)\exp\left(-E_a/RT\right) \tag{2}$$

$$x = (w_0 - w_t)/(w_0 - w_\infty) \tag{3}$$

where, x is the reacted fraction, w_0 the initial mass, w_t the mass remaining at time t, w_∞ the final mass , T the absolute temperature, E_a the activation energy, A the pre-exponential factor, R the universal gas constant and f(x) the algebraic function depending on the reaction mechanism. The temperature rises at a constant heating rate (β) expressed as shown in Equation 4.

$$\beta = dT/dt \tag{4}$$

Equation 5 is a result of differentiation of Equation 2

$$d^2x/dt = \left\{E_a\beta/RT^2 + Af'(x)\exp\left(-E_a/RT\right)\right\}dx/dt \tag{5}$$

The maximum rate occurs at a T_{peak}; approximations at T_{peak} condition yield Equation 6.

$$\ln\left(\beta/T_{peak}^2\right) = \ln\left(AR/E_a\right) - \left(E_a/RT_{peak}\right) \tag{6}$$

Equation 6 is a straight line graph, of $\ln(\beta/T^2_{peak})$ v/s $(1/T_{peak})$, The line slope is E_a/R and the intercept on the vertical axis is $\ln(AR/E_a)$, which are used to determine the values of E_a and A.

The fractional pyrolysis of the municipal solid waste component obtained by taking the ratio of the change in mass of the municipal solid waste component at time t and total reactive mass of a sample as shown in Equation 3

2.3. Results and Discussion

2.3.1. Proximate Analysis and Ultimate Analysis

The results of proximate and ultimate analysis shown in Table 1. The moisture content of the municipal solid waste as received ranges between 55.70 and 63.99 weight percentage, which is more than 50-weight percentage of the total weight of the sample. This high moisture content is prohibitive for combustion process as it lowers the combustion process due to high moisture contents which also reduces the calorific value of the fuel (Muthuraman *et al.*, 2010), the moisture could be reduced by drying. The volatiles released on dry basis of municipal solid waste for Kaloleni, Sakina and Central market are 74.43, 84.00 and 78.31 weight percentage, respectively, whilst the volatile matter contained in pure biomass such as forest residue, oak wood, and pine are 79.9, 78.1 and 83.1 weight percentage respectively (Vassilev *et al.*, 2010). Generally, fuels that contain high volatile, have low fixed carbon, the case for the municipal solid waste from Kaloleni, which has fixed carbon of about 17-weight percentage, which is higher than that of Sakina and Central market. The advantage of high volatile and low fixed carbon is rapid burning of a fuel, while a fuel with low volatile and high fixed carbon like coal need to be burnt on a grate as it takes long time to burn out, unless it is pulverized (McKendry, 2002a).

Therefore, the volatile matter and fixed carbon shows that the municipal solid waste is combustible. The ash range between 3.29 to 5.97 weight percentage, which is small; this is advantage to waste management and environment because the possibility of having small quantity of heavy metals, salts, chlorine and organic pollutant is small (Lam *et al.*, 2010). The ultimate analysis of the municipal solid waste shows that the concentration of phosphorus and chlorine are negligible, the carbon and hydrogen content were above 50-weight percentage and 5-weight percentage respectively. The oxygen content was more than 34-weight percentage. Sulfur is about 0.29 weight percentage this is lower compared to values from 1.1 weight percentage of bituminous coal analysis (Nakao *et al.*, 2006).

Table 1: Proximate Analysis, Ultimate Analysis and HHV of Arusha Municipal Solid Waste

Proximate Analysis in weight percentage							
Location	Moisture as received	Volatile dry basis	Ash dry basis	Fixed carbon dry basis	HHV (MJ/kg)		
Kaloleni	59.67	74.43	8.16	7.41	11.90		
Sakina	63.99	84.00	10.00	6.00	11.37		
Central market	55.70	78.30	13.48	8.22	12.76		
Ultimate Analysis in weight percentage							
Location	C	H	O	N	S	Cl	P
Kaloleni	55.57	5.34	34.88	2.09	0.31	0.04	0.10
Sakina	55.70	5.29	34.27	2.13	0.22	0.07	0.13
Central Market	53.20	5.24	34.71	2.86	0.37	0.04	0.11

2.3.2. Calorific Value

The municipal solid waste calorific value is about 12 MJ/kg. This value is smaller than average biomass heating value of about 17MJ/kg (Heylighen, 2001). This means that the energy release during combustion of municipal solid waste is smaller than the biomass combustion. This means that one needs to burn larger amount of combustion of municipal solid to get the same amount of energy. The energy content of combustion of municipal solid can be improved by pre-treating the combustion of municipal solid so as to reduce oxygen amount, since oxygen reduces the energy content of a fuel (McKendry, 2002a).

The MSW can be co-fired with coal for improving energy content (Sami *et al.*, 2001; Li *et al.*, 2004). Other processes to improve energy content of combustion of municipal solid are pyrolysis, gasification or torrefaction, used to produce bio-oil, syngas or char respectively.

2.3.3. Thermo Gravimetric (TG) Curves

The municipal solid waste from all collecting points degraded from 75-weight percentage to 85-weight percentage in the thermo gravimetric analyser as shown in Fig.3. The municipal solid waste from Central market degraded by 85-weight percentage while the Kaloleni degraded by 75-weight percentage. The residue formed is between 25-weight percentage and

15-weight percentage. The residue contains fixed carbon, ash, the high residue observed at municipal solid waste from Kaloleni, and the lowest residue observed at municipal solid waste from Central market and Sakina. The char can be used as a fuel, but municipal solid waste have high ash content that hinder the combustion of char due to the layer formed on the surface inhibited the diffusion of oxygen during the char combustion (Himawanto *et al.*, 2013).

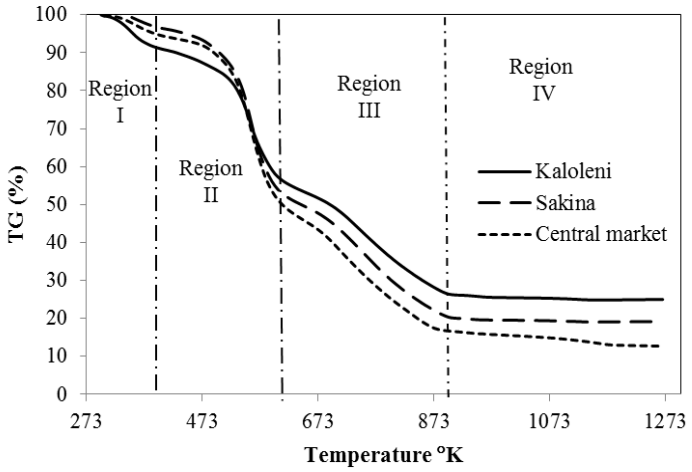

Figure 3: TG of Municipal Solid Waste

2.3.4. Derivative Thermo Gravimetric (DTG) Curves

Fig.4 shows the DTG analysis, which has four visible regions; these are moisture release region, lignocellulosic degradation region, plastic degradation region and char pyrolysis region (Lai *et al.*, 2011). The moisture release region is ranging between 303 and 423K. Lignocellulosic degradation region ranges between 423 and 643K, at these region volatile matters released; the region corresponds to pyrolysis of lignocellulosic biomass. The plastic degradation ranges between 643K and 913K, the char pyrolysis region ranges between 913 and 1273K (Lai *et al.,* 2011), also observed the same identified regions.

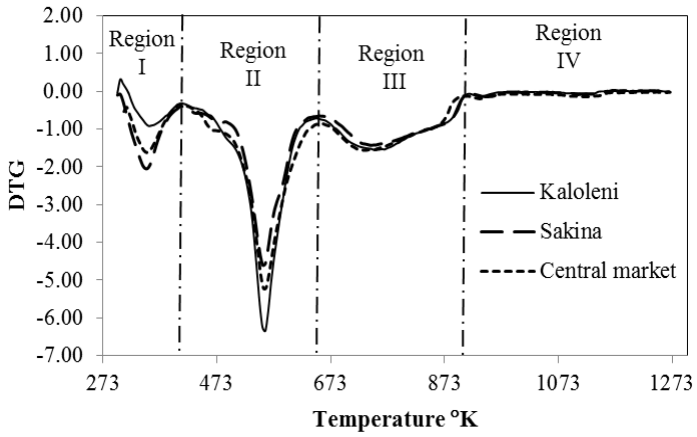

Figure 4: DTG Curves of Municipal Solid Waste

2.3.5. The Kinetics Parameters

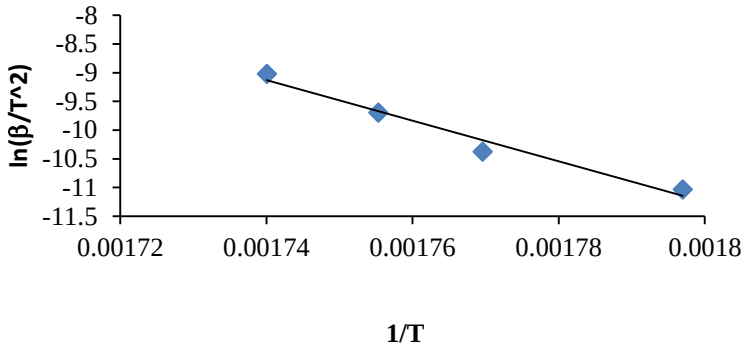

Figure 5: Determination of Kinetic Parameter of Arusha Municipal Solid Waste.

DTG curves at different heating rate used to develop Fig.5, which used to calculate the activation energy (Ea) and pre exponential factor (A), as given in Table 2. The activation energy of municipal solid waste ranged between 205.9 kJ/mol. and 260.6 kJ/mol. This value is higher than that of biomass and coal, which range between 50 to 180 kJ/mol. and 30 to 90 kJ/mol. respectively. The corresponding values of biomass observed by (Vhathvarothai *et al.*, 2013), for cypress wood chips and macadamia nut shells has the values of 168.7 and 164.5 kJ/mole respectively.

This shows that municipal solid waste need high energy to react as compared to biomass and coal. The reactivity of municipal solid waste can be increased by reducing the non-combustible

material such as oxygen and also to remove volatile material, these can be done by pre-treating the material through torrefaction process (Biswas, 2011).

Table 2: Activation Energy and Pre-Exponential Factor of Municipal Solid Waste

Location	**E_a (kJ/mole)**	**A (s^{-1})**
Kaloleni	258.680	9.142×10^{23}
Sakina	205.934	8.977×10^{18}
Central Market	260.60	1.186×10^{28}

2.3.6. Differential Scanning Calorimetry Curves

The Differential Scanning Calorimetry curves shown in Fig.6, reveal endothermicity between 303K and 423K, this is due to evaporation of moisture. In the temperature range of 423 to 1273K, the process undergoes exothermic reaction due to the devolatilization of the municipal solid waste and plastic pyrolysis. The energy absorbed due to evaporation of moisture for wastes from Kaloleni, Sakina and Central market collecting points were 0.11 MJ/kg, 0.20 MJ/kg and 0.15 MJ/kg respectively, whilst energy released from the same respective collection points were -7.6MJ/kg, -8.3 MJ/kg and -8.5 MJ/kg in respective manner. The energy released DSC by municipal solid waste was lower than higher heating value (12.54 MJ/kg). This energy is lower than that found in bomb calorimeter because some energy in TGA used to remove moisture while in bomb calorimeter the energy observed is for pre-treated waste (pellets).

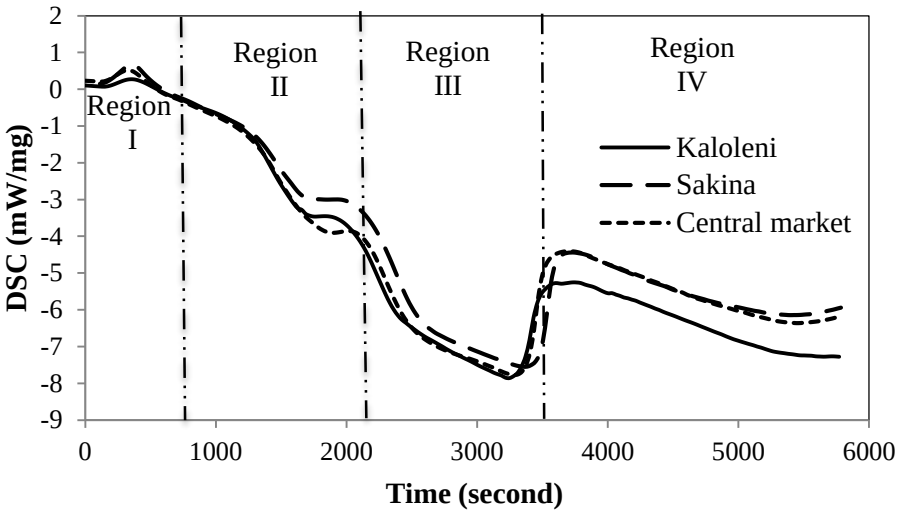

Figure 6: DSC Curves of Arusha Municipal Solid Waste Sites

2.4. Conclusion and Recommendations

This paper presents findings related to municipal solid waste characterization of Arusha city. The case represented the municipal solid waste found in Tanzania. The proximate analysis of municipal solid waste show that, the waste contains more than 50% and 5% of carbon and hydrogen respectively which may contribute to high calorific value of Arusha municipal solid waste. The ultimate analysis shows that average amount of nitrogen, sulfur, chlorine and phosphorus is small, these reduce emissions during combustion.

The energy content of waste determined by bomb calorimeter is about 12 MJ/kg this energy is about 30% of energy containing in coal and about 60% of energy containing in biomass. The activation energy was ranging between 205.9 and 260.6 kJ/mol. The municipal solid waste shows exothemicity property at the devolatilization zone. The devolatization zone shows that the municipal solid waste easily ignited at temperature above 423 K. Therefore, municipal solid waste has a good potential used as a fuel.

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CHAPTER THREE

POTENTIAL OF MUNICIPAL SOLID WASTE AS RENEWABLE ENERGY SOURCE: A CASE STUDY OF ARUSHA, TANZANIA

Abstract

This paper presents the study of municipal solid waste (MSW) as a potential source of renewable energy in Arusha city. The city of Arusha annual average MSW generated estimated to be 43 772 tonnes. Characterization revealed the main components of MSW to compose of biomass materials such as food, paper and wood waste. Based on the characteristics of the MSW, evaluation conducted to determine the energy potential to recover. Results from proximate analysis of MSW samples showed the average calorific value of about 12 MJ/kg, which indicate annual energy potential of 128.9 GWh. Results indicate there is a substantial energy potential to recover from MSW the largest share being renewable energy. The composition of waste from developing and developed countries further compared with that of Arusha city. Results indicated that in developing countries characteristics of MSW are mainly composed of food waste as was the case of Arusha city.

Key words: municipal solid waste, renewable energy, waste disposal, energy recovery

3.1. Introduction

3.2. Background Information

The utilization of fossil fuels practiced for many years as a source of energy, this utilization produce greenhouse gases such as CO_2, SO_2, NO_x and other pollutants, which increase global warming and acid rain. The fossil fuel resources are depleting while the consumption is increasing. This environmental effects and fossil depletion necessitates the effort in invention of alternative source of clean and renewable energy (Eddine and Salah, 2012).

Fossil fuel is coming from buried underground biomass deposits contains carbon, which locked for about 200 million years ago from the atmosphere. When combustion of fossil fuels occur

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the carbon react with oxygen to form CO_2 and releases to the atmosphere. The global concentration of CO_2 by May 2014 was 401.88 ppm. This is higher than the upper safety limit for atmospheric CO_2 which is 350 ppm (McGee, 2014). The CO_2 released from combustion of fossil fuels add up to the CO_2 concentration of atmosphere. The CO_2 in the atmosphere infuse heat radiating from the surface that would leak into space and radiate it back to the surface, thus raising the global surface temperature (Kaseva and Mbuligwe, 2005; Rodionov and Nakata, 2011).

The CO_2 released from combustion of fossil fuels add up to the CO_2 concentration of atmosphere. The CO_2 in the atmosphere infuse heat radiating from the surface that would leak into space and radiate it back to the surface, thus raising the global surface temperature (Gentil *et al.*, 2009) which economic development, enhance the growth in population, urbanization and industrialization and so increase the energy demand (Mohapatra, 2013). The prosperity and high quality of human life caused by these developments has also increase per capita solid waste and the rate of municipal solid waste generated from country to countries (Guermoud *et al.*, 2009).

Satisfying energy demand using renewable energy sources is the main agenda nowadays because of the fossil fuel depletion and environmental issues. Municipal solid waste is the result of human activities that, if an appropriate management system is not used, it may well lead to environmental pollution and endangers human's health. The massive municipal solid waste generations increases can be taken as an opportunity as source of energy for power generation. A big portion of biomass materials such as food, paper and wood waste composes municipal solid wastes in developing countries. The non-recyclable combustible materials from municipal solid waste can be used for energy recovery as they can reduce the utilization of fossil fuels thus assisting in minimizing global warming (Ryu, 2010).

The studies show energy recovery from municipal solid waste can be a better way of managing environment from pollution caused by municipal solid waste disposal Technologies (Yang *et al.*, 2012). The emission of CO_2 coming from biogenic combustion of municipal solid waste is

renewable and reduce the global warming because it completes the carbon cycle as it does in biomass (Sharholy *et al.*, 2008; Cheng and Hu, 2010).

The main objective of this paper is to study the potential of municipal solid waste as source of renewable energy. The analysis of generation capacity and composition of municipal solid waste will be focus to establish the amount of energy that recovered from Municipal solid waste.

3.2.1. Method of Waste Disposal for Energy Recovery

The energy from waste directly derived through conversion into biogas, syngas or heat. The technological methods in converting energy from waste can be physical, thermal or biological. These technologies outlined in Fig.7.

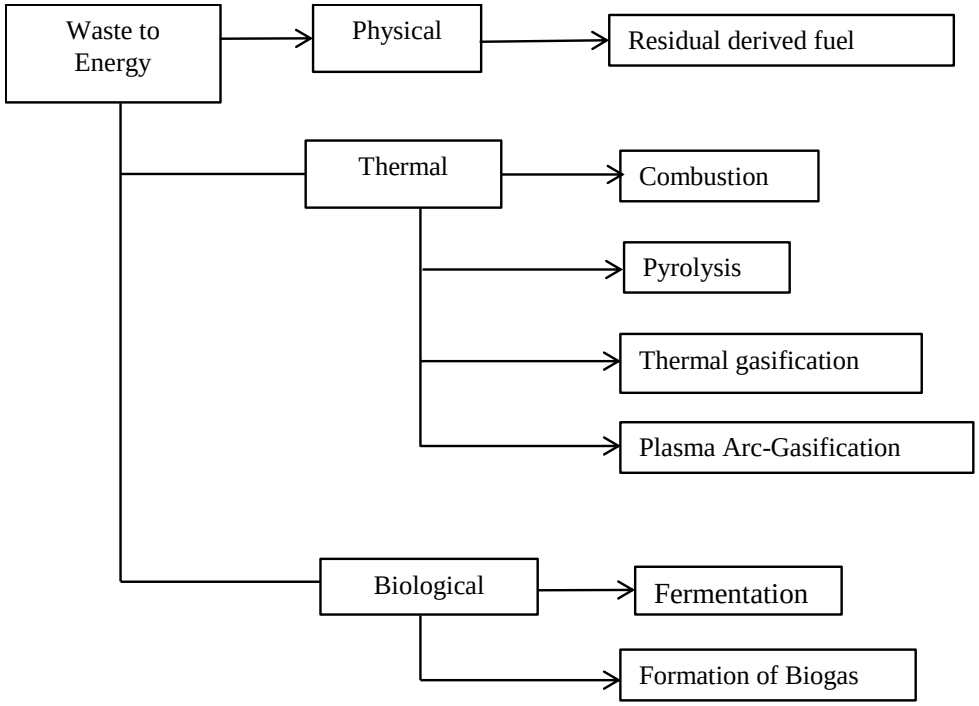

Figure 7: Technology Tree and Methods of Waste Disposal for Energy Recovery

i) The Physical Process

The physical process of waste treatment is when waste processed mechanically to produce suitable forms of objects for use as fuel. Examples are pellets, wood briquettes and wood chips.

ii) The Thermal Methods

The thermal method of waste treatment is by using heat of combustion to treat waste in the following processes:

a) Direct Combustion Incineration or Mass Burn

The heat from the combustion used to change water into steam and utilize the steam to run steam turbine for power generation.

b) Pyrolysis

Pyrolysis used to break down the material in the absence of oxygen to produce combustible gases, liquid and solid residues. The products from pyrolysis are such as methane, hydrocarbons, hydrogen and carbon monoxide.

c) Gasification and Plasma Arc Gasification

Gasification takes place in the limited amount of oxygen. Plasma arc gasification is the using a plasma arc torch to produce high temperature arc that breaks down waste and forming syngas and slag. The gas produced can be used to heat up boiler for heat generation or they can be used in combustion through internal combustion engines (Klein, 2002; Zhang *et al.*, 2012).

iii) Biological Method

Biological method is the technology of using microbes to produce fuel from waste.

a) The Biogas

This is the process of using anaerobic digestion to produce combustible gases. The waste placed in the airtight digester container. The combustible gases such as biogas, carbon monoxide and methane can then either be burned directly in boilers to generate electricity or used as combustible gases (Sharholy *et al.*, 2008).

b) Fermentation

By using yeast the biomass fraction of municipal solid waste can be fermented to generate ethanol which can be used to run internal combustion engines (Viitez *et al.*, 2000).

3.3. Material and Methods

3.3.1. Materials

The municipal solid wastes from Arusha city used as raw materials .The equipment and tools used are according to regulated standards.

3.3.2. Methods

The methods of waste flow analysis and waste composition analysis done by using standard operating procedure.

i) Analysis of Waste Flow of Arusha

The quantity of waste generated monthly at Arusha recorded daily by the office of a City Health officer. The recorded data were analysed for studying purpose. The data for consecutive 3 years collected and analysed.

ii) Waste Composition Analysis of Arusha

The case study done by sorting waste as they received from waste collecting centres of Kaloleni, Sakina and Central market within the Arusha city. The waste then sorted to categories and weighted. The work continued for five consecutive days. The percentage composition of the complete waste data for the whole period was calculated. The result taken as the sample for Arusha city.

iii) Waste Composition from Various Countries Worldwide

The waste compositions from various countries recorded randomly and grouped in three categories. The categorization falls to lower, middle and higher income countries.

iv) Proximate and Ultimate Analysis of Arusha Waste

The laboratory analyses for proximate and ultimate values of Arusha waste were taken from published work (Omari *et al.*, 2014b).

v) The Energy Content Analysis

The energy contents analysis of the waste studied using auto bomb calorimetry type WagtechGallen kamp model CAB001.AB1.C. The bomb fired and after the temperature stabilization, the difference noted and recorded. The calorific value of the municipal solid waste was calculated according to ASTM D240 standard method (ASTM, 2012).

3.4. Results and Discussions

3.4.1. Waste Flow Analysis

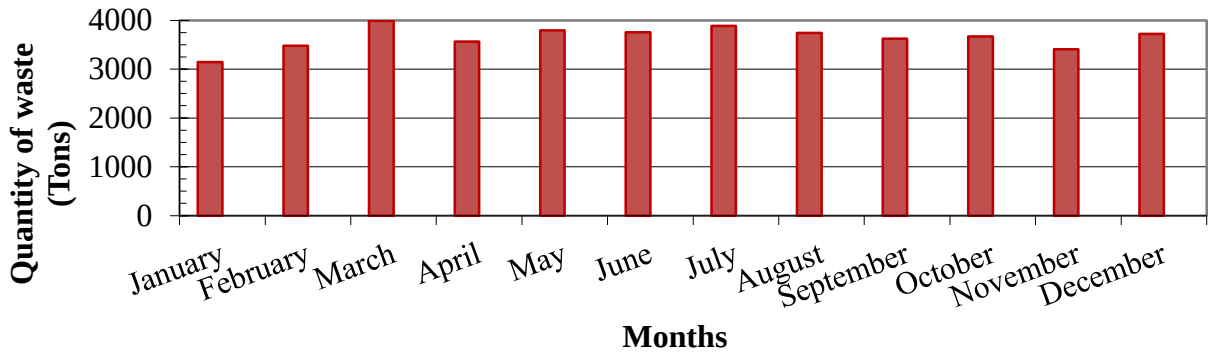

Figure 8: Waste Generated and Collected per Month

Fig. 8 and Fig. 9 show the average summary of the total waste generated within Arusha city for consecutive 3 years from 2010 and 2012. These wastes estimated to be about 20% of the total waste generated in Arusha. Large portions of the wastes generated between March and July. March is in a rainy season while July is the harvesting time. The value seems to be constant, this is due to the capacity of city trucks, which can handle and dispose waste to Murriet dumpsite at an average mass of not greater than about 100 to 120 tons daily.

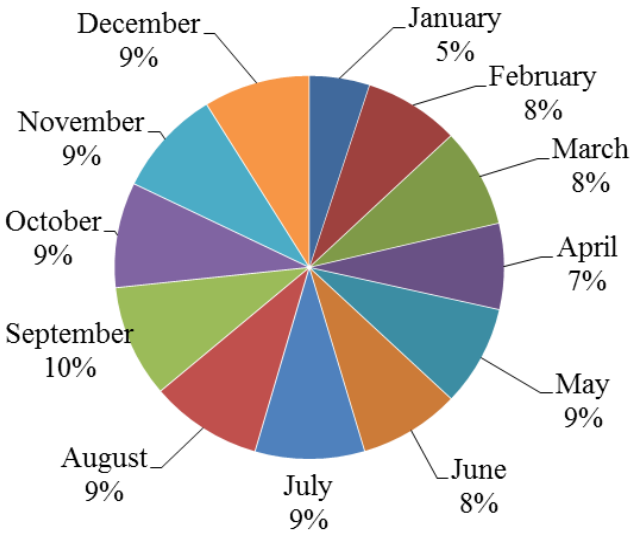

Figure 9: Arusha Waste Generation, Monthly Average Fraction Contribution for 2010 – 2012

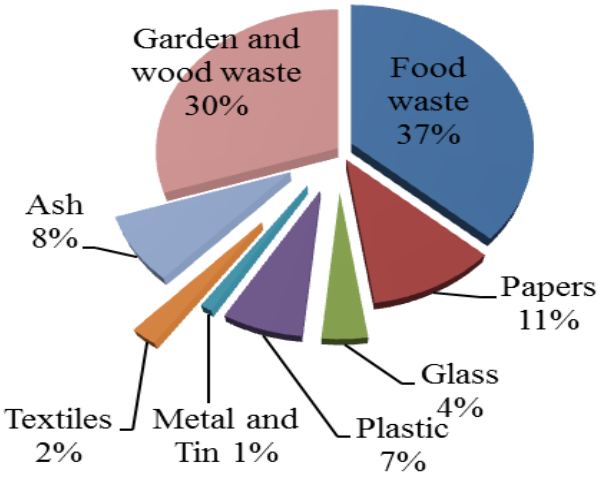

Figure 10: Waste Composition of Arusha, Tanzania

Fig. 10 shows the composition of municipal solid waste of Arusha city. The ratio taken based on the mass of the waste. The composition of the garden and wood waste is 30%, food waste 37%, Papers 11%, plastic 7%, glass 4%, metal and tin 1%, textiles 2% and ash 8%. The composition for combustible waste was 87%, while non-combustible waste composition is 13%. The combustible waste fraction has 89.7% biodegradable and 10.3% non-biodegradable waste. This implies that the waste of Arusha can be recovering its energy by either thermo or non-thermo degradation method. The recover technology for materials and energy from waste, the energy would otherwise be dispose-off to the dumpsite. By recovering these waste, the

released of greenhouse gases to the atmosphere will be minimized. The CO_2 equivalent reduced.

3.4.2. Waste Composition Analysis in various countries

Table 3: Waste composition in various countries

(a) Middle income countries

Country	Combustible Waste				Non-Combustible Waste			Source
	Food	Paper	Plastics	Textiles	Glass	Debris	Metal	
India	42	30	10.4	7	5	1.5	4.1	(Pattnaik and Reddy, 2010)
Nepal	60	7.5	12	12	1.3	6.7	0.5	(Dangi *et al.*, 2011)
Thailand	42.7	12.1	10.9	7.3	6.6	6.9	3.5	(Udomsri *et al.*, 2011)
Gaza strip	54	10	12	0	3	18	3	(AbdAlqader and Hamad, 2012)
Malaysia	61.5	16.5	15.3	1.9	1.2	0.4	0.3	(Saeed *et al.*, 2009)
Bangladesh	68.3	10.7	4.3	2.2	0.7	-	2	(Alamgir and Ahsan, 2007)
Indonesia	70.2	10.9	8.7	6.2	1.7	-	1.8	(Idris *et al.*, 2004)
S. Korea	32.8	23.8	0	40.6	2.8	-	0	(Idris *et al.*, 2004)
Philippines	49	19	17	9	-	-	6	(Idris *et al.*, 2004)
Poland	35	18	11	20	12	-	4	(Idris *et al.*, 2004)
China	67.3	8.8	13.5	4.5	5.2	-	0.7	(Idris *et al.*, 2004)
Average	**53**	**15.2**	**10.5**	**10.1**	**4.0**	**6.7**	**2.4**	

(b) High income countries

Higher Income	Combustible Waste				Non-Combustible Waste			Source
	Food	Paper	Plastics	Textiles	Glass	Debris	Metal	
Turkey	43	7.8	14.2	23	6.2	0	5.8	(Liamsanguan and Gheewala, 2008)
Japan	34	33	13	12	5	0	3	(Liamsanguan and Gheewala, 2008)
USA	13.9	28.5	12.4	8.4	4.6	19.8	9	(Gentil *et al.*, 2009)
UK	17.3	21.4	8.8	3.3	9	26.6	4	(Gentil *et al.*, 2009)
Greece	42	21	11	17	5.4	0	3.6	(Gentil *et al.*, 2009)
Germany	21	31	10	17	16	0	5	(Gentil *et al.*, 2009)
Denmark	39	23	7	21	6	0	4	(Gentil *et al.*, 2009)
Russia	34.9	15	11.3	4.8	14	15.1	4.7	(Rodionov and Nakata, 2011)
France	24	26	13	19	14	0	4	(Gentil *et al.*, 2009)
Average	**29.9**	**23**	**11.2**	**13.9**	**8.9**	**6.8**	**4.8**	

(c) Low income countries

Low Income	Combustible Waste				Non-Combustible Waste			Source
	Food	Paper	Plastics	Textiles	Glass	Debris	Metal	
Tanzania	37	11	7	2	4	8	1	-
Kenya	52	17.3	11.8	5.1	6.7	2.4	2.8	(Henry *et al.*, 2006)
Uganda	37.8	6.7	7.8	1.3	0.7	33.6	0.8	(Kaseva and Mbuligwe, 2005; Henry *et al.*, 2006)
Algeria	62	9	12	0	1	0	2	(Eddine and Salah, 2012)
Nigeria	47	6	10	7	7	18	5	(Ogwueleka, 2009)
Ghana	73	6.6	3.3	2.2	1.5	11.2	2.1	(Boadi and Kuitunen, 2005)
Average	**51.5**	**9.4**	**8.7**	**2.9**	**3.5**	**17.2**	**2.3**	

Table 3 shows the comparison of waste generated from other countries with Arusha municipal solid waste. The waste compositions categorized to middle-income countries Table 3(a), high-

income countries Table 3(b) and low-income countries Table 3(c). The results showed that there is a slight difference between Tanzania and other countries. From middle and lower income countries, much waste dominated by food waste with a higher portion from Indonesia followed by Bangladesh, China and Algeria. Thou South Korea followed by Poland, Thailand and Indonesia have a big portion in textile wastes while plastic waste is dominated by Malaysia followed by China and Thailand. In comparisons with high-income countries, such as the United States of America, Japan and United Kingdom, paper dominates the waste composition followed by food waste, textiles and plastics. In low-income countries, the waste from Nigeria, Kenya, Algeria and Ghana contains more food waste while wood and yard waste has higher portions in Tanzania and Uganda. Glass wastes have a big portion in Kenya and Nigeria.

Comparing the waste composition by the average of each group we found that food waste is generated more in middle-income countries followed by low income; textile waste is very little in low-income countries while glass waste and papers are much higher in higher income countries. Yard and wood waste are more in higher and lower income countries. In general, combustible waste has an average of 89% at middle-income countries, 78% in higher income countries and 73% in lower income countries. Despite of the average waste for energy recovery from lower income countries to be lower than higher and middle-income countries, the percentage of waste available for energy recovery is more than higher and middle-income countries, this caused by poor recycling technology.

3.4.3. Proximate and Ultimate analysis of Arusha Municipal Solid Waste.

Table 4: Proximate and Ultimate analysis of Arusha Municipal Solid Waste

(a) Proximate Analysis in weight percentage

Location	Moisture of received MSW	Volatile Dry Basis	Ash Dry Basis	Fixed Carbon Dry Basis	HHV (MJ/kg)
Kaloleni	59.67	74.43	8.16	17.41	11.90
Sakina	63.99	84.00	10.00	6.00	11.37
Central Market	55.70	78.30	13.48	8.22	12.76
Average Value	**59.79**	**78.91**	**10.55**	**10.54**	**12.01**

(b) Ultimate Analysis in weight percentage

Location	C	H	O	N	S	Cl	P
Kaloleni	55.57	5.34	34.88	2.09	0.31	0.04	0.10
Sakina	55.70	5.29	34.27	2.13	0.22	0.07	0.13
Central Market	53.20	5.24	34.71	2.86	0.37	0.04	0.11
Average Value	**54.8**	**5.29**	**34.6**	**2.36**	**0.3**	**0.05**	**0.1**

Source: (Omari *et al.*, 2014b)

3.4.4. Calorific Value and Energy Recovery from Municipal Solid Waste

The value of energy released as shown in Table 4(a) shows that the value obtained is about 12MJ/Kg. The energy value obtained using the bomb calorimeter is the energy containing in municipal solid waste in dry basis. In this case, the energy of 1kg of municipal solid waste is equivalent to energy of 1.60 kg of net municipal solid waste. This is because 60% of moisture taken out during bomb calorimetry. The energy required to remove moisture of 0.60 kg is 1.411MJ/kg. Make the balance of 10.6 MJ/kg the energy that one would recover per kg of dry municipal solid waste from the municipal solid waste energy conversion. For the case studied, the total waste generated is about 43 772 tons of waste per year. This is equivalent to the energy equivalent to 128.9 GWh.

3.5. Conclusion and Recommendations

This paper presents a report on waste quantity and quality for energy recovery.

i) Precise measurement of waste generation, its composition characteristics and availability is important in waste management plans. This study covers only Arusha city. There should be more researches for the entire country.

ii) The energy contents of the municipal solid waste are about 30% of the energy counting in coal and about 67% of energy contains in pure biomass. Utilization of waste from energy can be useful in energy recovery and for the environment.

iii) The waste generated and its composition analysis can help in decision making on which method of energy recovery utilized. For waste with a big portion of organic waste the composting or incineration utilized while, the presence of large recyclable waste pinpoints the possibility of material recovery from municipal solid waste. For the waste with a big fraction of construction waste, there is a possibility of utilizing waste material in road construction works.

iv) For every one kg of dry municipal solid waste, 10.6 MJ/kg of thermal energy expected to realize.

3.6. Acknowledgements

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CHAPTER FOUR

OPERATING CONDITIONS OF A LOCALLY MADE FIXED-BED INCINERATOR: A CASE STUDY OF BAGAMOYO IN TANZANIA

Abstract

To minimize the pollution from municipal solid waste incinerators, the study of operating conditions is imperative. The local design incinerators can be used for high performance combustion and minimize pollutions. The incinerator located at Bagamoyo hospital in Tanzania used as a pilot for this experiment. The emission and operating conditions show that the performance of the incinerator is at maximum peak of about 70% when the oxygen at exit is about 6.9% and when secondary temperature is between 1073 and 1173K and primary temperature maintained at 673K. The experiment shows that when the primary chamber temperature increases beyond 673K, the secondary temperature decreases this is due to complete combustion at primary chamber, which will cause insufficient incomplete gases and therefore limited combustible gases to burn.

Key words: waste incineration, emission, fixed bed, solid waste

4.1. Introduction

Waste is material or object which the holder may dispose-off or plan to dispose-off (Williams, 2013). Municipal solid waste generation increased as the results of human development and population growth. This is a big challenge of waste disposal in most countries (Hizami *et al.*, 2012). The rate of waste generation of these countries including Tanzania; has been increasing yearly with unchanging methods of waste disposal. This increase of municipal solid waste generated necessitates municipals to improve the method of waste disposal and handling (Henry *et al.*, 2006). Waste disposal method with improper safety conditions and regulations can cause environmental problems (Sharholy *et al.*, 2008; Rodionov and Nakata, 2011). Common method of waste disposal in most of developing countries, especially those in Sub Sahara Africa is dumping, open burning and landfill (Rothenberger *et al.*, 2006). The possibilities of recycling waste materials and energy recovery from waste are better methods

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of waste management system currently used. The utilization of municipal solid waste to energy will assist to mitigate fossil energy use (Rodionov and Nakata, 2011).

The municipal solid waste production rate is varying from place to place due to different levels of inhabitant economic and the seasonal or climatic conditions of the year and therefore the net energy content of municipal solid waste of different place also differs from each other (Cheng and Hu, 2010). The waste materials are dynamic and different in sizes and shape (Nasserzadeh *et al.*, 1994; Arshad *et al.*, 2006). Neither physical nor chemical properties of municipal solid waste are the same; the properties are varying seasonal and regional. When compared the properties of fossil fuels or biomass, the properties of municipal solid waste are dynamic. In this way, different type of wastes disposal system needed. There are three basic method of waste disposal; these include physical, biological and thermal methods (Kaosol, 2010). The physical method of waste disposal, is the disposal by converting waste to physical forms such as pellets, briquettes or chips for further use in thermal process (Omari *et al.*, 2014a). Biological methods of waste disposal are the process of waste disposal in which the organic waste recovering by composting or digestion. The results from compost materials can be used as compost manure (Bundela *et al.*, 2010). The emitted gas during the processes such as methane can be tapped and used as fuel for electricity generation, for driving internal combustion engines and heat generator in combine heat and power systems (Eriksson *et al.*, 2005; Cheng and Hu, 2010). Thermal waste treatment is the process of waste disposal that use heat to treat waste materials (Williams, 2013).The waste management disposal by using thermal method has many challenges (Shin *et al.*, 1999; Ryu and Shin, 2012). The incineration, gasification and pyrolysis are amongst the known techniques (DEFRA, 2013). The waste disposal by incineration may reduce waste volume by 90% and weight by 75-80% (Akkaya and Demir, 2010; Lam *et al.*, 2010).

The incineration is the common method of waste disposal in some hospitals in Tanzania, most of these incinerators are locally brick made with poor performance (Manyele and Anicetus, 2006). The utilization of the energy in combine heat and power can be used in boilers for the electricity generation (Ryu and Shin, 2012). The interactions that take place within the process

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

including pyrolysis, combustion, heat transfer, mass transfer and gas flow (Annunziato *et al.*, 2006).

In order to identify the proper operating procedures of incinerator that practiced on municipal solid waste incinerators, the study of flue gas emission associated with incinerator operating conditions is necessary. The incinerator can become a big polluter if not properly operated (Arshad *et al.*, 2006). The flue gas from incinerator contain particles and gases which are harmful and toxic to human and environment (Wey *et al.*, 2001). If the mixing level of the burnt wastes are better operated, the amount of pollutants to the environment will be reduced (Yang *et al.*, 2005). The emission gases from incinerator indicate the combustion behavior of the incinerator, design, operation and the mixing of waste materials in the combustion chamber (Glarborg, 2007; Manyele and Kagonji, 2012).

Pollution gases such as SO_x, NO_x and CO_2 which can be formed during the combustion of municipal solid wastes can dissolve in the atmosphere and form an acid rain (EPA, 1998; Pal, 2000). The NO_x produced in large amount when the temperature of combustion exceeds 1100℃. The concentration of SO_2 courses the formation of H_2SO_4, which increases the concentration of H^+ ion and therefore makes the rain water drops which are harmful to human and environment (Schindler, 1988). When rain water is too acidic, it can cause problem such as killing fish in water, damage crops (Haines, 1981; Driscoll *et al.*, 2003), erode buildings and roads (Schindler, 1988; Mustabeen and Khan, 2011).

The aim of this study is therefore, to analyze the flue gas emission from an existing incinerator for studying the operating conditions of the existing design in order to improve future incinerator designs.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

4.2. Materials and Methods

4.2.1. Materials

i) Sample Composition

The municipal solid wastes collected from Bagamoyo municipality dump located at Sanzale. The waste sample composition is studied and taken from the average composition ratio of the municipal solid waste studied from previous works reported by (Boadi and Kuitunen, 2005; Ogwueleka, 2009; Hoornweg and Bhada-Tata, 2012; Khamala and Alex, 2013; Omari *et al.*, 2014a). This composition taken as a standard for the current work. The wastes were sorted to separate the combustible and non-combustible wastes to conform to ASTM D5231-92 standard (ASTM, 2003). The waste mass of about 150 kg from dump packed in polythene bags of about 50 kg each and then transported to the incinerator ready for incineration. Diesel used as auxiliary fuel to run the burners.

ii) Sample Formula for Reactions

The samples formula of municipal solid waste used for this experiment were adopted from ultimate and proximate analysis results found in Arusha waste, Tanzania (Omari *et al.*, 2014b)

iii) Prototype Incinerator Design

The pilot incinerator for this study was the fixed bed incinerator located at Bagamoyo Hospital. A schematic diagram of the incinerator shown in Fig.11, 12 and 13.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

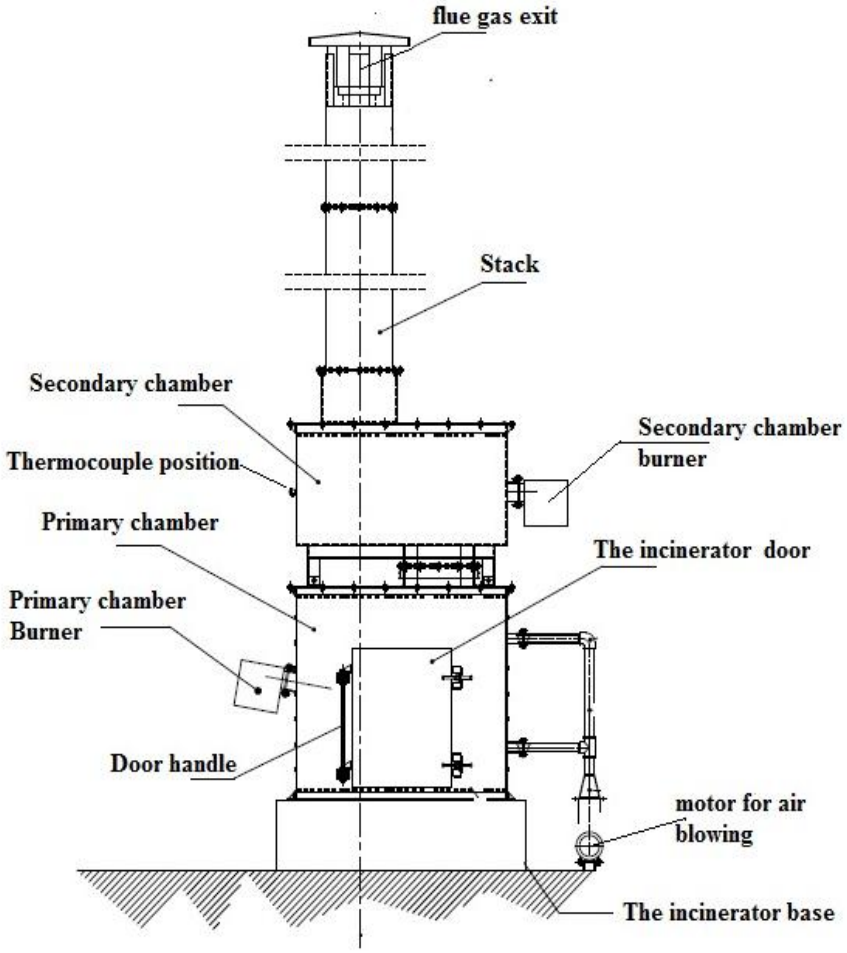

Figure 11: The Pilot Incinerator at Bagamoyo front view

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

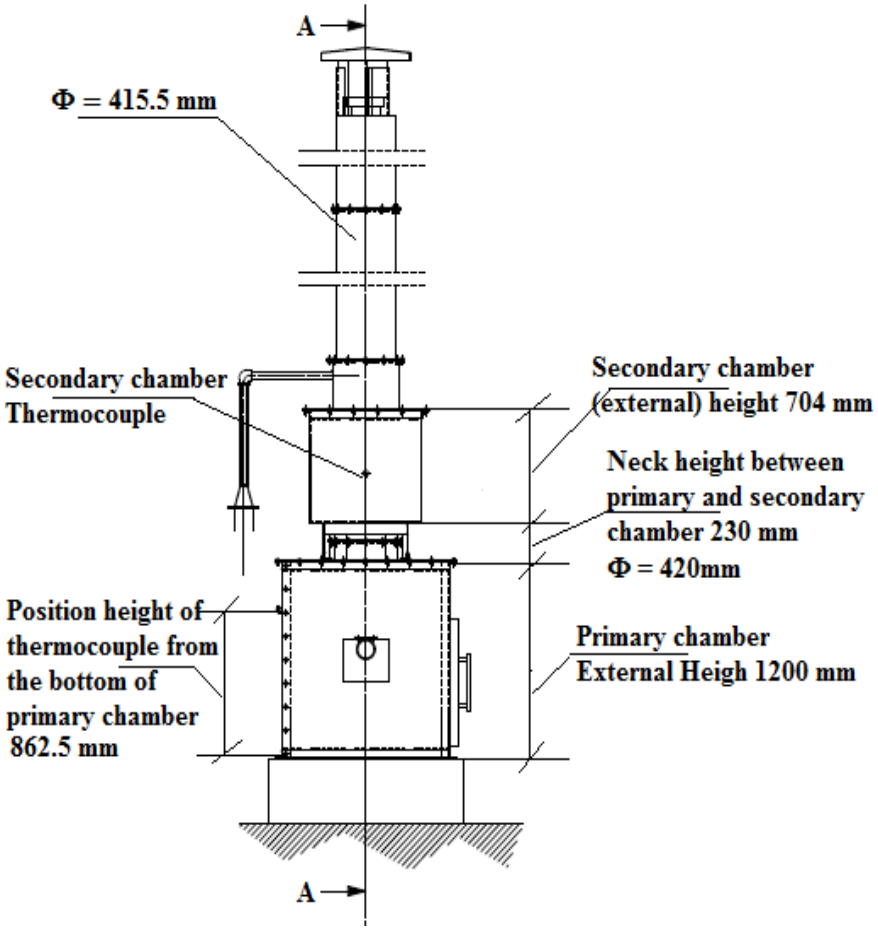

Figure 12: The Pilot Incinerator at Bagamoyo Side View

4.2.2. Working Principles of the Incinerator

This is the starved air incinerator; it composes of two combustion chambers with batch type feeding as shown in Fig.12. The two chambers have two different functions. The primary (ignition) chamber is to ignite the waste and secondary (combustion) chamber is for combustion. The operating temperature for primary chamber varied between 400 and 500℃ by adjusting the fuel supply to the burner while the secondary chamber temperature can vary from 800℃ to 1000℃. The primary chamber maintains minimum temperature sufficient to sustain combustion and killing microorganism in the waste. The minimum temperature need to prevent refractory damage and minimum generation of volatiles to the secondary chamber. This is because high temperatures at primary chamber causes vigorous burning, the solid metal evaporate and enter the secondary chamber as vapour, which will increase the particulate

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

matters to the flue gases. The high temperature at primary chamber can affect the combustion gas volume and rapid increase in flue gas volume at secondary chamber.

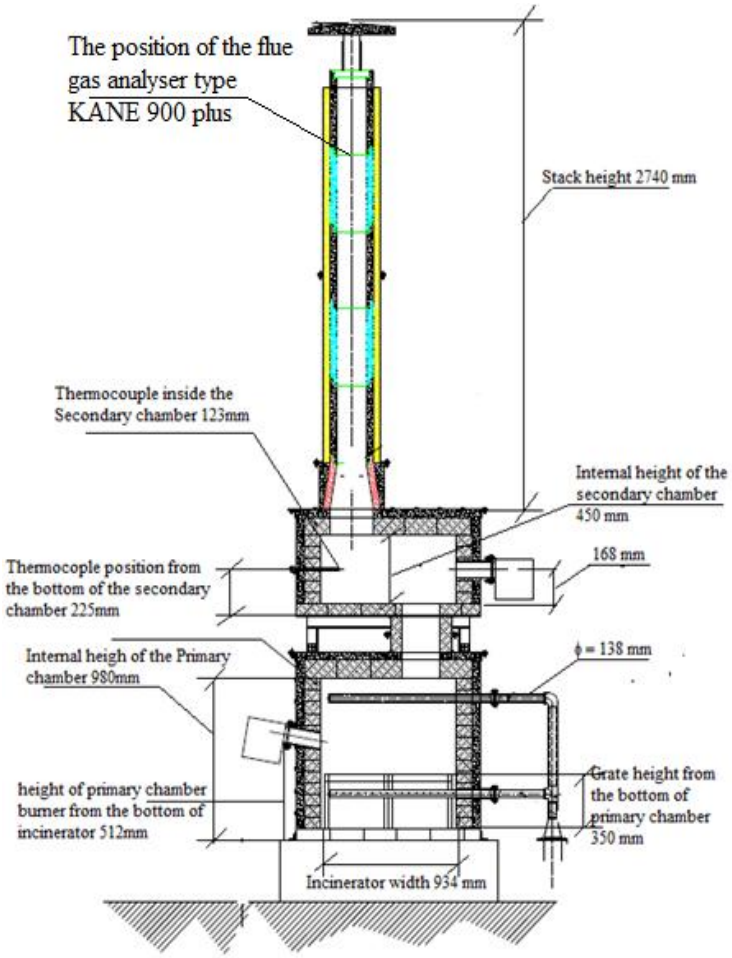

Figure 13: The Pilot Incinerator at Bagamoyo Cross Section View

This incinerator does not include an air control device. With proper combustion control through proper and precise operation, the system can meet the emission regulations.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

As an example, the Chinese standards of emission regulations for pollution for power plants shown in Table 5

Table 5: Emission Standards for Waste to Energy Power Plant

Standard	Item	Threshold Limit Value	Unit
GB 13233-2003	SO_2	400	ppm
	NO_x	450	ppm
GB 13233-2011	SO_2	100	ppm
	NO_x	100	ppm

Source: (Zhao *et al.*, 2012)

4.2.3. Methods

i) Operating Procedure of Incinerator

The first thing is to remove the ash, which left from the last cycle. The ash cooled down for more than 8 hours overnight. Second is charging the waste to the incinerator. This done manually. At this stage, the thing to consider is the heating value of waste materials and moisture contents. These affect the performance of an incinerator. The high moisture contents will provide insufficient thermal input and need excessive fuel consumption while the higher heating value waste may exceed the thermal capacity of the incinerator.

Prior to ignition of waste, the secondary burner used to preheat the secondary chamber to a predetermined temperature of 400℃. The combustion process in the primary chamber controlled to obtain starved air supply. This starved air supply causes the incomplete combustion products. The incomplete combustion products formed are the pyrolysis gases, which will burn again in the secondary chamber to complete the combustion process. The air blowers installed on the side of the incinerator for supply air to secondary and primary chambers as shown in Fig.11. The two thermocouples type K installed in the combustion chamber near the exit point in order to read the representative temperature of each chamber shown in Fig.12.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

The outlet of secondary chamber supplied with excess air to ensure the complete combustion Fig.12 while the primary chamber supplied by starved air to pyrolysed the waste. The burners installed within the combustion chambers to ignite the waste and to maintain the combustion temperature shown in Fig.12.

The flue gas measurements taken from the stack using Hand-held combustion analyzer type Kane 900 plus placed at 300 mm below the exit of the stack and 150 mm inside the stack. The flue gas analyzed including CO, CO_2, NO_x and SO_2. The operating with two combustion chambers with one starved and other with excess air enables to get synthesis gases, which burnt, to the secondary chamber. After the complete incineration process, the incineration switched off for cooling.

ii) The Operating Incinerator under Normal Conditions

The running of incinerator done parallel with the emission measurements of flue gas from the incinerator at the stack shown in Fig.11. Emission gases and temperature results from the incinerator under no load and with load tabulated and recorded. The operation of the incinerator was set with load of 50kgs with variation temperatures of primary and secondary chambers. The temperatures were in the range of 400℃ against 800, 900 and 1000℃ and 500℃ against 800, 900 and 1000℃ for primary and secondary chambers respectively. The flue gas emission released during the incineration process and the ash left out after the completing the incineration recorded.

iii) The Flue Gas Analysis with Variation of Primary Chamber Temperature

The flue gas emissions recorded by varying the primary chamber temperature for analysing the performance of the incinerator. The primary chamber temperature is set to 400℃ and 500℃. The flue gas emission reading recorded. The combustion product gases O_2, CO_2, CO and NO_x recorded and plotted.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

The efficiency of incinerator analysed by using CO_2 indicator, in this way a ratio in equation 7 utilized.

$$\frac{CO_2}{CO_2 + CO} \; x\, 100\% \qquad (7)$$

Where:

CO_2 – Concentration of carbon dioxide

CO – Concentration of carbon monoxide

The results tabulated in Table 10 and 11 and plotted in Fig.17 and 18.

4.3. Results and Discussion

4.3.1. The Waste Sample Composition.

The average value of waste samples composition from (Boadi and Kuitunen, 2005; Ogwueleka, 2009; Hoornweg and Bhada-Tata, 2012; Khamala and Alex, 2013; Omari *et al.*, 2014a) were tabulated in Table 6. These values used as the standard composition for this experiment.

Table 6: Waste Sample Composition of Municipal Solid Waste

	Combustible				Non Combustible	
Country	**Plastics**	**Papers**	**Food**	**Textiles**		
Tanzania	7	11	67	2	13	(Omari *et al.*, 2014a)
Kenya	13.8	11.3	58.8	7.8	8.3	(Khamala and Alex, 2013)
Nigeria	10	6	47	7	30	(Ogwueleka, 2009)
Ghana	3.3	6.6	73	2.2	14.9	(Boadi and Kuitunen, 2005)
Zambia	5	5	50	-	40	(Hoornweg and Bhada-Tata, 2012)
Uganda	1	3	78	-	18	(Hoornweg and Bhada-Tata, 2012)
Ethiopia	2	4	88	-	6	(Hoornweg and Bhada-Tata, 2012)
Average Percentage	**6.0**	**6.7**	**66.0**	**4.8**	**18.6**	

Table 7: The Combustibles Fraction of Municipal Solid Waste

Combustible Wastes	Plastics	Papers	Food	Textiles	Total
Percentage	7	8	82	3	100

The sample obtained shows that the composition of municipal solid waste has about 81.4% of combustible waste and 18.6 % of non-combustible waste as shown in Table 6. These values are also found by in (Mukwana *et al.*, 2014) in his research in Mirpurkhas city in Pakistan, where he revealed that the 60 – 70% of total waste generated from municipal solid waste is combustible.

The combustible waste fraction has the average of 82% of food and organic waste, 8% of paper waste, 7% of plastics and 3% of textiles. This gives the fraction of combustible waste 93% biodegradable and 7% non-biodegradable wastes as shown in Table 7.

This suggests that the energy from municipal solid waste recovered by either using biogenic method or by using thermal treatment method. Textiles and paper wastes are easily combusted because it composed of lignocelulosic biomass. The food and organic waste contains more than 60% of lignocelulosic biomass (Laureano-Perez *et al.*, 2005). Lignocelulosic biomass are poor and slow in hydrolysis rates and low cellulose digestibility (Zhang *et al.*, 2007).

Compared to non cellulosic biomass, cellulosic materials are not efficiently disrupt orderly hydrogen bonds among them and therefore slow down hydrolysis rates (ibid). The cellulose in biomass consists of unorganized crystaline structure, amorphous structure bundled together to form cellulose fibrils. Owing to the location of these cellulose within the cell walls, the accessibility of enzymes are restricted and interfered (Laureano-Perez *et al.*, 2005). The presence of lignin from the food and organic waste fraction of municipal solid waste, cause the waste impermeable and resistance against microbial, thus make degradation of waste by microbial very tough (Fengel and Wegener, 1984). The incineration is better option and faster energy recovery method than biogenic methods (Atabarut and Ekinci, 2006).

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

4.3.2. Empirical Formula for Waste Sample Formulation

For development of empirical formula for municipal solid waste, the ultimate analysis results used. The values tabulated in Table 8.

Table 8: Proximate and Ultimate analysis of Arusha Municipal Solid Waste

Proximate Analysis					
	As received	Dry Basis (weight percentage)			HHV
Location	MC	VM	Ash	FC	(MJ/kg)
Kaloleni	59.67	84.43	8.16	17.41	11.90
Sakina	63.99	84.00	10.00	6.00	11.37
Central market	55.70	78.30	13.48	8.22	12.76
Average	**59.79**	**78.91**	**10.55**	**10.54**	**12.01**

Ultimate Analysis							
Location	**C**	**H**	**O**	**N**	**S**	**Cl**	**P**
Kaloleni	55.57	5.34	34.88	2.09	0.31	0.04	0.10
Sakina	55.70	5.29	34.27	2.13	0.22	0.07	0.13
Central market	53.20	5.24	34.71	2.86	0.37	0.04	0.11
Average	**54.82**	**5.29**	**34.62**	**2.36**	**0.30**	**0.05**	**0.11**
Normalize to 100%	56.20	5.42	35.49	2.42	0.31	0.05	0.11
Calculate number of moles	$\frac{x_C}{m_C}$	$\frac{x_H}{m_H}$	$\frac{x_o}{m_o}$	$\frac{x_N}{m_N}$	$\frac{x_s}{m_s}$	$\frac{x_{cl}}{m_{cl}}$	$\frac{x_p}{m_p}$
Number of moles in 100kgs	$\frac{56.20}{12}$	$\frac{5.42}{1}$	$\frac{35.49}{16}$	$\frac{2.42}{14}$	$\frac{0.31}{32}$	$\frac{0.05}{32}$	$\frac{0.11}{28}$
	4.683	**5.423**	**2.218**	**0.173**	**0.010**	**0.001**	**0.004**

(Omari *et al.*, 2014b)

Where:

MC - Percentage of Moisture in Municipal Solid Waste

VM - Volatiles Matter

FC - Fixed Carbon

X_c, X_H, X_o, X_N, X_S, X_{cl}, X_p

- are the fraction composition of Carbon, Hydrogen, Oxygen, Nitrogen, Sulphur, Chlorine and phosphorus respectively.

m_C, m_H, m_O, m_N, m_S, m_{Cl}, m_P

- are the Atomic number of the Carbon, Hydrogen, Oxygen, Nitrogen, Sulphur, Chlorine and Phosphorus respectively.

The chemical formula for municipal solid waste for our case will be

Arusha Municipal solid waste

$$C_{4.683}H_{5.423}O_{2.218}N_{0.173}S_{0.010}Cl_{0.010}P_{0.004} \quad (8)$$

The empirical formula of a chemical compound is a simple expression of the relative number of each type of atom in it. It shows the proper ratio of atom to atom.

It can help in predicting chemical reactions which will assist in predicting the output result of the reaction.

4.3.3. The Operations of an Incinerator under Normal Conditions

The incinerator operates as normal, the variation of temperature in primary and secondary chambers with the flue gas emission tabulated in Table 9 and plotted in the Fig. 14 and Fig. 15.

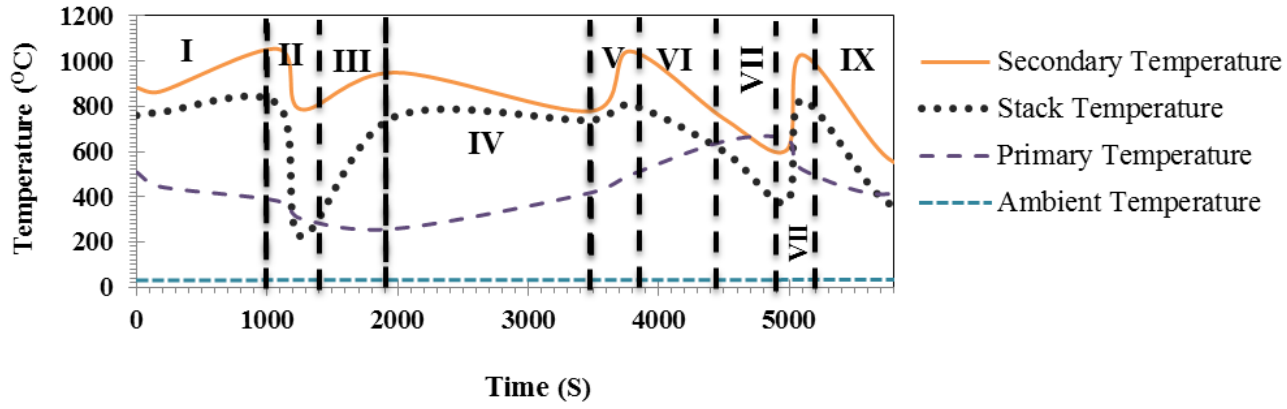

Figure 14: Typical Temperature Distribution in an Incinerator for One Complete Cycle

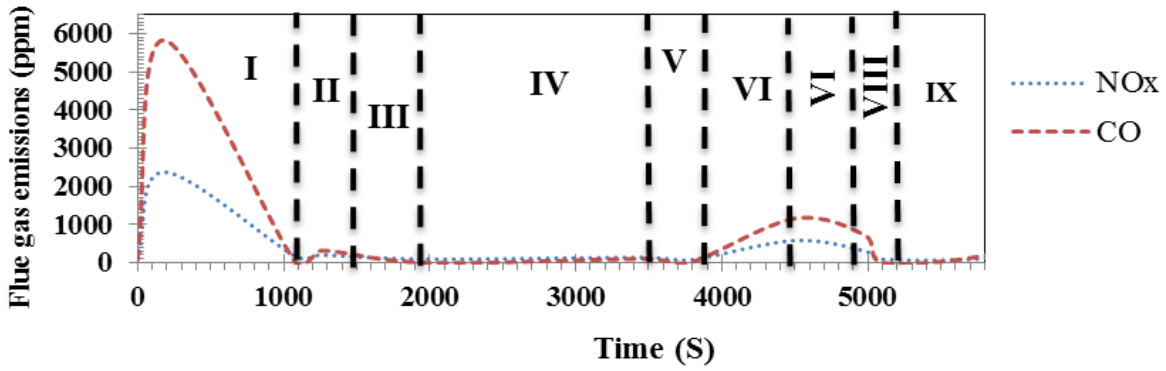

Figure 15: NO_X and CO Emissions from Incinerator for One Complete Cycle

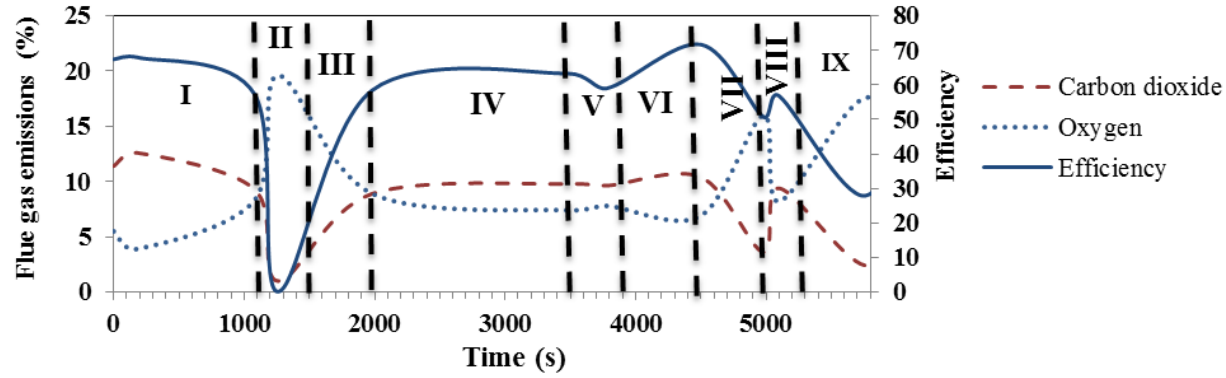

Figure 16: Efficiency, CO_2 and O_2 Emission from Incinerator

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

Table 9: The Operation for One Cycle with Emission from Incinerator

Time Sec.	Emissions						Temperature		The Operating Conditions
	O_2 %	CO ppm	CO_2 %	T_S ℃	$T_{Amb.}$ ℃	NO_x ppm	$T_{Pri.}$ ℃	$T_{Sec.}$ ℃	
0	5.5	101	11.4	760.3	30.9	71.3	509.3	883.3	Without Load
180	3.9	5832	12.6	774	31.5	2374	445	865.7	At start after feeding
1080	8.3	12	9.3	811	31.7	165	382	1054.3	Mid of incineration (Sec burner On)
1260	19.6	317	1	225.7	32.3	199	303.3	786.7	Sec. Burner OFF
1980	8.9	0	8.9	755.3	32.3	92	259	949.7	Sec. Burner ON, Near end
3480	7.4	100.7	9.8	739	32.1	136	418.3	779.3	400/800
3780	7.8	0	9.63	807.7	32.4	67	496.3	1044	500/1000
4500	6.9	1159	10.4	600.7	32.9	582	646	745.7	Door open slightly and burner off
4980	16	716.3	3.6	377.3	33.1	302.3	655.7	606.7	Burners off
5100	8.2	0	9.4	828	33.3	87	520.7	1027.7	Sec Burner On
5760	17.6	162	2.4	371.7	33.7	99	413.3	569	End of Incineration (Sec burner off)
6180	11.7	776.7	6.8	528.3	33.7	371.7	617.7	572	Burners off /Door slightly open

Where:
- O_2 Mass of oxygen to the total mass of the flue gas in percentage
- CO Mass of carbon monoxide to the total mass of the flue gas in parts per millions (ppm)
- CO_2 Mass of carbon dioxide to the total mass of the flue gas in percentage
- NO_x Mass of Nitrogen oxides to the total mass of the flue gas in parts per millions (ppm)
- $T_{s.}$ Temperature of the stack (℃)
- $T_{pri.}$ Primary chamber temperature of an Incinerator (℃)
- $T_{sec.}$ Secondary chamber temperature of an incinerator (℃)
- $T_{amb.}$ Ambient temperature (℃)

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

The measurement and results observed from an incinerator divided into regions. There are 9 regions division. Region I show that when the incinerator working under no load, the maximum combustion temperature attained for the stack was 1073K as shown in Fig. 14. The emission of NO_x and CO seems to be much higher at the beginning and then suddenly decreases. This is due to the incomplete combustion of the fuel at starting shown in Fig. 15. The NO_x formed in this case is prompt NO_x which normally coming from the combustion of Nitrogen bearing fuels. The fuel released nitrogen bound in them as free radical which are oxidized to NO_x (Stubenberger *et al.*, 2008).

At the second region the temperature of the incinerator falls. The stack temperature decreases to 520K. The primary chamber temperature decreases to 576K while secondary temperature falls to 556K, this is because at this time, the incinerator burners switched off and the feeding stock added to the incinerator. The incinerator efficiency also falls to zero since there is no combustion during the feedstock and all the burners switched off.

At region III, all the burners switched on. The temperature of the incinerator changes, the secondary and stack temperature rises while the primary temperature falls. The cause of primary chamber temperature to fall is due to the feedstock temperature, which is at room temperature from the dump. The emissions show that the CO_2 concentration increases while the O_2 concentration decreases as shown in Fig. 16. The concentration of carbon monoxide decreases while NO_X emissions become constant at 92 ppm, Fig. 15.

At region IV the temperature of the primary chamber increases while that of secondary slightly decreases, thus showing that the feedstock is already acquired the uniform temperature with the combustion chamber. The emission of NO_x and CO is at constant of about 136 and 100.7 ppm Fig. 15 while the O_2 and CO_2 emission are about 7.4 and 9.8% respectively. The efficiency of the incinerator combustion fluctuates between 63 and 59% as shown in Fig. 15. The decrease in secondary chamber temperature is caused by reduction of incomplete combustion gases which are expected from primary chamber to the secondary chamber such as CO which decreases from 136 to 100.7 ppm shown Fig. 5 (Chen and Chen, 2001).

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

At region V, the incinerator temperature of all chambers increases Fig. 14. The combustion efficiency is slightly decreases Fig. 16. The concentration of NO_x and CO is slightly decreases. The NO_x concentration decreases from 136 ppm to 67 ppm while concentration of CO decreases from 100.7 to 0 ppm as shown in Fig. 15. The decrease of NO_x and CO and the efficiency of the combustion caused by switching off the second burner for trying to maintain the desired temperature. The NO_x concentration decreased because the amount of diesel of combustion decrease as the burner switched off. The only NO_x formed at this temperature is a prompt NO_x (Stubenberger *et al.,* 2008) which is normally comes from the fuel used.

At region VI, the burner is switch on again to maintain the desired temperature. The temperature of secondary chamber and stack decreases while the temperature of the primary chamber increases. The emission shows that there is increase in CO and NO_x concentration. The CO increases from zero to 1159.3 ppm and that of NO_x increase from 67 to 582 ppm as shown in Fig. 15. The efficiency of combustion increased from 59% to 71.7% shown in Fig. 16. This is the highest efficiency of this incinerator in which the concentration of O_2 is 6.9% and that of CO_2 is 10.4%. These value approaches the recommended value of O_2 at the exit point, which studied in simulation of fixed bed thermal oxidizer for solid waste disposal. The value obtained and recommended for oxygen at exit point is 6% (Mtui, 2013).

At region VII, the incinerator door slightly opened to increase the excess air supply and the primary chamber burner switched off. The secondary and stack temperature are decreasing while the primary temperature is still increasing as shown in Fig. 14. This may be caused by complete combustion in the primary chamber by supplying excess air by opening the door and therefore decrease the incomplete combustion gases in the secondary chamber. The NO_x and CO is decreases from 582 to 302.3 ppm and from 1159.3 to 716.3 ppm respectively see Fig. 15. The efficiency also decreased from 71.7 to 50.7%.

At the region VIII, the secondary burner switched on for about 100s while the primary chamber burner is still off. This done in order to maintain the required temperature. The secondary and stack temperature rise rapidly (Fig. 14). The efficiency is slightly increased to 56% and then raised and fluctuate to 50% (Fig. 16)

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

At region IX, all the temperature decreases. The efficiency fall to 27% and CO_2 concentration decreased to 6% while O_2 increases to 20.1% (Fig. 16). The cause of temperature rise from secondary chamber is due to the high concentration of incomplete combustion gases at the chamber. These gases were combusted by the burner and suddenly they diminished.

4.3.4. Flue Gas Analysis with Variation of Primary and Secondary Chambers Temperatures

i) Analysis of O_2, CO_2, CO and NO_x at Primary Chamber Temperature Fixed at 400℃

Table 10: Flue Gas Emission at Primary Temperature 400℃

Primary Temp ℃	Secondary Temp ℃	O_2 (%)	CO (ppm)	CO_2 (%)	NO_x (ppm)
400	808.00	8.76	209.20	9.16	204.00
	902.00	11.96	47.20	5.66	92.00
	1005.00	11.70	3.20	4.20	51.00
	1069.00	12.20	0.60	4.26	57.60

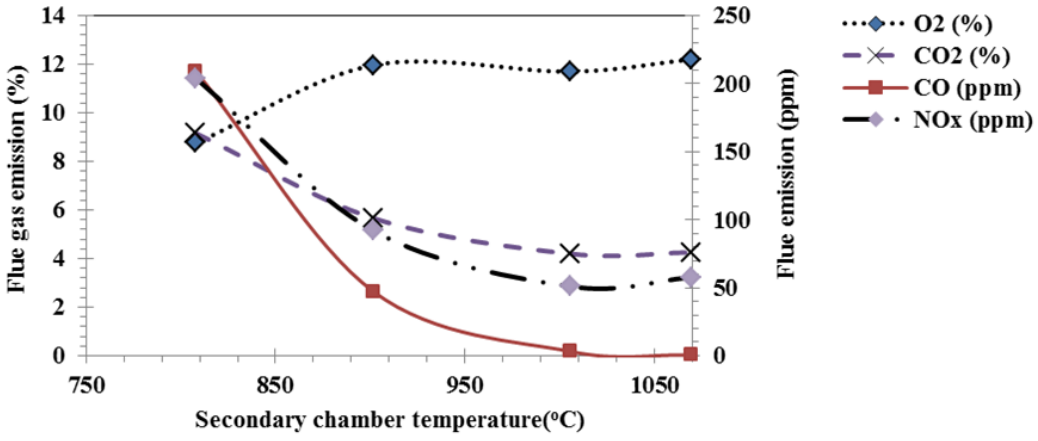

Figure 17: Flue Gas Emission at Primary Chamber Temperature 400℃.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

ii) Analysis of O_2, CO_2, CO and NO_x at Primary Chamber Temperature Fixed at 500℃

Table 11: Flue Gas Emission at Primary Temperature 500℃

Primary Temp. ℃	Sec. Temp.℃	O_2 (%)	CO (ppm)	CO_2 (%)	NO_x (ppm)
500	810.30	17.24	301.80	1.84	184.20
	913.70	17.32	250.40	1.80	156.60
	1055.30	8.64	64.40	6.06	351.80
	1088.00	12.26	0.00	4.06	47.00
	1093.70	10.64	0.80	4.96	168.20
	1102.70	12.26	0.00	3.70	155.80

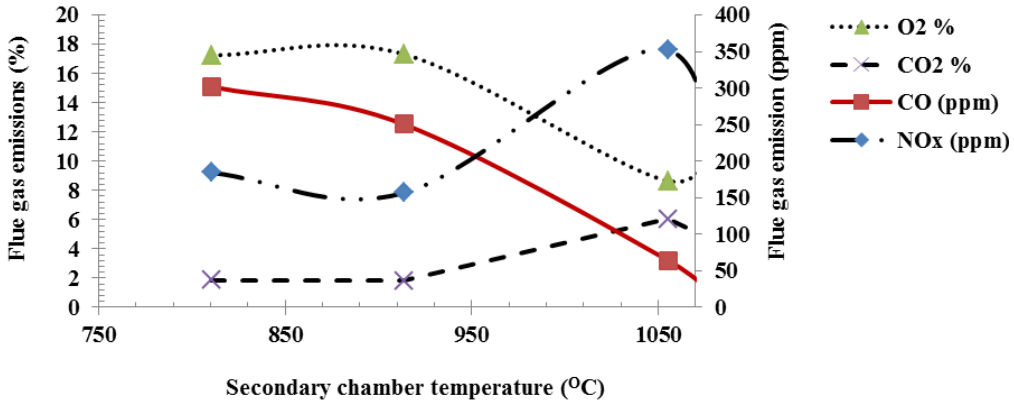

Figure 18: Flue Gas Emission at Primary Chamber Temperature Fixed 500℃

The flue gas shows that the relation between O_2 and CO_2 that, as the amount of CO_2 is increasing the amount of O_2 decreases. This indicates that at this point the efficiency of combustion is better.

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

iii) Analysis of Efficiency, Excess air and O_2 in Flue Gas when the Primary Chamber Temperature fixed at 500℃

The variation of stack temperature, excess air and the oxygen in the flue gas when changing the primary chamber temperature analyzed. The results were recorded and tabulated in Table 12 and plotted in Fig. 19.

Table 12: The Stack Temperature against Excess Air and Efficiency of incinerator with Primary Chamber Temperature 400℃

Pri. / Sec. Temp. ℃	Sec. Temp. ℃	O_2 (%)	η (%)	CO_2 (%)	$T_{stack.}$ ℃	$T_{amb.}$ ℃	X_{Air} (%)
	808.00	8.76	57.54	9.16	749.00	31.58	72.58
400/(800,900,	902.00	11.96	44.30	5.66	705.20	31.80	276.18
1000,1100)	1005.00	11.70	39.80	4.20	679.40	32.00	151.96
	1069.00	12.20	36.08	4.26	800.80	31.90	147.56

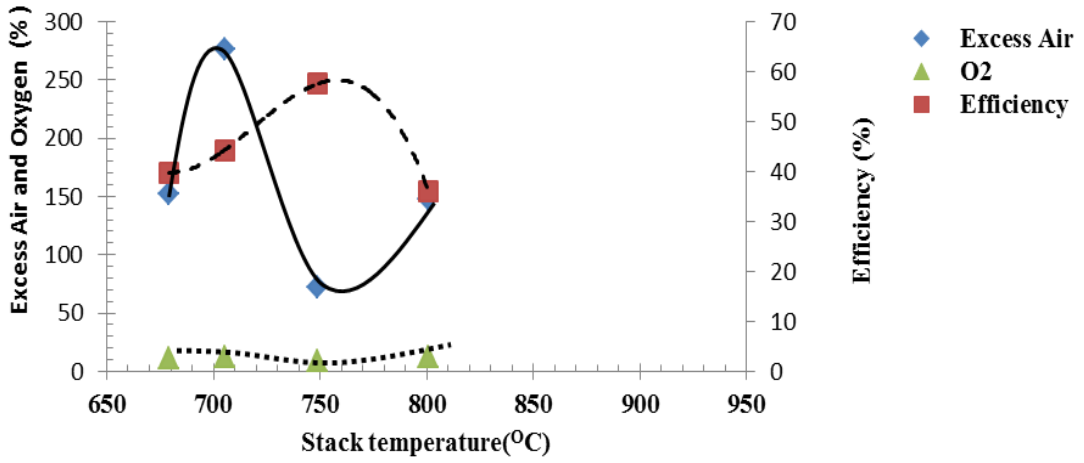

Figure 19: Variation of Efficiency against Excess Air and Oxygen with Primary Chamber Temperature 400℃

The curves shows that when the O_2 is about 6.9% the efficiency is at the highest and when the oxygen is closer to 20% the efficiency is lowest. This indicates that the combustion is poor when the flue gas composition has much O_2 concentration. The excess air also indicates the variation of temperature. As the excess air increases the temperature is decreases and the

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

efficiency is decreases. The efficiency of incinerator seems to increase with increase in temperature.

iv) Analysis of Efficiency, Excess air and O_2 in Flue Gas when the Primary Chamber Temperature fixed at 500℃

Table 13: The Stack Temperature against Excess Air and the Efficiency of Incinerator with Primary Chamber Temperature 500℃

Prim/ Sec Temp. ℃	$T_{sec.}$ ℃	O_2 (%)	η (%)	T_{stack} ℃	T_{Amb} ℃	X_{Air} (%)
500	810.30	17.24	2.78	522.60	32.40	469.60
	913.70	17.32	0.00	557.40	32.30	480.50
	1055.30	8.64	47.68	897.80	32.30	70.46
	1088.00	12.26	26.24	893.20	33.80	214.24
	1093.70	10.64	36.96	816.00	33.80	107.40
	1102.70	12.26	21.36	888.60	33.80	268.34

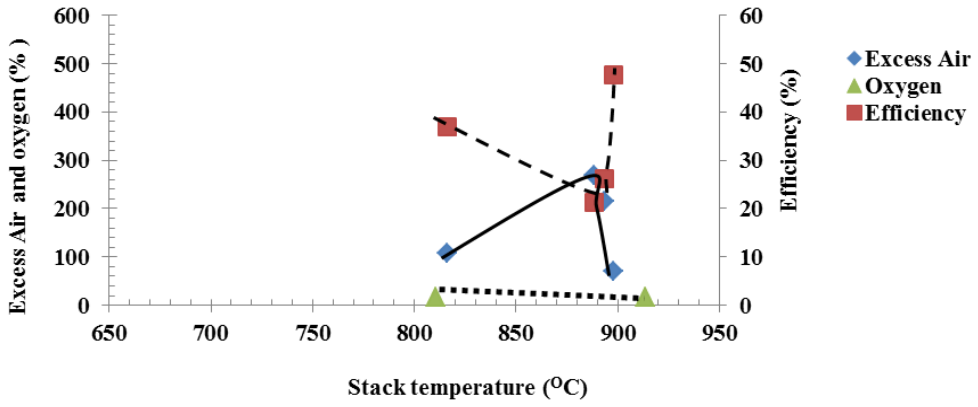

Figure 20: Variation of Efficiency against Excess Air and Oxygen with Primary Chamber Temperature 500℃

International Journal of Environmental Monitoring and Analysis Vol. 3, Issue 2, March 2015, pp. 80-90 doi: 10.11648/j.ijema.20150302.17, ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

With primary chamber at 500℃, the excess air shows to increase at the flue gas composition, as the stack temperature increases, and then it reaches a point when the excess air start to decrease. , At this point the O_2 concentration at flue gas decreases to about 8%, the efficiency start to increase, the efficiency reach its maximum value when the O_2 concentration reaches 6.9%, showing there is a better combustion at this stage.

4.4. Conclusion and Recommendations

i) The waste composition contains more composition of biodegradable and combustible waste and therefore used as the energy source.

ii) The excess air concentration in the flue gas affects the temperature; it needs to reach a certain point for maximum efficiency of the incinerator.

iii) The incinerator performance becomes better when the primary chamber set to 400℃ and the secondary chamber ranges between 800 and 900℃. At this point, CO_2 reach a maximum value of 10.4% whilst CO and NO_x level, are minimal at 100.4 ppm and 92 ppm respectively.

4.5. Acknowledgements

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CHAPTER FIVE

MASS AND ENERGY BALANCE CALCULATIONS FOR A FIXED BED INCINERATORS, A CASE STUDY OF A LOCALLY DESIGNED INCINERATOR IN TANZANIA

Abstract

An estimation of mass and energy balance of an incinerator is an important consideration toward the design and operation optimization of the incineration process. This paper aimed to study the mass and energy balance of a locally made fixed bed incinerator. The results show that the total mass rate of 49 kg/h of municipal solid waste and 9.75 kg/h of diesel consumed 458.9 kg/h of air. The incineration process generates 379 287.14 KJ/h with ash and flue gas emissions at a total mass rate of 528.51 kg/h.

Key words: municipal solid waste, incineration, fixed bed, mass balance, energy balances

5.1. Introduction

5.1.1. Background

Energy access is a key factor to social economic development. It is a known fact that energy generation depletes natural resource and contaminates the environment (Dolgen *et al.*, 2005). However, energy generated does not necessarily deplete the natural resources. It is also a fact that waste management and disposal in most of urban centers in developing countries is a major challenge. Urban centers are growing at a rate that does not match the economic growth of the countries, making it difficult to allocate resources for proper management of urban waste. For municipal solid waste crude dumping in open pits and open burning are among most practiced methods of municipal solid waste disposal in most developing countries. Open burning known to have a potential to pollute the environment due to incomplete combustion of the municipal solid waste. Incineration on the other hand is known method of waste disposal which reduces the volume of the waste with less time consuming compared to other methods of waste disposal (Zabaniotou and Giannoulidis, 2002; Kumar *et al.*, 2014). Incineration offers the possibility to

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control the ash and the flue gas emission to meet the environmental regulations. Under normal conditions the incineration can dispose more than 99% of organic waste (Kaneesamkandi, 2014). The incineration process involves conversion of elemental constituents in organic wastes to toxic gases and non-toxic gases (Shi *et al.*, 2009). The incineration process used to recover energy from waste. The amount of energy recovered depends on the contents of the waste and the degree of pre-treatment of wastes, activities of waste generating centers and season of the year (Udomsri *et al.*, 2011). Auxiliary fuel is required at the beginning of the process and during the process to maintain the desired temperature (Manyele and Kagonji, 2012).

Understanding the energy value of fuel is important in energy calculations of energy systems. The gross calorific value of municipal solid waste varies from 6 to 12MJ/kg (Guermoud *et al.*, 2009; Udomsri *et al.*, 2011). The heat released due to combustion of municipal solid waste must be controlled so as to maintain the desired temperature (Consonni *et al.*, 2005).

Incineration of municipal solid waste results into secondary products some which can cause serious environmental and health impacts. Control of combustion conditions alters the composition of the various secondary substances resulting from the incineration process. The primary toxic pollutants gases from incinerator are such as NO_x, SO_x, CO, HCl, dioxins and furans, their composition is influenced by combustion conditions (Wey *et al.*, 2008). The designers of the incinerator must know the amount of air needed for complete combustion, anticipated flue gas composition, air flow rate and exit temperature in order to control the emissions and toxic gases formed (Chang and Huang, 2001). Conditions such as oxygen concentration, residence time, temperature and mixing turbulence have big influence in the formation of these pollutants. High combustion temperature combined with high oxygen concentration, residence time, and mixing turbulence reduces the quantity of CO produced but increase the possibility of the formation of NO_x (Göerner, 2003). The formation of furans and dioxins is favoured by low oxygen concentration, high temperature and high residence time (Fuse *et al.*, 2002). The oxygen, carbon monoxide and carbon dioxide concentration in the effluent gas are a useful indicators of the combustion performance (Ujama *et al.*, 2013). The

mass and energy balances information enables the designer to predict the amount of auxiliary fuel needed, the size and capacity of the incinerator (Mörtberg *et al.*, 2006).

The steps of combustion of municipal solid waste are as follows;

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \qquad \Delta H^{o} = -393.5\,kJ\,mol^{-1} \tag{9}$$

$$C_{(s)} + CO_{2(g)} \rightarrow 2CO_{(g)} \qquad \Delta H^{o} = -221.06\,kJ\,mol^{-1} \tag{10}$$

$$H^{+}_{(aq)} + Cl^{-}_{(aq)} \rightarrow HCl_{(aq)} \qquad \Delta H^{o} = -167.2\ kJ\ mol^{-1} \tag{11}$$

$$H_{2(g)} + \frac{1}{2} O_{2(g)} \rightarrow H_2O_{(l)} \qquad \Delta H^{o} = 285.83\,kJ\,mol^{-1} \tag{12}$$

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)} \qquad \Delta H^{o} = -297\ kJ\ mol^{-1} \tag{13}$$

These reaction equations are the major input for consideration in energy balance calculations.

5.1.2. Mass and Energy Balances

Mass and energy balance of the incinerator described by mass and energy balances laws. The law of conservation of mass and law of conservation of energy is applied. The mass and energy balance of the system show the relation between the mass input to the mass output and the mass of remaining or generated in the system (Lee and Lin, 2007).

5.1.3. Mass Balance of the System

For the given mass change at time Δt say $t_2 - t_1$

$$\int_{t_1}^{t_2} m_{in}\,dt - \int_{t_1}^{t_2} m_{out}\,dt = \int_{t_1}^{t_2} \frac{d(m)}{dt}\,dt \tag{14}$$

$$\dot{m}_{in} - \dot{m}_{out} = \dot{\Delta m} \tag{15}$$

Where:

$\dot{\Delta m}$ - Mass generated within the system.

Figure 21: Mass Balance of the System

Fig. 21 shows the mass balance of the system, the inlet stream is composed of municipal solid waste, diesel and air. The outlet stream is composed of flue gases and bottom ash.

5.1.4. Energy Balance of the Incineration System

The energy balance of a system is done in accordance with the laws of thermodynamics. The law of conservation of energy which states that the total energy of an isolated system is constant. The energy cannot be created, but can be transformed from one form to another.

For the time $\Delta t = t_1 - t_2$

$$\int_{t_1}^{t_2} E_{in}dt + \int_{t_1}^{t_2} E_g dt - \int_{t_1}^{t_2} E_{out}dt = \int_{t_1}^{t_2} \frac{d(E)}{dt} dt \quad (16)$$

$$E_{in} + E_g - E_{out} = \Delta E \quad (17)$$

According to the first law of thermodynamics the sum of all energies is constant.

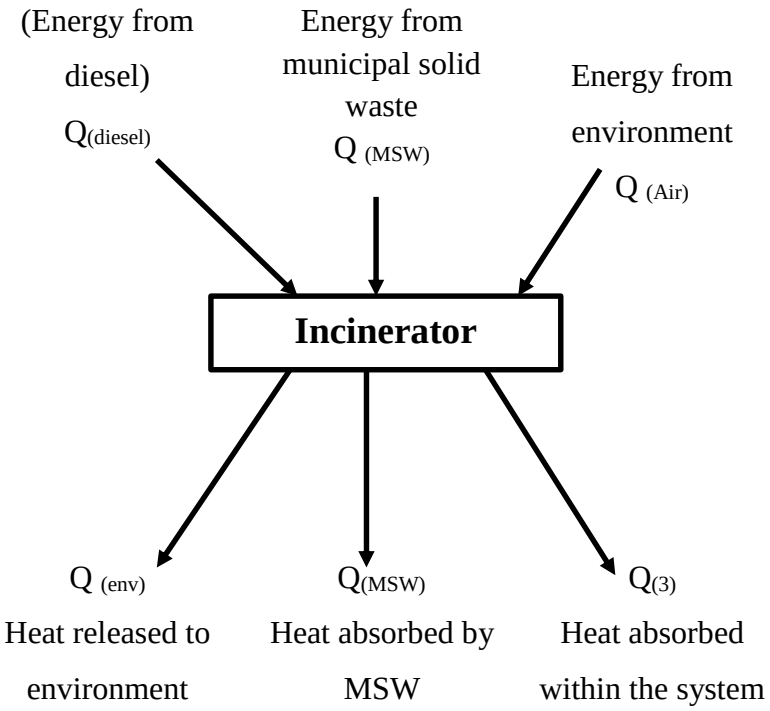


Figure 22: Energy Balance of the Incinerator

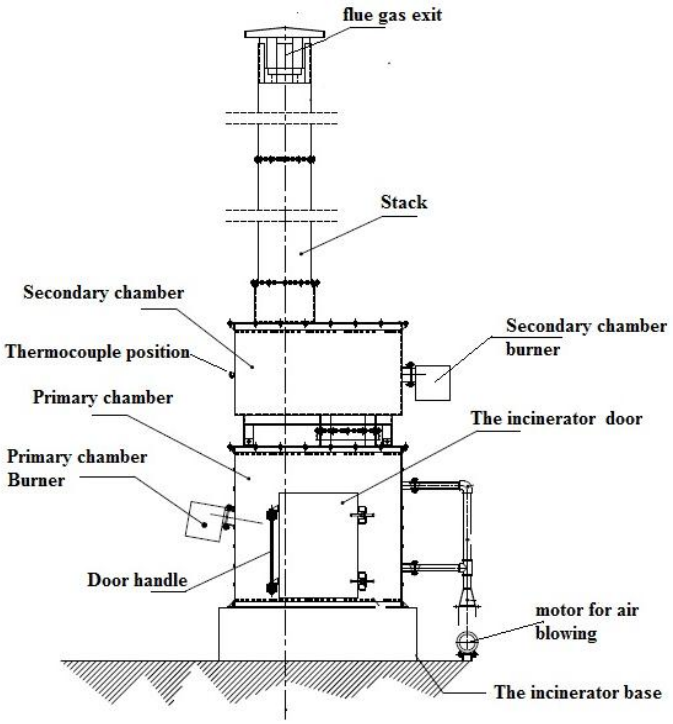
5.1.5. Stoichiometric Combustion

Theoretical oxygen requirement for the waste to burn is the minimum amount of oxygen, which is required for complete combustion. As air is composed of 21% moles of oxygen and 79% moles of nitrogen by mass, when assuming the composition of other gases negligible (Law, 2006). In practice the actual amount of oxygen supplied is normally greater than theoretical oxygen, this is due to imperfect mixing during combustion, the extra oxygen will fulfil the requirements at material time to ensure sufficient oxygen for combustion (Sterling, 1965; Basu, 2006). In most cases the fraction of excess oxygen (f) for incineration is set 20 - 50% (Menghini *et al.*, 2008).

5.2. Materials and Methods

5.2.1. Equipment

The mass and energy balance calculation for the locally made fixed bed incinerator located at Bagamoyo hospital, Tanzania conducted. This incinerator used by the Bagamoyo district hospital for incineration of hospital waste. In our case, it used as a pilot example for this study. The incineration layout shown in Fig. 23



Source: (Omari *et al.*, 2015)

Figure 23: The Fixed Bed Incinerator Layout

Table 14: Auxiliary Equipment of Incinerator

S/N	Equipment	Qty.	Type	Specification	Source
1	Burner	2	LO 20 Alpha Thermal	Fuel consumption 10-20*l*/*h*, thermal power 425 000 – 435 000 *kJ/h*, Motor power = 240W, pump pressure =10-12 bar	(Alfa_Therm, 2013)
2	Thermal couples	2	K Nickel-Chromium	Grade wire -270 to 1260℃ Extension grade wire 0 to 200℃. Melting point 1400℃	(Hernandez *et al.*, 2015)
3	Motor for air blowing	2	Induction motor	Single phase induction motor	Type: PME 0438-035 No: 04408278 kW 0.22, V=230, Hz=50 A=1.15 Year 2011

5.2.2. Materials Used

i) Municipal Solid Waste

The waste composition for this experiment and the and the proximate and ultimate values analysis as studied earlier by (Omari *et al.*, 2014a)

Table 15: Proximate, Ultimate Analysis and HHV Studied of Municipal Solid Waste

	Proximate Analysis in weight percentage				
Location	Moisture as received	Volatile Dry basis	Ash Dry basis	FC Dry basis	HHV (MJ/kg)
Kaloleni	59.67	84.43	8.16	7.41	11.90
Sakina	63.99	84.00	10.00	6.00	11.37
Central market	55.70	78.30	13.48	8.22	12.76

	Ultimate Analysis in weight percentage						
Location	C	H	O	N	S	Cl	P
Kaloleni	55.57	5.34	34.88	2.09	0.31	0.04	0.10
Sakina	55.70	5.29	34.27	2.13	0.22	0.07	0.13
Central Market	53.20	5.24	34.71	2.86	0.37	0.04	0.11

Source: (Omari *et al.*, 2014a)

The empirical formula calculated for municipal solid waste found to be

$$CH_{1.158}O_{0.474}N_{0.037}S_{0.002}Cl_{0.0001}P_{0.001} \quad (18)$$

By assuming negligible value of Cl and P the new empirical formula will be

$$CH_{1.158}O_{0.474}N_{0.037}S_{0.002} \quad (19)$$

This formula corresponds with other municipal solid waste formulas studied by (Arafat and Jijakli, 2013) and earlier studied in Klein theses work in 2002 (Klein, 2002). In their study, they show that the municipal solid waste has the mean hydrocarbon formula of $C_6H_{10}O_4$, mixed food waste $C_6H_{9.6}O_{3.5}N_{0.28}S_{0.2}$, mixed papers waste $C_6H_{9.6}O_{4.6}N_{0.036}S_{0.01}$ and Yard waste $C_6H_{9.2}O_{3.8}N_{0.01}S_{0.04}$. By using the results observed, the chemical formula for Bagamoyo municipal solid waste found to be $C_6H_{9.948}O_{2.844}N_{0.222}S_{0.012}$.

ii) The Diesel Consumed

The diesel used in this experiment is a general purpose diesel fuel grade No. 1-D S500 for use in diesel engine application with maximum sulphur content of 500 ppm (ASTM, 2011). The density of the diesel is 852 kg/m^3 at 21 ℃ with general formula of $C_{12}H_{23}$ and higher heating value of 45 013 kJ/kg, and sulphur and moisture contents of 170 ppm and 0.055 weight percentage, respectively.

iii) The Air Supply

The air supplied to the incinerator by using blowers connected to two motors sideways of the incinerator. The one connected at the right hand side is supplying the staved air to the primary chamber and bottom of the secondary chamber. The excess air to the incinerator supplied by the right hand side blower through the pipe closer to the exit of the secondary chamber.

5.2.3. Mass Balance of the System

i) The Mass Flow Rate of Municipal Solid Waste

This done by taking the mass of municipal solid waste at the beginning and the time taken to complete the incineration process. By measuring the mass of waste consumed and time taken, assumed constant flow rate, the mass flow rate of combustible waste calculated.

ii) The Mass Flow rate of Diesel

The mass flow rate of diesel consumed calculated by measuring the volume of diesel consumed, duration of the operation and the density, the value of mass flow rate obtained.

iii) Mass Flow Rate of the Oxygen and Air

The mass flow rate of oxygen used was determined by taking 21% of mass flow rate of air used. The mass of air used was determined by measuring the velocity of air used, knowing the standard air density of Bagamoyo, the cross section area of pipe used to supply air to the incinerator; the mass flow rate of air was obtained.

iv) Mass Out due to Bottom Ash Left

The mass of bottom ash left measured. The total time consumed was about 0.9264h and the mass flow rate of ash found to be 5.87 kg/h.

v) Mass Rate Out due to Effluent Gases

The mass of flue gases such as CO, CO_2, NO_X, O_2 and H_2O vapour measured by using Kane 900 plus emission meter. Kane 900 plus emission meter hand held combustion analyzer measures combustion efficiency, composition of O_2, CO_2, NO_X, SO_2 and excess air in the flue gas emission. Since each gas has the ability to conduct heat at a specific rate, thermal conductivity principle used in operating this instrument. The operation principle using Wheatstone bridge configuration shown in Fig. 24.

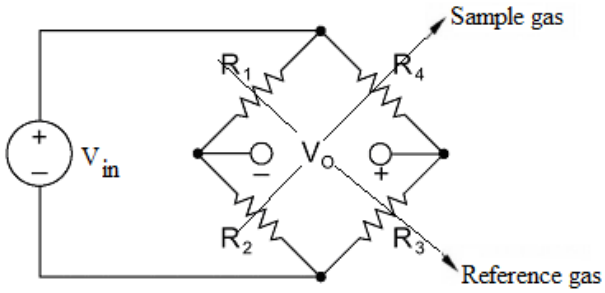


Figure 24: Wheatstone-bridge Configuration

When all the resistors are balanced, the voltage output is zero and the current passed through is balanced. Then, the electric current passed through the resistance bridge to heat the element. The sample gas is passing through one side differs with other side of the heated bridge. The temperature of the resistors of the side where sample gas passed will change according to thermodynamics laws. This change in temperature cause imbalance and therefore cause the potential difference. The current flow due to this potential difference caused by resistance change interpreted in the output signal (Matese *et al.*, 2009; Thomas and Haider, 2013). The output signal strength is set in such a way that when sample gas passed over one side of the bridge, the voltage value compared to a reference value that correlates to content of the sample gas and therefore the gas composition content identified.

5.2.4. Energy Balances Equations

$$Energy\ in = Q_{(Diesel1)} + Q_{(MSW1)} + Q_{(Air)} \quad (20)$$

$Q_{(diesel1)}$ = Energy from auxiliary fuel (Diesel)

$$= \dot{m}_{(diesel)} * HHV\ of\ diesel$$

$Q_{(msw1\ dry)}$ = energy from municipal solid waste

$$= \dot{m}_{(MSW)_{dry}} * HHV\ value\ of\ municipal\ solid\ waste$$

$$Energy\ Out = Q_{(Effluent)} + Q_{(MSW2)} + Q_{(3)} \quad (21)$$

$Q_{(Effluent.)}$ = Heat released to the environment (Heat released by flue gases)

$$\sum (m_{gases} * C_{p(gases)} * \Delta T_1) \quad (22)$$

Where:

$m_{(gases)}$ = the mass of gases (kg)

$C_{p(gases)}$ = specific heat capacity of gases ($kJkg^{-1}K^{-1}$)

ΔT_1 = the change in temperature between ambient and flue gases exit temperature (K)

$Q_{(msw2)}$ = the heat absorbed by municipal solid waste during pyrolysis.

Heat used to raise MSW (ash) from ambient temperature to maximum temperature + heat used to dry MSW (Heat to raise moisture from ambient temperature to 100℃ and the enthalpy of vaporization) + heat to raise the vapour from boiling point to exit temperature

$$= (m_{ash} * Cp_{(ash)} * \Delta T_2) +) m_{H2O} * Cp_{H2O(l)} * \Delta T_3 + m_{H2O} * hv_{(H2O)} * C_{pw(g)} * \Delta T_4) \quad (23)$$

Where:

$m_{(msw)}$ = mass of ash (kg),

$C_{p(ash)}$ = specific heat capacity of ashes ($kJkg^{-1}K^{-1}$),

ΔT_2 = Change in temperature between ambient and maximum temperature of incinerator (K),

$m_{(H_2O)}$ = mass of moisture present in waste (kg),

$C_{p(H_2O)(l)}$ = specific heat capacity of water ($kJkg^{-1}K^{-1}$),

ΔT_3 = Change in temperature between ambient and boiling point of water (K),

$h_{v(H_2O)}$ = enthalpy of vaporization of water (J/kg),

$C_{pw(g)}$ = specific heat capacity of water vapour ($kJkg^{-1}K^{-1}$),

ΔT_4 = Change in temperature between boiling point of water and exit temp of incinerator (K),

$Q_{(3)}$ = Heat loss due to radiation which is taken as 3-5% of the total heat available.

5.3. Results and Discussion

5.3.1. Mass Balance of the System

The mass of the materials used during incineration are changing as the chemical reactions occur between municipal solid waste, auxiliary fuel and air.

i) Mass Input by Municipal Solid Waste and Diesel

From the experiment, the mass of waste incinerated was 49 kg/h. The total mass of ash remaining after the combustion was 5.87 kg/h this shows that the mass of waste consumed in forming flue gases is 43.13 kg/h, which give the equivalent of mass reduction by 88.02 %. The value of unreacted material found to be 11.98 %. This value is closer to the value obtained in proximate analysis from various researches. Since the waste has 55% moisture, it implies that the total mass of dry waste will be 19.4 kg/h, and the total moisture will be 23.72 kg/h. The

volume flow rate of diesel consumed measured and found to be 0.011 439 m^3/h. Since the density(ρ) of diesel = 852 kg/m^3, the mass flow rate of the diesel = 0.011 439*852 = 9.75 kg/h

ii) The Mass of Air Supplied and Moisture Contents from the Air

The mass of air supplied and moisture contents from the air to the incinerator for municipal solid waste measured and calculated. The mass of air supplied to the incinerator measured by using an anemometer. The air-supplied velocity to the incinerator measured to be 6.2 m/s for pipe P_1 that is located at the bottom of the grate bed. The air velocity for pipe P_2, which is located at the exit of primary chamber, is 6.3 m/s while the air velocity of pipe P_3 located at the exit of the secondary chamber found to be 9.2 m/s. Their respective diameters are 0.05 m, 0.05m and 0.0625 m. Density of air $\rho_{(air)}$ and humidity of Bagamoyo at 22.75 are 1.292 kg/m^3 and 77.2% respectively (Infolinks, 2011). From the value of humidity the specific humidity calculated

The relative humidity 77% at 22.75℃, the specific humidity at a corresponding vapour pressure of 2701.3 found by the formula

$$x = \frac{0.621\ 98 * P_w}{(P_a - P_w)}$$

Where:

x = Specific humidity at saturation (kg $_{water}$ /kg $_{air}$),

Pa = Atmospheric pressure (Pa),

Pw = Partial pressure of water in moist air

The value of specific humidity found to be 0.017 404 2 kg $_{(water)}$/kg $_{(air)}$

The burner is set to operate with 50% excess air

$$C_{12}H_{23} + 17.75(O_2 + 3.76N_2) \rightarrow 12CO_2 + 11.5H_2O + 66.74N_2 \quad (24)$$

Table 16: Diesel and Air Consumption of Burners

	$C_{12}H_{23}$	O_2	N_2	CO_2	H_2O	N_2	O_2
	1	17.75		12	11.5	66.74	
Total mass	167	568	1 868.72	528	207	1 868.72	0
Normalize diesel	1	3.4	11.19	3.16	1.24	11.19	0
Diesel fired kg/h	9.75	49.74	163.65	30.83	12.09	163.65	16.58

According to the balance equation in equations (8) and (9), the total mass of air with a 50% excess will be 213.4 kg/h and the calculated value of specific humidity of 0.017 404 2 kg(water)/kg(air) the total mass of humidity was found to be 7.984 872 918 $kg_{(water)} / kg_{(air)}$

5.3.2. Mass Balance Analysis Summary

i) Mass Input and Output of the Incinerator

Mass input and output of the incinerator is calculated from measured value of the airflow rate. The value of mass output due to flue gas emission measured and calculated by assuming complete combustion. The concentration of the flue gases in percentage taken as the average values of O_2, N_2, CO_2, H_2O and SO_2. The flue gases velocity in m/s recorded, the measured value of gas concentration, and the density of each identified gas O_2, N_2, CO_2, H_2O and SO_2 were used to calculate the mass flow rate using

$$m_i = A_i \, x \, V_i \, x \, \rho_i$$

Where

m_i = mass flow rate of gas (kg/h),

V_i = Velocity of flue gas (m/s) and

ρ_i = density of the gases (kg/m^3).

Subsequently the respective mass flow rate were 39.21 (kg/h), 334.75 (kg/h), 75.28 (kg/h), 67.07 (kg/h) and 0.127 (kg/h) from their corresponding densities of 1.331 (kg/m^3), 1.165 (kg/m^3), 1.842 (kg/m^3), 0.804 (kg/m^3) and 2.279 (kg/m^3) respectively. The respective velocity of gases and stack cross-section area are constant with the values of 3.9

(m/s^2) and 0.031 42 (m^2) respectively. The total mass output due to flue gas is therefore will be 516.439 (kg/h).

ii) Mass of Particulate Left

The mass of solid ash left measured to be 5.87 kg/h. This value is different with calculated value by proximate analysis, which was 2.87 kg/h. The ash is higher than the calculated value, and the total mass is lower than expected, this may be due to some unreacted waste material left during the sorting exercise prior incineration and unaccounted mass of municipal solid waste burned and escape with flue gases during incineration. The value of the mass balance summarized in the Table 17.

Table 17: Mass Balance Summary Analysis of the System

Mass input	**Kg/h**	**Mass output**	**Kg/h**
Mass of air for incinerator combustion chamber	245.509	Mass of CO_2	75.282
Mass of air for burner	213.395	Mass of H_2O	67.065
Subtotal mass of air	**458.904**	Mass of N_2	334.75
Mass of moisture in combustion air	7.98	Mass of O_2	39.213
Mass of moisture in Diesel and MSW	26.95	Mass of SO_2	0.1267
Subtotal Mass, moisture	**34.93**	**Total mass of flue gases**	**516.44**
Mass of diesel	9.75	Mass of solid ash remains	5.87
Mass of dry municipal solid waste	22.05	Mass of unaccounted particulates	Variable
Subtotal mass fuel	**31.8**	**Subtotal particulates**	**Variable**
Mass of unreacted materials (13%)	2.867		
Total Weight in (kg/h)	**528.5**	**Total weight out (kg/h)**	**522.31**

5.3.3. Energy Balance of the Incinerator

i) Energy in = Energy (diesel) + Energy (MSW) + Air (Energy)

Assuming energy from air is negligible we have;

a) Energy Diesel = Mass of Diesel * HHV of Diesel

= 9.75 kg/h x 450 13 kJ/kg

= 438 876.75 kJ/h

b) Energy from municipal solid waste

= Mass of dry combustible waste * HHV of waste

(Mass of combustible dry waste – moisture (55%) – unreacted) * HHV of waste

= (22.05 - 2.867) kg/h x 12 010 kJ/kg

= 230 387.83 kJ/h

Total energy in = 438 876.75 +230 387.83

= 669 264.58 kJ/h

ii) Energy out = $Q_{(Out1)} + Q_{(Out2)} + Q_{(Out3)}$

a) Energy out due to flue gas release

$$Q_{(out1)} = \sum (m_{gases} * C_{p(gases)} * \Delta T_i)$$

$$= m_{CO_2} * C_{p(CO_2)} * \Delta T_1 + m_{O_2} * C_{p(O_2)} * \Delta T_2 + m_{N_2} * C_{p(N_2)} * \Delta T_2 + m_{SO_2} * C_{p(SO_2)} * \Delta T_1 + m_{1(H_2O)(g)} * C_{p(H_2O)} * \Delta T_1)$$

Where:

ΔT_1 = Temperature difference between exit temperature and ignition temperature of gases, which estimated to be 450℃. The gases of CO_2, SO_2 and $H_2O_{(g)}$ are formed from combustion reactions at 450℃.

ΔT_2 = Temperature difference between exit temperature and ambient temperature at 22.75℃. The gases N_2 and O_2 found from the combustion air at ambient temperature.

$m_{2(H_2O)(l)}$ = The mass of water from combustion air and moisture contents of the fuels at ambient temperature.

$m_{1(H_2O)(g)}$, $m_{CO_{2(g)}}$ and m_{SO_2} = Mass of H_2O, CO_2 and SO_2 formed due to the chemical reaction in the incinerator

Cp_{CO_2}, Cp_{O_2}, Cp_{N_2}, $Cp_{H_2O_{(l)}}$ $Cp_{H_2O_{(g)}}$

= specific heat capacities of Carbon dioxide, Oxygen, Nitrogen, water, and water vapour respectively with subsequent values of 0.844, 0.919, 1.04, 4.184, 1.185 kJ/kg℃ respectively.

The results tabulated in Table 18, which shows the total energy release, by flue gases from the incinerator at exit temperature of 1000℃

Table 18: Parameters due to Flue Gas Released

Type of Gas	Cp kJ/kg℃	ΔT_i (℃)	Mass (kg)	Energy Total (kJ)
CO_2	0.844	550	78.54	36 455.95
O_2	0.919	977.25	32.95	29 591.26
N_2	1.04	977.25	352.70	358 465.15
SO_2	0.64	550	0.14	48.87
$H_2O(l)$	4.184	77.25	34.93	11 289.87
$H_2O(l)$	2460 (kJ/kg)	enthalpy of vaporization	34.93	85 927.80
H_2O *(g)*	1.185	900	34.93	37 252.85
H_2O *(g)*	1.185	550	32.14	20 947.25
				Total 579 978.98

iii) Energy released due to chemical reaction. There is formation of CO_2, SO_2 and H_2O

a) Formation of CO_2

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \qquad \Delta H^o = -393.5 kJ\ mol^{-1}$$

Total number of moles of CO_2

$$= \frac{75.282}{44} = 1.710\,954\,545\,kmol$$

ΔH^o = -393.5 kJ/mol x 1.710 954 545 mol

= -673 260 613.64J

b) Formation of H_2O

$$H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(l)} \quad \Delta H° = 241.8\ kJmol^{-1}$$

Total number of moles of H_2O

$$= \frac{32\,731.527}{18} = 1\,818.42\ mol$$

$$\Delta H° = 1.818\,418 * 10^3 \text{mole} * 241.8 \text{ kJ mol}^{-1}$$

$$= 439\,693.517\text{kJ}$$

c) Formation of SO_2

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)} \qquad \Delta H^o = -297\ kJ\ mol^{-1}$$

Total number of moles of SO_2

$$= \frac{0.1267}{64} = 1.979\,687\,5\text{kmol}$$

$$\Delta H° = 1.979\,687\,5\text{kmol} * -297\text{Jmol}^{-1}$$

$$= -587\,967.19\text{J}$$

Therefore the total energy released during the chemical reaction will be -234 155 068J

= **234.16 MJ**

iv) The energy due to radiation and the losses it varies between 1-5% of the total heat available

$$= 5\%\ x\ 669\,264.58\ kJ/h$$

$$= 33\,463.23\text{kJ/h}$$

v) The energy use to heat up the incinerator before filling in the waste. The primary chamber heated up to 400℃ and the secondary chamber to 800℃. The total diesel of about 5 liters used.

Table 19: Energy Balance Summary

Total Energy Input				Total Energy Output	
Material	HHV (kJ/kg)	Mass flow rate (kg/h)	Energy input (kJ/h)	Energy consumption	(kJ/h)
MSW	12 010	19.18	230 351.80	Energy due to flue gas releases	579 978.98
Diesel	45 013	9.75	438 876.75	Energy due to chemical reaction	-234 155.07
				The heat released due to uncountable for heat loss of the system	Variable (13-15%)
				Energy to heat up incinerator Primary chamber 400℃ and Secondary chamber 800℃	289 941.41
	Total (KJ/h)		**669 228.55**	**Total (KJ/h)**	**635 765.32**

5.4. Conclusion and Recommendations

i) The excess air ratio to the incinerator during incineration optimized to minimize pollution and increase the performance of the incinerator.

ii) To acquire more energy from the incinerator, the municipal solid waste dried to reduce moisture contents.

iii) The incineration result generates energy of 379 287.14 kJ/h with ash and flue gases emissions of total mass of 579 978.98 kg/h. The 379 287.14 kJ is the energy difference, which needed to recover, this is equivalent to the energy used to heat up the incinerator to ignition temperature, the energy not considered during primary calculations.

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CHAPTER SIX

COMPUTATIONAL MODELLING OF LOCALLY MADE INCINERATOR FOR MUNICIPAL SOLID WASTE, A CASE STUDY OF BAGAMOYO – TANZANIA

Abstract

In this study, a CFD technique used to develop a model for the simulation and flow conditions of the incinerator. The small scale municipal solid waste incinerator modelling done by using a fluent solver. The case study of the existing incinerator at a Bagamoyo hospital in Tanzania used as a model and the obtained values compared with simulated results and other publications for validation.

Key words: Municipal Solid Waste, Incineration, Optimization, CFD

6.1. Introduction

6.1.1. Background Information

Municipal solid waste materials are heterogeneous in nature (Swithenbank *et al.*, 1999). They are heterogeneous in size, shape and geometry (Liang *et al.*, 2008) with lower energy contents, high moisture and pollution source materials (Sun *et al.*, 2016). Incineration is a process of oxidizing carbohydrates present in solid waste into carbon dioxide and water (Helsen and Bosmans, 2010). The remaining elements present in the waste are oxidized to acid gases (Cheng *et al.*, 2007) and solid particles to the volume reduction of approximate 5% of their original volume (Cheng and Hu, 2010). The physical and chemical interaction between particles complicates the incineration process (Nasserzadeh *et al.*, 1994).

The flow performance of the incinerator affected by two major parameters:

(i) Geometry shape of incinerator and (ii) Operational modes (Shin *et al.*, 1998).

The optimization is the best design alteration process (Parkinson *et al.*, 2013). Optimization is a condition in which certain needed parameters explored to result in best measurable performance in the given conditions. The incineration process can cause pollution to the environment if the input parameter, size and conditions not optimized. The variety of designs

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and input parameters to obtain the optimum output results during the incineration process cannot perform without affecting pollution to the environment (Lighty and Veranth, 1998; Shin *et al.*, 1998). The optimization process performed using simulation is preferred since it is faster and environmental degradation free (Hussain *et al.*, 2006; Chen *et al.*, 2013). There are abundant of complex information and data being generated by simulation (Sun *et al.*, 2016). Designers of incinerators need to understand the characteristics of input and output parameters and conditions (Yang *et al.*, 2007). The understanding of inputs such as proximate and ultimate analysis values, type of waste, primary chamber and secondary chamber airflow and the output parameters such as temperature, flue gas, bottom and fly ash composition are important information for designers (Kapitler *et al.*, 2011). Modelling to optimum operating conditions using CFD techniques is economical (Anderson *et al.*, 2005) and flexible (Yang *et al.*, 2003; Mtui, 2013). The optimization considers the maximization of economic performance, minimization of environmental degradation and increase the operation efficiency (Anderson *et al.*, 2005; Koziel and Yang, 2011). The main disadvantage of simulation is the cost of preparing a model and sometimes the difficulties in understanding and interpreting the simulation results (Robinson, 2014).

The incineration process undergoes drying, devolatilization and char gasification in the primary chamber (Shin and Choi, 2000). The reactions that take place are heterogeneous in which solid waste react with staved air to gasify the waste (Liu and Liu, 2005). The reactions that take place in the secondary chamber involve the burning of gasified waste with excess air to form carbon dioxide and water (Chen *et al.*, 2013). The high temperature and excess air in the secondary chamber enhance the complete combustion of gases and destroy the toxic gases formed during the incineration (Quina *et al.*, 2011).

Modelling heterogeneous and homogeneous reactions require simplifications and building a set of governing equations (Yang *et al.*, 2003). These various complicated processes such as combustion, radiations and multiphase flow, must be known to designers (Huai *et al.*, 2008). The incinerator two chambers are set with main reason that the primary chamber stays at low temperature and staved air in order to gasify the waste and minimize particulates to the secondary chamber (Hester, 2005). The secondary chamber is set to admit oxidant in order to

complete burn all gases generated at the primary chamber (Morcos, 1989) and destroy all incomplete combustion products (Shin *et al.*, 1998). The gases generated at primary chamber include CO, CO_2, H_2, H_2O, CH_4 and trace of hydrocarbons (Helsen and Bosmans, 2010). The speed and quantity of air inlet at the chambers are used to increase or decrease a residence time in a primary or secondary chamber and enhance combustion (Huai *et al.*, 2008).

Conditions such as oxygen concentration, residence time, temperature and mixing turbulence has a big influence in the formation of pollutants (Mudakavi, 2010). The higher amount of CO in the exit is a sign of incomplete combustion (Lighty and Veranth, 1998; Kumar *et al.*, 2014). The efficiency of an incinerator can be gauged by the concentration of effluent gases such as CO_2, O_2, CO, H_2 and NOx (Ujama *et al.*, 2013). Poisonous gases released in the effluent can be identified by using computational fluid dynamic techniques (Mor *et al.*, 2006).

6.1.2. Computational Fluid Dynamic Analysis and Technology

Computational fluid dynamic is numerical analysis methods which solve fluid flow related to physical process and biochemical processes (Wu, 2012). Computational fluid dynamic results may lead to better designs, low risk during testing and faster in improving the designs (Yang *et al.*, 2003; Thanh *et al.*, 2010). Computational fluid dynamic provides the necessary information on how the flow takes place in the incinerator (Yaghmaeian *et al.*, 2015). The Computational fluid dynamic techniques give a critical evaluation in design and operating performance (Frey *et al.*, 2003). Computational fluid dynamic plays a role in reducing the time and technical risks during the designing process (Mtui, 2013).

Computational fluid dynamic technology is divided into three major parts (Xia and Sun, 2002):

i) **Pre – Processing** – It includes the conceptual design, meshing and the formation of the computational model.
ii) **Processing** – after developing mesh, the series of solution for solving physical models. The input values specified for software to solve the equations for each cell until convergence achieved.
iii) **Post Processor** to visualize and interpret the data generated by the Computational fluid dynamic processing.

6.1.3. Governing Equations

Narvier Stokes equations of fluid dynamics are the conservation law of mass, momentum and energy (Ansys, 2015).

i) Conservation of Mass for Gaseous Phase

$$\frac{\partial}{\partial t}\alpha_g\rho_g + \nabla\cdot(\alpha_g\rho_g\vec{u}_g) = \sum_{g=1}^{n}\dot{m}_{gs} \tag{25}$$

ii) Conservation of Mass for Solid Phase

$$\frac{\partial}{\partial t}\alpha_s\rho_s + \nabla\cdot(\alpha_s\rho_s\vec{u}_s) = \sum_{s=1}^{n}\dot{m}_{gs} \tag{26}$$

iii) Conservation of Momentum for Gaseous Phase

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{u}_g\right) + \nabla\left(\alpha_g\rho_g\vec{u}_g\vec{h}_g\right) = -\alpha_g\nabla_p + \nabla.\vec{\tau}_g + \sum_{g=1}^{n}\left(R_{gs} + \dot{m}_{gs}\vec{u}_{gs}\right) + \alpha_g\rho_g\vec{F}_g \tag{27}$$

iv) Conservation of momentum for solid phase

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\vec{u}_s\right) + \nabla\left(\alpha_s\rho_s\vec{u}_s\vec{h}_s\right) = -\alpha_s\nabla_p + \nabla.\vec{\tau}_s + \sum_{s=1}^{n}\left(R_{gs} + \dot{m}_{gs}\vec{u}_{gs}\right) + \alpha_s\rho_s\vec{F}_s \tag{28}$$

v) Conservation of Energy for Gaseous Phases

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g h_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{u}_g h_g\right) = -\alpha_g\frac{\partial p_g}{\partial t} + \vec{\tau}_g.\nabla\vec{u}_g - \nabla\cdot\vec{q}_g + \sum_{g=1}^{n}\left(Q_{gs} + m_{gs}h_{gs}\right) + S_g \tag{29}$$

vi) Conservation of Energy for Solid Phases

$$\frac{\partial}{\partial t}(\alpha_s\rho_s h_s) + \nabla\cdot(\alpha_s\rho_s\vec{u}_s h_s) = -\alpha_s\frac{\partial p_s}{\partial t} + \vec{\tau}_s.\nabla\vec{u}_s - \nabla\cdot\vec{q}_s + \sum_{s=1}^{n}(Q_{gs} + m_{gs}h_{gs}) + S_s \tag{30}$$

vii) Conservation Equation of Mass Fraction of Species *i* in the Gaseous Phase

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g Y_g^{\,i}\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{u}_g Y_g^{\,i}\right) = \nabla\cdot(\alpha_g\rho_g\Gamma_g^{\,i}\nabla Y_g^{\,i}) + S_g^{\,i} \tag{31}$$

viii) The Conservation Equation of Mass Fraction of Species i in the Solid Phase

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s Y_s^{\,i}\right) + \nabla\cdot\left(\alpha_s\rho_s\vec{u}_s Y_s^{\,i}\right) = \nabla\cdot(\alpha_s\rho_s\Gamma^{i}\nabla Y_s^{\,i}) + S_s^{\,i} \tag{32}$$

6.1.4. Turbulence Model (k-ε Turbulence Model)

Turbulence kinetic energy, k and its rate of dissipation, ε, are obtained from the following transport equation (Fluent, 2006).

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial_{xi}}(\rho k u_1)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu t}{\tau_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\in-Y_m+S_k \tag{33}$$

and

$$\frac{\partial}{\partial t}(\rho\in)+\frac{\partial}{\partial x_i}(\rho\in u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma\in}\right)\frac{\partial\in}{\partial x_j}\right]+C_{1\in}\frac{\in}{k}(G_k+C_{3\in}G_b)-C_{2\in\rho}\frac{\in^2}{k}+S_\in \tag{34}$$

6.1.5. Radiation Model (John R. Howell and Siegel, 1992; Huai *et al.*, 2008)

Radiation flux $q_r=-\frac{1}{3(a+\sigma_s)-C\sigma_s}\nabla G$ (35)

Where: a is absorption coefficient, σ_s is a scattering coefficient, G is the incident radiation and C is the linear-anisotropic phase function coefficient,

$$\Gamma=\frac{1}{(3(a+\sigma_s)-C\sigma_s)} \tag{36}$$

We get (36) to

$$q_r=-\Gamma\nabla G \tag{37}$$

The transport equation G is

$$\nabla\cdot(\Gamma\nabla G)-aG+4a\sigma T^4=S_G \tag{38}$$

Where σ is the Boltzmann constant and S_G is a user defined radiation source.

Combining equation (37) and (38), the following equation obtained

$$-\nabla\cdot q_r=aG-4a\sigma T^4 \tag{39}$$

The expression $-\nabla\cdot q_r$ can be directly substituted into the energy equation to account for heat sources due to radiation (Fluent, 2006).

The technical algorithm shown in Fig. 25.

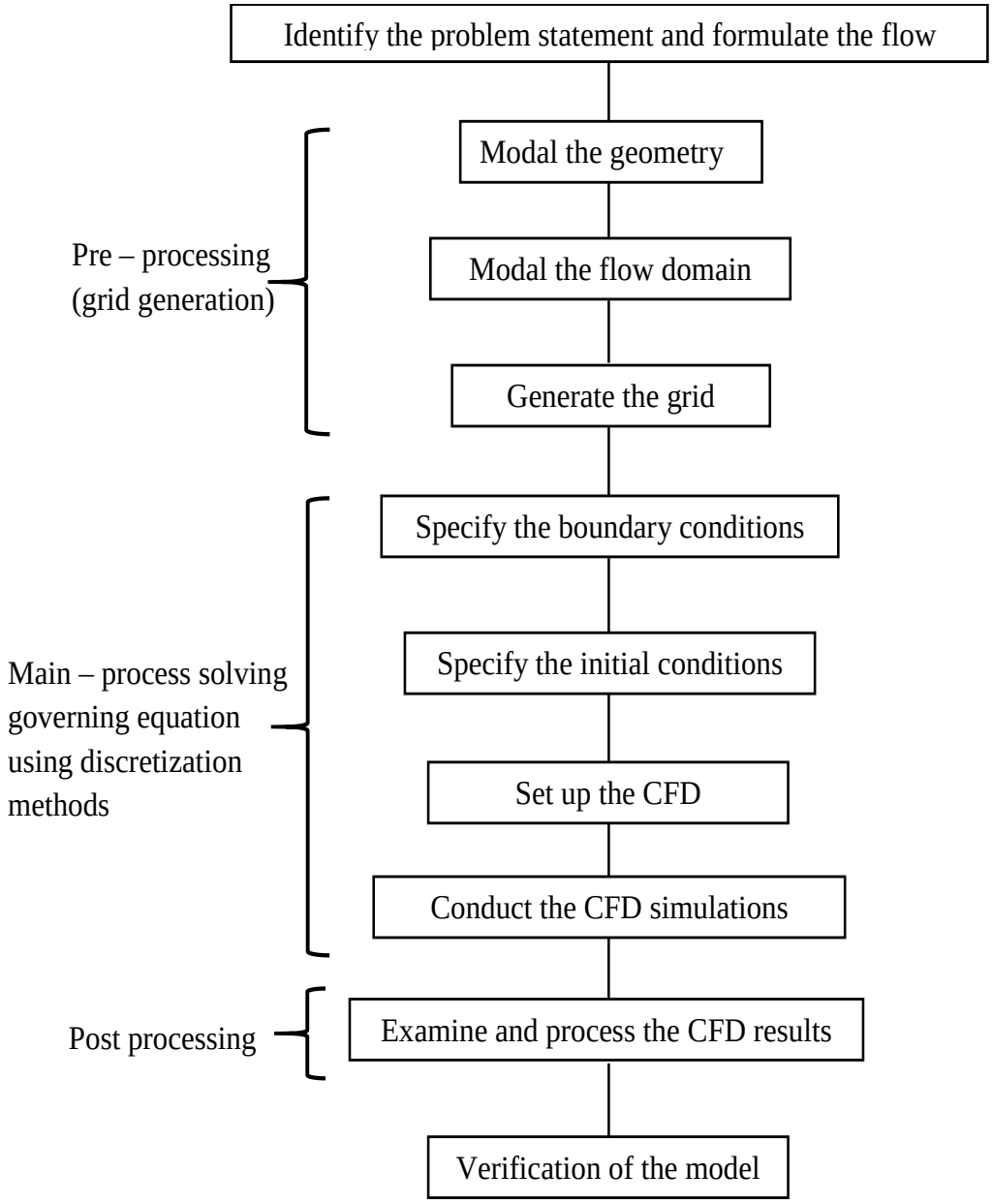

Figure 25: Computational Fluid Dynamic Analysis Process (Ayaa, 2012)

6.2. Model Description and Methodology

6.2.1. Geometry

The 3D incinerator geometry used in this study shown in Fig. 26. The incinerator geometry has a maximum width of 0.885 m, maximum depth of 1.195 m and maximum height of 4.043 m. The geometry meshed and value of meshes is determined using Ansys fluent software and gives 1.67 m^3. The geometry of a computational model was performed using the solid works v16 (Ansys, 2002).

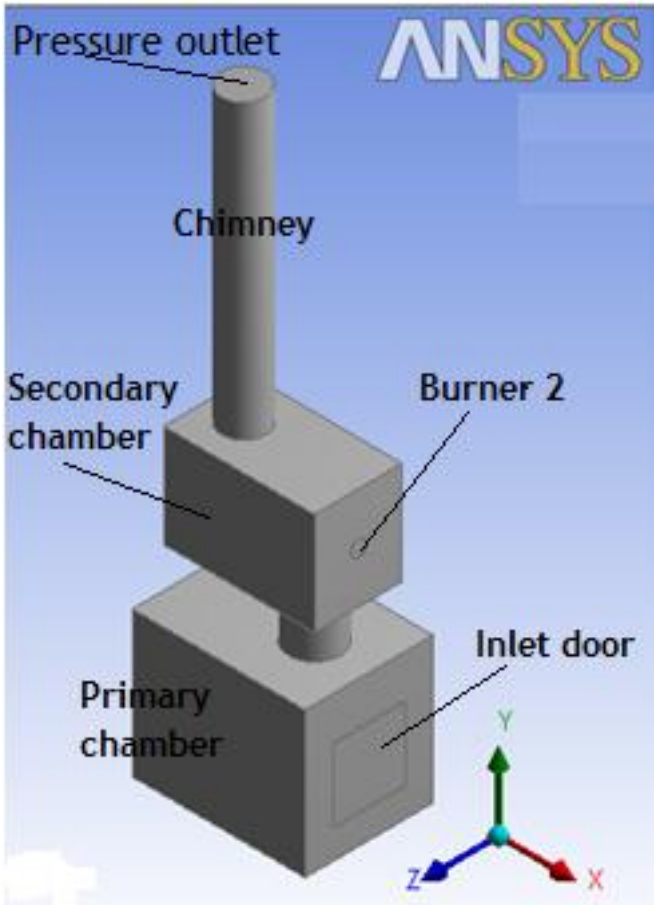

Figure 26: Incinerator Geometry

6.2.2. Meshing Domain

The meshing geometry is converted to tetrahedral cells (Ansys, 2002). The cells then converted to polygonal. The total converted cells were 83 406 in a manner indicated in Fig. 27.

6.2.3. Boundary and Initial Conditions

The converted polygonal cells were assigned a solver and boundary conditions (Ansys, 2009). The outflow, outlet-1 assigned as pressure outlet, the 3-air inlet pipes were assigned as an inlet-air $A_{1\text{-}1}$, an inlet-air $A_{2\text{-}1}$ and an inlet-air $A_{3\text{-}1}$. The boundary conditions for burners were assigned in which the primary chamber burner assigned as an inlet burner $B_{1\text{-}1}$ and secondary combustion chambers burner as an inlet burner $B_{2\text{-}1}$. The boundary condition for inlet door assigned as an inlet-door $D_{1\text{-}1}$. The meshed incinerator design shown in Fig. 27.

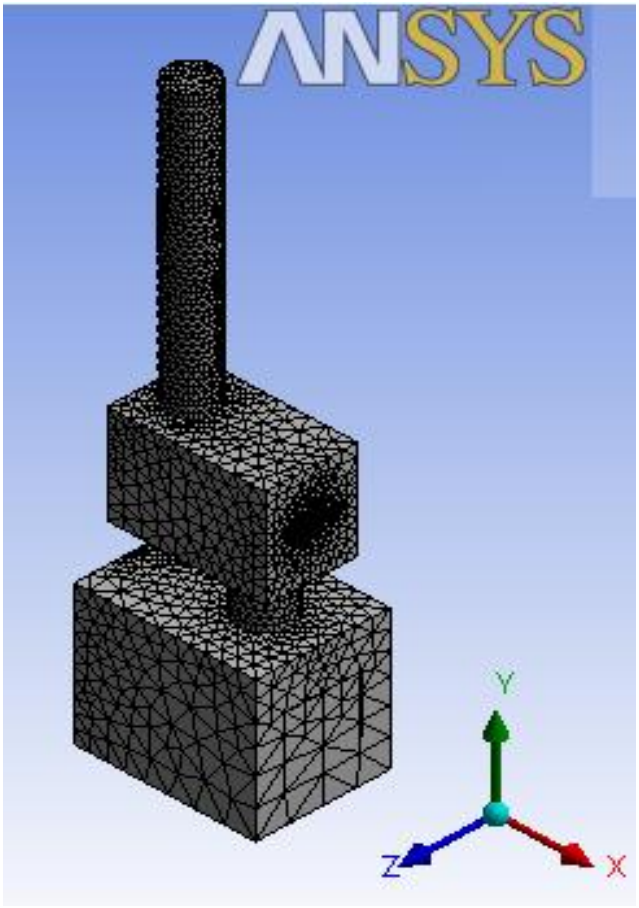

Figure 27: Meshed Incinerator Geometry

6.2.4. Fundamental Input Parameters to the Model

The input data to the model generated by the experimental practice to feed in the model for simulation and optimization. The fundamental data developed from the existing medical incinerator located in Bagamoyo district hospital Tanzania. The medical incinerator used in

place of municipal solid waste incinerator because there is no any physical incinerator for municipal solid waste available for this type of work in Tanzania. However, the incineration materials utilized were municipal solid waste.

The fixed bed incinerator has two chambers; the primary ignition chamber and secondary combustion chamber. There are two burners (B_1 and B_2) for primary and secondary chambers respectively. B_1 is inclined at an angle of 45^o to the grate to enhance the swirling effect in the primary chamber. Three air inlets, inlet air $A_{1\text{-}1}$, inlet air $A_{2\text{-}1}$ and inlet air $A_{3\text{-}1}$ for supplying air to the primary and secondary chambers. Inlet air $A_{1\text{-}1}$ is located under fire bottom of the grate to supply staved air for primary chamber. Inlet air $A_{2\text{-}1}$ is located at the upper part of the primary chamber to supply the excess air for primary chamber. Inlet air $A_{3\text{-}1}$ is located at the secondary chamber for supplying excess air in the secondary chamber. The excess air that varies between 20 to 150% stoichiometry is suitable for combustion of municipal solid waste (Surroop and Mohee, 2011). The increase in excess air may lead to reduce the temperature of combustion chamber, which may result in unwanted effluents. In this work, the excess air is set in such a way that the sufficient air obtained for complete combustion.

6.2.5. Modeling of Chemical Reactions

The empirical formula for municipal solid waste of Arusha was adopted (Omari *et al.*, 2014a). The process of dying, pyrolysis and gasification are taking place in the primary chamber. Under control temperature and staved air to form syngas such as CO, H_2 and CH_4 (Ayaa *et al.*, 2014). The gases escape from the primary chamber to the secondary chamber where complete combustion occurs (Williams, 2013; Reddy, 2016). The products of complete combustion gases CO_2 and H_2O exit through the chimney to the atmosphere.

These chemical reactions for drying, devolatilization, tar cracking, methanation and combustion of these gases in a single step reaction tabulated in Table 20.

Table 20: Chemical Equations Described using Single Step Reactions

	Process	Chemical Reactions	
i)	Drying:	$H_2O_{(l)} \rightarrow H_2O_{(g)}$	(40)
ii)	Devolatilization:	$C_6H_{10}O_4 \rightarrow 2.33CH_{2.92}O_{0.938} + 3.087C + 0.0272CH_4 + 0.233CO + 0.3298CO_2 + 0.6599H_2 + 0.9277H_2O_{(g)}$	(41)
iii)	Tar Cracking:	$CH_{2.92}O_{0.932} \rightarrow 0.7288C + 0.1429CH_4 + 0.0613CO + 0.0677CO_2 + 0.741292H_2O_{(g)} + 0.432972H_2$	(42)
iv)	Methanation : *(H_2 gasification)*	$C + 2H_2 \rightarrow CH_4$	(43)
v)	Char combustion	$C + O_2 \rightarrow CO_2$	(44)
vi)	Water gas shift reaction (forward)	$CO + H_2O \longrightarrow CO_2 + H_2$	(45)
vii)	Water gas shift reaction (reverse)	$H_2 + CO_2 \longrightarrow H_2O + CO$	(46)
viii)	Bourdard Reaction *CO_2 gasification*	$C + CO_2 \longrightarrow 2CO$	(47)
ix)	Water Gasification	$C + H_2O \longrightarrow CO + H_2$	(48)
x)	*CO* Combustion	$CO + \frac{1}{2}O_2 \longrightarrow CO_2$	(49)
xi)	H_2 Combustion	$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$	(50)
xii)	CH_4 Combustion	$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$	(51)

6.3. Results and Discussion

6.3.1. The Input Air

The measured value were adopted from published data in international journal as a result of the study of operating conditions of incinerator done at Bagamoyo-Tanzania (Omari *et al.*, 2015). The input staved air inlet $A_{1\text{-}1}$ located at the bottom of the primary chamber is deviated by 13.53% and it changes its original value from 0.031 47 kg/s to 0.036 39 kg/s, as shown in Table 21. The value of oxygen increased due to increase in municipal solid waste burned. The amount

of oxygen needs to increase so as to assist in the process of thermochemical oxidation process to convert the biomass substance into syngas (Ruiz *et al.*, 2013). Air inlet $A_{2\text{-}1}$ that supplies air to the primary chamber shows the deviation of 4.971%. It decreases its original value from 0.031 97 kg/s to a simulated value of 0.030 46 kg/s as shown in Table 21. The value of oxygen, reduced to a lower value; however, this deviation is allowable for such calculations. The pipe for supplying air to secondary chamber $A_{3\text{-}1}$ has decreased its value to 0.034 09 kg/s from its original value by 6.98%, this may be caused by slightly increasing the excess air supplied during the experimental process (Arena, 2012; Ruiz *et al.*, 2013). The maximum value of oxygen needed for optimum combustion is iteratively determined by fluent solver which gives the actual value needed to 0.034 09 kg/s (Ansys, 2015).

6.3.2. The Input Municipal Solid Waste

The optimized value for municipal solid waste mass flow rate shows the deviations, the simulation value shows that the incinerator has a capacity to incinerate municipal solid waste 26.48% more that its designed capacity. The simulation results from fluent solver show that the maximum capacity for one cycle can be 68 kgs instead of 50 kgs currently used.

6.3.1. Iterated Input Model and Experimental Parameters

Iterated input model parameters and the experimental input parameters are shown in Table 21

Table 21: The Comparison between Inputs Experimental and Simulation Parameters

Input Mass Flow Rate				
Item	Item symbol	Measured (Experiment) (Kg/s)	Predicted (Simulated) (Kg/s)	Deviation (%)
Door inlet	$D_{1\text{-}1}$	0.027 78	0.037 78	26.48
Staved air inlet	$A_{1\text{-}1}$	0.031 47	0.036 39	13.53
Primary excess air	$A_{2\text{-}1}$	0.031 97	0.030 46	4.97
Secondary excess air	$A_{3\text{-}1}$	0.036 48	0.034 09	6.98

Source: (Omari *et al.*, 2015)

6.3.2. The CFD Output Simulation Results

The CFD output simulation results and the experiment result tabulated in Table 22.

Table 22: The Comparison between Output Experimental and Simulation Parameters

Parameters in Mass Fraction				
Item	Symbol	Measured (Experiment)	Predicted (Simulated)	Deviation (%)
Velocity magnitude (m/s)	υ	4.0	3.75	6.25
Mass fraction of O_2 (%)	O_2	12.27	2.31	81.17
Mass fraction of CO (ppm)	CO	109.7	46	58.07
Mass fraction of CO_2 (%)	CO_2	6.4	7.07	10.39
Mass fraction of NO_x (ppm)	NO_2	152	372	144.74
Particle residence time (s)	t	2	1.73	13.50

Source: (Omari *et al.*, 2015)

i) Velocity Magnitude

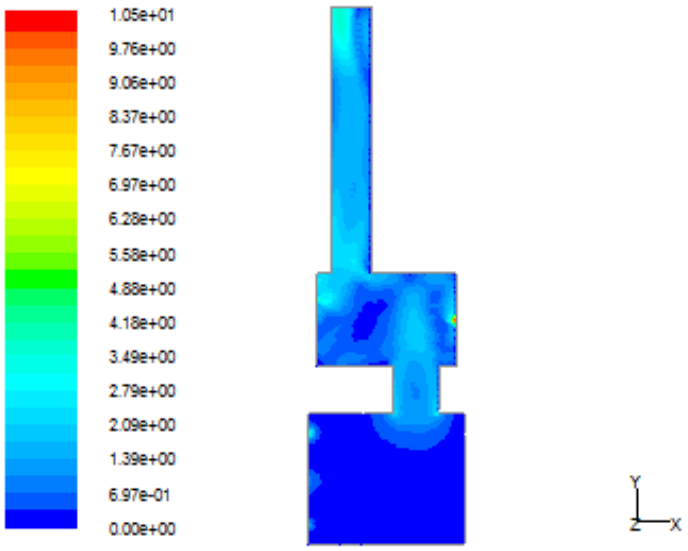

Figure 28: Contours of Velocity Magnitude (m/s)

The maximum velocity at the exit of the incinerator is ranging between 2.79 – 3.49 m/s with average velocity of 3.14 m/s shown in Fig. 28. Velocity has a minimum value at the primary chamber and higher value at the secondary chamber. The formation of gaseous material in the

primary chamber increases the velocity of gases. The O_2 concentration in the secondary chamber increases the velocity and residence time due to excess air supplied (Liang and Ma, 2010)

ii) The Temperature of the Incinerator

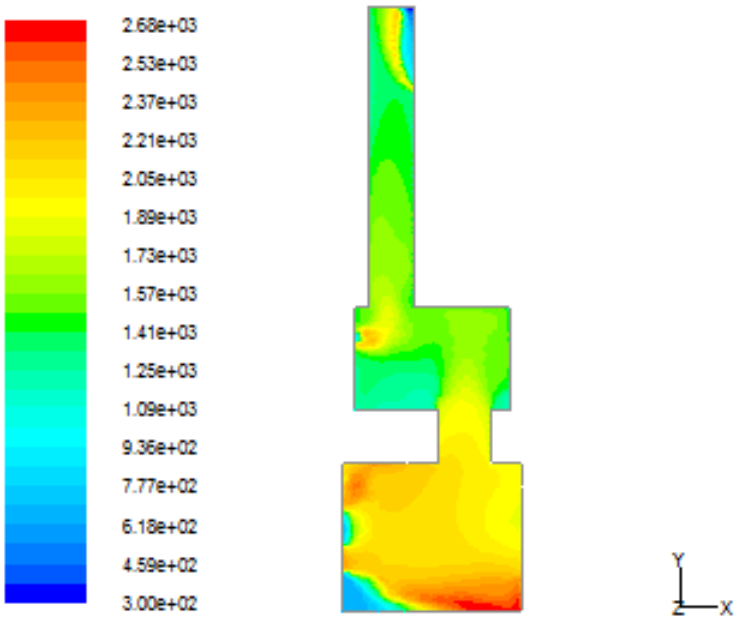

Figure 29: Contour of Static Temperature (k)

The temperature inside the incinerator shown in Fig. 29. The maximum temperature is 2400K and the minimum is 300K corresponding to room temperature and the feed-in temperature of municipal solid waste. The temperature is uniform in primary chamber, secondary chamber and in the chimney. The temperature in the secondary chamber is 1400K and the average temperature of the chimney is about 1800K but the core is 2000K, ash deposited at the bottom of the incinerator with a temperature of about 2400K. The temperature at the entrance of pipe is high; this may be due to the excess air at that particular point. The excess air increases the combustion efficiency. The low heat zone at the bottom of the incinerator caused by insufficient air due to its position. Indeed, there is anomaly in the observed temperatures. A direct explanation to what is happening can elucidated if further studies carried into these areas. The temperature at the entrance of pipe is high; this may be due to the excess air at that particular point. The excess air increases the combustion efficiency. The low heat zone at the bottom of

the incinerator caused by insufficient air due to its position. The temperature at the exit is about 1400K. There are two burners, which are located in primary and secondary chambers respectively. The ignition temperature of each burner is 480K, which assists in increasing the temperature of the incinerator and support combustion for both primary and secondary chambers.

iii) Mass Fraction of Oxygen

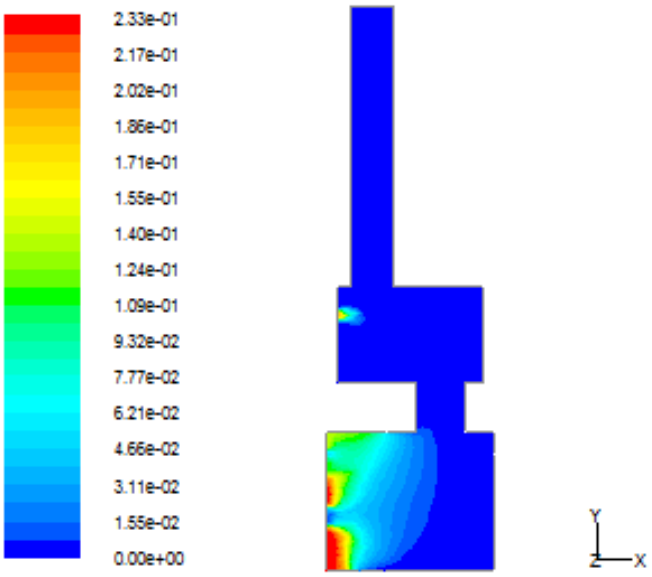

Figure 30: Contour of Mass Fraction of O_2

The mass fraction of O_2 decreased. The value of oxygen to the effluent is caused by excess air to the combustion process (Ryu *et al.*, 2002). In this case, the value of oxygen to the practical experiment was exceeding as shown in Fig. 30 and Table 22. The increasing oxygen may cause this during the period of refilling the waste by opening the door of the incinerator, there is recalculated air from the entrance door.

iv) Mass Fraction of CO Released

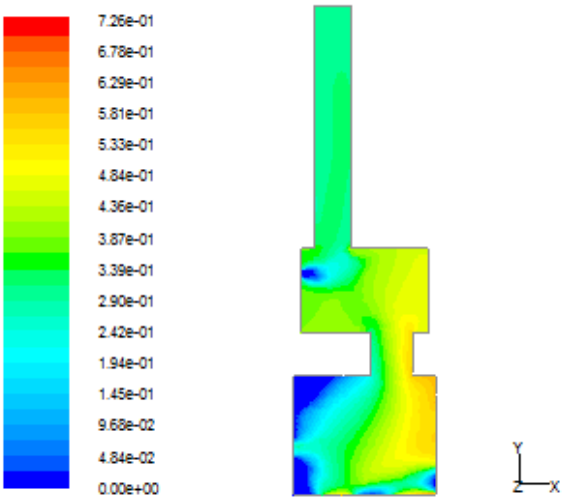

Figure 31: Contour of Mass Fraction of CO

The simulation values for Carbon monoxide were deviated from practical values by 58.07% as shown in Fig. 31; this value is highly deviated. The percentage of Carbon monoxide increases as compared to practical results. The value is, however, within the permissible value of Carbon monoxide allowed in the environmental protection values (Ryu *et al.*, 2002). This caused by opening the door during the process, adding excess oxygen into the combustion chamber: which not considered during simulation.

v) Mass Fraction of Carbon Dioxide Released

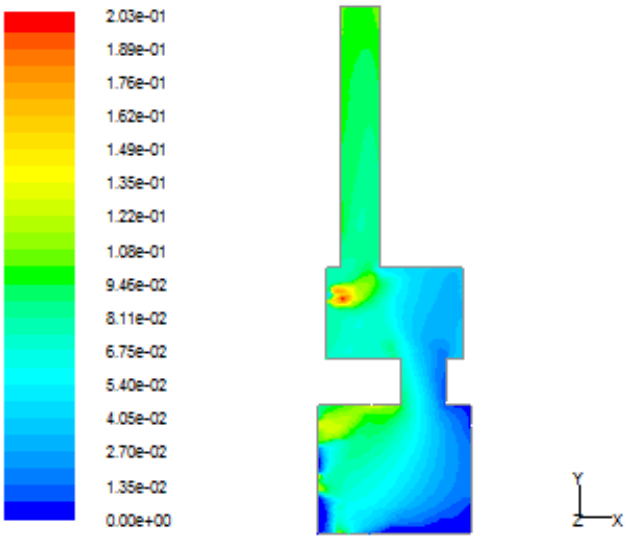

Figure 32: Contours of Mass Fraction of CO_2

The values show that CO_2 released were deviated by 10.39% from the value obtained practically. The percentage CO_2 in the effluent gases found to be 7.07%. The practical experiment obtained was 6.4% (Omari *et al.*, 2015). This variation is caused by increase in combustion efficiency of the incinerator (TSI, 2004; Urieli, 2010).

vi) Mass Fraction of NO_2 Emission (ppm)

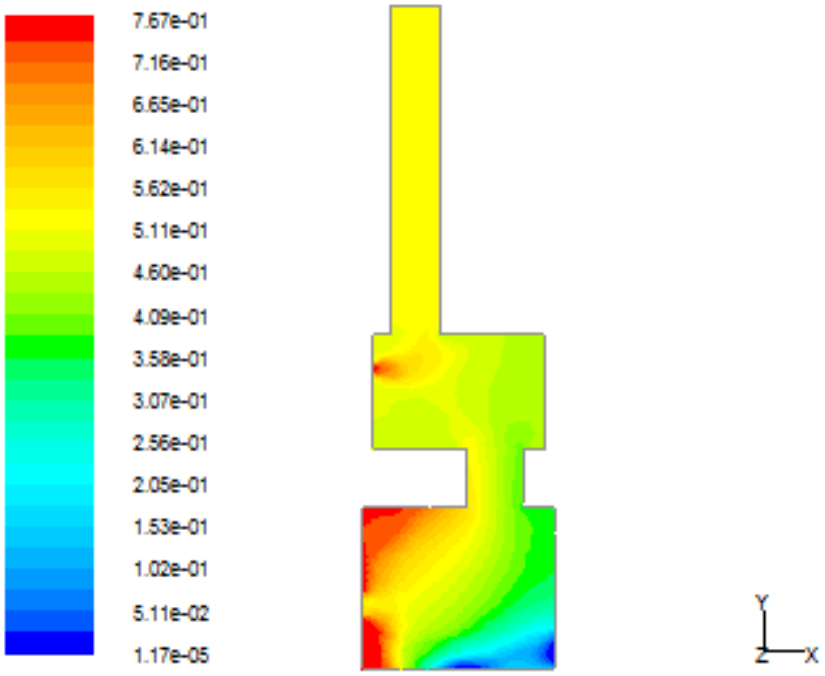

Figure 33: Contours of Mass Fraction of NOx

The emission values for NO_2 deviated from practical values as shown in Fig. 33 and Table 22. The deviation values were 144.74%. This value is more than the practical values because some of the Nitrogen from air under high temperature forms thermal NO_x (Feron and Hendriks, 2005). The increase the temperature of combustion may lead to the formation of more NO_x (Winter *et al.*, 1999). In the case studied, the highest concentration of NO_x found to be at the bottom of the incinerator where the ash drops with high temperature are concentrated. This may be due to the high temperature of ash and excess air enters to the primary chamber during filling the waste while the combustion process continues. The ash concentration and the filling of waste during second and other higher cycles of operation may cause this excess temperature and excess air to form thermal NO_x which was not considered during the practical experiments (Chen *et al.*, 2016).

vii) The Particle Residence Time

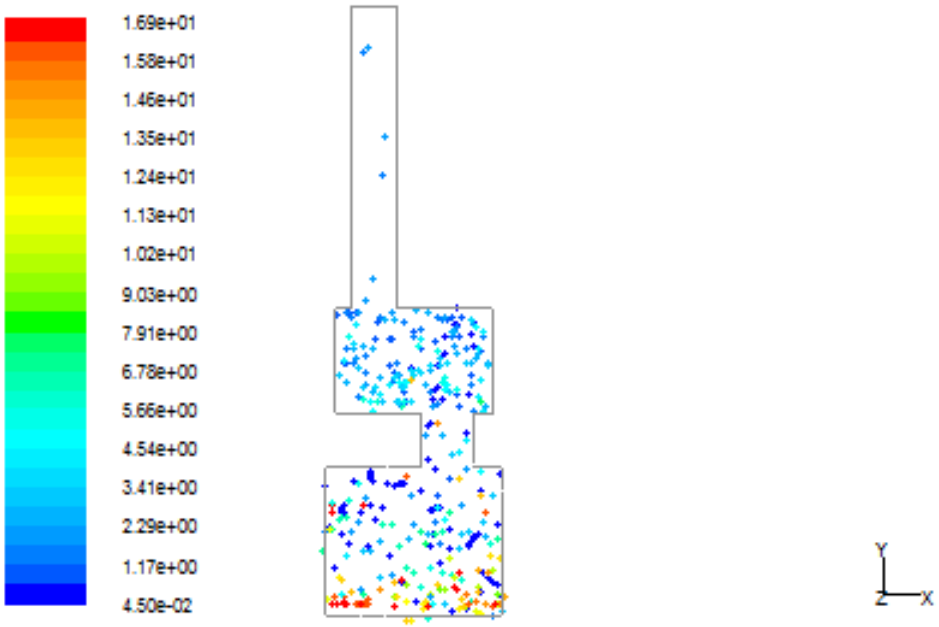

Figure 34: Particle Traces Colored by Residence Time(s)

The particle traces colored by residence time(s) as shown in Fig. 34. The particle residence time shows an average of 1.73 (s). These values correspond to various international standards for residence time such as Canadian standards which set the standard residence time to be not less than 1 second at a temperature not less than 1000°C (CCME, 1989). The value of residence time influenced by the speed of inlet gases. The value of residence time is also affected by temperature and that is why at secondary chamber the residence time is lower than in primary chamber due to high temperature in a secondary chamber (Yaghmaeian *et al.*, 2015).

viii) The Particle Path Lines

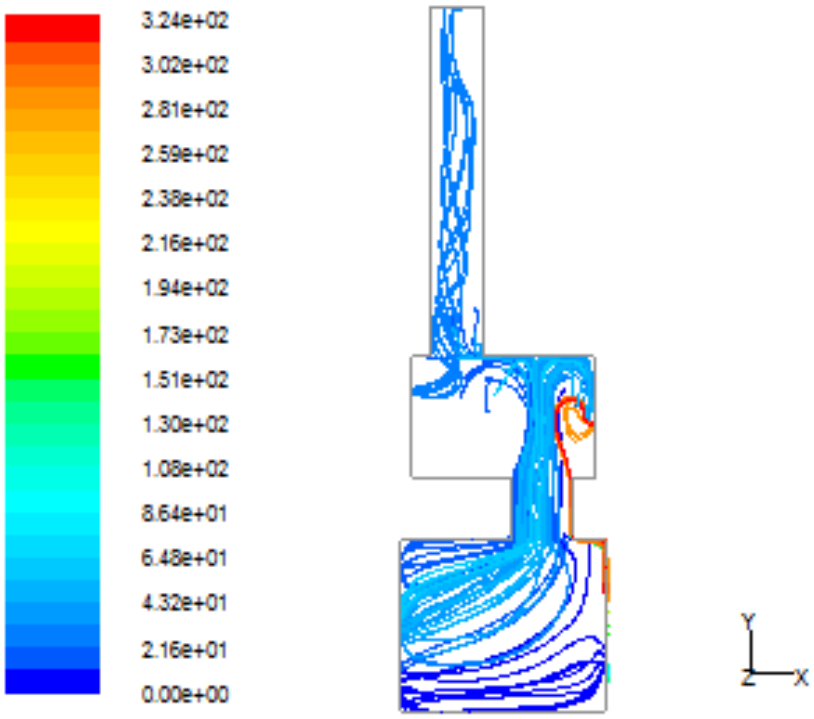

Figure 35: Pathlines Colored by Particle ID

The particle traces represent the path. Initially a path made by integrating the velocity with time. For transient flow path known as pathlines. In this work, the pathlines start from the boundary condition inlet $A_{1\text{-}1}$, inlet $A_{2\text{-}1}$, inlet $A_{3\text{-}1}$, inlet $B_{1\text{-}1}$, inlet $B_{2\text{-}1}$ and inlet $D_{1\text{-}1}$ and goes out through the outlet $_{1\text{-}1}$ as shown in Fig. 11. The results also show that there is a uniform flow of particles from bottom of the incinerator through the neck; then secondary chamber, the chimney to the exit. The detailed information of these pathlines contributes to the overall understanding of the flow of the particles (Nasserzadeh *et al.*, 1991).

ix) Particle Diameters

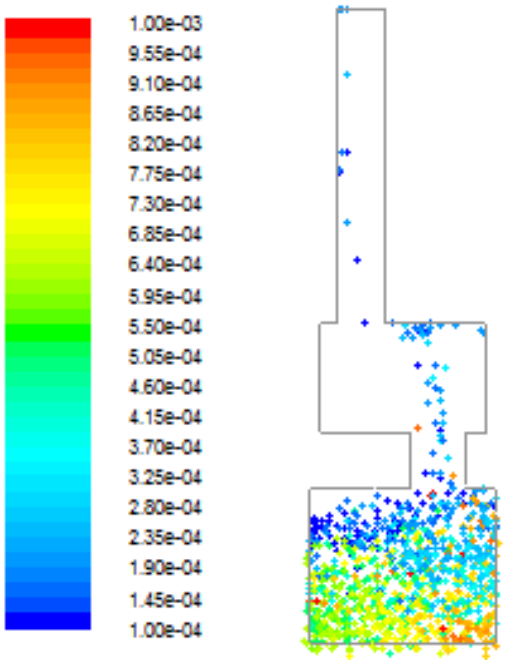

Figure 36: Particle Traces, Colored by Particle Diameter (mixture) (m)

The particle diameter decreased along the incinerator. The value of the particle diameter at the bottom is about 9.55e-4m while it decreases to 1.45e-4m just before the exit of primary chamber. In the secondary chamber there are very small and few particles. Their diameter is about 1.00e-4m. The bigger particles remain in primary chamber and the very small particles pass through the neck, secondary chamber and chimney to exit. This separation of particles caused by a two-chamber incinerator design in which the primary chamber solid particles gasified to combustible gases.

x) Average Temperature Vs Incinerator Height

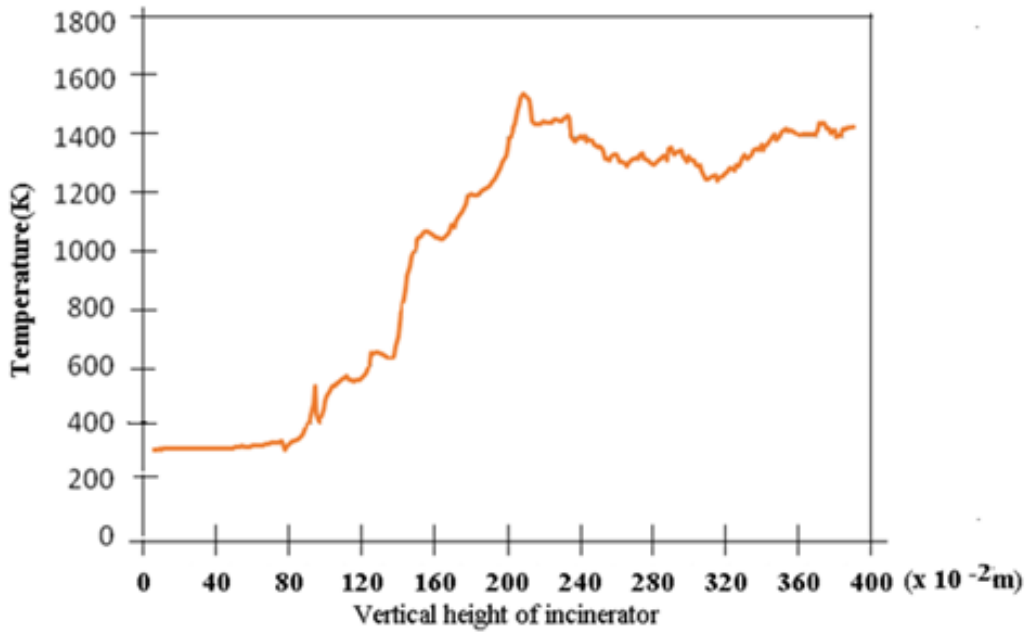

Figure 37: Temperature Variation with Incinerator Height

The average temperature is about 1400K at incinerator exit. The average temperature is increasing along the incinerator. The rapid change in temperature at 140 m is due to entering of gases from the primary chamber to secondary chamber. The temperature gradually increased and reached a maximum point at 210m. The temperature then fluctuates again between 1600k and 1400k to exit. The temperature in the chimney constant fluctuates between 1400 and 1600k. The fluctuation affected by the primary reaction in the combustion chambers.

xi) Average NOx at Incinerator Exit

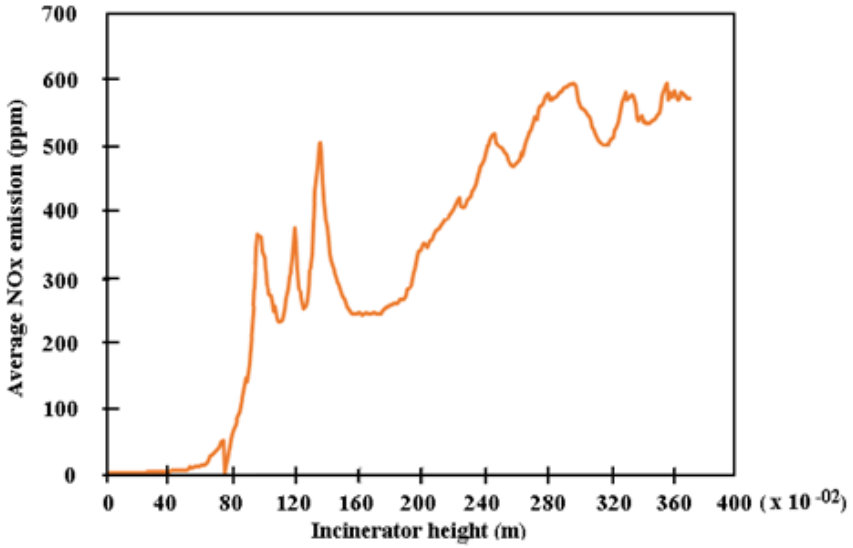

Figure 38: Average NO_x at Incinerator Exit

Average NO_x is about 600ppm at incinerator exit. This value is within the permissible value of NO_x gases, which react with oxygen to form acid rain.

6.3.3. Validation of Simulation Results Summary

Table 23: Validation of Simulation

	Input Velocity m/s	Exit gases				Residence Time (s)	Exit Temp(K)
		CO_2 (%)	NOx ppm	CO ppm	O_2 (%)		
Current model	3.75	7.07	152	46	4.62	1.73	1400
(Hussain, 2012) (Lin and Ma, 2012)	3.3	11	156.5	20	6.12	2.71	1300 - 1800
Deviation	14%	36%	3%	38%	25%	36%	8% -22%
(Huai *et al.*, 2008)	3.43	N.A	N.A	32.2	6.91	N.A	1420
Deviation	9%	N.A	N.A	30%	33%	N.A	1%

Where: N.A is the value, not available.

i) CO_2 Concentration

Comparison model result of the CO_2 obtained between current simulation and CO_2 obtained by (Hussain, 2012) shows the results deviated by 36%.

ii) NO_X Concentration

For the case NO_X. comparison between the current model results with those obtained by (Hussain, 2012), shows better agreement with deviation of 3%.

iii) O_2 Concentration

Comparison result obtains from the current model with (Huai *et al.*, 2008) on O_2 concentration shows the deviation of 33%, while the comparison between (Lin and Ma, 2012) show the deviation of 25%.

iv) CO Concentration

In the case of the CO concentration, the findings from the current model with (Huai *et al.*, 2008) shows the deviation of 32.2%, when compared with (Lin and Ma, 2012) model shows the deviation of 38%.

v) Velocity of Exit Gases

Comparison model result in velocity obtained from the current model and that of (Hussain, 2012) it shows good agreements. The model deviation was 14%, while the deviation obtained with (Huai *et al.*, 2008) is 9%.

vi) Exit Gas Temperature

The comparison of flue gas exit temperature to the current model, with (Hussain, 2012) show a good agreement. The highest deviation is 22% and lowest is 1%.

6.4. Conclusions and Recommendations

i) The experimental and simulation study is necessary information for input and operating parameters in the optimization of a fixed bed municipal solid waste incineration.

ii) The incineration design successfully optimized operating parameters using computational fluid dynamics techniques.
iii) The input parameters vary in such a way that the minimum cost of operation and pollution achieved.

6.5. Acknowledgements

The authors are grateful for the financial support of this work by the COSTECH and NM AIST Arusha, Tanzania. Tanzania Engineering Manufacture, design and organization for their prototype incinerator design and practical support.

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CHAPTER SEVEN

GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

7.1. General Discussion

In this work, I have studied the characterization of MSW, the incineration design and the optimization of incineration design for high efficiency incinerator with minimum pollution.
The characterization of MSW done in two approaches; the field work approach in which waste composition was sorted and categorize to different composition and laboratory analysis in which proximate analysis, ultimate analysis and thermal degradation analysis were studied.

7.1.1. Characterization of Waste Flow Analysis and Composition

The studies of waste flow records from Arusha city council for the consecutive 3 years from 2010 – 2012 were analysed. It estimated that only 20% of the total waste generated in Arusha collected. Large portions of the waste generated between March and July. March is a rainy season while July is the harvesting seasons. The value seems to be constant, which caused by the capacity of city trucks, which can handle and dispose waste to Murriet dumpsite at an average mass of not greater than 120 tons daily. Taking the average calorific value of 12MJ/kg, it estimated that, the total energy, which generated annually from municipal solid waste of Arusha, is about 128.9 GWh.

The waste generated and its composition analysis can help in decision making on which method of energy recovery to utilize. For waste with a big portion of organic waste the composting or incineration can be utilize while, the presence of large recyclable waste pinpoints the possibility of material recovery from municipal solid waste. For the waste with a big fraction of construction waste, there is a possibility for of utilizing waste material in road construction works.

The composition of the garden and wood waste together is 30%, food waste 37%, Papers 11%, plastic 7%, glass 4%, metal and tin 1%, textiles 2% and ash 8%. The composition of combustible waste was 87%, while non-combustible waste composition was 13%. The combustible waste fraction has 89.7% biodegradable and 10.3% non-biodegradable waste. This implies that the energy from waste can be recovered by either thermo or non-thermo methods. By recovering energy from municipal solid waste, the released of greenhouse gases to the atmosphere will be minimized.

Comparisons of waste composition of Arusha with other countries; the waste compositions are categorized to low income countries, middle-income countries and higher income countries. The results showed that there is a slight difference between Tanzania and other countries. From middle and lower income countries, much waste dominated by food waste with a higher portion from Indonesia followed by Bangladesh, China and Algeria. South Korea followed by Poland, Thailand and Indonesia have a big portion in textile wastes while plastic waste dominated by Malaysia followed by China and Thailand. In comparisons with high-income countries, such as the United States of America, Japan and United Kingdom, paper dominates the waste composition followed by food waste, textiles and plastics. In low-income countries, the waste from Nigeria, Kenya, Algeria and Ghana contains most in food waste. Wood and yard waste has higher portions in Tanzania and Uganda. Glass wastes have a big portion in Kenya and Nigeria.

Comparing waste composition by the average of each group, food waste generated more in middle-income countries followed by low-income countries; textile waste is very little in low-income countries while glass waste and papers are much higher in higher income countries. Yard and wood waste are more in higher and lower income countries. In general, combustible waste has an average of 89% of middle-income countries, 78% in higher income countries and 73% in lower income countries. Despite of the average waste for energy recovery from lower income countries to be lower than higher and middle-income countries, the percentage of waste available for energy recovery is more than higher and middle-income countries, this caused by poor recycling technology in low income countries.

7.1.2. Waste Characterization in Laboratory

The laboratory approach in which, the proximate analysis, ultimate analysis and thermal behaviors of municipal solid waste analyzed.

i) Proximate analysis study

The proximate analysis study shows that moisture content of the municipal solid waste as received ranges between 55.70 and 63.99-weight percentage, which, is more than 50 weight percentage of the total weight of the sample. This high moisture content is prohibitive for combustion process as it lowers the combustion process due to high moisture contents which also reduces the calorific value of the fuel (Muthuraman *et al.*, 2010). The moisture reduced by drying. The volatiles released on dry basis of municipal solid waste for Kaloleni, Sakina and

Central market are 74.43, 84.00 and 78.31 weight percentage, respectively, whilst the volatile matter contained in pure biomass such as forest residue, oak wood, and pine are 79.9, 78.1 and 83.1 weight percentage, respectively (Vassilev *et al.*, 2010). The fuels that contain highly volatile, have low fixed carbon, the case of the municipal solid waste from Kaloleni which has fixed carbon of about 17 weight percentage, which is higher than that of Sakina and Central market. The advantage of highly volatile and low fixed carbon is rapidly burning of a fuel, while a fuel with low volatile and high fixed carbon like coal need to be burnt on a grate as it takes long time to burn out, unless it is pulverized (McKendry, 2002a). This study reveals that the volatile matter and fixed carbon present in the municipal solid waste is combustible. The ash composition of municipal solid waste ranges between 3.29 to 5.97 weight percentage, which is small; this is advantageous to waste management and environment because the possibility of having a small quantity of heavy metals, salts, chlorine and organic pollutant is minimized (Lam *et al.*, 2010).

ii) Bomb calorimeter study

The municipal solid waste Bomb calorimetry study shows that the calorific value is about 12 MJ/kg. This value is smaller than the average biomass heating value of about 17MJ/kg (Heylighen, 2001). The energy content of MSW can be improved by pre-treating the MSW so as to reduce the oxygen amount, since oxygen reduces the energy content of a fuel (McKendry, 2002a). The MSW can be co-fired with coal for improving the energy content (Sami *et al.*, 2001; Li *et al.*, 2004). Other processes to improve the energy content of MSW are pyrolysis, gasification or torrefaction, these used to produce bio-oil, syngas and char respectively.

iii) The ultimate analysis study

The ultimate analysis study shows that the MSW has a negligible concentration of phosphorus and chlorine. 50% of carbon and 5% of hydrogen. The oxygen content was more than 34%. Sulfur is about 0.29%, this is very low compared to values of 1.1 weight percentage of bituminous coal (Nakao *et al.*, 2006).

7.1.3. The Characterization of MSW in Thermal Degradation

i) Thermo Gravimetric Analysis

The MSW from all collecting points degraded to 75 to 85-weight percentage in the thermo gravimetric analyser. The municipal solid waste from Central market degraded by 85-weight percentage, while the Kaloleni degraded by 75-weight percentage. The residue formed is between 25 and 15-weight percentage. The residue contains fixed carbon and ash, the high residue observed at municipal solid waste from Kaloleni (25-weight percentage) and the lowest residue observed at MSW from Central market and Sakina 15-weight percentage. The char can be used as a fuel, but MSW that has high ash content hinder the combustion of char due to the layer of ash formed on the surface it inhibited the diffusion of oxygen into the char (Himawanto *et al.*, 2013). The derivative of thermo-gravimetric analysis (DTG), shows four visible regions; these are moisture release region, lignocellulosic degradation region, plastic degradation region and char pyrolysis region (Lai *et al.*, 2011). The moisture release region is ranging between 303 and 423K. Lignocellulosic degradation region ranges between 423 and 643K. The plastic degradation ranges between 643 and 913K and finally the char pyrolysis region, which ranges between 913 and 1273K (Lai *et al.*, 2011).

ii) The Kinetics Parameters Study

The Differential thermal gravimetric study at different heating rates were used to develop the relation which was used to determine the activation energy (E_a) and pre exponential factor (A) of municipal solid waste of Arusha. The activation energy of municipal solid waste ranged between 205.9 kJ/mol. and 260.6 kJ/mol. This value is higher than that of biomass and coal, which range between 50 and 180 kJ/mole and 30 and 90 kJ/mole respectively. This corresponds to the value of E_a of biomass of cypress wood chips and macadamia nut shells observed by (Vhathvarothai *et al.*, 2013) having the value of 168.7 kJ/mol. and 164.5 kJ/mol., respectively. The results show that municipal solid waste need high energy to react as compared to biomass and coal. Reactivity of municipal solid waste can be increased by reducing the non-combustible material such as oxygen, to improve these municipal solid waste can be done by pre-treating the material through the torrefaction process (Biswas, 2011).

iii) Differential Scanning Calorimetry Study

The differential scanning calorimetry (DSC) reveals endothermicity between 303K and 423K; this is due to evaporation of moisture. In the temperature range of 423 to 1273K, the process undergoes exothermic reaction due to the devolatilization and pyrolysis of the municipal solid waste. The energy absorbed due to evaporation of moisture for wastes from Kaloleni, Sakina and Central market collecting points were 0.11 MJ/kg, 0.20 MJ/kg and 0.15 MJ/kg respectively, while energy released from the same respective collection points were -7.6MJ/kg, -8.3 MJ/kg and -8.5 MJ/kg. The energy released during DSC was lower than the higher heating value (12.54 MJ/kg). This energy found in bomb calorimeter is higher than energy found in TGA because some energy in TGA used to remove moisture while in bomb calorimeter the energy observed is for pre-treated waste (pellets).

7.2. Studying the Operation Conditions of Incinerator

7.2.1. The Operations of an Incinerator under Normal Conditions

The incinerator operates as normal, the variation of temperature in primary and secondary chambers with the flue gas emission plotted in the Fig. 39.

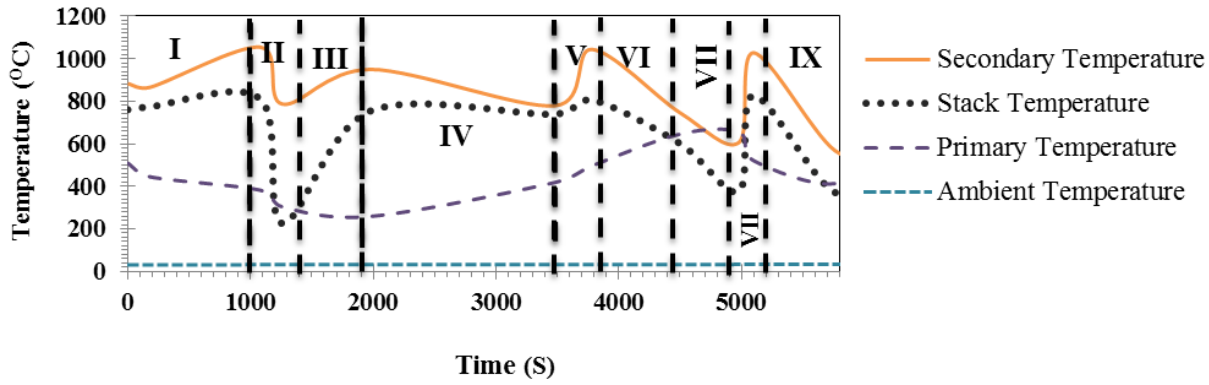

Figure 39: Typical Temperature Distribution in an Incinerator for One Complete Cycle at Bagamoyo

The results observed from an incinerator divided into 9 regions. Region I show that when the incinerator working under no load, the maximum combustion temperature attained for the stack was 1073K. The emission of NO_x and CO seems to be of much higher at the beginning and then suddenly decreases. This is due to the incomplete combustion of the fuel at starting due to low temperature. The NO_x formed in this case is fuelling NOx, which emitted by the

combustion of Nitrogen bearing fuels. The fuel released nitrogen bound in them as free radical which are oxidized to NO_x (Stubenberger *et al.*, 2008).

In the second region the temperature of the incinerator falls. The stack temperature decreases to 520K. The primary chamber temperature decreases to 576K while secondary temperature falls to 556K, this is because at this time, the incinerator burners switched off and the feeding stock added to the incinerator. The incinerator efficiency also falls to zero since there is no combustion during the feedstock and all the burners switched off. The O_2 is 21% since there is no combustion at this point.

In the third region, all the burners switched on. The temperature of the incinerator changes, the secondary and stack temperature rises while the primary temperature falls. The cause of primary chamber temperature to fall is due to the feedstock temperature, which is at room temperature from the dump. The emissions show that the CO_2 concentration increases while the O_2 concentration decreases. The concentration of carbon monoxide decreases while NO_X emissions become constant at 92 ppm.

At region IV the temperature of the primary chamber increases while that of secondary slightly decreases, thus showing that the feedstock is already acquired the uniform temperature with the combustion chamber. The emission of NO_x and CO is at constant of about 136 and 100.7 ppm while the O_2 and CO_2 emission are about 7.4 and 9.8% respectively. The efficiency of the incinerator combustion fluctuates between 63 and 59%. The decrease in secondary chamber temperature is caused by a reduction of incomplete combustion gases, which are expected from the primary chamber to the secondary chamber such as CO which decreases from 136 to 100.7 ppm (Chen and Chen, 2001).

At region V, the incinerator temperature of all chambers increases Fig. 14. The combustion efficiency is slightly decreases. The NO_x concentration decreases from 136 ppm to 67 ppm while the concentration of CO decreases from 100.7 to 0 ppm. The decrease of NO_x and CO and the efficiency of the combustion caused by switching off the second burner for trying to maintain the desired temperature. The NO_x concentration decreased because the amount of diesel of combustion decrease as the burner switched off. The only NO_x formed at this temperature is a prompt NO_x (Stubenberger *et al.*, 2008) which is normally comes from the fuel used.

At region VI, the burner switched on again to maintain the desired temperature. The temperature of secondary chamber and stack decreases while the temperature of the primary chamber increases. The emission shows that there is increase in CO and NO_x concentration. The CO increases from zero to 1159.3 ppm and that of NO_x increase from 67 to 582 ppm. The efficiency of combustion also increased from 59% to 71.7%. This is the highest efficiency of this incinerator in which the concentration of O_2 is 6.9% and that of CO_2 is 10.4%. These values approach the recommended value of O_2 at the exit point, which studied in simulation of fixed bed thermal oxidizer for solid waste disposal. The value obtained and recommended for oxygen at exit point is 6% (Mtui, 2013).

At region VII, the incinerator door slightly opened to increase the excess air supply and the primary chamber burner switched off. The secondary and stack temperature is decreasing while the primary temperature is still increasing. This may be caused by complete combustion in the primary chamber by supplying excess air by opening the door and therefore decrease the incomplete combustion gases in the secondary chamber. The NO_x and CO is decreases from 582 to 302.3 ppm and from 1159.3 to 716.3 ppm respectively. The efficiency also decreased from 71.7 to 50.7%.

At the region VIII, the secondary burner switched on for about 100s, while the primary chamber burner is still off. This done in order to maintain the required temperature. The secondary and stack temperature rises rapidly. The efficiency is slightly increased to 56% and then raised and fluctuate to 50%.

At region IX, all the temperature decreases. The efficiency falls to 27% and CO_2 concentration decreased to 6% while O_2 increases to 20.1%. The cause of temperature rise from secondary chamber is due to the high concentration of incomplete combustion gases at the chamber. These gases were combusted by the burner and suddenly they diminished.

The flue gas shows that the relation between O_2 and CO_2 that, as the amount of CO_2 is increasing the amount of O_2 decreases. This indicates that at this point the efficiency of combustion is the best method.

7.2.2. The Study of Variations in Primary Chamber Temperature against Efficiency, O_2 and CO_2 Concentration in Flue Gas Emission

The study shows that when the O_2 is about 6.9% the efficiency is at the highest and when the oxygen is closer to 20% the efficiency is lowest. This indicates that the combustion is poor when the flue gas composition has much O_2 concentration. The excess air also indicates the variation, as the excess air increases the temperature is decreasing and the efficiency decreased. The efficiency of incinerator seems to increase with increase in temperature.

7.2.3. The Study of mass and Energy Balance of the Incinerator

The mass of the materials used during incineration is changing as the chemical reactions occur between municipal solid waste, auxiliary fuel and air.

i) Mass input by municipal solid waste and diesel

From the experiment, the mass of waste incinerated was 49 kg/h. The total mass of ash remaining after the combustion was 5.87 kg/h this shows that the mass of waste consumed in forming flue gases is 43.13 kg/h, which give the equivalent of mass reduction by 88.02 %. The value of unreacted material found to be 11.98 %. This value is closer to the value obtained in proximate analysis from various researches. Since the waste has 55% moisture, it implies that the total mass of dry waste will be 19.4 kg/h, and the total moisture will be 23.72 kg/h. The volume flow rate of diesel consumed determined and found to be 0.011 439 m^3/h. Since the density(ρ) of diesel = 852 kg/m^3, the mass flow rate of the diesel = 0.011 439*852 = 9.75 kg/h

ii) The mass of air supplied and moisture contents from the air

To the incinerator for municipal solid waste were measured and calculated

The mass of air supplied to the incinerator measured by using an anemometer. The supplied air velocity to the incinerator calculated to be 6.2 m/s for pipe P_1 located at the bottom of the grate bed. The air velocity for pipe P_2, located at the exit of primary chamber, is 6.3 m/s while the air velocity of pipe P_3 located at the exit of the secondary chamber calculated to be 9.2 m/s. Their respective diameters are 0.05 m, 0.05m and 0.0625 m. Density of air $\rho_{(air)}$ and humidity of Bagamoyo at 22.75 are 1.2922 kg/m^3 and 77.2% respectively (Infolinks, 2011).

Table 24: The Burners Diesel and Air Consumption

	$C_{12}H_{23}$	O_2	N_2	CO_2	H_2O	N_2	O_2
	1	17.75		12	11.5	66.74	
Total mass	167	568	1868.72	528	207	1868.72	0
Normalize diesel	1	3.4	11.19	3.16	1.24	11.19	0
Diesel fired kg/h	9.75	49.74	163.65	30.83	12.09	163.65	16.58

According to the balance equation the total mass of air with a 50 % excess will be 213.395 kg/h and the calculated value of specific humidity of 0.017 404 2 $kg_{(water)}/kg_{(air)}$ the total mass of humidity was found to be 7.984 872 918 $kg_{(water)}/kg_{(air)}$

7.3. Energy Balance of the Incinerator

7.3.1. Total input energy

$Energy\ in = Energy_{(diesel)} + Energy_{(MSW)} + Air_{(Energy)}$ assuming energy from air is negligible we have

i) Diesel energy

Energy of diesel = mass of diesel * HHV of diesel

= 9.75 kg/h x 45 013 kJ/kg

= 438 876.75 kJ/h

ii) Municipal solid waste energy

Energy from municipal solid waste = mass of dry combustible waste * HHV of waste

(Mass of combustible waste – moisture (55 %) – unreacted) * HHV of waste

= (22.05 - 2.867) kg/h x 12 010 kJ/kg

= 230 387.83 kJ/h

Total energy in = 438 876.75 +230 387.83

= 669 264.58 kJ/h

7.3.2. Total output energy

$Energy\ out = Q_{(Out1)} + Q_{(Out2)} + Q_{(Out3)}$. We have

i) Flue gas energy

Energy out due to flue gas release

$$Q_{(out1)} = \sum (m_{gases} * C_{p(gases)} * \Delta T_i)$$

$$= m_{CO_2} * C_{p(CO_2)} * \Delta T_1 + m_{O_2} * C_{p(O_2)} * \Delta T_2 + m_{N_2} * C_{p(N_2)} * \Delta T_2 + m_{SO_2} * C_{p(SO_2)} * \Delta T_1 + m_{1(H_2O)(g)} * C_{p(H_2O)} * \Delta T_1)$$

Where:

ΔT_1 = Temperature difference between exit temperature and ignition temperature of gases, which estimated to be 450℃. The gases of CO_2, SO_2 and $H_2O_{(g)}$ are formed from combustion reactions at 450℃.

ΔT_2 = Temperature difference between exit temperature and ambient temperature at 22.75℃. The gases N_2 and O_2 found from the combustion air at ambient temperature.

$m_{2(H_2O)(l)}$ = The mass of water from combustion air and moisture contents of the fuels at ambient temperature

$m_{1(H_2O)(g)}$, $m_{CO_{2(g)}}$ and m_{SO_2} = Mass of H_2O, CO_2 and SO_2 formed due to the chemical reaction in the incinerator

Cp_{CO_2}, Cp_{O_2}, Cp_{N_2}, $Cp_{H_2O_{(l)}}$ $Cp_{H_2O_{(g)}}$ are the specific heat capacities of Carbon dioxide, Oxygen, Nitrogen, water, water vapour and Sulphur dioxide respectively with subsequent values of 0.844, 0.919, 1.04, 4.184, 1.185 and 0.64 kJ/kg℃ respectively. The results on Table 24 shows the total energy release, by flue gases from the incinerator at exit temperature of 1000℃

Table 25: The Flue Gas Parameters

Type of Gas	Cp kJ/kg℃	ΔT_i (℃)	Mass (kg)	Energy Total (kJ)
CO_2	0.844	550	78.54	36 455.95
O_2	0.919	977.25	32.95	29 591.26
N_2	1.04	977.25	352.70	358 465.15
SO_2	0.64	550	0.14	48.87
$H_2O(l)$	4.184	77.25	34.93	11 289.87
$H_2O(l)$	2460 (kJ/kg)	enthalpy of vaporization	34.93	85 927.80
H_2O *(g)*	1.185	900	34.93	37 252.85
H_2O *(g)*	1.185	550	32.14	20 947.25
				579 978.98

ii) Chemical reaction energy

Energy released due to chemical reaction. The formation of CO_2, SO_2 and H_2O

a) Formation of CO_2

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \qquad \Delta H^o = -393.5 kJ\ mol^{-1}$$

Total number of moles of $CO_2 = \frac{75.282}{44} = 1.710\,\text{kmol}$

ΔH^o = -393.5 *kJ/mol x* 1.710 *kmol*

= -673 260 613.64J

b) Formation of H_2O

$$H_{2(g)} + \frac{1}{2} O_{2(g)} \rightarrow H_2O_{(l)} \qquad \Delta H^o = 241.8 kJ\ mol^{-1}$$

Total number of moles of H_2O

$$= \frac{32\ 731.527}{18} = 1\,818.418\,\text{mol}$$

$$\Delta H^o = 1.818\,418 \text{ x } 10^3 \text{ mol x } 241.8 \text{ kJ mol}^{-1}$$
$$= 439\ 693\ 512.70\,\text{J}$$

Therefore the total energy released during the chemical reaction will be -234 155 068*J*

= 234.16 MJ

iii) Radiation and heat loss energy

The energy due to radiation and the losses it varies between 1-5% of the total heat available

= 5% x 669 264.58 kJ/h

=33 463.23 kJ/h

iv) Energy to heat up the incinerator

The energy use to heat up the incinerator before filling in the waste. The primary chamber heated up to 400℃ and the secondary chamber to 800℃. The total diesel of about 5 liters used.

7.4. The Simulation Model Results

The simulation model results were adopted from published data in international journal as a result of the study of operating conditions of incinerator done at Bagamoyo-Tanzania (Omari *et al.*, 2015). The input staved air inlet $A_{1\text{-}1}$ located at the bottom of the primary chamber is deviated by 13.532% and it changes its original value from 0.031 47 kg/s to 0.036 39 kg/s. The value of oxygen increased due to increase in municipal solid waste burned. The amount of oxygen needs to increase so as to assist in the process of thermochemical oxidation process to convert the biomass substance into syngas (Ruiz *et al.*, 2013). Air inlet $A_{2\text{-}1}$ that supplies air to the primary chamber shows the deviation of 4.971%. The values of original was 0.031 97 kg/s, which decreases to simulated value of 0.030 46 kg/s. The value of oxygen reduced to a lower value however; this deviation is allowable for such calculations. The pipe for supplying air to secondary chamber $A_{3\text{-}1}$ has decreased its value to 0.034 09 kg/s from its original value by 6.9% this may be caused by slightly increasing the excess air supplied during the experimental process (Arena, 2012; Ruiz *et al.*, 2013). The maximum value of oxygen needed for optimum combustion is iteratively determined by fluent solver which gives the actual value needed to 0.034 09 kg/s (Ansys, 2015).

7.4.1. The Input Municipal Solid Waste to the Model

The optimized value of the MSW mass flow rate shows the deviations, the simulation value shows that the incinerator has a capacity to incinerate MSW 26.48% more that its designed capacity. The simulation results from fluent solver show that the maximum capacity for one cycle can be 68 kgs instead of 50 kgs currently used.

7.4.2. The Output Results from the Fluent Solver

The CFD output simulation results and the experiment result tabulated in Table 25.

Table 26: The Comparison Output Between Experimental and Simulation Results

Parameters in Mass Fraction				
Item	Symbol	Measured (Experiment)	Predicted (Simulated)	Deviation (%)
Velocity magnitude (m/s)	υ	4.0	3.75	6.25
Mass fraction of O_2 (%)	O_2	12.27	2.31	81.17
Mass fraction of CO (ppm)	CO	109.7	46	58.07
Mass fraction of CO_2 (%)	CO_2	6.4	7.07	10.39
Mass fraction of NO_x (ppm)	NO_2	152	372	144.74
Particle residence time (s)	t	2	1.73	13.5

Source: (Omari *et al.*, 2015)

i) Velocity Magnitude

The maximum velocity at the exit of the incinerator is ranging between 2.79 – 3.49 m/s with average velocity of 3.14 m/s. Velocity has a minimum value at the primary chamber and higher value at the secondary chamber. The formation of gaseous material in the primary chamber increases the velocity of gases. The O_2 concentration in the secondary chamber increases the velocity and residence time due to excess air supplied (Liang and Ma, 2010)

ii) The Temperature of the Incinerator

The maximum temperature is 2400K and the minimum is 300K corresponding to room temperature and the feed-in temperature of municipal solid waste. The temperature is uniform in primary chamber, secondary chamber and in the chimney. The temperature at the secondary chamber is 1400K and the average temperature of the chimney is about 1800K but the core is 2000K, ash deposited at the bottom of the incinerator with a temperature of about 2400K. The temperature at the entrance of pipe is high; this may be due to the excess air at that particular point. The excess air increases the combustion efficiency. The low heat zone at the bottom of the incinerator caused by insufficient air due to its position. Indeed, there is anomaly in the observed temperatures. A direct explanation to what is happening elucidated if further studies carried in these areas. The temperature at the entrance of pipe is high; this may be due to the excess air at that particular point. The excess air increases the combustion efficiency. The low heat zone at the bottom of the incinerator caused by insufficient air due to its position. The temperature at the exit is about 1400K. There are two burners, which are located at primary and secondary chambers respectively. The burners assist in increasing the temperature of the

incinerator and support combustion for both primary and secondary chambers.

iii) Mass Fraction of Oxygen

The mass fraction of O_2 decreased. The value of oxygen to the effluent is caused by excess air to the combustion process (Ryu *et al.*, 2002). In this case, the value of oxygen to the practical experiment exceeded. The increasing oxygen may cause this during the period of refilling the waste by opening the door of the incinerator, there is recalculated air from the entrance door.

iv) Mass Fraction of CO Released

The simulation values for Carbon monoxide were deviated from practical values by 58.07% this value is highly deviated. The percentage of Carbon monoxide increases as compared to practical results. The value is, however, within the permissible value of Carbon monoxide allowed in the environmental protection values (Ryu *et al.*, 2002).

v) Mass Fraction of Carbon Dioxide Released

The values show that CO_2 released were deviated by 10.39% from the value obtained practically. The percentage CO_2 at the effluent gases found to be 7.07%. The practical experiment obtained was 6.4 % (Omari *et al.*, 2015). This variation may be caused by an increase in combustion efficiency of the incinerator (TSI, 2004; Urieli, 2010).

vi) Mass Fraction of NO_2 Emission (ppm)

The emission values for NO_2 deviated from practical values. The deviation values were 144.74%. This value is more than the practical values because some of the Nitrogen from air under high temperature forms thermal NO_x (Feron and Hendriks, 2005). The increase the temperature of combustion may lead to the formation of more NO_x (Winter *et al.*, 1999). In the case studied, the highest concentration of NO_x found to be at the bottom of the incinerator where the ash drops with high temperature are concentrated. This may be due to the high temperature of ash and excess air enters to the primary chamber during filling the waste while the combustion process continues. The ash concentration and the filling of waste during second and other higher cycles of operation may cause this excess temperature and excess air to form thermal NO_x which was not considered during the practical experiments (Chen *et al.*, 2016).

vii) The Particle Residence Time

The particle traces colored by residence time(s). The particle residence time shows an average of 1.73 (s). These values correspond to various international standards for residence time such as Canadian standards which set the standard residence time to be not less than 1 second at a temperature not less than 1000°C (CCME, 1989). The value of residence time influenced by the speed of inlet gases. The value of residence time is also affected by temperature and that is why at secondary chamber the residence time is lower than in primary chamber due to high temperature in a secondary chamber (Yaghmaeian *et al.*, 2015).

viii) The Particle Path Lines (PPL)

The particle traces represent the path. Initially a path made by integrating the velocity with time. For transient flow path, particle path lines known as pathlines. In this work, the pathlines start from the boundary condition inlet $A_{1\text{-}1}$, inlet $A_{2\text{-}1}$, inlet $A_{3\text{-}1}$, inlet $B_{1\text{-}1}$, inlet $B_{2\text{-}1}$ and inlet $D_{1\text{-}1}$ and goes out through the outlet $_{1\text{-}1}$ as shown in Fig. 11. The results also show that there is a uniform flow of particles from bottom of the incinerator through the neck; then secondary chamber, the chimney to the exit. The detailed information of these pathlines contributes to the overall understanding of the flow of the particles (Nasserzadeh *et al.*, 1991).

ix) Particle Diameters

The particle diameter decreased along the incinerator. The value of the particle diameter at the bottom is about 9.55e-04m while it decreases to 1.45e-04m just before the exit of primary chamber. At the secondary chamber there are very few particles and very small. Their diameter is about 1.00e-04 m. Big particles remain in primary chamber and the small particles pass through the neck, secondary chamber and chimney to exit. This separation of particles caused by a two-chamber incinerator design in which the primary chamber solid particles gasified to combustible gases

x) Average Temperature Vs Incinerator Height

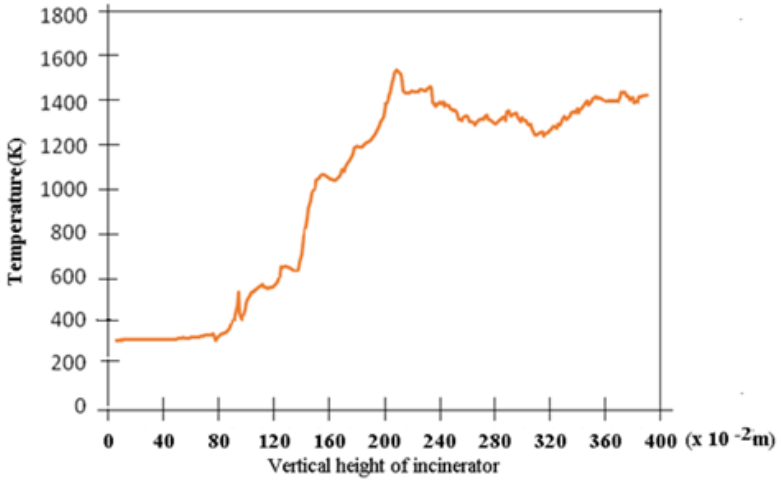

Figure 40: Temperature Variation with Incinerator Height

The average temperature is about 1400K at incinerator exit. The average temperature is increasing along the incinerator. The rapid change in temperature at 140 m is due to entering of gases from the primary chamber to secondary chamber. The temperature is gradually increased and reached a maximum point at 210m. The temperature then fluctuates again between 1600k and 1400k to exit. The temperature at the chimney constant fluctuates between 1400 and 1600k. The fluctuation affected by the primary reaction in the combustion chambers.

xi) Average NO_x at Incinerator Exit

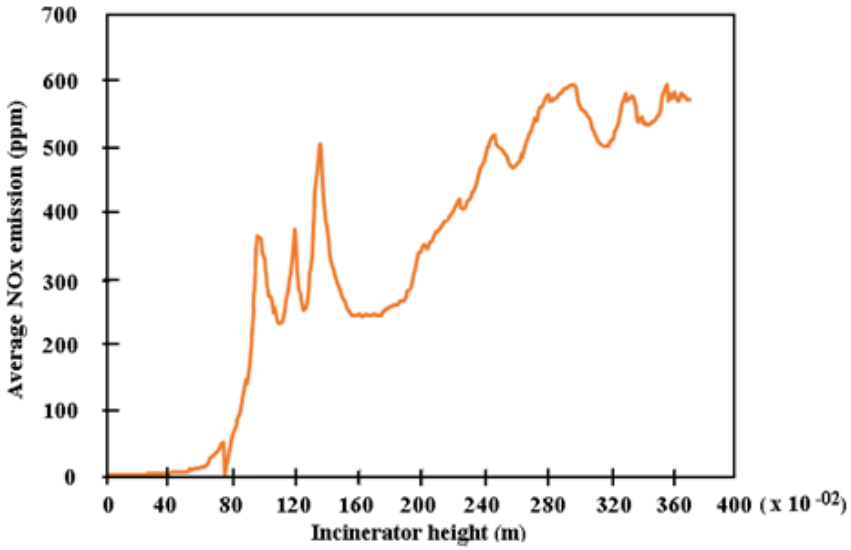

Figure 41: Average NO_x at Incinerator Exit

Average NO_x is about 600ppm at incinerator exit. This value is within the permissible value of NO_x gases, which can react with oxygen to form acid rain.

7.5. Conclusion and Recommendations

This work presents findings related to MSW characterization of Arusha city. The case represented the MSW found in Tanzania. The proximate analysis of the municipal solid waste show that, the waste contains more than 50% and 5% of carbon and hydrogen respectively which may contribute to high calorific value of Arusha MSW. The ultimate analysis shows that the average amount of nitrogen, sulphur, chlorine and phosphorus are small, these reduce emissions during combustion.

The energy content of waste determined by bomb calorimeter is about 12 MJ/kg this energy is about 30% of energy containing in coal and about 60% of energy containing in biomass. The activation energy was ranging between 205.9 and 260.6 kJ/mol. The MSW shows the exothemicity property at the devolatilization zone. The devolatization zone shows that the municipal solid waste can easily ignited at temperature above 423 K. Therefore, municipal solid waste has a good potential to use as a fuel.

The study reveals that for every one kg of dry MSW, thermal energy recovery of 10.6 MJ/kg expected to realize. The waste composition shows that the waste used as the energy source as it contains more composition of biodegradable and combustible waste. The excess air concentration in the flue gas affects the temperature; it needs to reach a certain point to maximize the efficiency of the incinerator. The incinerator performance becomes better when the primary chamber set to 400℃ and the secondary chamber set to ranges between 800 and 900℃. At this point, CO_2 reach a maximum value of 10.4% whilst CO and NOx level, are minimal at 100.4ppm and 92 ppm respectively.

The excess air ratio to the incinerator during incineration to optimized to minimize pollution and increase the performance of the incinerator. To acquire more energy from the incinerator, the municipal solid waste dried to reduce moisture contents. The incineration result generates energy of 379 287.14 KJ/h with ash and flue gases emissions of total mass of 579 978.98 kg/h. There is an energy difference of 379 287.14 KJ needs to recover or optimized. There is also the energy, which used to heat up the incinerator before putting waste, which not considered.

The experimental and simulation study is necessary information for input and operating parameters in the optimization of a fixed bed municipal solid waste incineration.

The incineration design successfully optimized parameters using computational fluid dynamics modelling fluent version 12.1. The process iterated to optimize the operating conditions. The input parameters vary in such a way that the minimum cost of operation and pollution achieved. The emission conditions simulated and the minimum pollution achieved.

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APPENDICES

Appendix 1: Operating Procedure for Measurements of Emissions from Locally Made Fixed Bed Incinerator, A case study of Bagamoyo Tanzania

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The Nelson Mandela African Institution of Science and Technology

Operating Procedure for Measuring Emissions from a Fixed Bed Incinerator Located at Bagamoyo Hospital. Onsite Operating Procedure

#001

September 2014

By

Arthur Mngoma Omari – PhD Candidate at NM AIST

This SOP will use to measure the combustion emission coming from fixed bed incinerator located at Bagamoyo hospital.

APPROVED: Supervisors

1. *(Signature and Date):* _____
2. *(Signature and Date):* _____

Appendix 2: Conference paper 1 - Energy Recovery from Municipal Solid Waste. In the 9th SIDA Regional Collaboration Conference, Entebbe. Uganda 20th -23rd July 2014.

Abstract

Energy flow analysis and thermal degradation of municipal solid waste carried out using differential scanning calorimetry and thermo-gravimetric analyzer at heating rates of 10 K/min, 20 K/min, 30 K/min and 40 K/min in a nitrogen atmosphere and temperatures between 308 K and 1273 K. The activation energy ($E_{a.}$) is the energy barrier, which overcome for reaction to occur. Thermal degradation behaviour experiments show that the municipal solid waste is less reactive than biomass or coal with an activation energy ranging between 205.9 to 260.6kJ/mole. These values are higher than the typical wood activation energy, which ranges between 50 and 180 kJ/mole and coal with a range between 30 and 90 kJ/mole

Keywords: Municipal Solid Waste, Thermal behaviour, Thermo-gravimetric analyzer.

The 9th Regional Collaboration Conference July 20 – 23, 2014 Imperial Resort Beach Hotel, Entebbe, Uganda

Appendix 3: Conference paper 2 Non-Isothermal kinetics of Agriculture, forestry and Municipal solid waste. A Case of Arusha, Kilimanjaro and Mbeya – Tanzania. In the International Conference on Energy, Environment and Climate Change (ICEECC 2015). Mauritius, 8th -9th July 2015.

Abstract

The Agriculture, forestry and municipal solid waste disposal methods for energy recovery is a crucial problem. The understanding of thermal behaviour, chemical kinetics and reactions of waste disposal are useful in deciding the thermal method of waste treatment and disposal. The kinetic analysis shows that the activation energy (E_a) has different values which varying with variation of temperature. The rice husk has the value of 71.59 KJ/mole, 73.05 KJ/mole and 191.5 KJ/mole with a temperature range between 300 to 400K, 600 to 750K and 550 to 600K respectively. The pine sawdust activation energy (E_a) values are 26.19 KJ/mole, 87.46 KJ/mole and 54.58 KJ/mole with temperature ranges between 350 - 400K, 550 - 650K and 700 - 800K respectively. Municipal solid waste activation energy values are 72.91 KJ/mole and 139.1 KJ/mole with temperature ranges between 700 - 900K and 500 - 600K respectively. The Pre exponential factor shows that the rice husk has the values of 1.31×10^{10}, 1.87×10^{17} and 6.87×10^{4} (s^{-1}) with temperature ranges of 300 - 400K, 500 - 600K and 600 - 750K respectively. The value of the pre exponential factor of pine sawdust has the value of 2.46×10^{4}, 1.6×10^{10} and 5.32×10^{16} (s^{-1}) with temperatures of 350 - 400K, 550 - 650K and 700 - 800K respectively. Municipal solid waste values are 3.01×10^{12} and 7.31×10^{3} (s^{-1}) with temperature range of 500 - 600K and 700 - 900K respectively.

Keywords: Municipal Solid Waste, Rice husk, pine sawdust, Thermo-gravimetric analyzer.

The International Conference on Energy, Environment and Climate Change (ICEECC 2015). Mauritius, 8th -9th July 2015.

Appendix 4: Conference paper 3 Chemical kinetics of forest and municipal solid waste. A case study of Arusha - Tanzania. In the 4th International Conference on Mechanical and Industrial Engineering. 1st – 2nd September 2016. Arusha International Conference Centre, Arusha, Tanzania

Abstract

The main economic activity in most of developing countries includes the exploitation of natural resources and agriculture. The wastes generated from these sectors are such as forest wastes and municipal solid waste. The main purpose of this paper is therefore to study the kinetics and reactions of these wastes. The kinetic analysis shows that the activation energy varies with temperature. The analysis of pine sawdust shows that it has activation energy (E_a) values of 26.19 kJ/mol., 87.46 kJ/mol. and 54.46 kJ/mol. In respective temperature ranges between 350 – 400K, 550 – 650K and 700 800K. Municipal solid waste has an activation energy between 72.91KJ/mole and 139.1 KJ/mole. Temperature ranges between 700 – 900K and 500 – 600K respectively. The estimated value of pre exponential factor for pine sawdust has the values of 2.46×10^4, 1.6×10^{10} and 5.32×10^{16} (s^{-1}) with a temperature of 350 – 400K, 550 – 650K and 700 800K respectively. Municipal solid waste has the values of 3.01×10^{12} and 7.31×10^3 (s^{-1}) with temperature range of 500 – 600K and 700 – 900K respectively.

Keywords: municipal solid waste, pine sawdust, thermo-gravimetric analyzer.

The 4th International Conference on Mechanical and Industrial Engineering, 1st – 2nd September 2016. Arusha International Conference centre Arusha, Tanzania.

Appendix 5: Conference paper 4 Computational Analysis of a Locally Made Municipal Solid Waste Fixed Bed Incinerator Combustion Chambers. In the fifth International Conference on Mechanical and Industrial Engineering MIE'2018 "Promoting Engineering Innovations for Sustainable Development" 16th - 17th August 2018, the Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha-Tanzania.

Abstract

In this study, a Computational Fluid Dynamics (CFD) technique used to develop a model for the simulation and flow conditions of the incinerator. The small scale municipal solid waste incinerator modelling done by using a fluent solver. The case study of the existing incinerator at a Bagamoyo hospital in Tanzania used as a model input and the obtained values compared with simulated results and other publications for validation.

Key words: Municipal solid waste, Incineration, Optimization, CFD

The 5th International Conference on Mechanical and Industrial Engineering, 16th – 17th August 2018. Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania.