SCAVENGING HEAT FROM INCINERATORS: CASE OF A MEDICAL WASTE INCINERATOR AT ZOMBA CENTRAL HOSPITAL, MALAWI.

MASTER OF SCIENCE (ENVIRONMENTAL SCIENCE) THESIS

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BSc (Environmental Science and Technology-Physics) - University of Malawi

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By

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Submitted to the Faculty of Science, in Partial fulfilment of the requirements for the degree of Master of Science (Environmental Science)

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DECLARATION

I, the undersigned hereby declare that this thesis/dissertation is my own original work which has not been submitted to any other institution for similar purposes. Where other people's work has been used acknowledgements have been made.

TAWINA KAPUSA MLOWA

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Name

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Signature

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Date

CERTIFICATE OF APPROVAL

The undersigned certify that this thesis represents the student's own work and effort and has been submitted with our approval.

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CO-SUPERVISOR

DEDICATION

To the God of all wisdom, knowledge and understanding, I dedicate this work. I would never have done it if it was not for His power upon my life.

ACKNOWLEDGEMENTS

Many thanks should go to God in Jesus' name for giving me His Spirit of wisdom to be able to do this work.

I thank the Malawi Polytechnic College for sponsoring my studies at Chancellor College. On sponsorship, I especially thank the Heads of Physics & Biochemical Sciences Department during this time (Dr D. Lakudzala and Mr M. Tsakama) for helping me to have access to the education funding program. I also thank my supervisors, Dr J.S.P Mlatho and Dr C. Mikeka for the guidance and effort put into this work. Further to that, I also thank the following people for their timely dedication to this work as assistants; C. Daka, Zomba central Hospital staff (Mr Chilunda, Mr A.Gomani and Mr Monjeza). During the study period, I enjoyed the company of great classmates. I appreciate their friendship, inspiration and help in understanding many academic and professional issues.

I am very grateful for my family: Samuel, Chiyanjano and Chigomezgo Mlowa. They had to endure having their mother (and wife) away from home for some time. Their love, understanding and encouragement are so greatly appreciated. For my parents (Mr and Mrs A.P Kapusa); I am also grateful for the parental blessings and encouragement throughout my studies.

ABSTRACT

A medical waste incinerator is an application of combustion in a furnace for thermal treatment of wastes. Energy can be recovered from medical waste incinerators and utilized for other purposes as a means of energy conservation. The aim of this study was to recover heat generated in the medical waste incinerator at Zomba Central Hospital for possible reuse. This was achieved by measuring temperature distribution in the incinerator so as to determine optimum position for a heat exchanger, designing an optimum heat exchanger based on the temperature distribution and assessing the performance of the whole heat scavenging system. Highest and consistently higher temperatures (up to 500°C) were observed at the back of the incinerator compared to the front which reached 148°C. This was due to the insulation of the incinerator's back surface. Hence the heat exchanger optimum position was found to be the back of the incinerator. Optimum flow rate of water through the heat exchanger was found to be $3.75 \times 10^{-5} m^3/sec$. At this flow rate, heat gained was 10.87 J/s or 39.132 kWh. The use of the heat-scavenging system would save the hospital about MK1590 (US$ 2.21) worth of electricity bill per every 810L of water heated per day and MK47670 (US$ 66.17) per month against an investment cost of MK80000 (US$ 112).

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ABBREVIATIONS

ZCH	Zomba Central Hospital
GHG	Green House Gas
PVC	Polyvinylchloride
MGDS	Malawi Growth and Development Strategy
MDG	Millennium Development Goals
MSW	Municipal Solid Waste
CFD	Computational Fluid Dynamics
NSO	National Statistics Office
Min	Minutes

NOMENCLATURE

$\dot{q}$	Heat gained by water per unit time (J/s) (W)
m	Mass (kg)
$\dot{m}$	Mass flow rate of water (kg s^{-1})
c	Specific heat capacity (J kg^{-1} $^{0}C^{-1}$)
ΔT	Change in temperature
$\dot{V}$	Volume flow rate of water through the heat exchanger(m^3/s)
ρ	Density (kg/m^3)
CO_2	Carbon dioxide
T_2	Temperature sensed by thermocouple 2 (^{0}C)
T_3	Temperature sensed by thermocouple 3 (^{0}C)
T_4	Temperature sensed by thermocouple 4 (^{0}C)
T_6	Temperature sensed by thermocouple 6 (^{0}C)

CHAPTER 1

INTRODUCTION

1.1 Introduction

A medical waste incinerator is an application of combustion in a furnace for thermal treatment of medical wastes at high temperature (Warhurst & Watson 2006). The waste includes devices and supplies used to treat patients as well as biological waste such as blood or tissue. The objective of medical waste incineration, in common with most waste treatments, is to treat waste so as to reduce its volume and hazard, whilst capturing (and thus concentrating) or destroying potentially harmful substances (European Commission, 2006).

Zomba Central Hospital (ZCH) is one of the largest hospitals in Malawi, located in Zomba district. The hospital has one medical waste incinerator in which all medical wastes from the hospital are burnt. The incinerator is operated manually and about 25 L of diesel is used as fuel per week. Temperatures in the incinerator can reach up to about 500^0C.

1.2 Problem statement

According to the NSO (2008), 97 % of Malawian households depend on biomass mainly derived firewood, charcoal, agricultural and industrial wastes for heating. Presently, only 8% of the population has got access to hydropower which accounts 95% of electricity whereas thermal energy generation only accounts for the remaining 5% (Mkandawire, 2012). The unsustainable harvesting of forests coupled with climate change has brought increasing concerns and hence the requirement in the Malawi Growth and Development Strategy (MGDS) II (2011-2016) to have energy generation as one of the major priority areas. This has resulted in the requirement to have alternative energy sources for heating, cooking and lighting. Thermal energy has the potential to augment the conventional energy sources for heating in Malawi as one of the ways of meeting the requirements in the MGDS. Hospitals in Malawi are one of the organization facing challenges in the provision of energy for heating water. In such hospitals like Zomba Central Hospital, the challenge is greater when patients' numbers exceed design capacities which often stretch the available energy resources. The provision of hot water for patients and other users is therefore costly in monetary and environmental value. As a result to this, the other challenge is that the patients' care-takers in the hospital have to spend money and fuel wood to heat water for their patients. Ironically, heat generated by the hospital's medical waste incinerator is not being properly utilized despite the energy challenges being faced.

This study therefore explored the feasibility of using the already available heat energy in the incinerator for heating water. Most studies in Malawi have focused on air pollution and incineration.

1.3 Objectives

The main objective of the research was to determine the feasibility of recycling waste heat from an incinerator at Zomba Central Hospital.

The specific objectives of this research were to:

1 Evaluate temperature distribution in the incinerator so as to determine the optimum position of a proposed heat exchanger

2 To design an optimum heat exchanger based on the temperature distribution in the incinerator

3 Determine the optimum operating flow rate of the heat exchanger

Following the specific objectives, the study had the following research questions:

1. Is there a significant difference between temperature values at the back and front of the incinerator furnace?
2. What design of heat exchanger would be optimum for the heat recovery system?
3. What would be the highest water temperature achieved?
4. At what flow rate does the heat recovery system give the highest water temperature (with water still in its liquid state)?
5. What effect does the water flow rate in the heat exchanger have on the temperature of the water at the outlet?

This thesis evaluates the possibility of scavenging heat from the medical waste incinerator. The thesis has five chapters which include the introduction, theory, method, results and discussion and lastly recommendations. The main theme in this thesis is

Energy use; hence the chapters given will cover the study on the feasibility of reusing the heat from a medical waste incinerator to fulfill other energy requirements.

1.4 Project Justification

This study is in line with goal 7 of the MDGs which outlines the need to develop alternative energy sources. This study will provide information which will contribute to the ways of utilizing energy from the medical waste incinerators in Malawi. Many studies on energy recovery have been done on advanced incinerators outside Malawi, but no such studies have been done on the incinerators available in Malawi. If the heat exchange system is to be implemented, it will not just be for academic benefit but it will also be both an economically and environmentally benefit.

CHAPTER 2

LITERATURE REVIEW

This section gives literature review and a theory of incineration, heat exchange systems and heat energy.

2.1 Literature review

A number of studies have been conducted on incineration, incineration and energy recovery, heat exchangers and use of computational fluid dynamics in energy technologies.

In Malawi energy contributes a lot to the economy but yet there is a deficiency in its resources. Hence, the Millennium Development Goals (goal 7) aims at achieving environmentally sustainable development and one of the ways of achieving this goal is the development of renewable energy sources.

A study on incineration with energy recovery was done by Sundberg et.al (2004) to evaluate its efficiency in waste treatment as compared to other waste treatment methods such as landfill and bio-treatment. In the evaluation waste treatment options such as landfilling, material recycling and biological treatment plants were compared to incineration with energy recovery to come up with the best option from the environmental point of view. The results of this evaluation showed that to reach the best environmental results for material recycling and biological treatment of organic combustible material, waste incineration is necessary for treating residue arising during pre-treatment and processing of materials. In all comparison studies, landfilling showed to be the best waste treatment option. A similar study in UK by Jeswani et al. (2013) showed that waste incineration offers significant savings of greenhouse gas emission compared to disposal by landfill. The study showed that incineration could save around 1.29×10^8 kg of CO_2 per year compared to land filling with biogas recovery, with both systems co-generating heat and electricity. At the UK level, diverting all municipal solid waste that is currently land filled to incineration with energy recovery could save around 8.38×10^9 kg of CO_2 per year or 1.5 % of the total UK GHG emissions. Incineration therefore remains a better option than land filling under all the conditions considered in the study. Therefore from these studies it is very relevant to have studies that contribute to the incineration and energy recovery.

Kelly (2010) gave an emphasis on the need to make the built environment more energy sustainable. His results showed that a lot of money can be saved when buildings are built in such a way that energy consumption is reduced. One of the ways of doing this is by having systems that recycle the energy being used. As such scavenging heat from an incinerator would also be a good example of making an infrastructure environmentally friendly. A further advantage is in investment; Münster & Meibom (2010) analyzed several waste-to-energy technologies and showed that production of energy from waste incineration is one of the best investments. The focus of their analysis was on different uses of waste for energy production. The waste-to-energy technologies analyzed included co-combustion of coal and waste, anaerobic digestion and thermal gasification. Using a mathematical model Münster & Meibom (2010) showed that a combination of these waste-to-energy technologies would be more effective and that effectiveness would depend much on the type of waste, storage of heat and geological scope.

Furthermore, in Japan, waste-to-energy municipal solid waste (MSW) incinerators were analyzed to find if they are really greenhouse gas (GHG) reducers. Net GHG emission is affected by the type of wastes and amount of energy being produced, Tabata (2013). The analysis by Tabata showed that 16.2% of Japan's electricity household demand and up to 25% of hot water demand could be met by the waste-to-energy incineration plants. Similarly, Fruergaad et al. (2010) showed that in Denmark, MSW incineration contributes 20% of the heat supplied to the more than 400 district heating networks. Results from the investigation on MSW incineration in Denmark showed that waste incineration in one network caused a CO_2 saving of 48 kg CO_2/GJ energy input while in the other network a load of 43 kg CO_2/GJ. This was caused mainly by differences in operation mode and fuel types of the other heat producing plants attached to the networks.

In incineration, heat parameters are operation temperature, turbulence level and residence times. The operation temperature is the temperature of the furnace in which the wastes are being thermally treated, the temperature, therefore, depends on the type of wastes in the furnace, type of additional fuel used and the furnace design. The residence time is the total time that the wastes stay in the furnace. These parameters are important because they give guidance when developing waste-to-energy technologies. A study on these parameters showed that if they are fixed for a certain fuel supply rate, it is possible to increase the residue consumption rate using enriched air (Lacavaa, et al., 2005).The amount of heat lost through the wall is the parameter that determines the chamber efficiency. For example, a chamber with an efficiency of 80% means that 20% of the heat liberated by combustion of the fuel is lost through the wall and is not available to the incineration process (Zhang', 2008).

Trulli et.al (2013) evaluated the potential energy recovery using a combined cycle for the incineration of mechanically pre-treated municipal solid waste in Basilicata, Southern Italy. Co-generative (heat and power production) plant was compared to other MSW management solutions such as direct landfilling, also considering the environmental impact in terms of greenhouse gases (GHGs) emissions. In this evaluation heat exchangers were used in the power generation process. The heat exchangers were used to transfer heat between gas and water to generate the steam required to drive turbines. The analysis demonstrated the potential of co-generative incineration residual MSW for energy recovery after sieving, an effective and low cost pre-treatment process.

In Malawi, many studies on methods of heating water with other sources of renewable energy, apart from electricity, have focused on the use of solar energy. Nkhonjera (2011) studied the effects of installing thermo siphon solar water heating system (TSWHS) on total energy bill at Mzuzu University (MZUNI). The results showed that indeed the installation of the TSWHS would bring about positive savings on the total energy bill. The study systematically determined the average monthly energy bill at MZUNI and the students' daily hot water demand. Nkhonjera (2011, p.38) found that:

> 76% of the time in a year, the energy consumption of the TSWHS would be met by solar energy; even with the incorporation of auxiliary electric heating, electric water heating bill would be reduced from 9% to 0.8% of the total annual energy bill; 107 MWh of utility energy can be saved annually; and the system's payback period of 9 years can be realized with a 10% rate of return on investment. It can therefore be concluded that installation of a TSWHS at MZUNI is both economically viable and saves utility energy.

These findings are very helpful in this study as they provide an idea that scavenging heat from a medical incinerator can help to reduce the hospital's monthly expenditure on utility bills and also provide the much needed hot water for the patients.

In another heat exchange modeling study, computational fluid dynamics (CFD) was used (Mlatho & McPherson, 2011) for performance optimization of solar receivers. In this work it was shown that CFD models can be used to optimize the heat receivers that use oil as heat transfer fluid.

2.2 Incineration

An incinerator is a plant that combusts wastes in a controlled environment (Warhurst, 2006). Incineration is one of the high temperature waste treatment systems where by the wastes are converted into ash and flue gas. Potentially harmful substances in the wastes are destroyed by the heat at the same time the volume of the wastes is reduced (European

Commission, 2006) and such wastes are then disposed off in different ways such as in a landfill.

A medical incinerator is a type of incinerator used to destroy medical waste products which can include devices and supplies used to treat patients as well as biological wastes such as blood or tissue (Picken & Bennet, 2005). Some incinerators are located on hospital or medical center premises, while others are situated in separate locations. Incineration is taken as one of the best ways of treating medical wastes because it kills any potentially harmful and infectious disease which may be present in such waste. This converts the waste materials into ash which is totally disinfected and safe for removal if needed.

Due to the medical wastes' hazardous nature, it is highly recommended to take all necessary infection preventive measures to avoid the spread of disease from the wastes. Such measures include securing the wastes into thick biohazard bags and sealed air tight to prevent leaks, labeling the wastes' bags, closing the door of the incinerator to make sure that fumes do not spread anyhow (Nikera, 2009). Personnel handling the wastes also have to take some infection preventive measures such as washing their hands with disinfectant soap and drinking milk after handling the wastes and wearing protective gear.

Heat Parameters in an incinerator are determined by the type of wastes being burnt and the type of fuel used and these include operation temperature, turbulence level, residence time and fuel supply rate (Lacavaa et al., 2005). Apart from adding fuel, the temperature in the incinerator can be increased with addition auxiliary oxygen input into the system. Calorific value of the wastes plays a big role in the combustion process such that even without supplementary fuel, the wastes can burn off. The other factor that affects incineration efficiency is the furnace design. Low-grade fuels require a design that minimizes heat loss and allows the waste to dry before ignition. During incineration, water vapors from the combustion process and the moisture content of the fuel disperse with the flue gasses. A good incinerator furnace design should therefore be designed for stable and continuous operation and complete burnout of the waste and flue gases (World Bank , 1999).

2.3 Incineration and the environment

The major environmental benefits of incineration are:

a. Reduction in the volume and weight of wastes especially of bulky solids with a high combustible content: Incineration can reduce volume of wastes up to 90% and weight by 75% (Petts, 1994). This reduced volume makes waste disposal in landfills easier and less costly to transfer.

b. Reduction in pollution: Destruction of some wastes and detoxification of others renders them more suitable for final disposal, for example combustible carcinogens and pathologically wastes. Burning wastes in an incinerator also reduces pollution level through heat recovery technologies. It has to be noted, though, that the reduction of pollution depends on how effective the incinerator is. For medical waste incinerators, reduction of pollution has to be a priority since most of these incinerators are located right at the hospital. This helps to protect patients in the hospital from any possible contaminations.

c. Use of heat energy from the incinerator as an alternative source of energy: The combination use of incinerators and ‘energy from waste technologies’ helps to reduce use of energy from non-renewable environmental resources (Covanta Energy, 2013). This advantage may mean higher costs of plant installation but there is an assurance of positive economic benefits apart from the environmental benefits.

The major environmental challenges of incineration are:

a. All combustion results in the production of exhaust gases, which can be harmful to human health or to the environment, and often both. The fuel used in the incinerator such as diesel can also be the source of harmful gases.
b. Wastes are often loaded into the incinerator without their chemical constituents being known. Thus the type and extent of pollutants may not be known (Picken & Bennett, 2005). Ignorance of the chemical constituents of the wastes may result in inappropriate furnace controls such as amount of fuel and temperature for combustion of the wastes; hence the combustion may result in the production of carcinogens such as dioxins and furans.
c. Both refractory materials and steel used in the construction may deteriorate due to either excessive temperature or repeated cycles of heating and cooling, leaving the users with a defective incinerator.

Due to these challenges other countries have codes of practice for incineration which include strict control of combustion temperatures, monitoring of emissions and regular inspections of the incinerator. Unfortunately there are no such codes in Malawi. Hence the challenges stated above are the same involving the use of the medical waste incinerator at ZCH.

2.4 Incineration and Energy recovery systems

Energy from incinerators can be recovered as heat or steam or a combination of these. The overall thermal efficiency of an incinerator for energy recovery depends on the end use of the recovered energy.

Efficiency of the energy recovery systems can be achieved by considering the following factors in the design;

a. **Proximity to energy distribution networks**

   Energy recovery systems need to be constructed with minimum costs so that they can actually be preferred as compared to other commonly used energy sources (European Commission, 2006). Therefore the systems should be near the energy distributing networks or near the users.

b. **Energy requirements pattern**

   Energy use patterns are important since most incinerators do not operate for 24 hours a day. It is important to check if the time that the incinerators are in operation tally with the times that the customers require the energy (World bank, 1999). For example other hospitals use the medical waste incinerator during the night only. In this case an analysis is required to check if this is also the time that energy is required by the users, otherwise there may be a need for a system that can store the energy to be used when need arises.

c. **Market and costs**

Costs involved with the heat recovery systems include material, construction and operating costs (European Commission, 2006). These costs should be weighed against the possible gains from the market so that the system can be beneficial not only environmentally but also economically.

2.5 Heat exchangers

Waste heat is heat which is generated in a process by way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose. One of the major components in the systems used to recover this heat is the heat exchanger.

Heat exchangers are equipments that transfer heat from one medium to another (Hesselgreaves, 2001). A heat exchanger consists of heat transfer elements such as a core or matrix containing the heat transfer surface, and fluid distribution elements such as headers, manifolds, tanks, inlet and outlet nozzles or pipes, or seals. Usually, there are no moving parts in a heat exchanger; however, there are exceptions, such as a rotary regenerative exchanger (in which the matrix is mechanically driven to rotate at some design speed) or a scraped surface heat exchanger. The heat transfer surface is a surface of the exchanger core that is in direct contact with fluids and through which heat is transferred by conduction. The portion of the surface that is in direct contact with both the hot and cold fluids and transfers heat between them is referred to as the primary or direct surface. The heat transfer area can be increased by using coils or appendages which are connected to the primary surface to provide an extended, secondary, or indirect surface. Heat exchangers are very useful in technologies of energy conservation, conversion, recovery, and development of new energy sources. Their importance is also increasing from the standpoint of environmental concerns such as thermal pollution, air pollution, water pollution, and waste disposal(Shah & Sekulic, 2003).

According to Hesselgreaves (2001), the proper design, operation and maintenance of heat exchangers will make the process energy efficient and minimize energy losses. Heat exchanger performance can deteriorate with time, off design operations and other interferences such as fouling and scaling. Therefore it is necessary to assess periodically the heat exchanger performance in order to maintain them at a high efficiency level.

2.5.1 Classification of heat exchangers

Heat exchangers can be classified according to transfer processes, number of fluids, and heat transfer mechanisms. Conventional heat exchangers are further classified according to construction type and flow arrangements. Another arbitrary classification can be made based on the heat transfer surface area/volume ratio, into compact and noncompact heat exchangers. This classification is made because the type of equipment, fields of applications, and design techniques generally differ.

2.5.2 Heat transfer performance of heat exchangers

Heat exchange performance for a heat exchanger is evaluated using the following equation:

$$Q = U \text{ x } A \text{ x } LMTD \qquad \text{(Birla Institute of technology \& Science)} \qquad 2.1$$

where Q is heat transfer in J/s, A is the heat transfer surface area in m^2, LMTD is the Log Mean Temperature Difference in ^0C and U is the overall heat transfer Coefficient $J/s/m^2/^0C$.

This equation is useful in determining how much is transferred by a particular heat exchanger.

CHAPTER 3

DATA AND METHODS

This chapter presents methods and procedures used in this study to set up the data logger that was used in temperature measurements. This is followed by the description of how the temperature distribution inside the incinerator was measured and the experimental setup of the whole heat scavenging system that was installed in the incinerator.

3.1 Setting up of the Data Acquisition System

A CR10 model data logger was used to record temperature data collected from the incinerator. Communication between the computer and the data logger was supported by Campbell Scientific's PC200W (version 4) software. The software was used to write a program that was loaded into the data logger; the appendix gives the lists of the sensors that were connected to the data logger. In the program, the internal temperature (°C) of the data logger was used as the wiring panel reference temperature. The data logger was powered by a battery which was charged by a 10W solar panel. Solar energy was used instead of using the hospital's electricity source in order to save on electricity bills by utilizing renewable and environmentally sustainable energy.

3.2 Calibration and Insulation of the thermocouples

Temperature distribution was measured in order to find an optimum position to place the heat exchanger and also to determine the best type of materials to be used in fabricating the heat exchanger. Before the temperature could be measured, the thermocouples that were to be used for the measurement were first calibrated. K-type thermocouples were used since they are able to withstand high temperatures (up to 1200°C). This was followed by insulation and calibration of the same to make sure that they give accurate readings and comparable readings.

Fig. 1 shows the thermocouple wires which were insulated so as to protect them from the high heat in the incinerator. The insulation was done by coating the thermocouple wires with clay and cement. These materials were chosen because of their high thermal insulation properties and durability. Only the tip of the thermocouple wire was left at the front to measure the temperature. Before putting the coat of clay or/and cement, the thermocouples were also coated with aluminum foil paper to prevent the thermocouples from any possible contaminations.

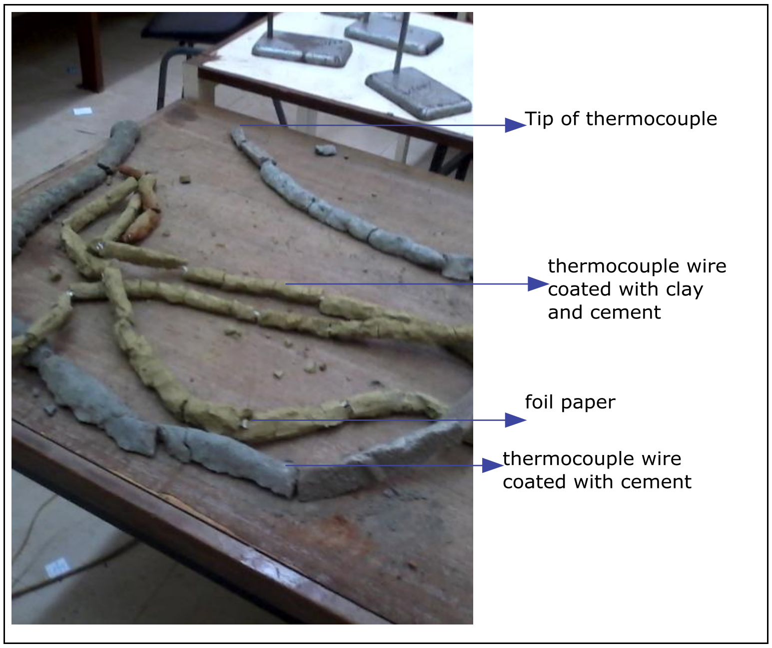


Fig.1: Insulated thermocouples

Calibration was done both at low and high temperatures. At low temperatures, calibration was done by placing all the thermocouples on the same point in a beaker of water to check if they would all give the same temperature readings. The readings of the thermocouples where then compared against temperature measured by a digital multimeter. At higher temperatures the calibration was done by placing the tip of the thermocouples on a hot plate, as shown in Fig. 2.

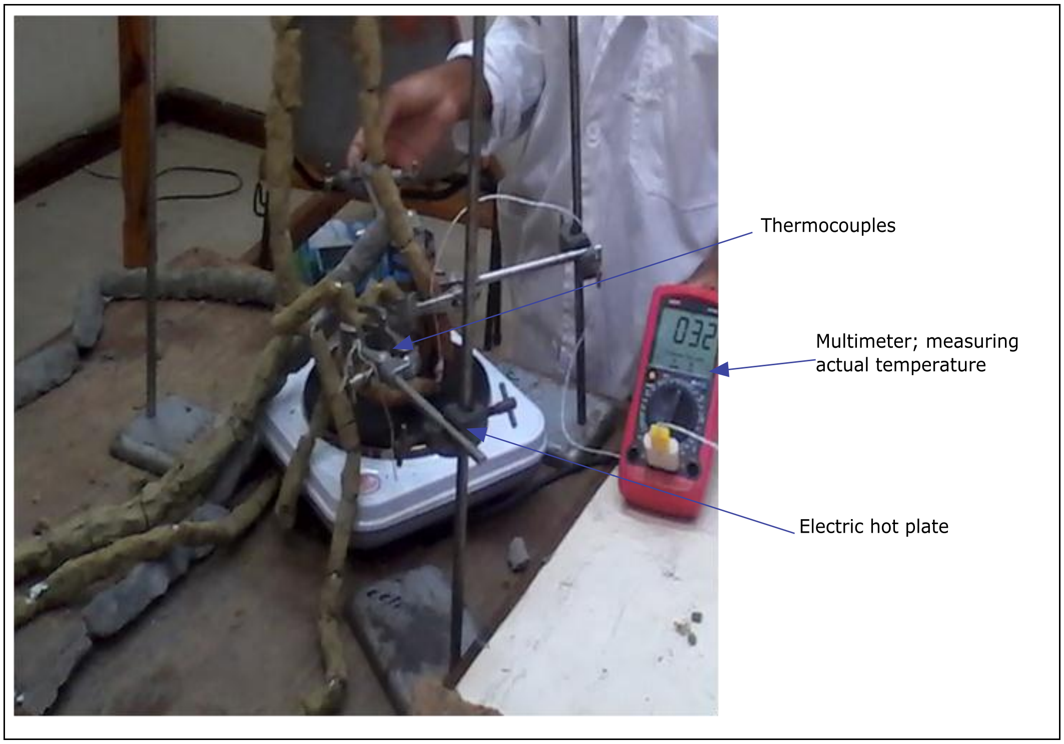


Fig. 2: Calibration of the thermocouples

Percentage errors were calculated as follows:

$$E = A - T_i \qquad \textbf{3.1}$$

$$E\,(\%) = {}^{E}/_{A} \times 100 \qquad \text{(Breithaupt, 2010)} \qquad \textbf{3.2}$$

Where *E* is the error, *A* is the actual temperature value recorded by digital meter, *T* is the temperature value recorded by thermocouple, *i* is the number allocated to a thermocouple and E (%) is the percentage error. Possible source of error could have been inefficiency if the thermocouples since they were not new and also technical errors such as mishandling of the thermocouples.

3.3 Measurement of temperature distribution inside the incinerator

In order to determine the optimum position to place the heat exchanger inside the incinerator, temperature distribution inside it was measured when it was in operation. The temperature was measured using thermocouples that were connected to the data logger. The data logger scanned the channels to which the thermocouples were connected every 10 seconds and the values were then stored to the memory of the data logger. The power to the data logger was provided by a solar panel that was connected to a charge controller. Fig. 3 shows the diagram of how the data logger was powered by the solar panel.

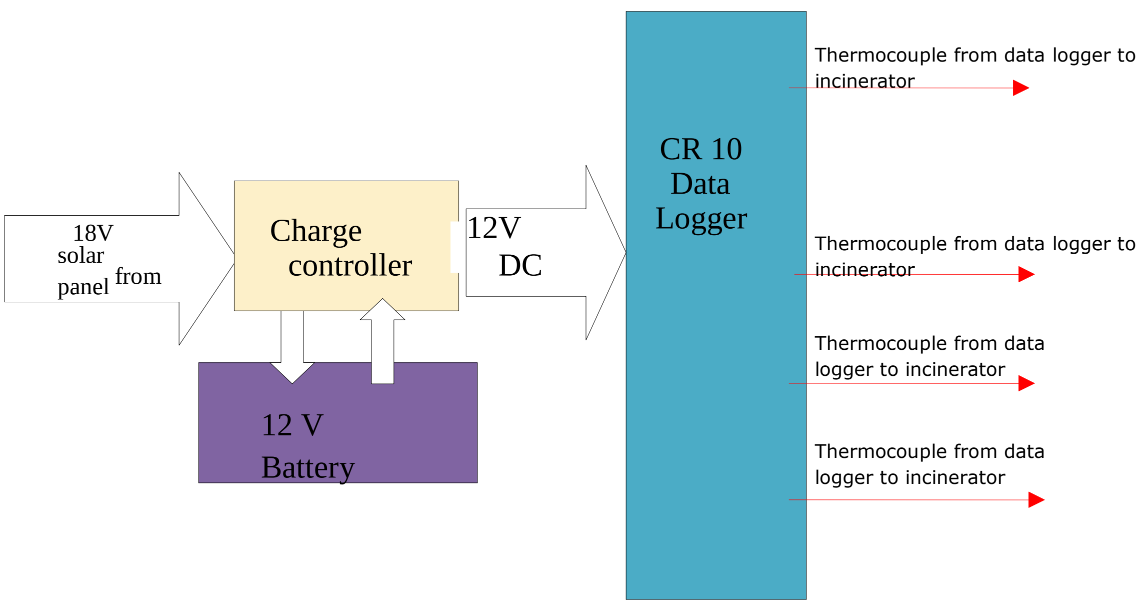


Fig. 3: Powering of the data logger using a solar panel

The thermocouples were connected to the data logger and then placed at various positions in the incinerator to measure the temperature (figure 4). The setup has also been shown in Fig. 5.

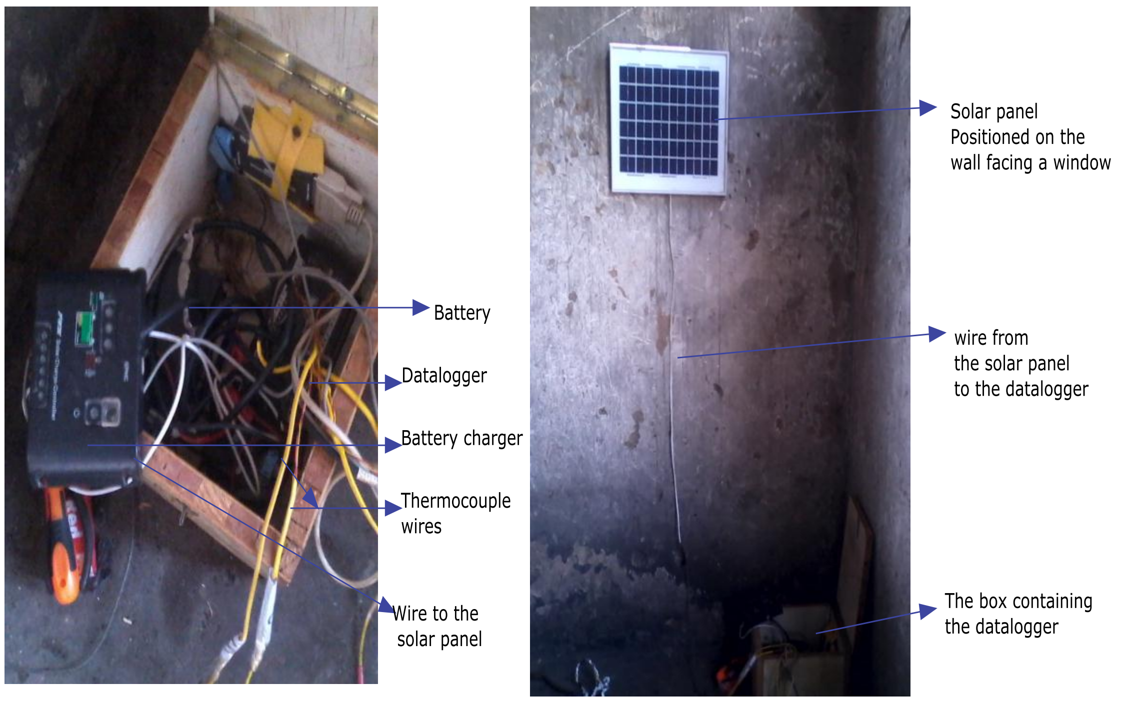


Fig. 4: Experimental setup for temperature records

The internal wall of the incinerator is made up of mud bricks for insulation but the outside wall is made up of metal. The dimensions of the incinerator's furnace are 1.76 m by 0.71 m and about 0.8 m high. Thermocouples were installed in the incinerator at various points as shown Fig. 5. Thermocouples for measuring temperature $T_{3\text{-front}}$ and $T_{2\text{-front}}$ were positioned near the opening/door of the burning chamber. $T_{2\text{-front}}$ and $T_{3\text{-front}}$ were 0.6 m apart. The thermocouples for measuring temperature $T_{4\text{-back}}$ and $T_{6\text{-back}}$ were positioned at the back of the chamber, 1.76 m away from the opening/door of the chamber. $T_{4\text{-back}}$ and $T_{6\text{-back}}$ were installed about 0.6m apart. The inter-thermocouple distances were deliberately chosen to be near the walls of the incinerator. This was done to avoid interrupting with the processes of loading wastes, stirring and removal of ash. The ventilation opening at the back of the incinerator was used as passage for the thermocouples $T_{4\text{-back}}$ and $T_{6\text{-back}}$ installed at the back.

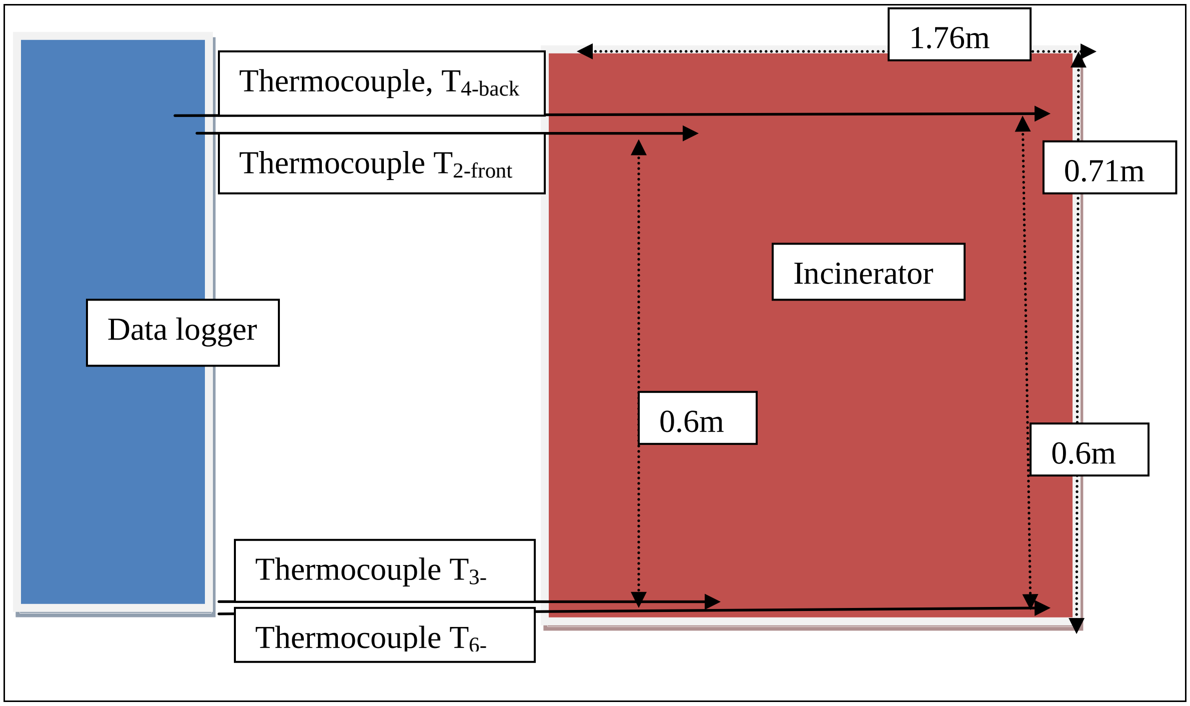


Fig. 5 Schematic drawing of thermocouple positions inside the incinerator

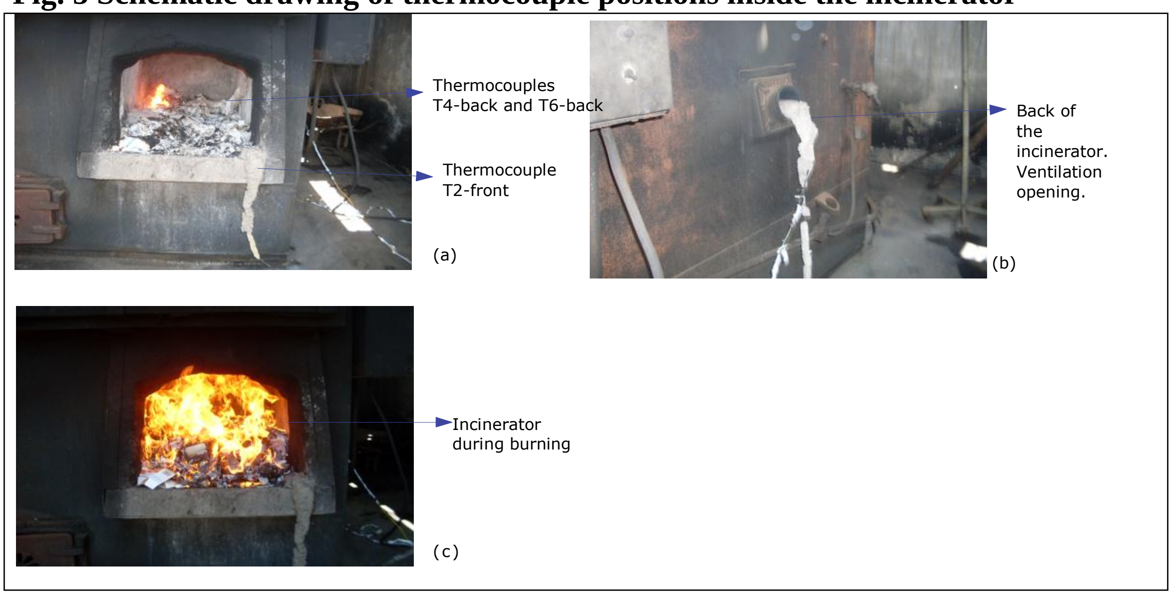


Figure 6: Thermocouples in the incinerator

3.4 The heat exchanger

The heat exchanger was designed using the data on distribution of temperature inside the incinerator and the temperature distribution data was used to find the optimum position to install the heat exchanger and suitable material for the construction of the heat exchanger. Fig. 7 shows the heat exchanger inside the incinerator. The heat exchanger element was made of galvanized steel pipe of ¾ inch diameter.

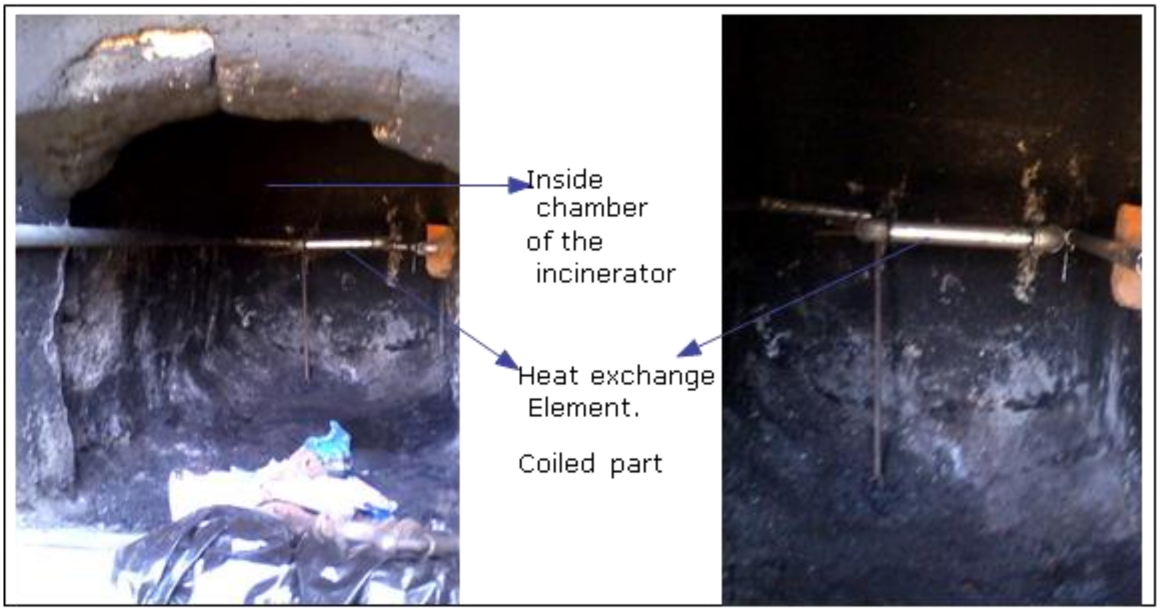


Fig.7: Installation of the heat exchanger inside the incinerator.

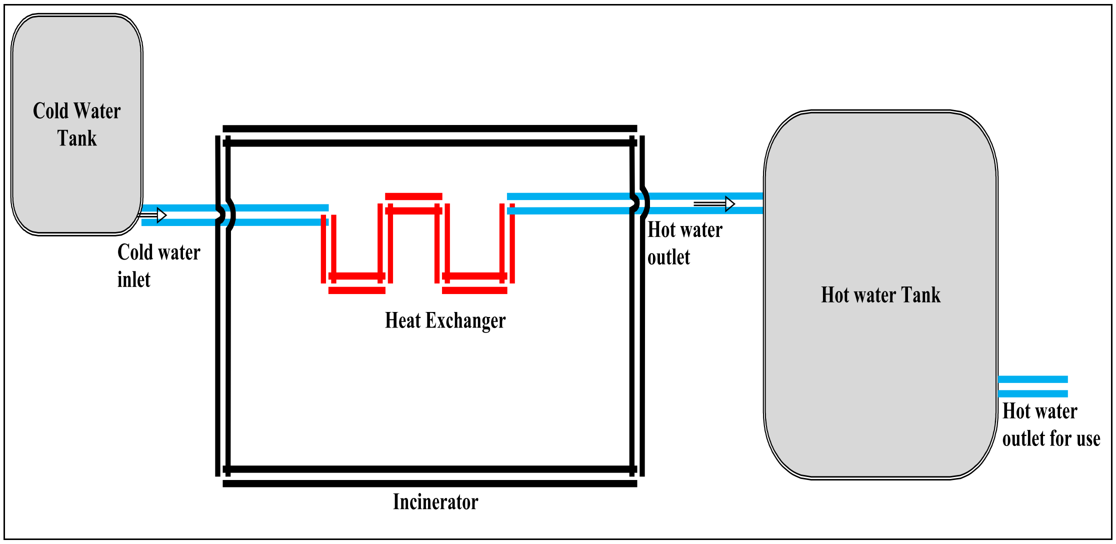


Fig. 8: Schematic diagram of the heat exchanger system.

Fig. 8 shows how the heat exchange system worked. Water that was at low temperature was stored in the tank labeled cold 'water tank' which was elevated at a height of 1.8 m from the ground. The tank was positioned at this height in order for the water to flow by gravitational force. The height of 1.8 m was used convenient depending space inside the building that accommodates the incinerator. Changing this height may also change the flow rate; however, flow rate can be controlled by the gate valve. The gate valve was connected near the bottom of the tank to serve as a control for cold water flow through the heat exchanger into the incinerator. Galvanized steel pipes were used as a heat exchanger because of its high melting point and hence was able to withstand high temperatures in the incinerator. A problem with this type of steel is that when in contact with water it rusts easily. It is for this reason that galvanized steel was only used for experimental purposes due to finance constraints, but the recommended type of pipe would be copper pipes. This pipe was coiled and the coiled part was installed at the back of the incinerator. The pipe as the heat exchanger was coiled so that the water inside it would stay longer in the incinerator to achieve desirable temperatures. Both the inlet and outlet temperatures of the water through the heat exchanger were measured.

From the incinerator, the heated water was stored in the tank labeled 'hot water tank'. A PVC pipe was connected to the hot water tank as an outlet point from the tank to users. The temperature of the water was measured at two points; in the cold water tank and in the pipe just before it enters the hot water tank. Temperature here, just as in the incinerator, was measured using thermocouples and recorded by the data logger.

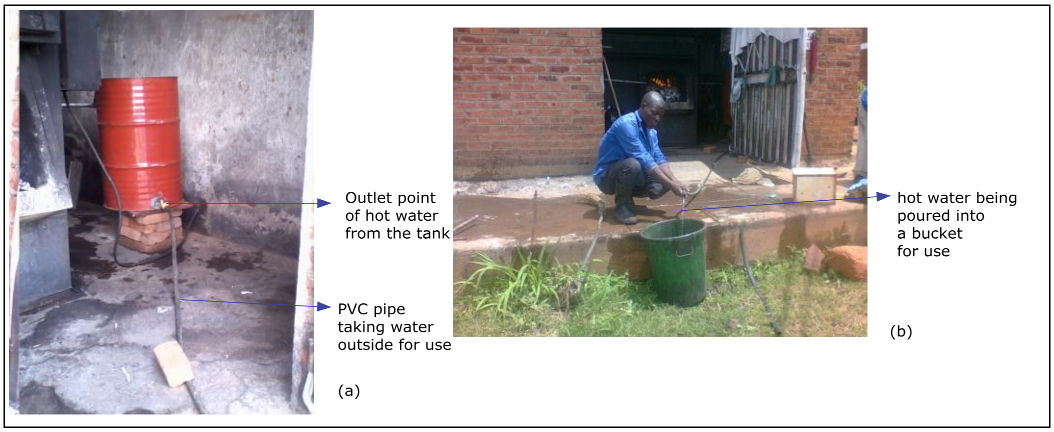


Fig. 9: Outlet of the hot water

Fig. 9(a) shows a pipe taking water from the outlet point of the hot water tank to where it is required. Fig. 9(b) shows a pipe taking the water from the hot water tank to be used. The pipes used here is a PVC pipe since the water is at a lower temperature of below 100^0C. The hot water tank was placed on a stand built using bricks of about 40 cm for the water to flow out using gravitation force. Due to the type of wastes being burnt in the incinerator, there is a risk of contamination through the fumes. This risk is higher for this particular incinerator since it does not have a door for the front opening. Therefore as a way of preventing users from being affected by the fumes from the incinerator, the pipe was taken outside the room which contains the incinerator.

3.5 Measuring water flow rate

Measuring water flow rate was very challenging because of lack of a flow meter. Measuring flow rate using a flow meter would have required a pump powered by electricity, and since this study aimed at minimizing use of such energy, a manual way of measuring the flow rate had to be improvised.

Water rise in the hot water storage tank was recorded every 5 minutes by a measuring tape and the rise in water was measured in centimeters and then this rise was calculated into liters. Total volume of the tank was 200L with a height of 0.9m; therefore every cm represented a volume of 2.2L. Volume flow rate (V_f) was then calculated by the following expression of volume (V) and time (t)

$$V_f = \frac{V}{t} \qquad \text{(Tippens,2007)} \qquad 3.3$$

CHAPTER 4

RESULTS AND DISCUSSIONS

Presented in this chapter are the results found after experiments and measurements done as per methods explained in the methodology chapter. Presented first are the results and discussions from thermocouple calibration using a digital meter and the data logger setup that was used to make temperature measurements. This is followed by results for temperature distribution inside the incinerator. The water flow rate and variations of water temperature through the heat scavenging system are also discussed.

4.1 Thermocouple calibration

This section presents thermocouple calibration results presented using graphs of water temperature against time. Figures 10(a) and (b) shows hot-plate temperature records by 3 thermocouples which were going to be used for collecting temperature in the incinerator. Figure 10 (a) includes the temperatures measured by the digital meter while figure 10 (b) shows water temperature results at room temperature. Different colors show different thermocouples as labeled on the graph's key.

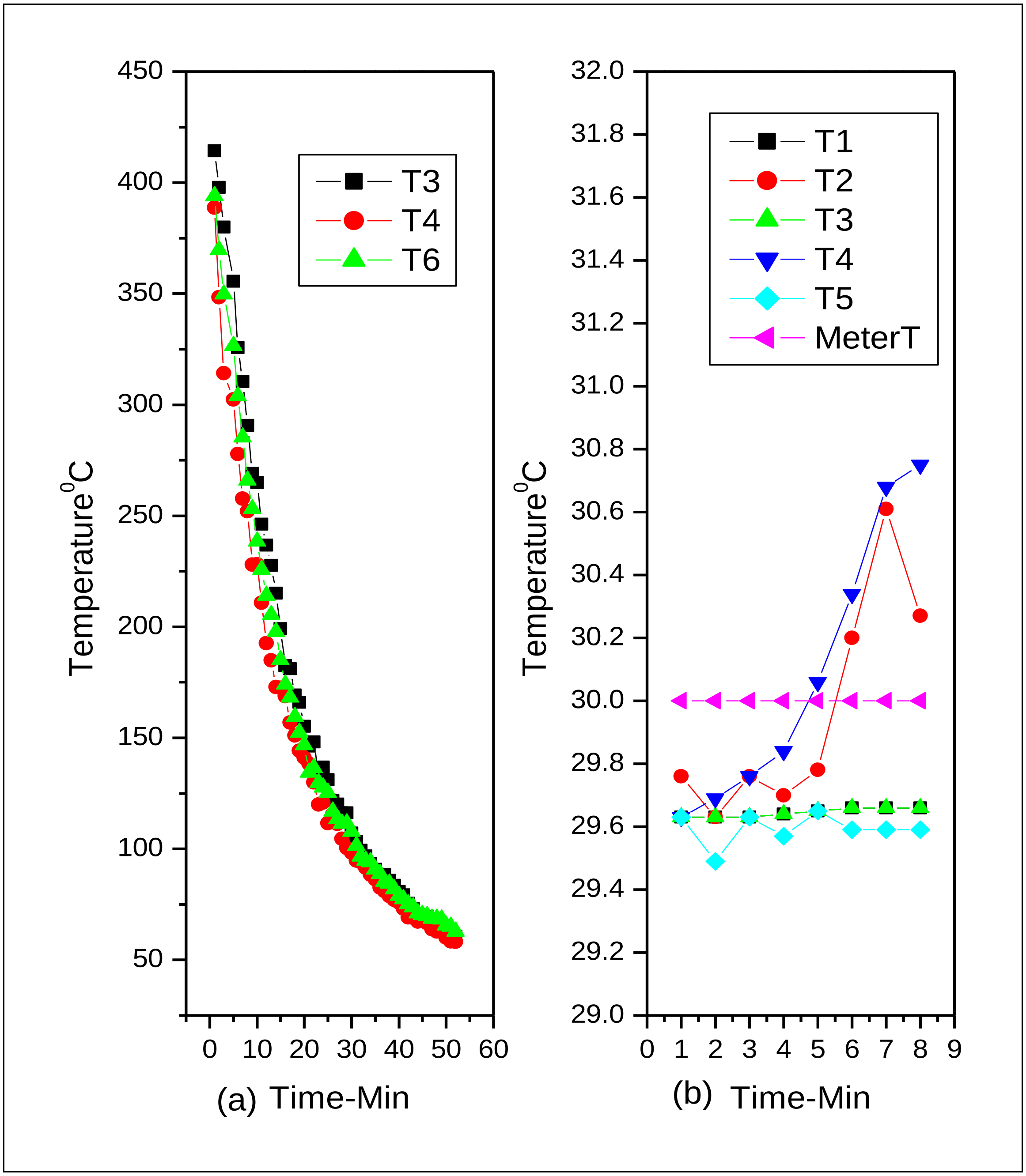


Fig. 10: Comparison of temperature measured by thermocouples and digital meter

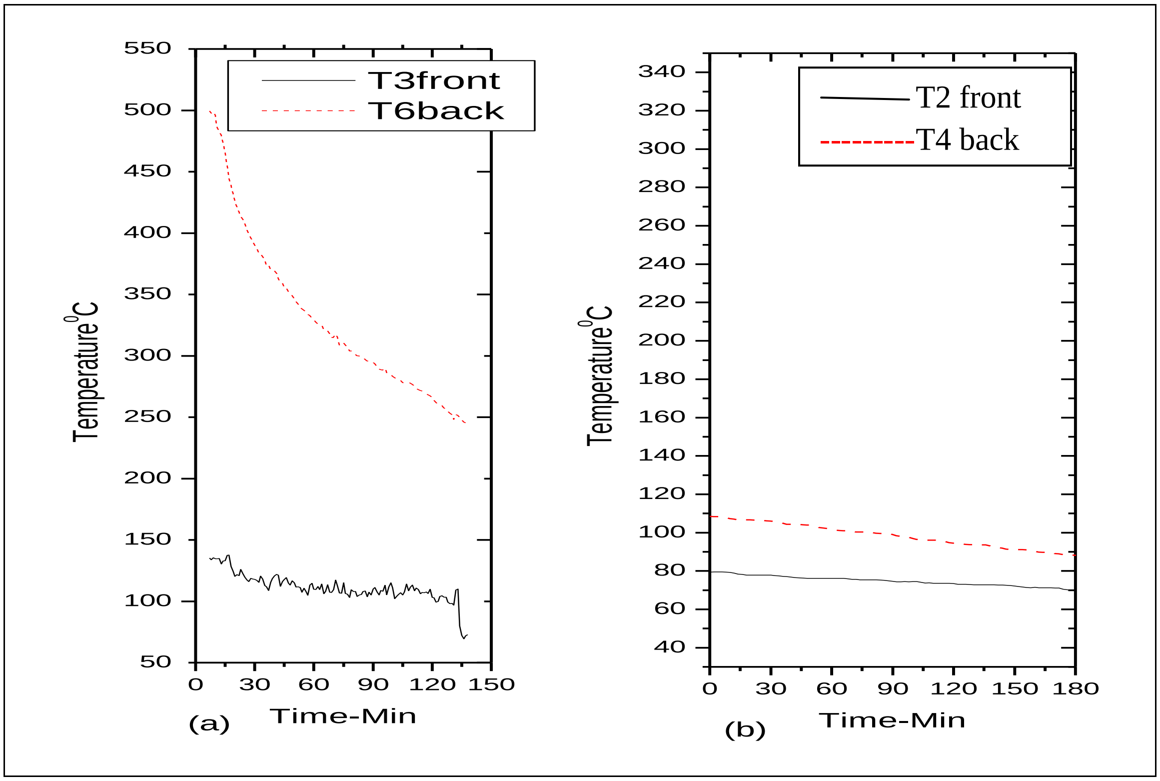
The main aim here was to cross check if the thermocouples would give the same temperature reading given all other variables such as position are held constant.

The thermocouples did not give same values; therefore, percentage errors were calculated using equations 3.1 and 3.2.

At lower temperatures, the percentage error was low, ranging from 0.1% to 1%. But at higher temperatures the error increased slightly to a range of 4% to 6%. These values were derived from the figure 10 and calculations were done using equation 4.2. Using the same equations for error and actual value, these errors were then used to get correct values of temperature sensed by the same thermocouples in the incinerator during temperature distribution measurements. These thermocouple calibration results may be different from exact values since the K-type thermocouple calibration equation was not used. The equation could not be used because there are some coefficients required such as which were not available in the experiment.

4.2 Temperature distribution in the incinerator

Fig. 11 shows temperature distribution in the incinerator measured at 4 points. Both plots (a) and (b) of Fig.11 show that temperature values at the back, measured by $T_{6\text{-back}}$ and $T_{4\text{-back}}$, of the incinerator were always higher than those measured at the front, measured by $T_{2\text{-front}}$ and $T_{3\text{-front.}}$ The highest temperature values recorded at the back of the incinerator were 500°C and at the front was 148°C. This difference is due to heat loses at the front because the incinerator does not have a door and there is a lot of convection losses to the external surrounding since the incinerator is left open during burning. Further to that, the back of the incinerator is well insulated such that temperatures remain high for a longer time than at the front. According to Kanyele and Kangonji (2012) temperatures in the incinerator burning chamber may drop when there is excess air entering the chamber. The air may enter through deformed seals, holes or warped doors. In this case, having the incinerator without a door meant that a lot of air enters the incinerator and hence the drop in temperatures near the front. In the study by Kenyele and Kangonji the range of temperature reached in the burning chambers was 400°C -700°C which is still higher than the temperatures in this study.



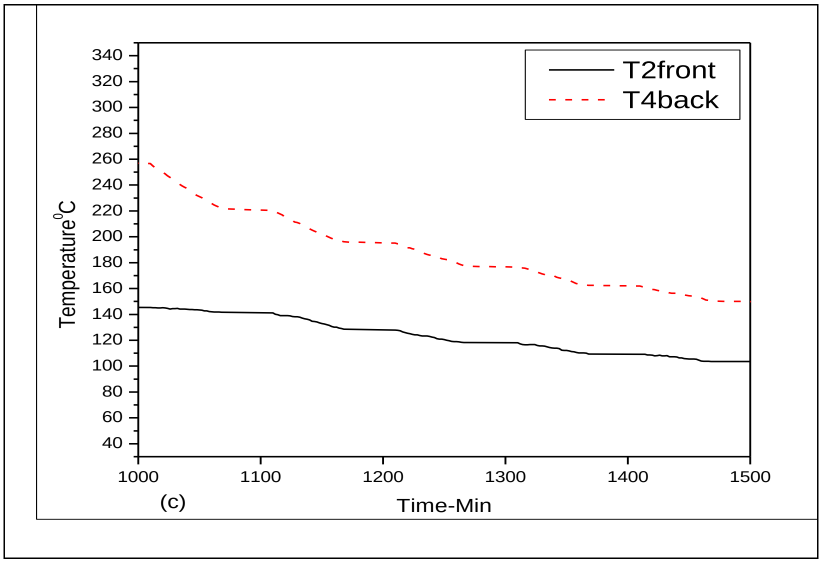


Fig. 11: Temperature distribution in the incinerator

Fig. 11 (c) shows how the temperatures reached by the incinerator varied with time during waste burning. Temperature drop and increase because the burning of wastes is done as a batch process; therefore temperature drops as another batch of wastes is brought into the incinerator and then the temperature increases as the wastes start to burn. Temperature variation is also caused by the type of wastes being burnt. Hard wastes like sharp objects and bottles or wet wastes such as wastes stained with blood are burnt using additional fuel (diesel) and they are the ones usually put at the back of the incinerator, hence the higher temperature recordings.

Considering that the temperature values were consistently higher at the back of the incinerator, the heat exchanger was then installed at the back of the incinerator.

4.3 Effects of the heat exchanger on the incinerator efficiency

The design of the heat exchanger was such that it did not remove a lot of heat to significantly reduce the incinerator temperature. Therefore the performance efficiency of the incinerator was not affected. Corrosion damage is one of the major challenges in incinerators and requires constant repair. The corrosion happens as a result of reactions between the metallic parts of the incinerator and chlorides of sodium and potassium produced from the combustion of wastes (Mudgal, Singh, & Prakash, 2014). Therefore with the heat exchanger made of a metallic surface, there could be some corrosion effects if the pipes are not repaired frequently enough. However, in this study, there was not enough time to test for the corrosion effects.

4.4 Flow rate of water

This section discusses the results found after conducting experiments on the whole heat scavenging system. Having installed the heat exchange system into the incinerator, water was made to flow through the system and optimum flow rate of water was calculated based on the required temperature. The optimum flow rate was the flow rate which resulted in outlet water with temperature of around 90^0C -95^0C.

Table 1 shows the volume flow rate of water through the heat exchanger. The average flow rate was 3.75×10^{-5} m^3/s. Increasing the flow rate above 3.75×10^{-5} m^3/s resulted in temperature drop for the water that came out of the incinerator since the water was required to stay in the heat exchanger for some time to be heated. Reducing the flow rate below this rate caused the water temperature to rise too high resulting in steam only coming out of the outlet pipe.

Table 1: Flow rate of water through the heat exchanger

Volume (L)	Time (min)	Flow rate L/min
40.0	0	
49.3	5	1.86
63.0	10	2.74
75.5	15	2.50
85.5	20	2.00
94.0	25	1.70
103.3	30	1.86
114.0	35	2.14
124.0	40	2.00
136	45	2.40
149.2	50	2.64
162	55	2.56
175	60	2.60
Average flow rate		**2.25L/min**

At this flow rate the water temperature results recorded are shown in Fig. 12

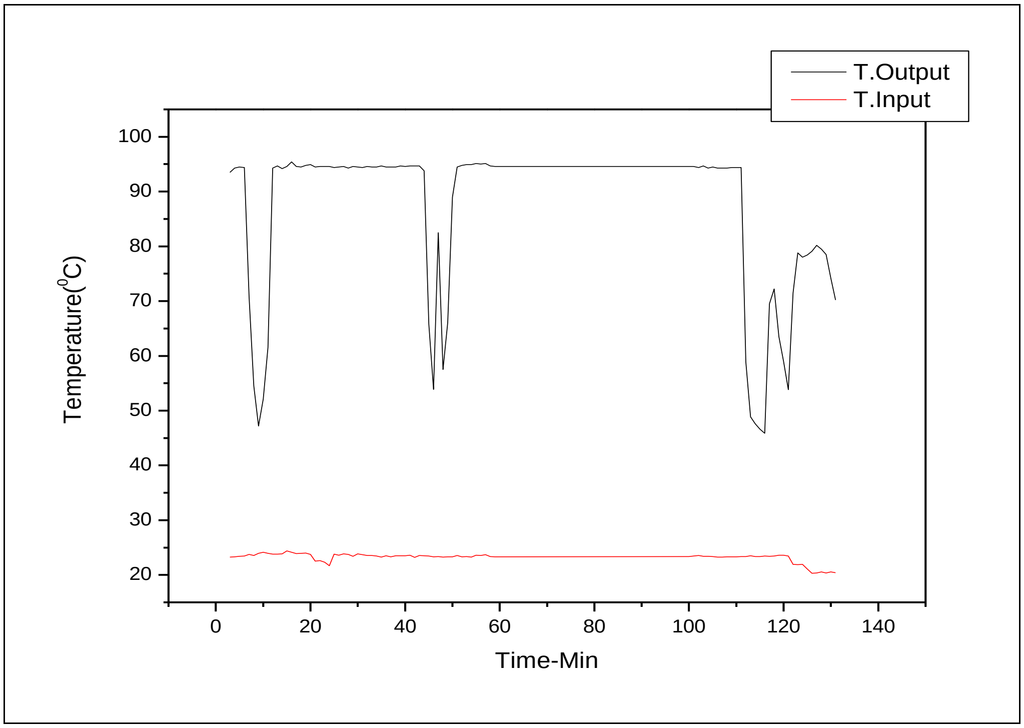


Fig. 12 Variation of water temperature

Fig. 12 shows temperature of water as it flowed through the heat exchanger. T_{input} is the temperature of the water as it came from the storage tank before entering the heat exchanger in the incinerator. This temperature was almost constant at room temperature of 23°C. $T_{output,}$ temperature of the water coming out of the heat exchanger was at most times constant between 94°C and 96°C. There are some major fluctuations in water temperature such as at time 10 minutes, 45 minutes and 115 minutes due to temperature changes in the incinerator. As already explained, temperature changes in the incinerator were due to mode of burning the wastes at that time such as whether extra fuel (diesel) was added or not.

Having the average flow rate of heated water through the heat exchanger as 2.25L/min, which, in international system of units (SI) is, 3.75 x 10^{-5} m^3/s . Heat energy gained per second, Q′, gained by the water was calculated as follows:

$$Q' = m'c\,\Delta T \qquad \text{(Breithaupt, 2010)} \qquad 4.3$$

$$Q' = V'\rho c\Delta T$$

$$Q' = 3.75 \times 10^{-5} \times 961.9033 \times 4.1855 \times (95 - 23) = 10.870 \text{ J/s}$$

where Q′ is heat energy gained in Joules per second, ρ is the density of water at 95°C, V′ is water flow rate in m^3/s, c is specific heat capacity of water in J/kgC and ΔT is change in temperature.

For every second 10.870J of heat energy was transferred to the water as the water flowed through the heat exchanger. At this average flow rate of heated water (3.75 x 10^{-5} m^3/s) and within the 3 hours that temperatures in the incinerator are above 150°C, a minimum amount of 0.405 m^3 (405L) of water can be heated. Since the burning of wastes is done twice a day, then 0.810 m^3 (810L) of hot water would be produced per day. Hence this is the amount that can be used by patients and other users within the hospital. According to the possible users that were asked, 10L of the hot water would be enough for a bath, since the 10L would be mixed with cooler water. Therefore the 810L would carter for 81 users. The hospital has about 600 inpatients therefore about 14% of these could use the facility. Energy required to heat 810L of water to 90^0C is 61.4kWh; if electricity provided by ESCOM is used then a cost of MK1589.6 would be incurred since 1kWh costs MK25.88

for domestic use. The cost of installing the whole heat recovery system is about MK60000 (USD 100.2). After the initial investment, the only operation cost is labor charge of the operator of about MK5000 (USD 8.5) since this would just be an addition pay on his current wage. The use of the heat-scavenging system would save the hospital about MK1590 (USD 2.7) worth of electricity bill per every 810L of water heated per day and MK47670 (USD 80) per month. Therefore the investment amount could be paid off in about five months.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Having designed the heat scavenging system and evaluating its performance, the following conclusion and recommendations were made.

5.1 Conclusion

Temperatures reached by the incinerator are higher at the back of the incinerator where the walls are well insulated than at the front where the door is left open due to breakage of the front door (according to the responsible hospital officers, the door had stayed a long time in that broken state due to complications in the hospital financing systems). Loading of wastes in the incinerator causes the temperatures to fluctuate (decrease when waste is added) in between the loading times. But temperatures at the back of the incinerator remain constantly high for longer periods. Therefore the back of the incinerator was taken as the optimum position to install the heat exchanger. For optimum outlet temperature (about 95°C) of the water from the incinerator, the flow rate of the water was determined to be 3.75×10^{-5} m^3/s and this gives a heat energy gained per unit time of 10.870J/s. The use of the heat-scavenging system would save the hospital about MK1590 (US$ 2.21) worth of electricity bill per every 810L of water heated per day and MK47670 (US$ 66.17) per month. The cost for the system for this study's experiments was MK80000 (US$ 112). This MK80000 (US$ 112) would be approximately the minimum investment required for the 810L of hot water a day which means that this investment could be paid off within 3 months of operation. After installation, costs involved would be maintenance and training and additional allowances for the already existing incinerator operators. Hence it can be concluded that recovering heat from the medical waste incinerator would be one of the many ways of providing hot water at the hospital. This system, once installed, would only use up the already available heat energy in the incinerator hence a good way of conserving energy and reducing electricity bills.

5.2 Recommendations

Based on these findings, a number of recommendations are proposed:

1. There is a need to upscale this project to provide hot water for all the wards in the hospital. In that up scaled design, copper pipes should be used to prevent rusting/corrosion that hot water causes in steel pipes.
2. Since the outlet temperature of the water flowing from the heat exchanger can reach boiling point at lower flow rates, it therefore implies that it is possible to use the steam generated for other purposes like mechanical power, electricity power generation and process steam as it has been seen in most of the literature reviewed that most high technology incinerators are combined with power generation.

3. There is also need for a social-economic follow up study to investigate the actual amount of money and energy saved when the heat scavenging system is used instead of having people to heat their own water using other sources of energy in their homes and then brings it to the hospital for their patients.

4. During the study it was noted that the burning efficiency was affected by malfunction of the incinerator such as having a broken door for its opening and a broken automatic fuel loading system. Hence it is highly recommended to conduct a study on how much energy (and therefore resources) is being wasted due to this. Having the incinerator operating with no door reduces the efficiency of the incinerator and also increases the amount of diesel added to burn each batch of wastes. Information on how much energy is was due poor maintenance of the furnace could be a driving force for authorities to pay attention to repairs which may actually be cheap.

5.3 Limitations

The most serious limitation to the study was the poor condition of the medical waste incinerator at the hospital. The incinerator was designed to operate with an automatic fuel pump and temperature regulator but at the time of study, these functions were not working. Further to that the door for the incinerator broke leaving the front open. This made it difficult to collect temperature data since being near the incinerator while burning was in process was risky. The condition of the incinerator may have also affected the amount of water which could have been heated in a given period. However, it was difficult to verify this since there was no opportunity to do the experiments with the incinerator operating at optimum conditions. The other limitation was lack of a flow meter to regulate and measure flow rate automatically. Due to this, flow rate had to be measured manually.

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APPENDICES

Appendix 1 : Data acquisition for data logger

-Wiring for CR10-

Type K (chromel-alumel) Thermocouple (1)

1H: Yellow 1L: Red

Type K (chromel-alumel) Thermocouple (2)

2H: Yellow 2L: Red

Type K (chromel-alumel) Thermocouple (3)

3H: Yellow 3L: Red

Type K (chromel-alumel) Thermocouple (4)

4H: Yellow 4L: Red

Type K (chromel-alumel) Thermocouple (5)

5H: Yellow 5L: Red

Type K (chromel-alumel) Thermocouple (6)

6H: Yellow 6L: Red

-Measurement Labels-

Default Measurements

1 BattV 2 ProgSig

Datalogger Internal Temperature

3 ITemp_C

Type K (chromel-alumel) Thermocouple (1)

4 Temp_C_1

Type K (chromel-alumel) Thermocouple (2)

5 Temp_C_2

Type K (chromel-alumel) Thermocouple (3)

6 Temp_C_3

Type K (chromel-alumel) Thermocouple (4)

7 Temp_C_4

Type K (chromel-alumel) Thermocouple (5)

8 Temp_C_5

Type K (chromel-alumel) Thermocouple (6)

9 Temp_C_6