Addis Ababa University

Addis Ababa Institute of Technology

School of Graduate Studies

Energy Center

Design, and Development and Performance Evaluation of Thermoelectric Stove using CFD

A Thesis Submitted to The School of Graduate Studies of Addis Ababa University Addis Ababa Institute of Technology in Partial Fulfilment of Requirements for The Degree of Masters of Science of Energy Technology

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DECLARATION

I, declare that this thesis is my original work and which is does not presented in other universities for fulfilment of degrees. All review materials are acknowledged and published. The work basically focused in modification and knowledge translations and localizations.

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Abstract

Thermoelectric stove is kind of improved cooking stove, can able to reduce the wastage of energy, reduce fuel consumption. Thermoelectric stoves able to convert partially wasted energy in to useful electrical energy in stove. They are designed and developed to harvest energy for home-made utilization. The utilized energy used for lighting application, phone charging, radios, and other home utilities.

Due to essentiality of improving cooking stove to minimize wasted energy, and the limitation access of electrical energy, thermoelectric stove is one option cup up such problems. Design, development and performance evaluation of thermoelectric stove is able to generate energy for the one family members, which live in rural community. The conducted computational fluid dynamics (CFD) in stove and thermoelectric module (TE) improves efficiency of stove and the performance of thermoelectric module (TE) significantly.

This research work focused on the development and performance evaluation of thermoelectric stove by computational fluid dynamics (CFD), development of performance evaluation includes; specifying size of stove, optimizing of air gap, and determining of location thermoelectric generator (TEG) in stove. This design and development prime concern is to increase performance of stove and performance of thermoelectric module (TE). In this research, size parameters of stove are ($D_{\text{cham..wall}}$=150mm,$h_{cham.wall}$=205mm,$he_{air\ gap}$ =25mm, D_{pot}=160mm, R_{flame} =89mm, L_{flame} =25mm),and size parameters of thermoelectric module are:(T_1=326 ^{0}C, T_2= 88 ^{0}C, T_R= 298.9 ^{0}C, A_{clay}= A_{al}= 0.056×0.056 m^2, A_{cer} = A_{cu} = 0.04×0.04 m^2).Some tools were used to conduct simulations. Solid work 2019 used to draw solid 3D model for both stove and thermoelectric module. ANSYS 2019 used to conduct CFD simulation heat transfer analysis in stove and for meshing, temperature distribution simulation, numerical temperature distribution. Thermoelectric simulation used to conduct thermoelectric heat transfer analysis, voltage developed (V_{de}) and Power developed (P_{de}).

Research results show that 3.133W of electrical power is developed with ***27%*** thermal efficiency of stove. The obtained improved air gap that leading increment of performance of the thermoelectric stove. The results obtained from simulations were discussed in accordance with temperature distribution and power developed per module.

Key words: Thermoelectric stove, Thermoelectric Generator, Thermoelectric module

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Nomenclature

Symbol

ZT	Figure of merit
c_p	Specific heat constant
$\dot{Q}_h$	Heat flow in hot side TEG
$\dot{Q}_c$	Heat flow in cold side TEG
T_S	Temperature of heat source
$\hat{W}$	Electrical work
V_{oc}	Open circuit voltage
V_{mp}	Voltage at maximum power
I_{sc}	Short circuit current
I_{mp}	Current at maximum power
P_{dev}	Power developed
Re	Reynold number
Pr	Prandtl number
NU	Nusselt number
α	Seebeck coefficient
σ	Electrical conductivity
ρ	Electrical resistivity
η	Conversion efficiency of TEG
σ	Stefan-Boltzmann constant
ε	Emissivity

Table of Contents

List of Figures

List of Tables

CHAPTER ONE

1. Introduction

Introduction deals with the work performed during this research and explains over all highlight of research, and the purpose of it.Introduction briefly describes research background by considering technological relation and significances among different stoves, also includes objectives of the research, research methodology, and scope and limitation of the study are provided in chapter.

1.1 Background

Biomass cooking stove is the major thermal energy conversion device to fulfil the energy needed for cooking, heating, and other basic needs. The biomass stove is one of the primitive forms of thermal energy conversion devices. Even now, 38% of world populations are using biomass stoves to fulfil their cooking needs[1].As developing country; in Ethiopia large number of populations are still dependent on biomass for cooking purpose using a variety of traditional cooking stoves [2].

Now days different types improved biomass cooking stoves are being developed in Ethiopia by governmental and nongovernmental organizations. For example, it includes such as Lakech stove, Metal stove and Tikikil stove for heating and cooking application, and like; Mirt stove and Gounziye stove used for biomass Injera cooking[3]**.** For this research work the Tikikl stove is selected. Because of performance and heat transfer analysis will be carried out by related reviews, which is widely used type stove, and the geometry is cable to coupling of thermoelectric modules to harvest electrical energy from the stove.

More than 20% of the world's population in the developing countries like Ethiopia is still living without electricity [4]. In order solve to such problem partially, using thermoelectric generator (TEG) in the Tikikil cooking stove is a very interesting option to provide such amount of electricity.

Thermoelectric stove is a device that harvests waste energy and convert some of it in to useful power. It operates on a fundamental principle termed the Seebeck effect that states when a temperature gradient is established between two different metals or semiconductors; a corresponding voltage gradient is induced.

Basically, some thermoelectric stoves are developed with different scholars and universities. Namely Jordan University of Science and Technology thermoelectric Stove (JUST), was constructed by metal, tested with 12 thermoelectric modules, and the generated electrical power (7.9 W). Lertsatitthanakorn thermoelectric stove, constructed by metal, the results showed that the system generates approximately 2.4 W per module. And fan is used to improve combustion efficiency and cooling performance of module. Champier thermoelectric stove, was developed from metal,10W electrical power is generated, an experimental had been carried out laboratory in gas heater simulates.H.B.Gao thermoelectric stove, 9.5W electrical power is generated, experimentally cooling mechanism carried out to improve performance of the thermoelectric module in power generation in the thermoelectric stove. Due to metals have high thermal conductivity, there is high heat wastage from stove.

As a result, the aim of this research is to design, development and performance evaluation of thermoelectric stove by coupling thermoelectric module with Tikikl stove, including improving thermal efficiency, improving performance power generation, conducting CFD simulation in stove, and conducting thermoelectric module simulation.

1.2 Statement of problem

Traditional stoves are characterized by low overall efficiency and high wastage heat energy which results in inefficient use of biomass fuel, and traditional stoves are well known to lead to high emissions that lead to indoor air pollution and health damaging air pollutants. Also, it causes environmental degradation and climatic change because of incomplete combustion. Above problems can be addressed by using different improved cooking stove. Due to high heat loss occurred in improved cooking stove, additional heat recovery mechanism is needed. Appropriate technology is thermo electric stove, which improve the wastage of energy, in addition it provides electrical energy for family members rural community in Ethiopia.

1.3 Objectives

1.3.1 General objective:

The main objective of this research is to design, development and performance evaluation of thermo electric stove by using CFD, which could provide electrical energy for a family member, live in rural community.

1.3.2 Specific objectives:

The research has the following specific objectives:

- ✓ improving performance of thermo electric stove.
- ✓ Determine geometrical dimensions of the stove and thermoelectric module
- ✓ Select a proper thermoelectric module by using power developed from the module
- ✓ Perform performance simulation of stove using CFD.
- ✓ Conducting steady state thermoelectric simulation in thermoelectric module
- ✓ Analyze CFD and steady state simulation result and interpret the results.
- ✓ Verify results obtained using the related data.

1.4 Scope of the Study

The scope of the study is to design, development and performance evaluation model of thermoelectric stove by using CFD, and perform CFD analysis of a thermoelectric stove predict the performance of the stove, and steady state thermoelectric simulation analysis improve performance of thermoelectric module. This thesis will provide a contribution in both performance improvement of stove and the waste heat management by converting into electrical energy.

This study would collect and analyze relevant data and select the available thermo electric module, and modelling that can configure an optimum design performance to have a contribution in efficiency improvement and supply electrical energy for a family member.

1.5 Limitation

As the technology is new in Ethiopia, there is the access problem of thermoelectric module that faces the challenge for the present research work. Further, generally thermoelectric materials have low conversion efficiency due to the thermal conductivity increased with increasing the temperature.

1.6 Methodology

The methodology briefly describes design, which determines way of energy wasted and energy generated from stove that affects performance of stove. The simulation was undertaken by ANSYS 2019, and CFD fluent simulation is used for heat transfer analysis in stove and, AIM Discovery or Thermoelectric simulation for the thermoelectric module. Evaluating the analytical result with respect to related data.

The design methodology procedure shown by graphical in Fig.1 below.

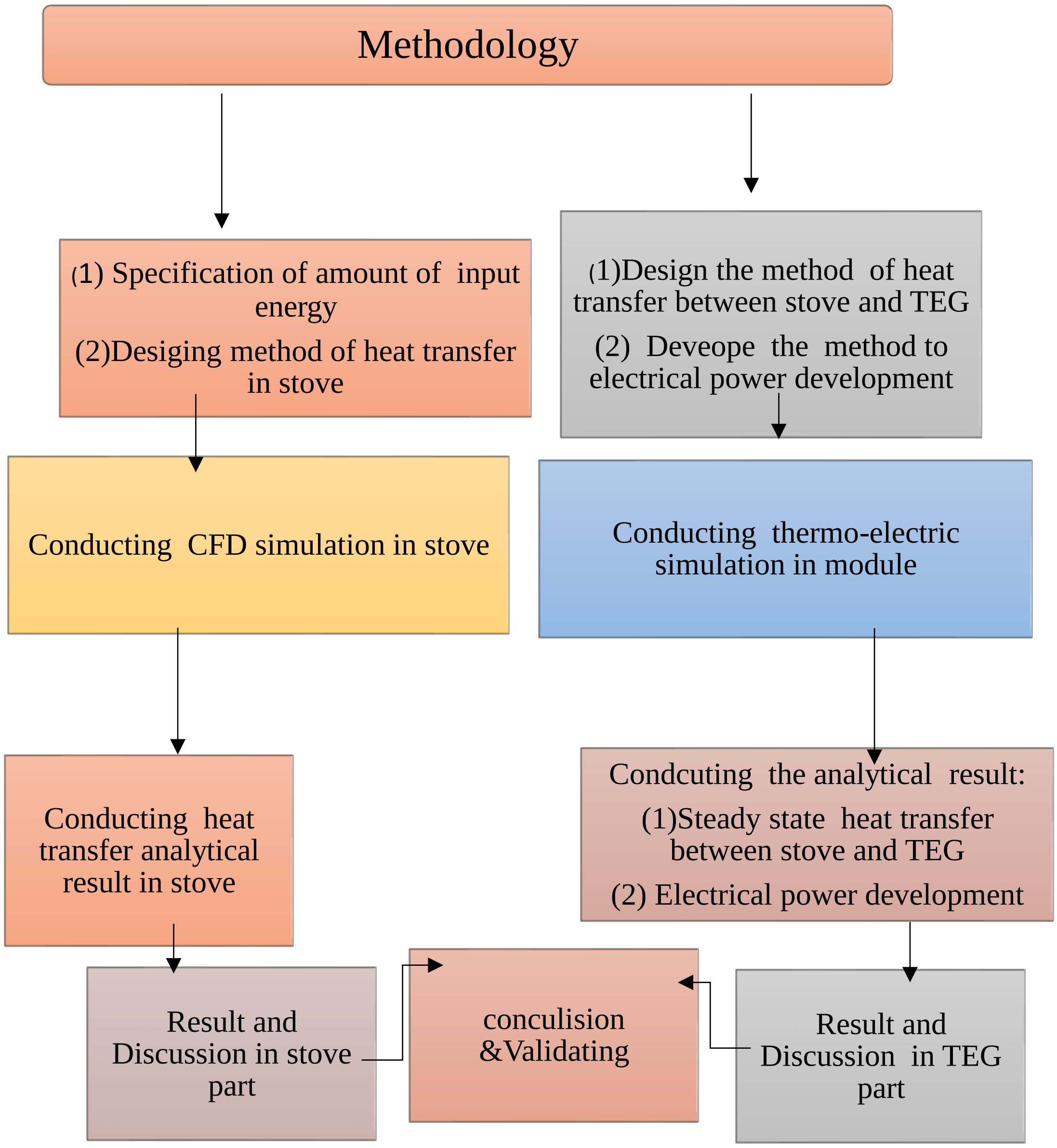


Fig.1.1 Detailed Methodology procedure

CHAPTER TWO

2. Literature review

2.1 Introduction

This chapter is a literature review part in which different literatures related to the thermo-electric properties and thermoelectric material are discussed. In addition, different literatures related to design, development, and performance of thermoelectric stoves are briefly discussed. Some of short comings of the technologies used by the previous researchers compared to the present work are reviewed at the end of this chapter.

2.2 Thermo-electric properties

Thermo-electricity is the process of producing electricity from heat, and vice versa. The processes are referred as ‘‘Seebeck effect,” having been named after a German scientist, Thomas Seebeck. In 1821, Thomas Seebeck heated one end of two twisted wires by heat source that are made from different metals. Thomas observed a small current flow through the wires. Such flow is enhanced by the electrons which move from one end to another hence determining the direction of flow of the current. He concluded that electricity could be generated from heat. Peltier discovered the reverse phenomenon later in 1834. Peltier discovered and stated that when direct current went through the twisted wires, cooling and heating effect was observed from each side [7–10].

This paper gives intention to explicate thermo-electric generator (TEG). Thermo-electric efficiency is a parameter that indicates the performance and was derived by Altenkirch in 1911. It is called a thermo-electric figure of merit denoted simply as Z. The result of this is a dimensionless thermoelectric figure of merit, ZT, given as follows:

$ZT=\alpha^2\sigma T/K$……………………………………………………………………….2.1

Where:

α is the thermo-power or the Seebeck coefficient, the value α is the voltage produced in every difference in temperature in a good conducting material.

σ is the electrical conductivity of the conductor.

K denotes the thermal conductivity.

These three parameters, (α, σ, K) closely depend on one another. Particularly, α and σ are inversely proportional to one another. This describes is hard to increase the thermoelectric figure of merit due to these two parameters inversely related [9]. The two parameters, thermo power and electrical conductivity are mostly constant. A thermo-electric material that is of good quality has a low thermal conductivity, high thermo power and an increased conductivity of electricity. The figure of merit can therefore be maximized by increasing the electrical conductivity and reducing the thermal conductivity. A practical ZT of a suitable and high performance thermo-electric material should be higher than 4. However, to achieve such high ZT remains to be a formidable challenge [10]. ZT is important in determining the efficiencies of different thermoelectric generators working at similar temperature. A good TEG has high ZT, which is roughly, a result of improvement over the years [10].

In semiconductors, the net thermal conductivity is a sum of two contributions: When a single type of charge carrier is predominant in a material, the total thermal conductivity (k) is the sum of the lattice thermal conductivity ($K_{lattice}$), and the charge-carrier thermal conductivity (K_C).

That means:

$$K = K_C + K_{lattice} \qquad \text{2.2}$$

A lower thermal conductivity can be attained by maximizing the $K_C/K_{lattice}$ ratio. This is achieved by lowering the lattice thermal conductivity [6], [13–16]. The charge-carrier thermal conductivity (K_C) can be estimated from the Wiedemann–Franz law ($K_C = L\sigma T$), where L is the Lorenz constant (~ $2.4\times10^{-8}V^2/K^2$ for metals and ~$1.5\times10^{-8}V^2/K^2$ for non-degenerate semiconductors).

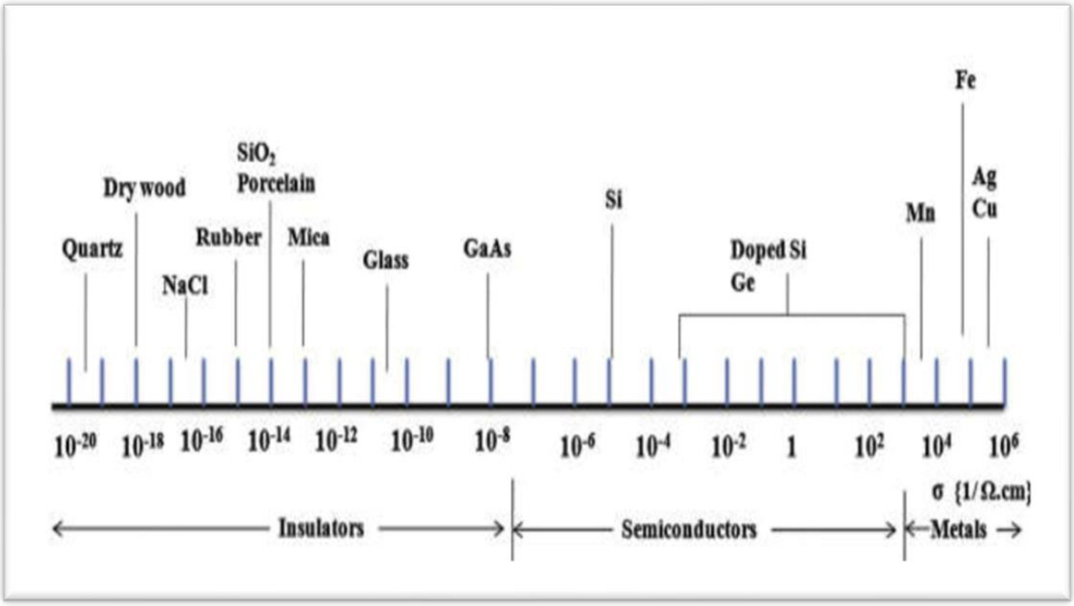


Fig.2.1 Schematic shows the room-temperature electrical conductivity of various materials [16].

2.3 Thermoelectric material

A thermoelectric (TE) module consist legs of n-type and p-type semiconducting materials connected thermally in parallel and electrically in series. Material structures and compositions are used to classify thermoelectric materials. Some of the main classifications are Clathrate, Chalcogenide, Half-Heusler, Skutterudite, Silicide, and Oxide. Thermoelectric material properties are highly temperature-dependent and face multiple challenges in application, such as specific materials choice. Thermoelectric conversion efficiency can be improved by maximizing the Seebeck coefficient and by lowering the electrical resistivity and thermal conductivity [17].

Doped semiconductors can be used as thermoelectric materials and can be grouped into three depending on the temperature range of the operation. Those based on Bismuth Telluride materials, Lead Telluride and Silicon-Germanium alloys [18]. The variation of the Seebeck coefficient and the electrical conductivity as a function of the reduced Fermi energy, serves for the optimization of the power factor, $\alpha^2\sigma$ [19]. Materials based on Bismuth Telluride have the highest figure-of-merit (3.4×10^{-3} K^{-1}) but are restricted to operate below 250 °C. Lead Telluride has the next highest averaged figure-of-merit (2.0×10^{-3} K^{-1}) over an operating temperature range of up to 500 °C. Finally, Silicon Germanium has the lowest figure-of-merit (0.8×10^{-3} K^{-1}) but is able to operate for long lengths of time at temperatures around 1000 °C [20–22]. The complex structures helped to improve the ZT with various approaches mainly by Clathrates, Skutterudites and Zintl phase. The substructure approach and incorporating nanostructures opened up a new opportunity. The super lattice materials show ZT up to 2.5 at room temperature, but are not suitable for mass production [22]. Nanostructures have been demonstrated to be a powerful tool to achieve record thermal efficiencies. The power conversion efficiency of a thermoelectric device (η) can be defined as follows:

The conversion efficiency (η)

$$(\eta)=\frac{\Delta T}{T_{hot}}.\frac{\sqrt{1+ZT}-1}{\sqrt{1+Z7}+\frac{T_{cold}}{T_{hot}}}\ldots\ldots 2.3$$

Where: The product of the Carnot efficiency ($\Delta T/T_{hot}$) and The ZT dependent quantity gives the efficiency T_{hot} and, T_{cold} denote the hot-end and cold-end temperatures, respectively.

2.4 Thermoelectric power generator-working principle

A thermoelectric generator is a heat engine in which charge carriers serve as the working fluid. It is silent in operation, has no moving parts and is very reliable [23]. TEG consists of a large number of thermocouples connected electrically in series to form a thermoelectric module. The module is the backbone of the generator and it is available commercially. Heat is supplied by a variety of sources to the hot side of the module (heat source) and is rejected at a cooling side of the module (heat sink).

Thermoelectricity is based on the fact that charge carriers can be set in motion by temperature differences. Generally, two main physical phenomena are relatively related, such as the Seebeck effect and the Peltier effect [24]. A certain open-circuit voltage is generated in a material kept between the two different temperatures. The Seebeck coefficient α (V/K) is a property of the material that relates to the open-circuit voltage V_{OC} or (V) with the temperature difference ΔT (K) [24], or

$$V_{ed} = \alpha\Delta T\ldots\ldots 2.4$$

The Peltier effect (Pp) states that when a direct current I (A) passes through a circuit of dissimilar materials, heat is absorbed or rejected, which depends on the direction of the current.

$Pp = v_p I = \alpha I T_j$…………………………………………………………………… 2.5

Where v_p (V) is the Peltier coefficient, T_j is the junction temperature. The well-known Joule heating and the Thomson effect (PT) phenomenon occur in thermoelectric devices.

$PT = C_t \, I \Delta T$……………………………………………………………………2.6

Where C_t (V/K) is the Thomson coefficient, defined as

$C_t = T_{avg} \, d\alpha / \Delta T$………………………………………………………….……. 2.7

2.5 Development of different types of the Thermo electric stove

1.3 billion People – about 20% of worldwide population – are still without access to electricity, almost all of whom live in developing countries [4]. Providing a minimum amount of electricity can actuate the basic needs such as light, radio and some medical electronic devices. Thus, making a lot of difference in their lives. TEG coupled to the stove can be a very interesting option to provide such amount of electricity. TEG is a device that harvests waste energy and convert some of it to useful power. It operates on a fundamental principle termed the Seebeck effect. The major advantage of a TE generator in this case is requiring almost no maintenance, since there are no moving parts. Only the battery needs to be charged when needed.

The Drawback and challenges involved in this technology, thermoelectric generators are mainly the low efficiency of the technology itself is below about 10% [25] , and the high price of the TEG models. The low efficiency problem can be solved by new technologies investigated over time. The price will decrease with more adoption of such technology.

2.6 Jordan University of Science and Technology thermoelectric Stove

A multi-task thermoelectric JUST stove (Jordan University of Science and Technology Stove) was designed and tested to help the people living in remote poor regions and deprived of electricity. This JUST stove designed for purposes like space heating, cooking and water heating besides producing electric energy by using TEG. The latter will give serves different aspects of life including: lighting, charging the cellular phone, listening to the radio and operating some medical instruments and much more. Hence, the objective of this work was to design, construct and test a stove with 12 TE modules coupled to it in order to generate electricity about electric power (7.9 W), evaluate the power output, efficiency and compare the results with other stove models.

The design covered the whole components including the combustor with special aero thermal design.TEG base and heat sink and the cooker were designed to give optimum spacing and performance. Water heater was designed with a copper tube exposed to the exhaust gases to recover most of the remained energy. To simulate the real circumstances of those living in remote areas, different fuels including wood, manure and peat were utilized. Heat transfer analysis was especially considered with JUST stove as a case study.

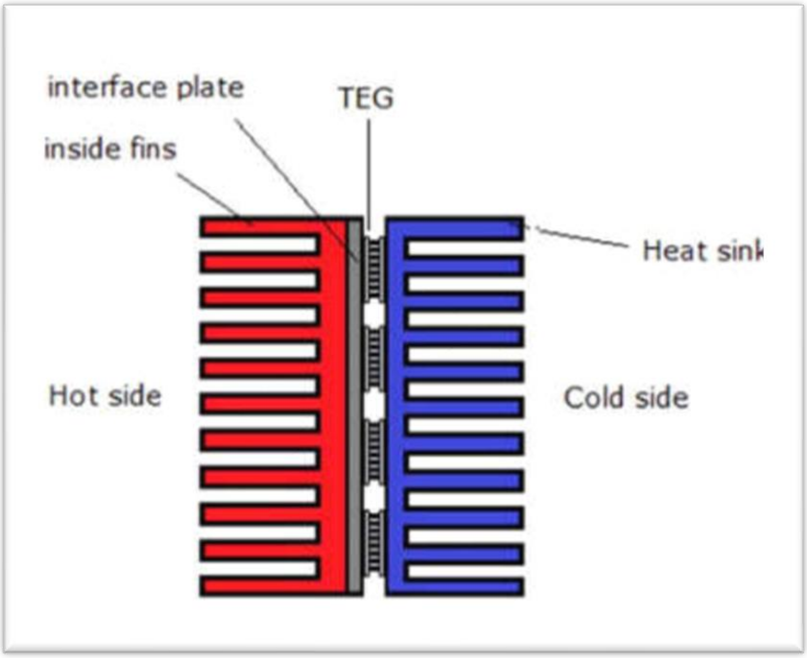


Fig.2.2 Detailed design top view of TEG [26]

2.7 Lertsatitthanakorn thermoelectric stove

Lertsatitthanakorn investigated the feasibility of adding a commercial TE module made of bismuth-telluride based materials to the stove's side-wall, thereby creating a TE generator system that utilizes a portion of the stove's waste heat[25]. The results showed that the system generates approximately 2.4W when the temperature difference is 150 ^{0}C. This generated power is enough to run a small radio or a low power incandescent light bulb. With the use of TE generators, the different functions of the domestic stove can be increased (cooking, water heating, space heating and electricity supply). Even if the conversion efficiency is low, the electric power is sufficient to supply a small fan to improve the combustion in the stove, charge a battery and light high brightness low power LEDs. The fan forces the air through the stove, leading higher combustion efficiency as the result gives higher temperatures and a better air/fuel ratio. This results in a cleaner burning and a more efficient use of fuel. This paper reports a study conducted in order to investigate the feasibility of using a TE generator in an improved biomass fired stove already developed. Performances for other conditions (temperature difference, heat exchangers on both sides of the module) can be evaluated with a simple numerical simulation presented below. The modules are evaluated and finally a TE power generator experimental set up is presented showing that a 6-watts ready to use electrical production is possible with the biomass cook stove.

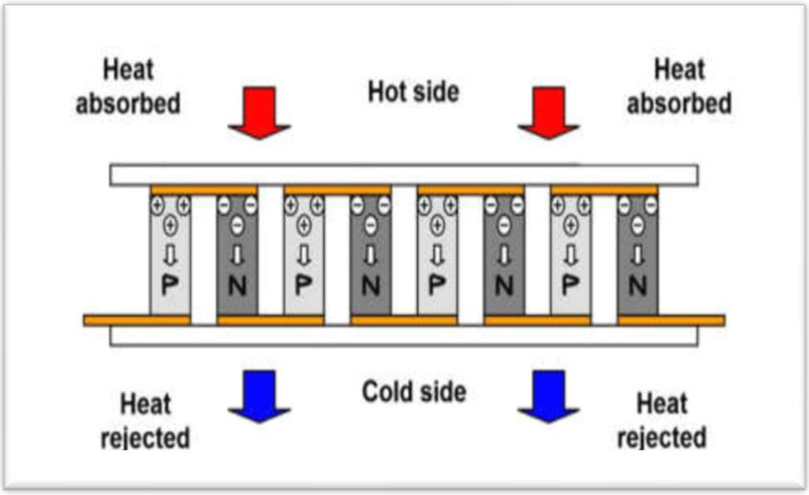


Fig.2.3 The working principle of a Seebeck cell [4].

The voltage is created in the presence of a temperature difference between two different semiconductors. Typical TE modules are composed by a set of semiconductor components Formed from two different materials as shown in Fig.2.3 These components are connected thermally in parallel and electrically in series. Two ceramic plates are stuck on each side for electrical insulation. Semiconductors are divided, depending on the material they are made of, into P-type and N-type components Fig.2.3. When heat flows through the cell, the N-type components are loaded negatively (excess of electrons) and P-type components are loaded positively (default electron), resulting in the formation of an electric flow.

2.8 Champier thermoelectric stove

The aim of research was to study the feasibility of using thermo-electric module modules in this stove in order to generate electricity. The generated power is about 10W, for both the fan and basic needs: lighting, radio and charging cell phones as well as other small electronic devices. Thermoelectric (TE) modules an experimental device has been carried out in our laboratory where a gas heater simulates the stove.

Champier et al. [4] studied the use of thermoelectric generator to produce electric power to run a fan and ensure complete combustion and emit light. They installed a thermoelectric model under the water tank which serves as the heat sink for the cold side and to ensure enough pressure for good contact in the assembly of the TEG model. They got a maximum power output per model of 10 W. In the second prototype [2], and they used a different type of thermoelectric model that works at higher temperatures.

Module type Thermonamic (14 W for 67V∈), was chosen for our prototype for their study. Thermonamic model TEP1-12656-0.6 with 126 couples and a size of56 mm×56 mm. These modules can work at the temperature of as high as 320^0C continuously and stand with up to 400^0C heat source at the hot side but the temperature of the cold side of the module cannot go above 200^0C. The specification of the designed and built a TE power generator (see Fig2.4). Bi_2TE_3 modules from Taihuaxing Co. Ltd. are used in the experiment. The operation or running condition of the module are as follows for the hot-side temperature at 230 C and the cold side at 30 C:

- Size: 56mm 56 mm.
- Open-circuit voltage: 8.7 V.
- Internal resistance: 1.7 U.
- Match load output-power: 10.5 W.

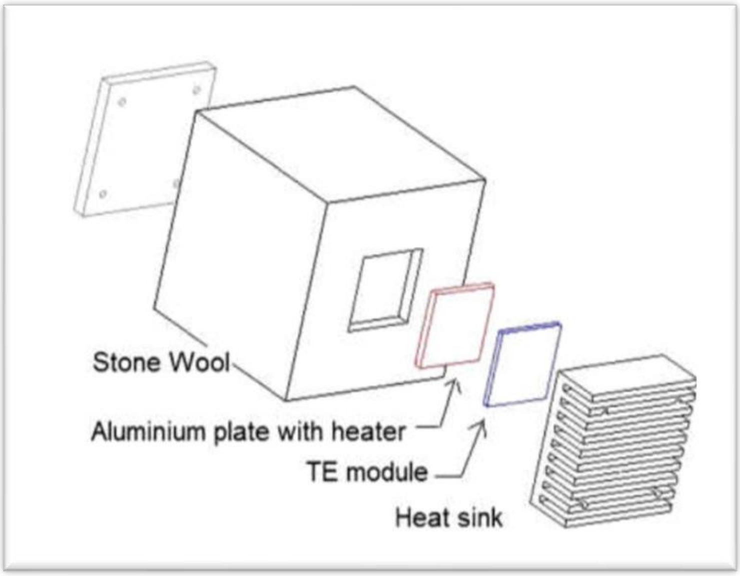
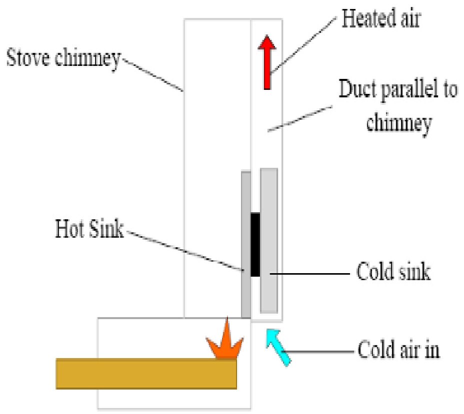


Fig.2.4 Experimental TE power generator test system [4].

2.9 H.B. Gao thermoelectric stove

In his review paper, He was investigating by giving intention different mechanism of cooling system designing alternatives for the TEG (thermoelectric). To obtain higher power and high efficiency of module, the temperature hot-side temperature should be higher than cold-side temperature, and the temperature difference between hot side and cold side should be as high as possible. Commercially available modules have a maximum efficiency of 5–6%, while the efficiency of new materials is higher than 10% in the laboratory. In order to get higher efficiency, have to increase the temperature difference. Therefore, cooling mechanism is significant at cold side of TEG to increase generator performance. Generally, there are four types of cooling mechanism were applied in the review paper. The four cooling mechanisms are affecting the power generation in the thermoelectric module. thermoelectric power generation are given the respect to cooling mechanism sections:

- ✓ air-cooled natural convection -2.4W
- ✓ air-cooled forced convection -5.4W
- ✓ water-cooled natural convection -5.5W and
- ✓ water-cooled forced convection-8 W



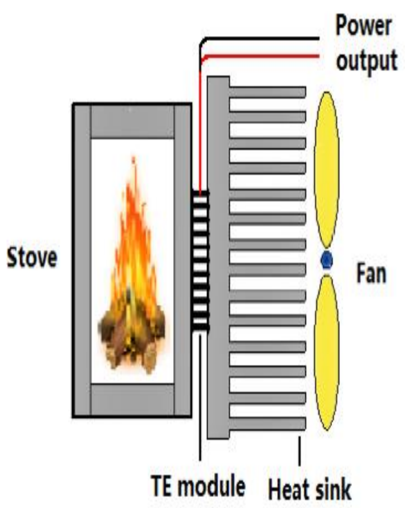


Fig.2.5 Setup for natural convection operation and Schematic of TEG system cooled by air forced convection [10].

CHAPTER THREE

3. Methodology

3.1 Introduction

This chapter describes the design procedure that describes way of energy developed in thermoelectric stove. The mechanisms of heat transfer, which exposed to wastage of energy are briefly discussed. Detailed theories related to performance of thermoelectric stove are stated, different empirical formulas, design steps, and underlying assumptions are described in detail.

3.2 The amount of energy obtained from biomass fuel

All biomass fuels, such as wood, straw, charcoal, briquettes and others, contain carbon, hydrogen and oxygen, which are prepared by the chemical reaction called photosynthesis and described in this chemical formula composition of. $C_nH_mO_x$. When in a complete combustion is done, organic fuels react with oxygen molecules in the atmosphere to form carbon dioxide CO_2 and water H_2O, during the process of combustion the heat energy is released.

The general form of complete combustion reaction of organic fuels below as follows:

$$C_nH_mO_x + (2n+\frac{m}{2} - x)\, O_2 \longrightarrow nCO_2 + \frac{m}{2} H_2O + \text{Heat energy} \quad \ldots\ldots 3.1$$

Where: n is the number of carbon element

m is the number of hydrogen element

x is the number of oxygen element

3.2.1 Specified variables in water boiling test

During the combustion process, most of the time the combustion occurs above the boiling point temperature of water. Due to this the combusted biomass organic fuel possess two form of energies. These energies are the energy obtained from fuel and energy of condensation due to the moisture and water content in the biomass fuel. The energies are termed as the gross caloric (dry wood) (kJ/kg) value or higher heating value (HHV) which is indicate the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel if it is completely combusted, and the combustion products are cooled to room temperature such that the water produced by the reaction of the fuel-bound hydrogen is condensed to the liquid phase [27].

HHV of wood used for this design = 19,500kJ/kg ……………………………………….3.2

The next is termed as lower heating value (LHV) and it also called Net calorific value (NCV) (dry wood) (kJ/kg) is defined as maximum amount of energy that can be extracted from the combustion of the moisture-free fuel if it is completely combusted, and the combustion products are cooled to room temperature but the water produced by the reaction of the fuel-bound hydrogen remains in the gas phase.

LHV of biomass wood used for this design = 18,595kJ/kg……………………………….3.3

In order to calculate the amount of energy of obtained from biomass fuel, first have to obtained equivalent dry fuel (Dry $_{fuel}$ [Kg]) consumed. It is determined by the mass of dry fuel consumed is the moist fuel consumed minus the mass of water in the fuel:

Dry $_{fuel}$ [kg] = $m_{fuel\ consumed}$.[1-MC] ……………………………………………………3.4

The amount of heat energy obtained from the organic biomass fuel is generally formulated by the following formula.

Q $_{heat}$ [KJ] =LHV[KJ/kg]. dry mass fuel [kg]

=LHV[KJ/kg]. Dry $_{fuel}$ [kg

=18,595kJ/kg. $m_{fuel\ consumed}$. [1-MC] ……………………………………3.5

3.2.2 Some Basic calculation

The mass of water content in the fuel ($\boldsymbol{m_{water_{fuel}}}$): is the amount of water mass in the biomass fuel and it is simply calculated by the total mass of fuel ($m_{fuel\ consumed}$) multiplied percentage of water content in the fuel(MC)

$\boldsymbol{m_{water_{fuel}}} = (m_{fuel\ consumed})$. (MC)……………………………………………….3.6

The moisture energy ($\Delta \boldsymbol{E_{H_2O}}$): the amount of energy that is needed to remove moisture from the fuel and it is calculated by mass of water in the fuel ($\boldsymbol{m_{water_{fuel}}}$) multiplied by change of specific of water($C_p \Delta T$ +$\Delta h_{H_2O,fg}$).

$\Delta \boldsymbol{E_{H_2O}}$ =$\boldsymbol{m_{water_{fuel}}}$.$C_p \Delta T$ +$\Delta h_{H_2O,fg}$) and Where:

$C_p \approx$ 4.186 kJ/kg K $\Delta h_{H_2O,fg} \approx$ 2,257 kJ/kg, $\Delta T = T_f - T_i$ by substituting the give value, we have

$\Delta \boldsymbol{E}_{\boldsymbol{H_2O}} = \boldsymbol{m}_{\boldsymbol{water}_{\boldsymbol{fuel}}}$ (4.186 kJ/kg K $(T_f - T_i)$K +2,257 kJ/kg)

$= \boldsymbol{m}_{\boldsymbol{water}_{\boldsymbol{fuel}}}(4.186(T_f - T_i) + 2{,}257)$ ……………………………………………3.7

water Mass of water evaporated from stove ($\boldsymbol{m_{evap}}$): is the amount of mass of water that is evaporated during the experiment and it is obtained by subtracting the total mass of pot and water after the experiment from the total mass of pot and water before the experiment[27].

$\boldsymbol{m_{evap}} = weight_{tot}\ before - weight_{tot} after$…………………………………3.8

Mass of boiled water ($\mathbf{mass_{water\ boiled}}$): the amount of water remained after the experiment at local boiling temperature .It is simply obtained by subtracting the weight of pot and water at the end of experiment and weight of pot .

$\mathbf{mass_{water\ boiled}} = \mathrm{Total_{weight}}$ end exp $- \mathrm{weight_{pot}}$……………………………………3.9

3.3 Development of heat transfer analysis in the stove

Heat energy generated in the combustion chamber is the amount of energy that converted from chemical energy (fuel) to heat energy. Also, it contains all energy generated in combustion chamber such as energy absorbed by the stove in the form of conduction, convention, radiation, energy lost due to incomplete combustion and useful energy during cooking, this useful part is transfer to the cooking pot and the food. In order to minimize the losses to the surroundings and maximize the transfer of heat to the food in the pot a thorough knowledge of heat transfer mechanisms and their underlying principles is required to determine the reasons for the losses [27].

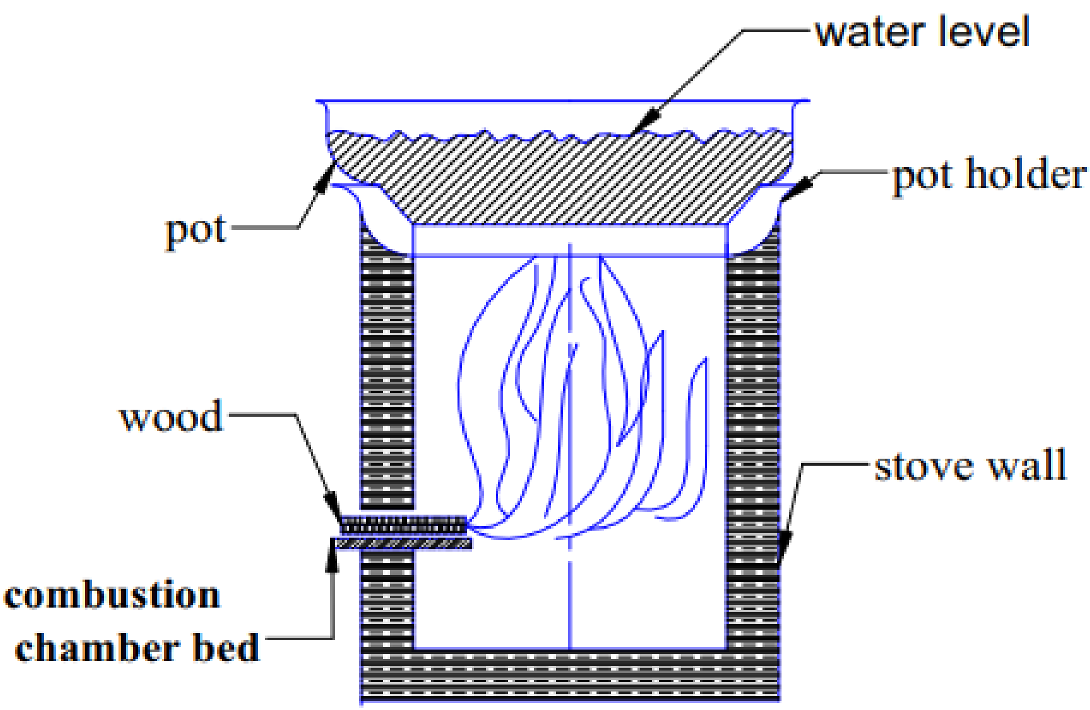


Fig.3.1 Total heat development mechanism in a stove

3.3.1 General mechanisms of heat transfer

Heat transfer is energy in transit, which occurs as a result of a temperature gradient or difference. This temperature difference is thought of as a driving force that causes heat to flow. Heat transfer occurs by three basic mechanisms or *modes: such as* conduction, convection, and radiation.

3.3.2 Heat transfer by conduction

The mechanism of transmission of the heat through a substance without particle motion or without motion of the substance itself. Heat can be conducted through gases, liquids, and solids. In the case of solids general, conduction is the primary mode of heat transfer when the fluid has zero bulk velocity. In opaque solids, conduction is the only mode by which heat can be transferred.

Conduction heat transfer mode in cooking stove has small significant contribution in total amount of heat energy transfer.

$$Q_{con.} = -KA\frac{\Delta T}{\Delta X} \quad \text{.........} 3.10$$

Where

Q_{con} is conductive heat energy flux [KJ]

K is coefficient thermal conductivity[W/M]

A is surface area of cooking stove [m^2]

ΔT is change temperature [^0C]

ΔX is thickness of stove wall[m]

3.3.3 Convection heat transfer method

The convection transfer mode is sustained by both random molecular motion and by bulk motion of the fluid within the boundary layer. The contribution due to the random molecular motion (diffusivity) dominate near the surface where the velocity is low.

In cooking stove, the convection heat transfer form of energy occurred during the heat is transferred to the wall of stove and heat is transferred to the bottom of pot. The rate of convection heat transfer is observed to be proportional to the temperature difference and is conveniently expressed by Newton's law of cooling as [27]:

$$\boldsymbol{Q}_{\mathbf{conv}} = hA_s(T_s - T_\infty)(\text{ W}) \quad \ldots\ldots 3.11$$

Where:

h convection heat transfer coefficient, W/m2 ˚C

As heat transfer surface area, m^2

Ts temperature of the surface, ˚C

T_∞ temperature of the fluid sufficiently far from the surface, ˚C

3.3.4 Heat transfer by radiation

Energy of radiation field is transported by electromagnetic waves (alternatively by photons). while energy transfer in conduction, convection requires presence of material medium. Radiation do not, radiation transfer occur mostly in vacuum.

In stove most of the time the radiation energy is radiate or transferred to the direction of stove wall and the remain is to the direction bottom of pot. The convenient expression for radiative energy is given by the following equation.

Radiation is modelled by the Stefan-Boltzmann Law,

$\boldsymbol{Q}= \varepsilon\,\sigma\,[T_s^4 - T_\infty^4]$ ……………………………………………………………………3.12

Where;

Q= heat transfer

σ = Stefan-Boltzmann constant

α = Absorptivity

ε = Emissivity

T s = Surface Temperature

T∞ = Ambient Fluid (air) Temperature

3.4 Heat transfer losses in the system

3.4.1 Conduction heat transfer losses

Conduction heat transfer losses are occurred due to contact between two materials. If there is pot skirt in the stove, there is conduction losses between pot and pot skirt and calculated the following formula [27]:

$\mathbf{Q}_{\text{con loss.}} = -KA\frac{\Delta T}{\Delta X}$ ……………………………………………………………………….3.13

Where

Q_{con} is conductive heat energy flux [KJ]

K is coefficient thermal conductivity[W/M]

A is surface area of cooking pot skirt [m^2]

ΔT is change temperature [^0C]

ΔX is thickness of pot skirt[m]

3.4.2 Convection heat loss in combustion chamber (wall inner of stove)

Q_{conv} stove wall $= h_{\text{stove wall}} A_{\text{stove wall}} (T_{gas} - T_{\text{stove wall}})$ …………………………3.14

D chamber -wall = Effective diameter of lower chamber if it were circular

H chamber = Effective chamber length

A = Effective chamber surface area

T = Average upper chamber wall surface temperature

Friction factor between gases and walls of combustion chamber will be;

Assuming fully developed internal flow contained by smooth walls

3.4.3 Convection heat transfer from gases to pot bottom

$$\mathbf{Q}_{\mathbf{conv\ pot}} = h_{conv.pot} A_{pot} (T_{gas} - T_{pot}) \quad \ldots 3.15$$

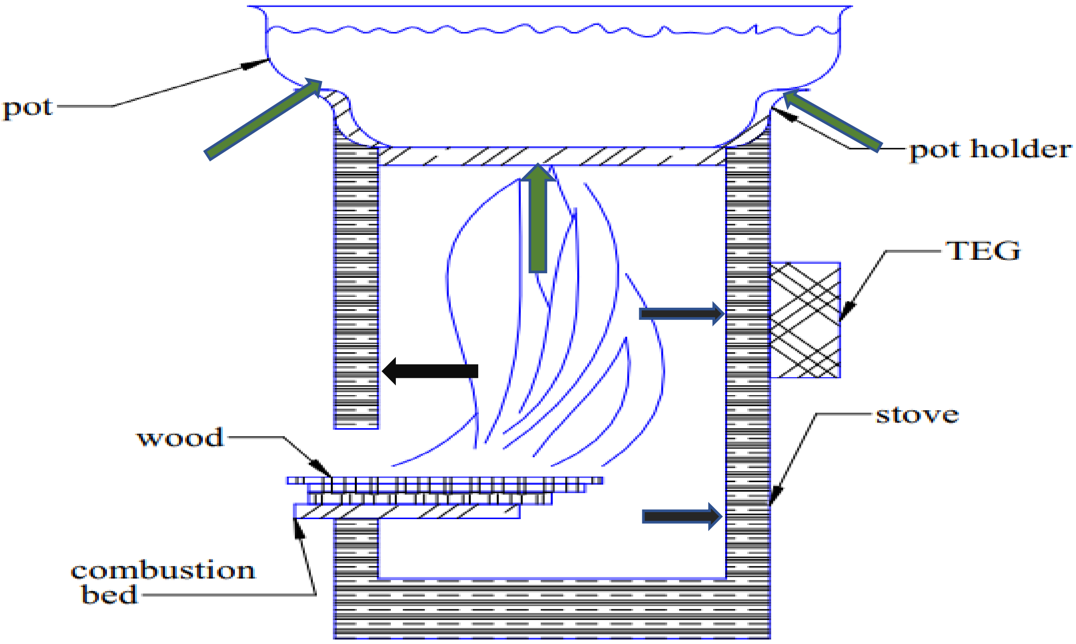


Fig.3.2 The overall losses and amount of energy generated by convection

3.4.4 Radiation loss to walls of stove

Due to radiation heat transfer between the flame and inner part of cylinder, there will be radiation loss to the wall of the ceramic part. This amount of steady state heat loss can be calculated as [28]:

$$Q_{\text{radiation loss to stove}} = \frac{\delta \text{stefan .constant.wall } A \ (T^4_{\text{inener stove wall}} - T^4_{avg})}{\frac{1}{\varepsilon} + \frac{1-\varepsilon \text{ inner radius of stove}}{\varepsilon \text{ outer radius of stove}}} \quad \ldots 3.16$$

The average steady surface temperature of flames and wood

$$\mathbf{T}_{\mathbf{avg}} = T_{flame} + T_{wood}$$

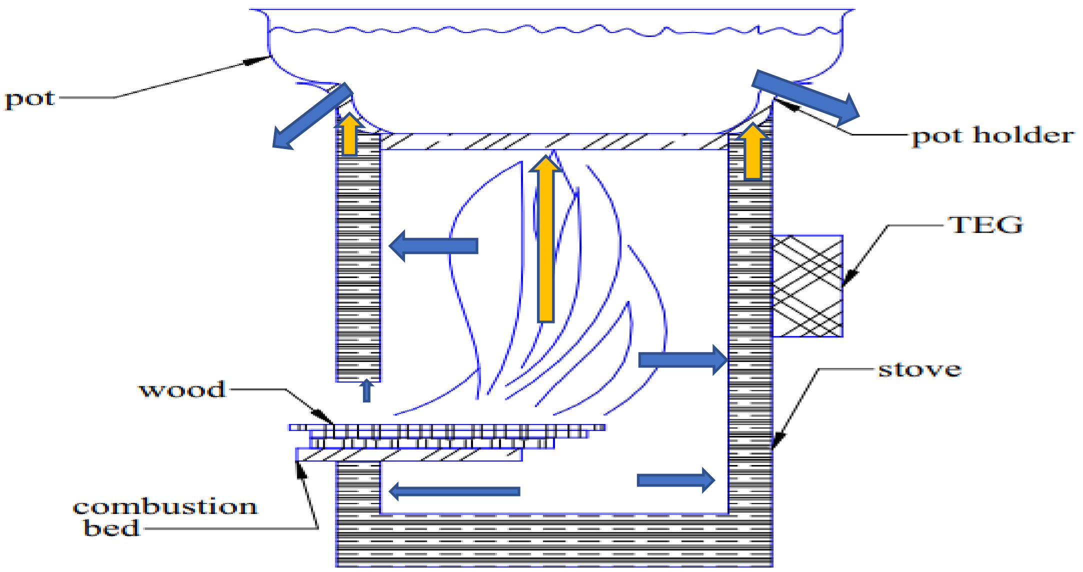


Fig.3.3 The total heat losses and heat generated by radiation

The total heat transfer losses in the stove can be evaluated is the summation of all losses of heat transfer losses convective heat transfer in the inner wall of stove, convective heat transfer losses in the bottom of pot and radiation heat transfer loses in the surface of inner wall of the stove.

$\mathbf{Q}_{\textbf{loss total}} = Q_{\text{convect loss .wall}} + Q_{\text{convect.loss bottom pot}} + Q_{\text{radiative loss stove wall}}$ 3.17

3.4.5 Thermal balance of the system

The thermal power coming from the heat source is mostly converted into internal energy of water and pot materials which increasing their temperature. The remaining fraction amount is lost through evaporation, convection and radiation [28].

The thermal balance of the system is given by Equation

$Q_{\text{utilized}} - \Sigma Q_{\text{losses}} = \frac{\partial u\ water}{\partial t} + \dot{m}_{\text{eva}} \Delta h_{\text{eva}}$ 3.18

3.4.6 Thermal efficiency of stove

In general, thermal context, Thermal efficiency in stove (η) is defined as the ratio of work done by heating or internal energy of water and evaporation of water to the energy produced by burning biomass [29].

$(\boldsymbol{\eta}) = \{ \frac{\dot{m} c_{p\Delta T} + \dot{m}_{\text{eva}}\, \Delta h_{\text{eva}}}{\text{NHV.Dry fuel}} \} \times 100\%$

Where:

$\dot{m}$ is Mass of water taken in kg

c_p is Specific heat of water in kJ/kg°C

ΔT is Difference between final and initial water temperature in °C

$\dot{m}_{eva}$ is Mass of water evaporated kg

Δh_{eva} is Latent heat of vaporization of water in kJ/kg°C

NHV is Calorific value of biomass consumed in kJ/kg

Dry fuel is Equivalent Mass of dry biomass consumed in kg

3.5 Designing and specification of thermoelectric module

This part in general includes two parts

1, Thermal analysis: includes the basic idea of thermoelectric module.

- ✓ Calculating of heat transfer analysis and the amount heat developed in thermoelectric modules,
- ✓ Evaluating the heat (thermal) and energy balance in thermoelectric (TE) modules,
- ✓ Designing the cooling mechanism of cold side temperature of the module,
- ✓ Selection and specification of TE module type,
- ✓ Position of the TE module in the stove,

2, Electrical analysis

- ➢ Designing the power developed from the TE modules,
- ➢ The voltage developed from the TE module,
- ➢ Current developed from the TE module,

3.5.1 Heat transfer analysis and heat developed from the thermoelectric module

During evaluation of heat transfer analysis in TE modules, there are some general assumption consideration is under taken. These are the important assumptions for thermoelectric ideal (standard) equations [30]:

1. The Thomson effect is negligible. It has been proven analytically and experimentally that the Thomson effect has a very small effect on the performance of TE module.

2. The electrical and thermal resistances between ceramic plates and thermoelectric elements are negligible.
3. The convection and radiation losses are negligible.
4. The materials properties are assumed to be independent of temperature.

Consider two dissimilar(P-type-type) semiconductor elements, which are interconnected by copper plates or called conductive tabs, each element is called a thermoelectric leg or pellet, and thermoelectric legs are either p-type material (positive) or n-type material (negative). These element properties are highly dependent in temperature specifically in these properties, which are See beck coefficient (α), electrical resistivity (ρ), and thermal conductivity (k).

At steady state condition that *all* properties are unchanging in time in the hot side of TE module. That means T_1I steady state condition, the heat balance is given the following equation [30].

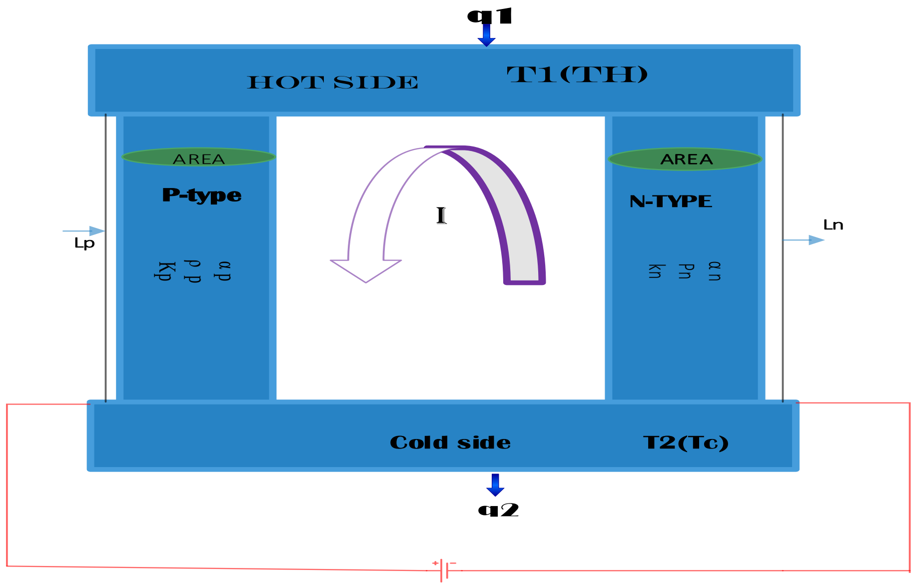


Fig.3.4 Longitudinal cross-section of a TE couple and differential element at steady state heat balance

$$Q_1 = q_p + q_n \qquad \text{......3.19}$$

Where Q_1, q_p and q_n are the heat supplied from the stove to the hot side of TE, heat flow in p-type and the heat flow n-type. According to Peltier heat and Fourier's law of conduction. Heat flow can be stated as follow [30]:

$$q_p = \alpha_p T_1 \, I + (-K_P A_p \frac{dT}{dx}) \qquad \text{......3.20}$$

$$q_n = -\alpha_n T_1 I + (-K_n A_n \frac{dT}{dx}) \qquad 3.21$$

By applying heat balance in Fig.3.4, then differential in the TE module, it has to be obtained the equation in consideration temperature gradient.

$$q_x - (q_x + \frac{dq_x}{dx})d_x + \frac{I^2 p_P}{A_P} d_x = 0 \qquad 3.22$$

Heat transfer across the element

Joule heating value

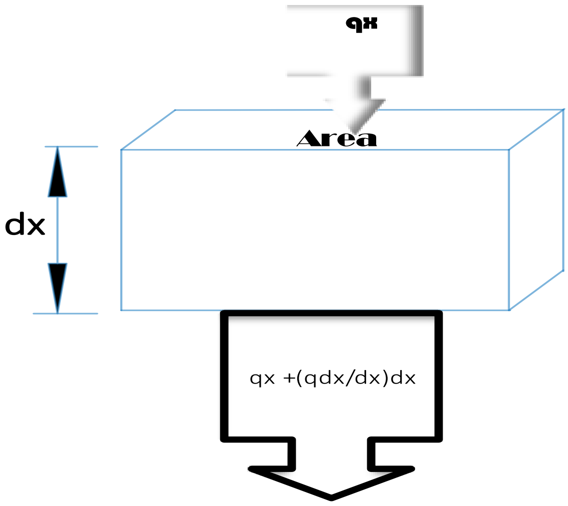


Fig.3.5 Heat balance in thermoelectric module leg

By differentiating equation (3.20) with respect to x, we have the following equation

$$\frac{dp_p}{dx} = -K_p A_p \frac{d}{dx}(\frac{dT}{dx}) \qquad 3.23$$

By equating eq (3.23) in eq (3.22), we have the following equation

$$-\frac{d}{dx}(-K_p A_p \frac{dT}{dx}) + \frac{I^2 \rho_P}{A_P} = 0 \text{ or}$$

$$\frac{d}{dx}(-K_p A_p \frac{dT}{dx}) = -\frac{I^2 \rho_P}{A_P} \qquad 3.24$$

By integrating the above eq (3.24). Let the boundary conditions $x_1 = 0$ when T_1 and $X_2 = X$ when reads T_2, we have

$$K_P A_p \int d(\frac{dT}{dx}) = -\frac{I^2 \rho}{A_p} \int d_x \rightarrow \frac{dT}{dx} = -\frac{I^2 \rho}{K_P {A_p}^2} X + C1 \qquad 3.25$$

by using the boundary condition, the integration is started from 0 to L,

$$\int_{T1}^{T2} dt = -\frac{I^2\rho}{K_P A_p{}^2}\int_0^L x + \int_0^L XC1 \rightarrow (\mathrm{T2 - T1}) \ldots\ldots 3.26$$

From the above equation C1 can be obtained in this form

$$\mathrm{C1} = \frac{I^2\rho}{2K_P A_p{}^2} L_p + \left(\frac{T_2 - T_1}{L_p}\right) \ldots\ldots 3.27$$

Substituting eq (3.27) in eq (3.25) where x = 0 gives

$$\frac{dT}{dx}\Big|_{X=0} = -\frac{I^2\rho}{2K_P A_p{}^2} L_p - \left(\frac{T_2 - T_1}{L_p}\right) \ldots\ldots 3.28$$

Substituting eq (3.28) in eq (3.20), we have

$$q_p = \alpha_p T_1 \mathrm{I} - \frac{1}{2} I^2 \frac{\rho_{PL_p}}{A_p} + \frac{K_p A_p}{L_p}(T_2 - T_1) \ldots\ldots 3.29$$

Similarly, n-type is obtained

$$q_n = -\alpha_n T_1 \mathrm{I} - \frac{1}{2} I^2 \frac{\rho_{nL_n}}{A_n} + \frac{K_n A_N}{L_N}(T_2 - T_1) \ldots\ldots 3.30$$

3.5.2 Heat Transfer Analysis Design in Thermoelectric Module

$$\dot{Q_1} = q_p + q_n$$

$$= \alpha_p T_1 \mathrm{I} - \frac{1}{2} I^2 \frac{\rho_{PL_p}}{A_p} + \frac{K_p A_p}{L_p}\left(\frac{T_2 - T_1}{L_p}\right) + \left(-\alpha_n T_1 \mathrm{I} - \frac{1}{2} I^2 \frac{\rho_{nL_n}}{A_n} + \frac{K_n A_N}{L_N}(T_2 - T_1)\right)$$

$$= (\alpha_p - \alpha_n) T_1 \mathrm{I} - \frac{1}{2} I^2 \left(\frac{\rho_{PL_p}}{A_p} + \frac{\rho_{nL_n}}{A_n}\right) + \left(\frac{K_p A_p}{L_p} + \frac{K_n A_N}{L_N}\right)(T_2 - T_1) \ldots\ldots 3.31$$

By reverse direction of current(I) and applying of pelter effect mechanism, we can have the following equation $\dot{Q_2}$ As:

$$\dot{Q_2} = \alpha_p T_2 \mathrm{I} - \frac{1}{2} I^2 \frac{\rho_{PL_p}}{A_p} + \frac{K_p A_p}{L_p}\left(\frac{T_2 - T_1}{L_p}\right) + \left(-\alpha_n T_2 \mathrm{I} + \frac{1}{2} I^2 \frac{\rho_{nL_n}}{A_n} + \frac{K_n A_N}{L_N}(T_2 - T_1)\right)$$

$$= (\alpha_p - \alpha_n) T_2 \mathrm{I} + \frac{1}{2} I^2 \left(\frac{\rho_{PL_p}}{A_p} + \frac{\rho_{nL_n}}{A_n}\right) + \left(\frac{K_p A_p}{L_p} + \frac{K_n A_N}{L_N}\right)(T_2 - T_1) \ldots\ldots 3.32$$

The general governing equation for the thermal energy in TEG module is obtained from above eq (3.29) and eq (3.30) and it indicate the amount of energy obtained from module.

$$\dot{Q_h} = \alpha T_h \mathrm{I} - \frac{1}{2} I^2 \mathrm{R} + \mathrm{K}(T_h - T_c) \ldots\ldots 3.33$$

$\dot{Q_c} = \alpha T_c I + \frac{1}{2} I^2 R + K(T_c - T_h)$ ……………………………………………………3.34

Where:

2α is the sum which means $(\alpha_p + \alpha_n)$, because α_p and α_n have same value

R is electrical resistance which is equal to $(\frac{\rho_{PL_p}}{A_p} + \frac{\rho_{nL_n}}{A_n})$

2K is equal to $(\frac{K_p A_p}{L_p} + \frac{K_n A_N}{L_N})$ because $\frac{K_p A_p}{L_p}$ and $\frac{K_n A_N}{L_N}$ have same value and is called thermal resistance of module

$(T_h - T_c)$ is temperature difference between hot side and cold side of module.

Lastly to summarize the above equations, it has three fundamental categories. These are the first term [αT_hI] is an indicator seebeck of effect of the material, is indicator of conversion performance of the material; the second term [$\frac{1}{2} I^2 R$] is expresses factor of joule heating which irreversible process, and the last term [K$(T_h - T_c)$] thermal conductance indicator and it irreversible process .

3.5.3 Heat loss between source or ambient temperature in thermoelectric module junctions

There is heat loss between the heat source(T_S) and hot junction of thermoelectric module(T_h) similarly there is heat loss between cold junction of thermoelectric module (T_c) and ambient temperature(T_a). We can generalize the above idea in to two groups as follows [31]:

I. Heat transfer analysis and heat loss between heat source and hot junction of the thermoelectric module.
II. Heat transfer analysis and heat loss between ambient temperature and cold junction of the thermoelectric module.

Because of the heat source material and hot side thermoelectric generators are manufactured from different materials, therefore they have different electrical and thermal properties. On account of basic fundamental parameters, like thermal resistance between heat source and hot junction of thermoelectric module, likely thermal resistance between cold junction and ambient fin temperature, by analyzing namely a finite time heat transfers between them [32]. Similarly, by employing Newton's law of heat transfer and with analysis mentioned above, Q_S and Q_a can be expressed respectively as follows in the Fig.3.6 below:

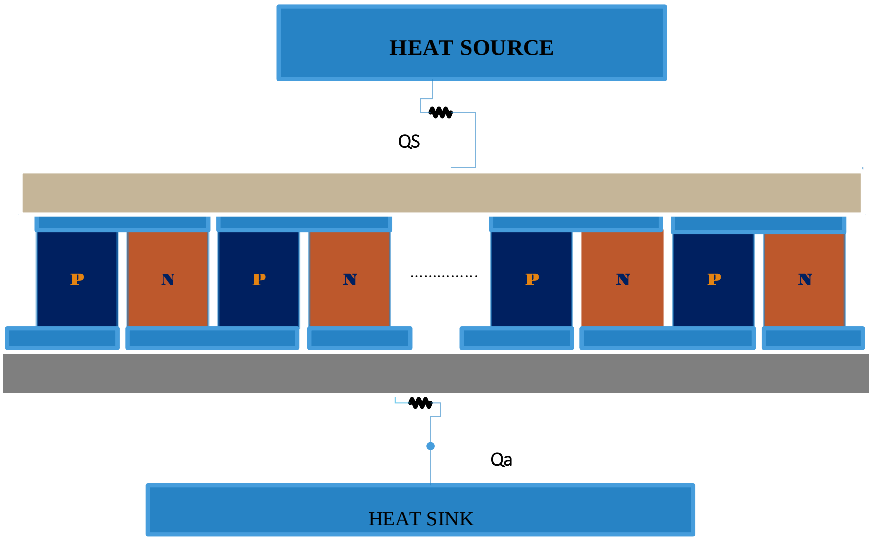


Fig.3.6 Represent heat transfer analysis between heat source and hot junction of thermoelectric module, and heat transfer analysis between cold junction of thermoelectric module and ambient temperature.

$Q_S = K_s A_s (T_S - T_h) = n\,[Q_h + Q_K - 0.5 Q_j]$

$= K_s A_s (T_S - T_h) = n\,[\alpha T_h I + K(T_h - T_c) - 0.5 I^2 R\,]$……………………………..3.35

where Q_h ,Q_K and Q_j ,are given by αT_hI , K($T_h - T_c$) and I^2R respectgrively , and K_s, A_s and T_S *are* heat transfer coefficient of heat source material , contact surface area of heat source and temperature of heat source respectively[31] . In similar manor at steady state heat transfer analysis in cold junction of thermoelectric module. We have

$Q_a = K_a A_a (T_a - T_c) = n\,[Q_c + Q_K + 0.5 Q_j]$

$= K_a A_a (T_a - T_c) = n\,[\alpha T_c I + K(T_h - T_c) + 0.5 I^2 R]$ ………………………………3.36

Where K_a, A_a, and $T_a$are heat transfer coefficient of ambient surface, contact surface area of ambient fin and ambient temperature respectively.

From equation eq (3.34) and eq (3.35), we can obtain the values of (T_S) and (T_a)

T_h=[$K_s A_s\, K_a A_a T_s$+nk($K_s A_s\, T_s$+$K_a A_a T_a$)-n$\alpha K_s A_s\, T_s I$+(.5n$K_a A_a$+$n^2 K$) $I^2 R$-0.5R$\alpha n^2 I^3$] × [$K_s A_s\, K_a A_a + nk(K_s A_s + K_a A_a) + n\alpha(K_a A_a - K_s A_s) I - n^2\alpha^2 I^2]^{-1}$…………………………………………………………………………3.37

T_c=[$K_s A_s\, K_a A_a T_a$+nk($K_s A_s\, T_s$+$K_a A_a T_a$)-n$\alpha K_s A_s\, T_a I$+(.5n$K_a A_a$ +$n^2 K$) $I^2 R$ -0.5R$\alpha n^2 I^3$] × [$K_s A_s\, K_a A_a + nk(K_s A_s + K_a A_a) + n\alpha(K_a A_a - K_s A_s) I - n^2\alpha^2 I^2]^{-1}$…………………………………………………………………………3.38

3.5.4 Energy Balance, Power Developed and The Efficiency

When heat energy is applied in TEG module which is made from with many pairs of p-type and n-type semiconductor legs connected electrically in series and thermally in parallel, heat energy is partiality converted to electrical energy. Heat energy is developed p-type module and n-type thermo-couples; these two forms of energy is given by below in two equations respectively [30].

$$\dot{Q_h} = \alpha T_h I - \frac{1}{2} I^2 R + K(T_h - T_c) \quad \ldots\ldots 3.39$$

$$\dot{Q_c} = \alpha T_c I + \frac{1}{2} I^2 R + K(T_c - T_h) \quad \ldots\ldots 3.40$$

In order to get the energy balance and the electrical work done, have to apply the first law of thermodynamics. Therefore, finally we have:

$$\hat{W} = \dot{Q_h} - \dot{Q_c}$$

$$= \alpha T_h I - \frac{1}{2} I^2 R + K(T_h - T_c) - [\alpha T_c I + \frac{1}{2} I^2 R + K(T_c - T_h)]$$

$$= \alpha I(T_h - T_c) - I^2 R \quad \ldots\ldots 3.41$$

Electrically we know that $\hat{W} = I^2 R_L$ where is the load resistance from the Ohms laws

$$V = IR_L = \alpha(T_h - T_c) - IR \quad \ldots\ldots 3.42$$

From eq (3.20) we have

$$I = \frac{\alpha(T_h - T_c)}{R_L + R} \quad \ldots\ldots 3.43$$

3.5.5 Conversion efficiency (η_{con})

The conversion efficiency is crucial an indicator of the performance of thermoelectric generator. The conversion efficiency or thermal efficiency of the TEG module is defined as the work rate of module [Ŵ] to the heat input by the module [$\dot{Q_h}$] and is gives as:

$$\hat{W} = \frac{\alpha^2 T_c^2 [(\frac{T_h}{T_c})^{-1} - 1]^2 (\frac{R_L}{R})}{R(1 + \frac{R_L}{R})^2} \quad \ldots\ldots 3.44$$

from this equation we have

$$\eta_{con} = \frac{\hat{W}}{\dot{Q_h}}$$

$$= \frac{(\frac{\alpha(T_h - T_c)}{R_L + R})^2 R_L}{\alpha T_h I - \frac{1}{2} I^2 R + K(T_h - T_c)}$$

$$= \frac{(1 - \frac{T_h}{T_c})(\frac{R_L}{R})}{(1 - \frac{R_L}{R}) - \frac{1}{2}(1 - \frac{T_h}{T_c}) + \frac{(1 + \frac{R_L}{R})^2 \frac{T_h}{T_c}}{ZT_c}}$$

The maximum thermal efficiency of the TEG module is obtained by differentiation of efficiency with respect to $\frac{R_L}{R}$. we have:

$\frac{d(\eta_{con})}{d(\frac{R_L}{R})}$ =0 it gives as $\frac{R_L}{R} = \sqrt{1 + ZT}$ where T is the temperature between hot junction is given by T $= \frac{T_h + T_c}{2} = \frac{1}{2} T_c [1 + (\frac{T_h}{T_c})^{-1}]$ finally the conversion efficiency of the TEG is

$$\eta_{con} = \frac{\Delta T}{T_h} \frac{\sqrt{ZT+1} - 1}{\sqrt{ZT+1} + \frac{T_h}{T_c}} \quad \text{..........3.45}$$

3.5.6 Selection and specification of thermoelectric (TE) type

Selection and specification of TE module type is under taken by consideration of basic performance indicator parameters of the TE module. These basic indicators are undertaken by comparing with other commercially available form of module, such basic performance indicator parameters are commercially availability, efficiency(η_{con},) interval of operating range of temperature ($\Delta \boldsymbol{T}$), open circuit voltage (V_{oc}), voltage maximum power (V_{mp}),short circuit current (I_{sc}), current maximum power (I_{mp}),maximum power(P_{max}),and internal resistance(R) [33].

3.5.7 The working principle of the TEG module

Thermoelectric effect was first discovered in 1822 by Thomson Seebeck. During his observation voltage is developed by a circuit which is made from two different conductive materials, and when one of the junctions heated. When a temperature difference between two junctions is created, a voltage (V) is produced between its open ends [2].

The developed voltage (V) is proportional to the temperature difference between the junctions of the materials. The proportionality constant called seebeck effect and given by equation as:

$$V = \alpha(T_h - T_c) \quad \text{..........3.46}$$

Where:

α and $(T_h - T_c)$ are the coefficient of seebeck effect, which the material performance conversion of heat to voltage and the temperature difference between hot side junction and cold side junction.

The parameter is the figure of merit ($\boldsymbol{ZT}$) which can be highly affect performance of efficiency is defined as dimensionless parameter and the product ($\boldsymbol{Z}$) and absolute temperature ($\boldsymbol{T}$). The figure of merit ($\boldsymbol{Z}$) is given as:

$$(\boldsymbol{Z}) = \frac{\alpha^2\sigma}{\boldsymbol{K}} = \frac{\alpha^2}{\boldsymbol{K}\rho}$$

Where

K, σ, ρ are thermal conductivity of module, electrical conductivity, and electrical resistivity of the module. The figure of merit is highly affected by above those mentioned parameters such as electrical conductivity, thermal conductivity and electrical resistivity. When the temperature rise thermal conductivity property and electrical resistivity also increases, due to this the resistivity of voltage developing (V) and current flow (I)is decreases in the TE.

3.5.8 Electrical power development in module

From the thermal or energy theorem, by using the first law of thermodynamics and from Forier heat transfer analysis equation in the TE module, the governing equation can be obtained from the heat input rate ($\dot{Q_h}$) in hot side and heat output rate ($\dot{Q_c}$) from cold side. Then power (P_{dev}) is developed between the hot side (T_h) and the cold side (T_c), and is obtained by energy balancing around the hot junction and cold junction, respectively [30].

$$\dot{Q_h} = 2\alpha T_h \mathrm{I} - \frac{1}{2} I^2 \mathrm{R} + 2\mathrm{K}(T_h - T_c) \qquad 3.47$$

$$\dot{Q_c} = 2\alpha T_c \mathrm{I} + \frac{1}{2} I^2 \mathrm{R} + 2\mathrm{K}(T_c - T_h) \qquad 3.48$$

Because of $\alpha = 2\alpha$ which means $(\alpha_p + \alpha_n)$ because α_p and α_n have same sign and magnitude , R is electrical resistance which is equal to $(\frac{\rho_{PL_p}}{A_p} + \frac{\rho_{nL_n}}{A_n})$ and K = 2K is equal to $(\frac{K_pA_p}{L_p} + \frac{K_nA_N}{L_N})$ because $\frac{K_pA_p}{L_p}$ and $\frac{K_nA_N}{L_N}$ have same sign and magnitude and is called thermal resistance of module.

Therefore, the power developed or produced per couple P_{dev} is the difference between $\dot{Q_h}$ And $\dot{Q_c}$ Gives as:

P_{dev} = Q_h- Q_c

= $2[\alpha I(T_h - T_c) - I^2 R]$

=$2(\alpha I\Delta T - I^2 R)$ where R=$\frac{\rho L}{A}$ therefore

P_{dev}=$2(\alpha I\Delta T - I^2 \frac{\rho L}{A})$……………………………………………………………3.49

Where: ΔT is $T_h - T_c$, A is the area of the thermo element (leg), L is its length, k is the thermal conductivity, ρ is the electrical resistivity, and I is the electrical current.

The open circuit voltage (V_{oc}) is the maximum voltage because of the circuit is open and resistance at whole, the open circuit voltage (V_{oc}) is given by the equation:

$(V_{oc}) = 2\alpha\Delta T$…………………………………………………………………………3.50

The current through module is given by ohms' law:

I =$\frac{\alpha A(T_h - T_c)}{\rho L(R_L + R)}$ where ΔT=$T_h - T_c$ and R_L + R= (1+$\frac{R_L}{R}$)

I = $\frac{\alpha A\Delta T}{\rho L(1+\frac{R_L}{R})}$, let m=$\frac{R_L}{R}$ and R_L is external load resistance

I =$\frac{\alpha A\Delta T}{\rho L(1+m)}$ ……………………………………………………………………3.51

In order to get the power produced with respect to material property and geometry of thermoelectric module, at a given operating temperature power is evaluated by equating eq (3.49) in eq (3.47), we have

$p_{del\,max}$ =$2\frac{m}{(1+m)^2}\frac{\alpha^2}{\rho}\frac{A}{L}\Delta T^2$ ………………………………………….……………….3.52

In consideration number of the thermo couples in module, by applying the same relationship in open circuit voltage(V_{oc},) in short circuit current (I_{SC}), and in maximum power cases(p_{max}) formulated as follows:

V_{oc} = $2\alpha N\Delta T$……………………………………………………………………….3.53

V_{mp} =$\frac{V_{oc}}{2}$ = $\alpha N\Delta T$………………………………………………………………......3.54

I_{SC} =$\frac{\alpha}{\rho}\frac{A}{L}\Delta T$ …………………………………………………………………........3.55

$$I_{mp} = \frac{1}{2}\frac{\alpha}{\rho}\frac{A}{L}\Delta T \qquad 3.56$$

$$P_{max} = V_{mp}.I_{SC}$$

$$P_{max} = \frac{1}{2}\frac{\alpha^2}{\rho}\frac{NA}{L}\Delta T^2 \qquad 3.57$$

In general form, heat transfer development in a thermoelectric module and the amount electrical energy developed from the module is correlated with different formulas, theorems, principles, and postulates. Finally, it indicates the principles of conservation energy and conversion energy from one form to other.

CHAPTER FOUR

4. Analytical modeling of heat transfer and simulation in non-skirt stove

In this chapter, the basic stove performance indicator parameters were evaluated. These parameters are stated and evaluated by using fundamental theories, formulas, estimation, assumption and other mechanism from related literature reviews. The parameters listed as below:

- The amount of heat energy developed from the biomass fuel during the combustion,
- Heat transfer analytical modeling heat flow from the fire flame to the wall of combustion chamber, and interior wall of stove by convection heat transfer method and radiation heat transfer method,
- Heat transfer analytical modeling heat flow from flame to the bottom surface of the pot by both convection heat transfer method and radiation heat transfer method,
- Heat transfer losses in entire stove walls due to convection heat transfer method and radiation heat transfer method,
- The contribution of both convection heat transfer and radiation heat transfer in the stove performance,
- The energy balance and thermal efficiency,
- Validation of result with simulation and related literature reviews.

4.1 Analytical modeling of heat transfer in non-skirt Tikikl stove

4.1.1 The amount of heat energy developed from the biomass fuel during the combustion:

Energy developed from biomass fuel was obtained by taking assumption from estimated values are [27]:

Initial mass of fuel m_f = 5kg

Combusted mass m_c =4.6kg

NHV wood fuel = (18,595kJ/kg experimental acceptable

HHV of wood fuel = 19,500Kj/kg experimental acceptable

The input energy (q_i) =NHV $_{\text{wood fuel}}$ $\times m_f$ - HHV $_{\text{wood fuel}}$ $\times \mathrm{m_c}$

q_{in} =5kg×18,595KJ/kg - 4.6kg ×19,500KJ/kg = 3.275 x10^3 KJ

4.1.2 Conduction heat loss to base plate

$A_{\text{ceramic comustion chamber bed}} = 0.02835287m^2$

$K_{\text{ceramic comustion chamber bed}} = 1\frac{w}{k.m}$

$L_{\text{ceramic comustion chamber bed}}$= 0.025m and

$R_{\text{ceramic comustion chamber bed}} = \frac{L_{\text{ceramic comustion chamber bed}}}{K_{\text{ceramic comustion chamber bed}}}$ =0.025m

$T_{\text{ceramic comustion chamber bed}} = 582\ ^0K$

$T_{\text{stove intire}} = 453.4\ ^0K$

$Q_{\text{cond.loss comb.chamber bed}} = \frac{A_{\text{ comustion chamber bed}} \cdot (T_{\text{comb.chamber bed}} - T_{\text{stove intire}})}{R_{\text{ceramic comustion chamber bed}}}$ = 147 W

4.1.3 Heat transfer analysis between flame and inner combustion chamber wall by convection heat transfer and radiation heat transfer

Before doing the heat transfer analysis some of specified parameters to be done for simplification of assumption and this value were obtained from simulation from basic ideal gasses equation and from.

$m_{\text{ flow rate}} = 5.34\times10^{-3}\ {kg}/{s}$

$T_{gas} = 800\ ^0K$ flame gas temperature

$T_{pot} = 368.5\ ^0K$ average pot surface temperature

$R_{\text{ univesal gas const.}} = 8.3143\frac{K}{k.mol}$ mo. Mass of air at $P_{\text{ atm}}$ = 76 KPa $m_{\text{mass of air}} = 28.97 \frac{gm}{mol}$

Diameter of combustion chamber wall is about $D_{\text{chamber wall}}$ =150mm

$R_{\text{ air}} = \frac{\mathbf{R}_{\textit{ univesal gas const.}}}{m_{\text{mass of air}}} = \frac{8.3143\frac{K}{k.mol}}{28.97\frac{gm}{mol}} = 287\frac{J}{K.Kg}$ is the specific gas constant of combusting gases.

$\rho_{gas} = \frac{P_{\text{ atm}}}{R_{\text{ air}} \cdot T_{gas}} = \frac{1.01325\times10^3\ pa}{286.997\frac{J}{K.Kg}\times800\ k} = 0.4\frac{Kg}{m^3}$

$$A_{combustion\ chamber} = \frac{\pi\ D_{\text{chamber wall}}^{2}}{4} = \frac{\pi\ 150^2}{4} = 17.66\times 10^{-3} m^2$$

$$v_{gasses\ chamber} = \frac{\text{m}_{\text{ flow rate}}}{A_{\text{combustion chamber}} \cdot \rho_{gas}} = \frac{5.34\times10{-3}\ {kg}/{s}}{17.66\times10^{-3} m^2 \times 0.4 \frac{Kg}{m^3}} = 0.755\ \frac{m}{s}$$

From basic Bernoulli's equation:

$\frac{P_1}{\rho} + \frac{1}{2} v_1^2 + gz_1 = \frac{P_2}{\rho} + \frac{1}{2} v_2^2 + gz_2$ and initial boundary condition inlet velocity assumed to be $v_1 = 0$ .Then Bernoulli's equation can reduced as follows

$\frac{P_2 - P_1}{\rho} + \frac{1}{2}(v_2^2 - v_1^2) + gz_2 - z_1$ where $z_2 = z_1 = 0$ and $\frac{P_1 - P_2}{\rho} = P_{guage} = \frac{1}{2}(v_2^2 - v_1^2)$

$$P_{guage} = \frac{1}{2}\rho\,(gasses\ \ chamber)^2 = \frac{1}{2}\times 0.4\frac{kg}{m^3}(0.755\ \frac{m}{s})^2 = 0.114 \text{ pa}$$

Nominal absolute viscosity of air at 1atm and $T_0 = 273\ ^0K$

$\mu_0 = 1.71\times10^{-5}$ kg/m. s and μ gas $= \mu_0 \left(\frac{T_{gas}}{T0}\right)^{.7} = 3.6\times10^{-5}$kg/m. s

$$Re_{com.chamber} = \frac{\rho\ v_{gasses\ chamber} \cdot D_{\text{chamber wall}}}{\mu \text{ gas}} = \frac{0.4\frac{Kg}{m^3}\times .0.755\ \frac{m}{s}\times .15m}{3.6x\ 10^{-5}kg/m.s.} = 1.258\times10^3$$

For fully developed internal flow Reynolds number less than 2300 (Re < 2300) are laminar flow Reynolds number approximation for fully developed internal flow through circular pipe [27].

4.1.4 Convection heat transfer loss in inner combustion chamber wall

$$Q_{conv\_cham.wall} = h_{cham.wall} \times A_{chamber\ wall}\,(T_{flame} - T_{wall\ surface})$$

Where

$h_{cham.wall} = 205$mm

$D_{\text{chamber wall}} = 150$mm, and

$A_{\text{chamber wall}} = \pi h_{cham.wall} \cdot D_{\text{chamber wal}} = 0.0966m^2$ Is Effective chamber surface area

$T_{flame} = 800\ ^0K$ Average chamber wall surface flame temperature

$T_{wall\ surface} = 792\ ^0K$ average chamber wall surface temperature.

The friction factor between flame gases and wall surface of combustion chamber is assumed to be fully developed internal flow contained by smooth walls:

$f=\frac{64}{Re_{com.chamber}}$ = 0.051 Prandtl number (ration of thermal dissipation conduction)

$pr = \frac{\mu\, gas.c_{p.gass}}{K_{gass}} = \frac{3.6\times10^{-5}\times1006.43}{10.5\times10^{-2}}$ =.345

Nusselt Number for flow in circular tube. The effects of wall roughness and laminar flow conditions (Re <2300) may be considered by using the Gnielinski correlation, Nusselt Number represents a dimensionless temperature gradient at the surface. (Equation 8.57, cengel, Incropera) [34] .

$$NU = \frac{h_{cham.wall.}D_{\text{chamber wall}}}{K_{gass}} = .3 + \frac{.62\, Re_{com.chamber}{}^{1/2}.pr^{1/3}}{[1+(.4pr)^{2/3}]^{1/4}}\left[1+\left(\frac{Re_{com.chamber}}{282000}\right)^{5/8}\right]^{4/5}$$

$$=3+\frac{.62\times(1258)^{1/2}.345^{1/3}}{[1+(.4/.345)^{2/3}]^{1/4}}\left[1+\left(\frac{(1258)}{282000}\right)^{5/8}\right]^{4/5} = 16.15, \text{ and}$$

$h_{cham.air} = \frac{NU.K_{gass}}{D_{\text{chamber wall}}} = \frac{16.15\ \times.105}{.15} = 11.3\ \frac{w}{K.m^2}$, Then the heat transfer loss in inner combustion chamber wall is evaluated as:

$$q_{conve.chamber} = h_{cham.air}.\, A_{\text{chamber wall}}\, (T_{flame} - T_{wall\ surface})$$

$$= 11.3 \times 0.0966(800\text{-}792) = 90.4 \text{ w}$$

4.1.5 Heat transfer by Radiation

Radiative heat transfer does not require a medium to pass through. Thus, it is the only form of heat transfer present in vacuum. It uses electromagnetic radiation (photons), which travels at the speed of light and is emitted by any matter with temperature above 0 degrees Kelvin (-273 °C). Radiative heat transfer occurs when the emitted radiation strikes another body and is absorbed.

Radiation is modelled by the Stefan-Boltzmann Law,

$$Q = \varepsilon\, \sigma\, [T_s^4 - T_\infty^4]$$

Where; Q= heat transfer

σ = Stefan-Boltzmann constant

α = Absorptivity

ε = Emissivity

T_s = Surface Temperature

T_∞ = Ambient Fluid (air) Temperature

- Estimated length of combustion chamber (L) = 205mm
- Estimated effective perimeter of inner combustion chamber (P) = 0.471 m
- Estimated effective perimeter of outer steel cover wall (P) = 0.64684
- Effective radius of outer steel cover walls (R) = 103 mm
- Effective radius of inner combustion chamber (R) = 75mm
- Surface area of inner combustion chamber (A) = 0.096555 m^2
- Surface area of ceramic base plate (A) = 28352.87 mm^2

$T_{inner\ cylinder}$ = 792 ^{0}KAverage steady state surface temperature of inner cylinder

ϵ_{flame} = 0.72 Estimated emissivity value of diffusion flame from literature

ϵ_{wood} = 0.85 Estimated emissivity value of burning wood from literature

ϵ_{clay} = 0.75 = ϵ inner cylinder Estimated emissivity value of ceramic baseplate

ϵ_{metal} = 0.26 Emissivity metal chamber

σ = 5.67 x 10^{-8} $\frac{w}{m^2K^4}$ Stefan –Boltzmann constant

4.1.6 Radiation loss to walls of combustion chamber (inner cylindrical parts of the stove):

Due to radiation heat transfer between the flame and inner part of cylinder, there will be radiation loss occurrences between the flame and wall of the ceramic part. This amount of steady state heat loss can be calculated as;

$$Q_{rad.loss\ com.chamber} = \frac{\sigma_{stefan} \cdot A_{inner\ com.chamber}\,(T^4_{surface\ tem.com.chamber\ wall} - T^4_{ave.temperature})}{\frac{1}{\epsilon} + \frac{1-\epsilon R_{inner\ combustion\ chamber}}{\epsilon R_{outer\ combustion\ chamber}}}$$

Average steady state surface temperature of flames and wood is estimated as follow: estimated temperature of fire wood is equal 353 ^{0}K

$T_{averge} = 0.6T_{flame} + 0.4T_{wood}$ = .6(792) +.4(353) = 616.4 ^{0}K

length of combustion chamber (L) = 205mm

radius of inner combustion chamber (R) = 75mm

perimeter of inner combustion chamber (P) = 0.471 m inner combustion chamber ($A_{inner\ com.chamber}$) = 0.097 m^2

Area weighted average emissivity for this region (i.e. metal and clay)

$$\epsilon = \frac{\epsilon_{clay}A_{clay}+\epsilon_{meta}A_{metal}}{A_{clay}+A_{metal}} = \frac{0.75(0.028)+.26(.11)}{0.028+.11} = .35$$

$$Q_{\text{radiation loss to wall of combustion chamber}} = \frac{5.67\text{x }10^{-8}\text{ x }(0.097)\text{x}(792^4-616.4^4)}{\frac{1}{.35}+\frac{1-.35}{.35}(\frac{0.075}{.103})} = 326.2 \text{ w}$$

4.1.7 Convection heat transfer from gases to pot bottom

$$Q_{conv\ pot.bottom} = h_{pot.bottom} \times A_{pot.bottom}(T_{gas} - T_{pot.bottom})$$

Where

Assume the space created by pot gap and stoves pot holder behaves like two parallel plates

$he._{air\ gap}$ =25mm

D_{pot} =160mm, and

$A_{pot.bottom} = \frac{D_{pot}{}^2\pi}{4}$ = 0.0201 m^2 Is Effective bottom pot exposed surface area to flame gasses

$A_{air\ .gap} = \pi h_{air\ gap}.\ D_{pot}$ = 0.01256 m^2

Estimated flame gas velocity flowing through pot and stove gap area can evaluated by

$v_{gair\ .gap} = \frac{m_{\text{flow rate}}}{A_{air\ .gap}\cdot\rho_{gas}} = \frac{5.34\times10{-3}\ ^{kg}/_{s}}{0.01256\text{ m}2\times 0.4\frac{Kg}{m^3}}$ =1.063 $\frac{m}{s}$ and Hydraulic diameter definition between two parallel plates $D_h = 2h_{air\ gap}$ =50 mm

$Re_{air\ .gap} = \frac{\rho\ v_{gair\ .gap}\ .D_{pot}}{\mu_{gas}} = \frac{0.4\frac{kg}{m^3}\times 1.063\frac{m}{s}\times .16\text{ m}}{3.6\text{x }10^{-5}\text{kg/m.s.}}$ = 1,889, the flow through pot gap is less turbulent than in the gap between pot and flame

Prandtl number (ration of thermal dissipation conduction)

$pr = \frac{\mu_{gas}.c_{p.gass}}{K_{gass}} = \frac{3.6\times10^{-5}\times624}{10.5\times10^{-2}}$ = 0.214 , where both specific heat capacity of air and Thermal conductivity of air are depending on average gas temperature.

$$NU = \frac{h_{air\ gap}.D_{pot}}{K_{gass}} = .3 + \frac{.62\ Re_{air\ .gap}{}^{1/2}.pr^{1/3}}{[1+(.4pr)^{2/3}]^{1/4}}[1+(\frac{Re_{cair\ .gap}}{282000})^{5/8}]^{4/5}$$

$=3+\frac{.62\times(1,889)^{1/2}.214^{1/3}}{[1+(.4/.214)^{2/3}]^{1/4}}[1+(\frac{1,889}{282000})^{5/8}]^{4/5}=16.24$, and

$h_{air\ gap}=\frac{NU.K_{gass}}{D_{pot}}=\frac{16.24\times.105}{.16}=10.66\frac{w}{K.m^2}$

During combustion flame radiation can increase the magnitude of the convective heat transfer coefficient anywhere from 2.3x to 3.4x (Viskanta, R.) This is more realistic expression of impinging flame jet flow exhibited in stove [35].

$h_{conv,low\ flame}=2.3h_{conv}=2.3\times10.66\frac{w}{K.m^2}=24.5\frac{w}{K.m^2}$

$h_{conv,high\ flame}=3.4h_{conv}=3.4\times10.66\frac{w}{K.m^2}=36.244\frac{w}{K.m^2}$, by taking assumption value for the convective heat transfer coefficient $h_{air\ gap}$ is about 36.244

$T_{gass}=786\ ^0K$Average estimated gasses pot bottom surface flame temperature

$T_{pot.bottom}=397\ ^0K$ average estimated pot surface temperature.

$Q_{conv\ pot.bottom}=h_{pot.bottom}\cdot A_{pot.bottom}(T_{gas}-T_{pot.bottom})$

$=36.244\times0.0201(786-397)=283.4$ W

4.1.8 Radiation heat transfer from flame to pot bottom

It is total radiation heat transfer supplied to pot bottom from the flame sheet. Assuming pot is a black body (i.e. ε = α = 1, radiation is diffuse, or directionally independent), and reflectivity of flames is negligible.

$Q_{ra.gain\ pot\ bottom}=\sigma_{stefan}F_{flame}\cdot A_{pot\ bottom}(\epsilon_{flame}\cdot T^4_{flame\ temp.}-T^4_{pot\ surface\ temp.})$

$T_{flame\ tempterure}=789.7\ ^0K$ Average temperature of emitting area

$T_{pot\ surface}=396.5\ ^0K$ Average temperature of pot surface

$R_{flame}=89$ mm radius of effective emitting flame area

$R_{pot.bottom}=80$ mm radius of pot bottom

$L_{flame}=25$ mm separation distance between two effective areas

$A_{flame}=\pi R^2_{flame}=0.02487\ m^2$ effective emitting flame area

$A_{pot\ bottom}=\pi R^2_{pot.bottom}=0.020096\ m^2$ effective area intercepted by pot bottom

Variable simplification for view factor calculation

$$s_{\text{flame-veiw}} = 1+\frac{1+(\frac{R_{\text{pot.bottom}}}{L_{\text{flame}}})^2}{(\frac{R_{\text{flame}}}{L_{\text{flame}}})^2} = 1.9$$ and View factor ($F_{\text{flame-in out}}$):

$$F_{\text{flame-in out}}= \frac{1}{2}[s_{\text{flame-veiw}} - [s^2_{\text{flame-veiw}} - 4(\frac{R_{\text{flame in}}}{R_{\text{flame out}}})^2]^{\frac{1}{2}}]$$

$$= \frac{1}{2}[1.9 - [1.9^2 - 4(\frac{80}{89})^2]^{\frac{1}{2}}] = 0.64$$

There fore

$$Q_{\text{rad.gain to pot bott}} = \sigma_{stefan} F_{flame} \cdot A_{pot\ bottom} (\epsilon_{\text{flame}} \cdot T^4_{\text{flame tempt.}} - T^4_{\text{pot surface temp.}})$$

$$= 5.67 \text{ x } 10^{-8} \text{ x } 0.64 \ \ 0.02487\text{x}(0.72 \cdot (789.7)^4 - (396.5)^4)$$

$$= 230.\text{W}$$

4.1.9 Convection heat transfer from pot holder to the surface pot

$$Q_{\text{conv}\ pot.holder} = h_{\text{pot.holder}} \cdot A_{\text{pot.holder}} (T_{gas} - T_{pot.holder})$$

Where

Gas temperature as it exits the pot gap and travels up the sides of the pot is estimated the outlet temperature of flame gases is 730 ^{0}K.

T_{gas} = 730 ^{0}K estimated flame gas temperature surface of pot holder

$T_{pot.holder}$ =452 ^{0}K estimated average temperature of pot holder

$he._{\text{pot.holder}}$ =25mm

$Do._{\text{pot.holder}}$ =160mm,

$t._{\text{pot.holder}}$ =3mm

$Di._{\text{pot.holder}} = Do._{\text{pot.holder}} - 2t._{\text{pot.holder}}$ =154mm

$A_{pot.holder} = 2\pi he._{\text{pot.holder}} \cdot Di._{\text{pot.holder}}$ = 0.0121 m^2 and Hydraulic diameter definition between two parallel plates $D_h = 2he_{\text{pot.holder}}$ =50 mm

$$v_{\text{air gap pot.holder}} = \frac{m_{\text{flow rate}}}{A_{pot.holder} \cdot \rho_{\text{gas}}} = \frac{5.34\times10{-3}\ kg/_s}{0.0121\ \text{m2}\times 0.4\frac{Kg}{m^3}} = 1.1\frac{m}{s}$$

$Re_{\text{air gap } pot.holder} = \frac{\rho \, v_{\text{air gap pot.holder}} \cdot Di_{pot}}{\mu_{gas}} = \frac{0.4\frac{kg}{m^3} \times 1.1\frac{m}{s} \times .154 \text{ m}}{3.6x\,10^{-5} kg/m.s.}$ =1,882 , the flow through pot holder and air gap is less turbulent than therefore it is fully laminar flow.

$pr = \frac{\mu_{gas} . c_{p.gass}}{K_{gass}} = \frac{3.6\times10^{-5}\times624}{10.5\times10^{-2}} = 0.214$, where both specific heat capacity of air and thermal conductivity of air are depending on average gas temperature. The Nusselt number, assuming fully developed laminar flow, and near the wall of pot holder perfectly insulated and side pot surface held at uniform temperature.

$$NU = \frac{h_{pot.holder} . Di_{pot}}{K_{gass}} = .3 + \frac{.62 \, Re_{pot.holder}^{1/2} . pr^{1/3}}{[1+(.4pr)^{2/3}]^{1/4}} [1 + (\frac{Re_{pot.holder}}{282000})^{5/8}]^{4/5}$$

$$= 3 + \frac{.62\times(1{,}882)^{1/2} .214^{1/3}}{[1+(.4/.214)^{2/3}]^{1/4}} [1 + (\frac{1{,}882}{282000})^{5/8}]^{4/5} = 16.2 \text{ and ,}$$

$$h_{pot.holder} = \frac{NU * K_{gass}}{Di_{pot.holder}} = \frac{16.2 \times 105}{.154} = 11 \frac{w}{K.m^2}$$

And by taking $h_{conv,high\,flame} = 3.4 h_{conv} = 3.4 \times 11 \frac{w}{K.m^2} = 37.4 \frac{w}{K.m^2}$

$$Q_{conv\, pot.holder} = h_{pot.holder} \times A_{pot.holder} (T_{gas} - T_{pot.holder})$$

$$= 37.4 \times 0.0121 \,(730 - 452) = 126. \text{ W}$$

4.1.10 Radiation deflected from pot holder to pot bottom:

The rate at which radiation leaves flames and is intercepted by pot holder. i.e. the rate at which radiation leaves and deflected pot holder and is intercepted by pot.

$$Q_{Rad\_flames\ to\ pot\ holder} = A_{flame-\ to\ pot\ holder} \times F_{flame-to\ pot\ holder} \times J_{flame-to\ pot\ holder}$$

Where

$R_{\text{pot holder inner}} = 154mm$

$A_{\text{pot holder inner}} = 0.0186 m^2$

$L_{\text{pot holder}} = 25mm$

$\epsilon_{\text{pot holder}} = 0.26$

$\rho_{\text{pot holder}} = 1 - \epsilon_{\text{pot holder}} = .74$

$$J_{flame-to\ pot\ holder} = \sigma_{stefan} \times \epsilon_{flame} \times T^4_{flame\ tempterure} = 15{,}876.8 \frac{W}{m^2}$$

Variable simplification for view factor calculation

$$s_{\text{flame-veiw}} = 1 + \frac{1+\left(\frac{R_{\text{pot holder inner}}}{L_{\text{pot holder}}}\right)^2}{\left(\frac{\text{pot holder outer}}{L_{\text{pot holder}}}\right)^2} = 1.95$$ and View factor ($F_{\text{flame-in out}}$):

$$F_{\text{flame-in out}} = \frac{1}{2}\left[s_{\text{flame-veiw}} - \left[s^2_{\text{flame-veiw}} - 4\left(\frac{R_{\text{flame in}}}{R_{\text{flame out}}}\right)^2\right]^{\frac{1}{2}}\right] = 0.82$$,For emission + reflected irradiation from flame to pot holder surface. Assuming flames have negligible reflectivity.

$$Q_{\text{Rad \_ flames to pot holder}} = J_{\text{flame-to pot holder}} . F_{flame - \text{to pot holder}} . A_{\text{flame-to pot holder}}$$

$$= 15{,}876.8 \times 0.82 \times 0.0186 = 242.4 \text{ W}$$

4.1.11 Wasted heat out the top of the stove

$$Q_{\text{waste}} = m_{\text{flow in stove}} . C_{p \text{ gass out let}} (T_{\text{gass out let}} - T_{\text{ambeint}}) = 881 \text{ w}$$

Where

$T_{\text{gass out let}} = 461\,^0K$

$T_{\text{ambeint}} = 300\,^0K$

$C_{p \text{ gass out let}} = 1.025 \times 10^3\ {}^{K}/_{kg.K}$ depends in temperature (cengel heat transfer)

$m_{\text{flow in stove}} = 5.34\times10^{-3}\ {}^{kg}/_{s}$

Total heat utilized (Q_{utilized}) = the summation of both convection heat transfer energy and radiative heat transfer energy total gained by the stove.

$$Q_{\text{utilized}} = Q_{\text{conv } pot.bottom} + Q_{\text{conv } pot.holder} + Q_{\text{rad.gain pot bottom}} + Q_{\text{Rad flames to pot holder}}$$

$$= (283.4 + 126 + 230 + 242.4) \text{ W}$$

$$= 881.8\text{W}$$

Total heat losses (Q_{losed}) = the summation of all form of the heat transfer losses. Such conduction loss, convection heat transfer loss and radiative heat transfer loss in the stove.

$$Q_{\text{losed}} = Q_{\text{cond.loss chamber bed}} + Q_{\text{conv \_cham.wall}} + Q_{\text{rad.loss com.chamber}}$$

$$= (147 + 90.4 + 326.2) \text{ W}$$

= 563.6W

Thermal Efficiency ($\eta_{th\ stove}$) = $\frac{\text{Total heat utilized}}{Total\ heat\ produced}$ = $\frac{881.8\text{ W}}{3.275\text{ x}10^3\ kw}$ × 1oo

=**27**%

4.2 System simulation by Computational Fluid Dynamics

The simulation undergoes over combination of stove system. Which contains stove, flame, pot holder, pot, and water in pot. In this system simulation all type of heat transfer mechanism or modes such conduction, convection (forced and natural), and radiation addressed.in the modelling of Computational Fluid Dynamics is fluid flow Fluent. The computational fluid dynamics (CFD) heat transfer analysis in the tikikl cook stove is modelled by the considering; 3D heat transfers fluent simulation,3D model assembled geometry, incompressible and laminar flow. It is also assumed to be steady where the flow variables become independent of time.

4.2.1 Governing Equations

The fluid flow fluent modelling in cook stove have to be governed by basic thermodynamics laws and by newton’s laws flows. Governing equations are such as; conservation of mass (continuity) equation, conservation of momentum (Naiver- stokes equation) and conservation of energy (energy equation). These basic governed equations used to evaluate unknown fundamental variables those determines the performance and efficiency of cook stove. these variables are: the temperature distribution, enthalpy h (or internal energy, *u*), velocity *v*, pressure p, viscosity μ, density ρ, and thermal conductivity k.

4.2.2 Energy Equation

One of the most fundamental laws in nature is the **first law of thermodynamics,** also known as the **conservation of energy principle,** which provides a sound basis for studying the relationships among the various forms of energy and energy interactions. This means that the amount of energy entering a system must equal the amount of energy leaving them system. The 3-dimensional energy equation for fluid flow is provided below in equation

$$\frac{\partial}{\partial t}(\rho c_p T)+\frac{\partial}{\partial x}(\rho v_x c_p T)+\frac{\partial}{\partial y}(\rho v_y c_p T)+\frac{\partial}{\partial z}(\rho v_z c_p T)=\frac{\partial}{\partial x}(K_{xx}\frac{\partial}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial}{\partial y})+$$
$$+\frac{\partial}{\partial z}(K_{zz}\frac{\partial}{\partial z})+Q_V \quad \ldots\ldots 4.1$$

4.2.3 The energy balance of the system

The energy balance of the system is defined as: the net rate at which heat transfer energy is being transferred in *rate at time(T)* minus the net rate at which energy is being transferred out by work at *time* T. A cook stove is evaluated assuming isobaric steady-flow conditions where bulk mass flow rate remains constant. These assumptions ignore transient effects since these add significant complexity to the energy balance calculations with minimal gains in accuracy. In general energy balance can expressed in cooking stove in differential form is:

$dE = \delta Q - \delta W$……………………………………………………………………….4.2

where:

dE is the differential of energy, a property. Since δQ and δW are not properties, therefore their differentials are written as Q and W, respectively.

$dE/dt = \frac{dQ}{dt} - \frac{dW}{dt}$ then Based on these assumptions, the energy balance of a cook stove is evaluated through the following relationships;

The rate of Energy transfers in = The rate of Energy transfers out

$q_i' + \hat{W}_i' + \sum_i \dot{m}_i \theta = q_o' + \hat{W}_o' + \sum_o \dot{m}_o \theta$……………………………………………4.3

$(q_i' - q_o') = \dot{m}(\theta_o - \theta_i)$

$= \dot{m}(h_o - h_i)$

$= \dot{m} c_{p.average}(T_o - T_i)$

Where: subscripts *i* and *o* – initial and final variables, respectively.

$q^{\cdot}$ Is rate of heat transfer

$\hat{W}$ is the rate work

$c_{p.average}$ is average constant pressure specific heat

T is Gas temperature

4.3 variables for fluent fluid flow heat transfer simulation and temperature distribution

4.3.1 Reynold number

Is Used to identify the type of fluid flow, and if Reynolds number is less than or (Re < 2300) is laminar flow. In this simulation the laminar flow model is fully developed because the fluid flow smooth. In the internal fluid flow Reynolds number is given as Cngel.Y(Heat transfer practical approach. Eq (6-13))[34].

$$\text{Re}_{\text{number}} = \frac{inetial\ force}{viscous\ force} = \frac{\rho\, v_{f\ liud}\, .D_{\text{flow path}}}{\mu\ \text{fliud}} \quad \text{.....................................4.4}$$

Where:

ρ is fluid density

$v_{f\ liud}$ is fluid velocity

$D_{\text{flow path}}$ is dimeter of cross-section area of the flow, and

μ fliud is kinematic viscosity of the fluid

Re < 2300) is laminar flow

$2300 \leq \text{Re} \leq 4000$ Is transitional flow

$\text{Re} \geq 4000$ is turbulent flow

4.3.2 Prandtl Number

The relative thickness of the velocity and the thermal boundary layers is best described by the *dimensionless* parameter Prandtl number, defined as Cengel. Y (Heat transfer practical approach. Eq (6-12))[34].

$$\mathbf{Pr} = \frac{molecular\ diffusivity\ of\ momentum}{molecular\ diffusivity\ of\ heat} = \frac{\nu}{\alpha} = \frac{\mu\ \text{fluid}\ c_{pfluid}}{K_{fliud}} \quad \text{.....................................4.4}$$

Where:

μ fluid is kinematic viscosity of the fluid,

c_{pfluid} is the specific heat capacity of the fluid,

K_{fliud} is the thermal conductivity of the fluid

4.3.3 Nusselt Number

It is common practice to nondimensionalize the governing equations and combine the variables, which group together into *dimensionless numbers* in order to reduce the number of total variables in Cngel.Y(Heat transfer practical approach. Eq (6-8))[34].

$$NU = \frac{h_{fluid} . L_C}{K_{fluid}} = .3 + \frac{.62\, Re_{fluid}^{1/2} . pr^{1/3}}{[1+(.4pr)^{2/3}]^{1/4}} [1 + (\frac{Re_{fliud}}{282000})^{5/8}]^{4/5} \quad \text{.....................4.5}$$

Where

h_{fluid} . is convection heat transfer coefficient

K_{fluid} is the thermal conductivity of the fluid

L_C is the characteristic length.

Re_{fluid} is Reynold number of fluids or flame

pr *is* Prandtl Number of the fluid or flame

Hydraulic diameter: For flow through noncircular pipes, the Reynolds number is based on the hydraulic diameter *Dh* given as below

$$D_h = \frac{4A_c}{p} = \frac{4\,(\pi D^2/4)}{\pi D} = D \quad \text{..4.6}$$

Where:

D_h is hydraulic diameter

A_c is the cross-sectional area of the pipe,

p is its wetted perimeter.

D is for circular pipes diameter, and finally the hydraulic diameter is defined such that it reduces to ordinary diameter D

4.4 The main procedures during the simulation

Geometry of tikikl cook stove is modelled on SOLID work 2019 and simulated in ANSYS 19R1 FLUENT.

- 3-D part drawing like stove, flame part, pot holder, pot and water part are drawn by SOLID work 2019 and assembled.

- Imported to ANSYS $19R_1$ then, the body and its parts are changed in to ANSYS format.
- Differentiation of fluid parts from solid parts. then nominating and naming of the parts.
- After that denoting and naming the boundary condition and meshing the components.
- Inserting the input variables such as temperature, pressure. Velocity, and thermal properties for the denoted boundary conditions.
- Assuming the thermal properties and fluid properties like thermal conductivity, specific heat constant, density …et for boundary conditions and walls.
- Finally computing the result and evaluating result with related literature reviews.

4.4.1 Materials Initial conditions

Material condition in this CFD simulation includes the material and thermal properties of the components of the system that affect the performance of heat transfer and temperature distribution of the stove. The assigned properties in CFD post are used to determine the temperature distribution, the amount of energy developed from the system, Determine the velocity of fluid domain and other related variables. These properties are:

1. Component and its material properties
2. Working fluid and its thermal properties
3. Testing fluid(water) and its thermal properties

4.4.2 Components and material properties

The overall component of this simulation contains stove which made up from clay that has high thermal specific heat capacity with low thermal conductivity factor, and other two components are called pot and pot holder and they are made from steel metal with thermal properties with high thermal conductivity constant.

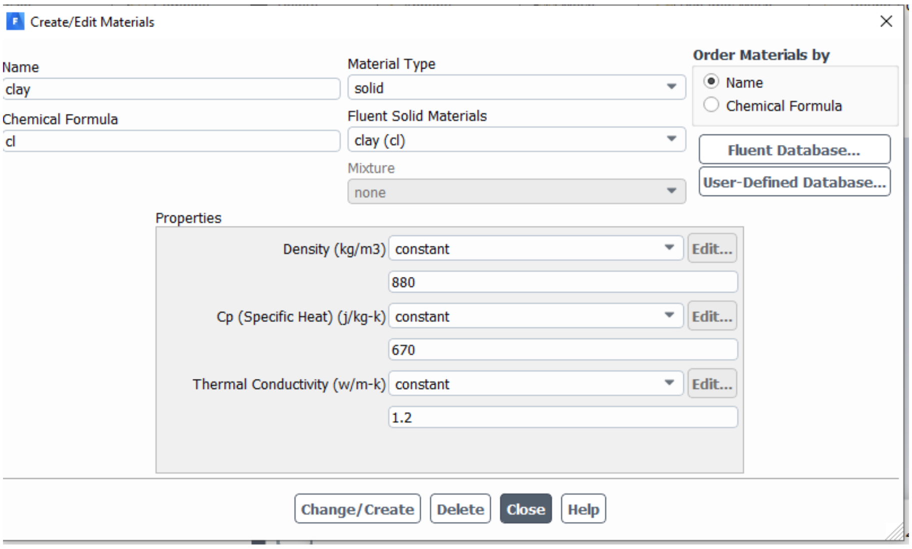


Fig.4.1 Properties of stove material

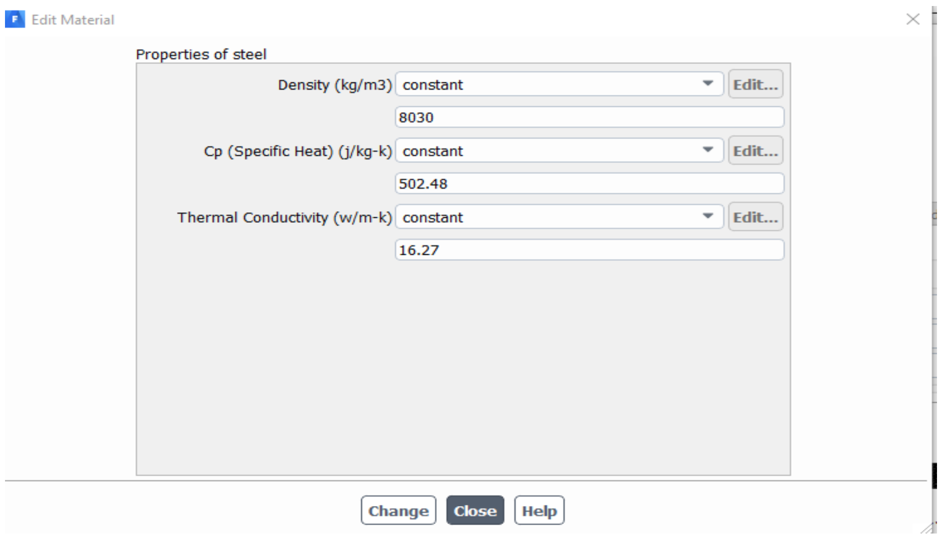


Fig.4.2 Properties pot and pot holder materials

4.4.4 Working fluid and its thermal properties

Air is the **working fluid** specified for the fluid phase occurring in the domain, and even the flame gas rising from the fuel bed is specified as air. The property of air which is available from the FLUENT materials library is used illustrated below.

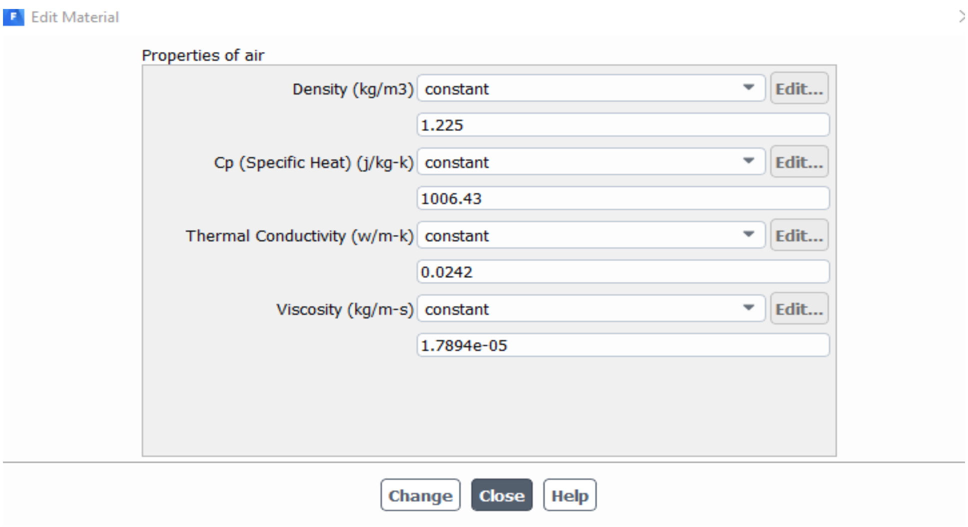


Fig.4.3 Properties of working fluid

4.4.5 Testing fluid(water) and its thermal properties

The water has high thermal or heat capacity (latent heat of evaporation and specific of boiling), used as protocol water boiling test, and as the result it is undertaken in simulation. The following CFD post properties below

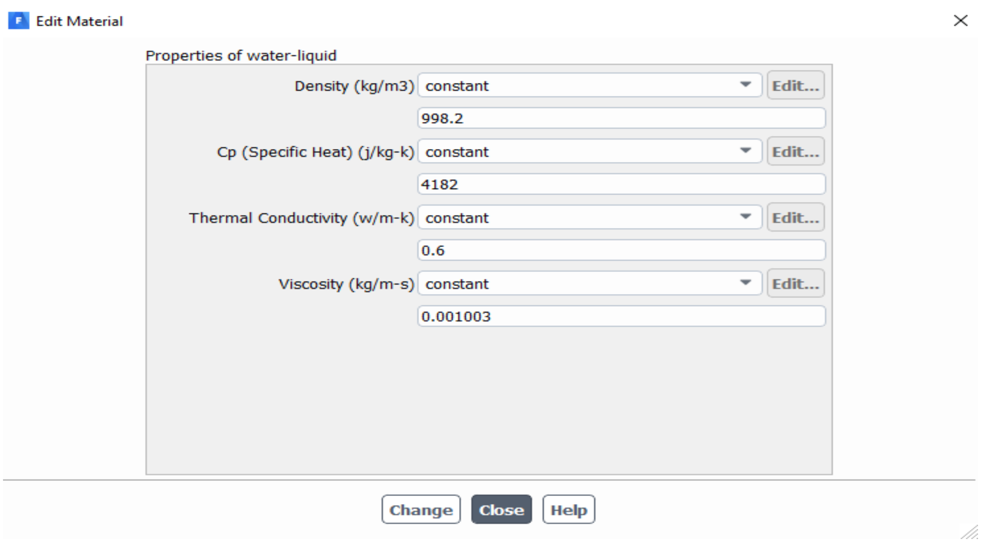


Fig.4.4 Water properties

4.5 Initial and Boundary conditions

Initial conditions are as follows: the burning process is initiated at the top of the combustion chamber bed. Both the flame gas and biomass fuel temperatures are set as 800 K (ignition source temperature), the inlet air entered to the stove initial with velocity of 0.20m/s and with the ambient temperature of 300k by consuming heat from burned fuel, then air temperature became to 500k assuming flame front travels with maximum possible velocity which is about 0.209m/s

4.5.1 Initial condition

t = 0 and x = 0 (At the bottom of fuel bed) [36].

T =300 ^{0}K

ρ =1.225$\frac{Kg}{m^3}$

p = 1tm

v =o $\frac{m}{s}$

4.5.2 Boundary conditions

Air inlet (inlet air)

It is vent where air inters to combustion chamber, the flow property of the entering air is taken from experimental result from literature reviews and also the following assumptions are taken for this velocity inlet boundary condition.

- Stagnation pressure is ambient pressure
- Neglect the viscous losses due to acceleration of fluid from the surrounding of stove inlet.
- The temperature at stove inlet is assumed to be temperature to burn wood = 500k
- Fluid velocity at air inlet = 0.20 $\frac{m}{s}$
- µ - Absolute viscosity air, 1atm and 237k, $\frac{\text{kg}}{\text{m}\,.s}$

The heat energy of air inlet assumed to be positive energy, because of it absorb heat from the wasted flame temperature.

Inlet (flame ignition temperature)

It is bottom of the flame domain and where air and wood fuel start combustion (ignition source temperature is about 800K for both flame and wood), there is few distance differences between inlet of flame and combustion chamber bed in order to minimize conduction loss between combustion chamber and fire wood flame. The flow property of the flame air and wood is taken from experimental result and also the following assumptions are taken for this velocity inlet boundary condition.

- Neglect the viscous losses due to acceleration of fluid from the surrounding of stove inlet.
- The temperature at stove inlet is assumed to be temperature to burn wood and flame = 800k
- Fluid velocity at inlet = 0.20 $\frac{m}{s}$

Flame Outlet

This boundary condition is considered as pressure outlet and pressure value will be extrapolated from the flow CFD post in the flame and stove interior. Also, all other flow quantities are extrapolated from the interior of flame and determines other extrapolated results for pot, pot holder and testing water such temperature distribution, energy distribution, velocity of flow and……etc.

- Static pressure = ambient pressure
- Velocity outlet = velocity obtained from ANSYS
- Fluid temperature extrapolated from upstream value

solid body walls boundary condition

The solid wall boundary condition includes walls, solid part stove (which is made from clay), and pot and pot holder (both made up from steel). The Flow inside the wall is surrounded by clay and steel body which is considered as solid wall. The interior wall of pot is faced to the testing water (which is fluid domain). The thermal boundary condition at walls includes as follow in fig 4.5:

- Heat flux, temperature, Convective heat transfer, External radiation and Combined external radiation and external convective heat transfer but for this simulation process temperature at wall is specified = 300 ^{0}K.
- No slip conditions.
- On bottom cylindrical part heat changes are negligible but there is conduction heat loss to base plate.

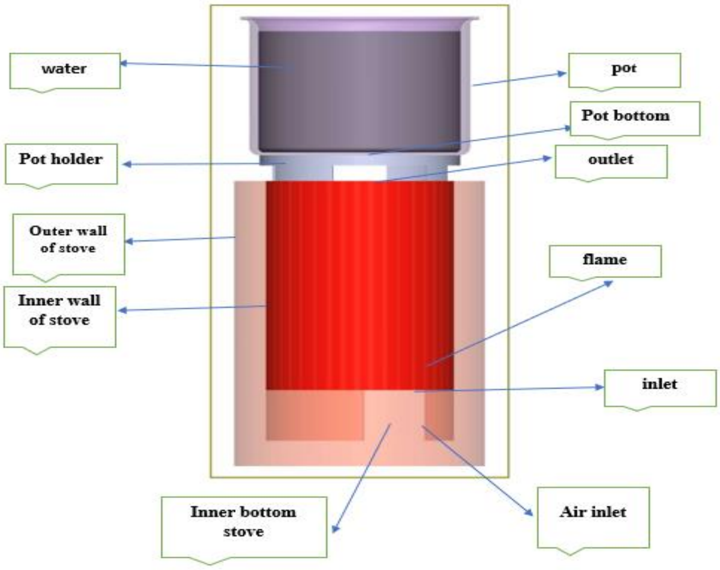


Fig.4.5 Full assembly of stove and boundary condition

4.5.3 Meshing

Developing of a good quality mesh is vital for successful and reliable CFD analysis. The role of the mesh is to physical discretization of the domain in to small volumes, and decompose the flow domain and solid domain into small control volumes called cells or elements. The total number of elements are nodes used in CFD and the sizes od element is described in fig 4.6.

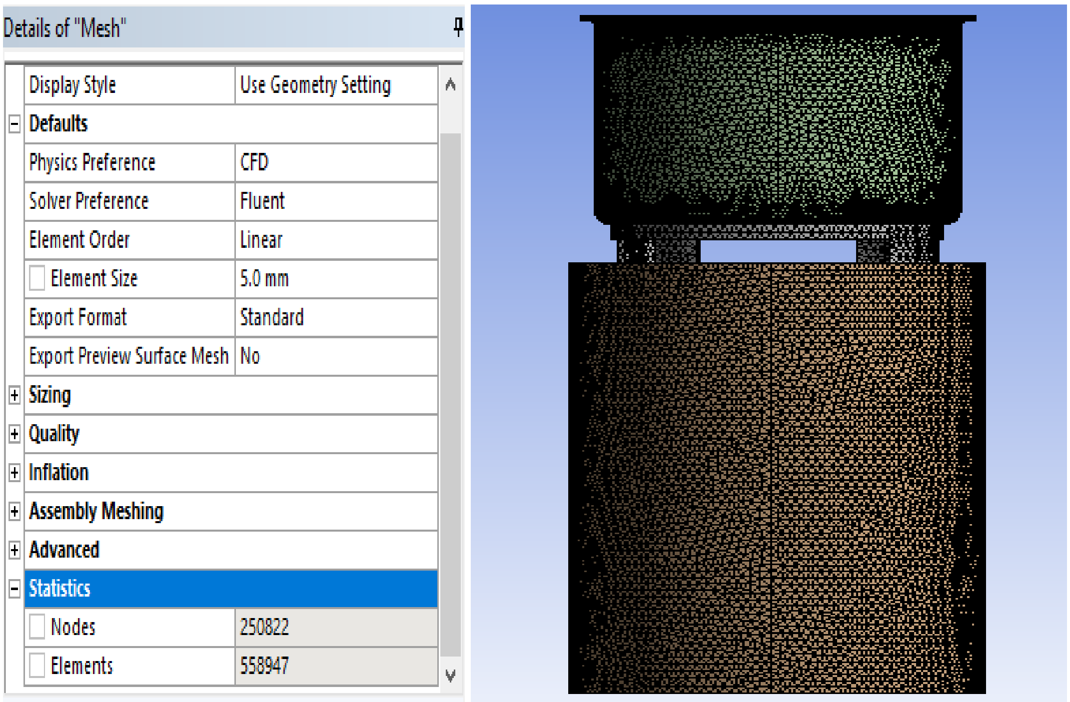


Fig. 4.6 Over all mesh for fluid and solid domain

4.5.4 System simulation (CFD) result

It can be through graphical display or numerical report. In graphical display the overall flow, overall heat transfers and some of basic fluent features can be examined. The numerical reporting is necessary to take and to examine values some basic quantities such as temperature distribution, the rate of heat transfer. The amount of energy developed; velocity distribution and overall mass transfer which be computed at boundaries of the flow domain.

The results of the analysis in FLUENT can be shown by using graphical displays and numerical outputs. The outputs illustrated in Fig. (4.7 - 4.9) below the graphical display and numerical output of Tikikl stove.

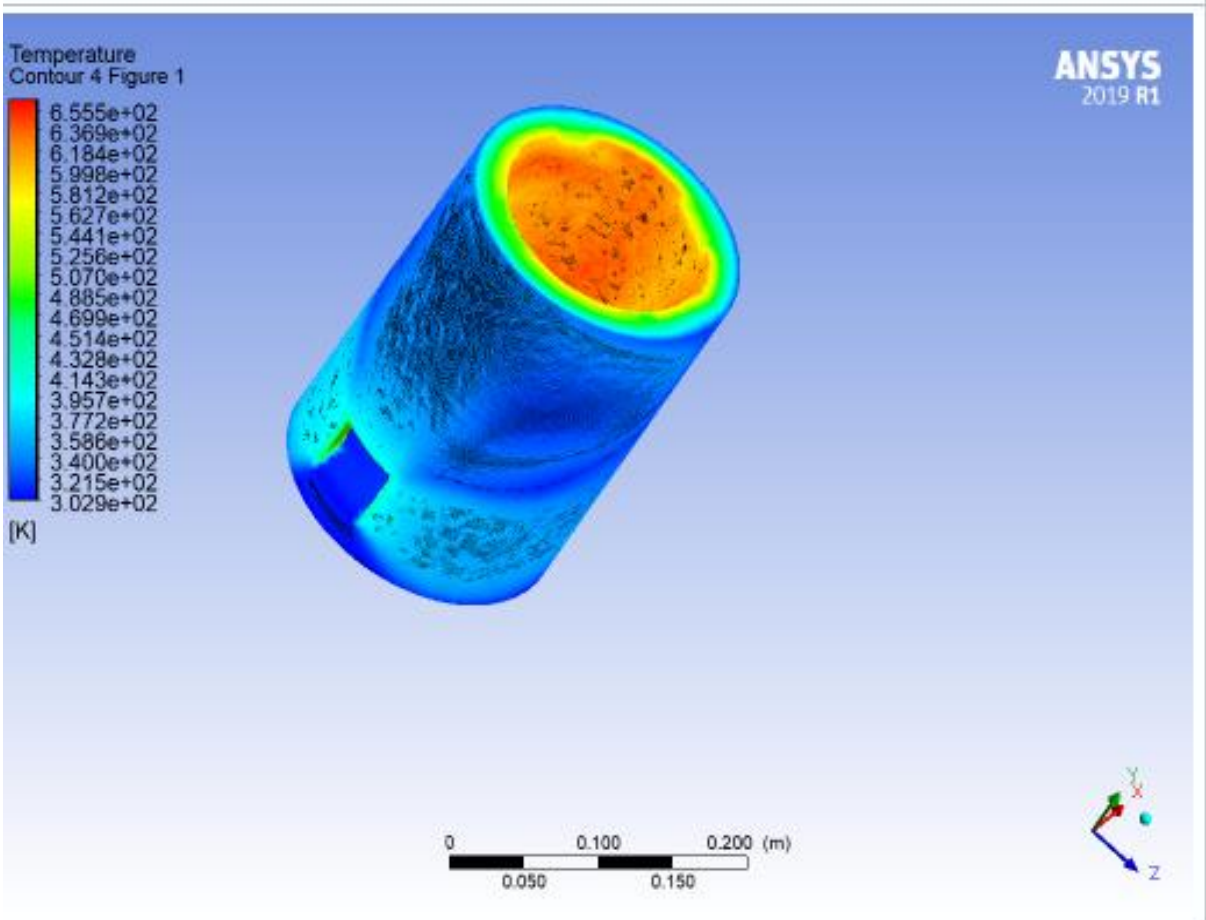


Fig.4.7 Counter temperature distribution

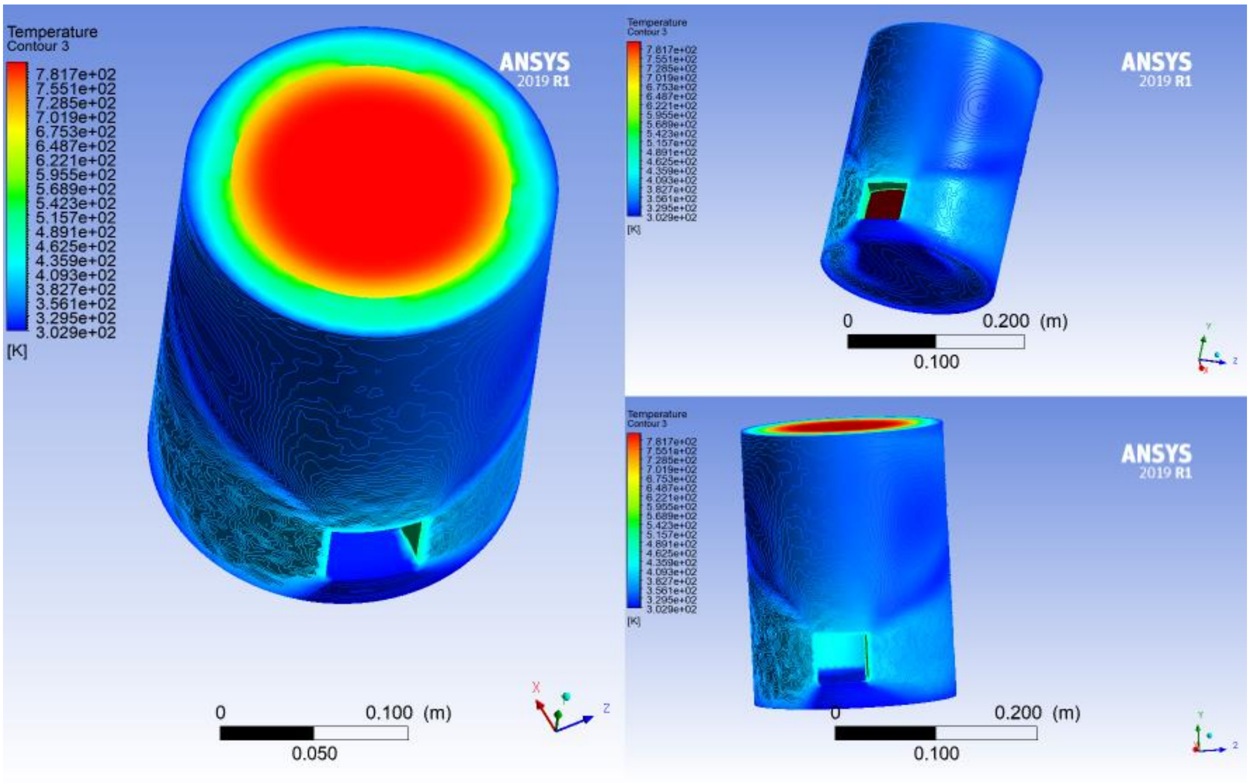


Fig.4.8 Contour temperature profile of flame and stove

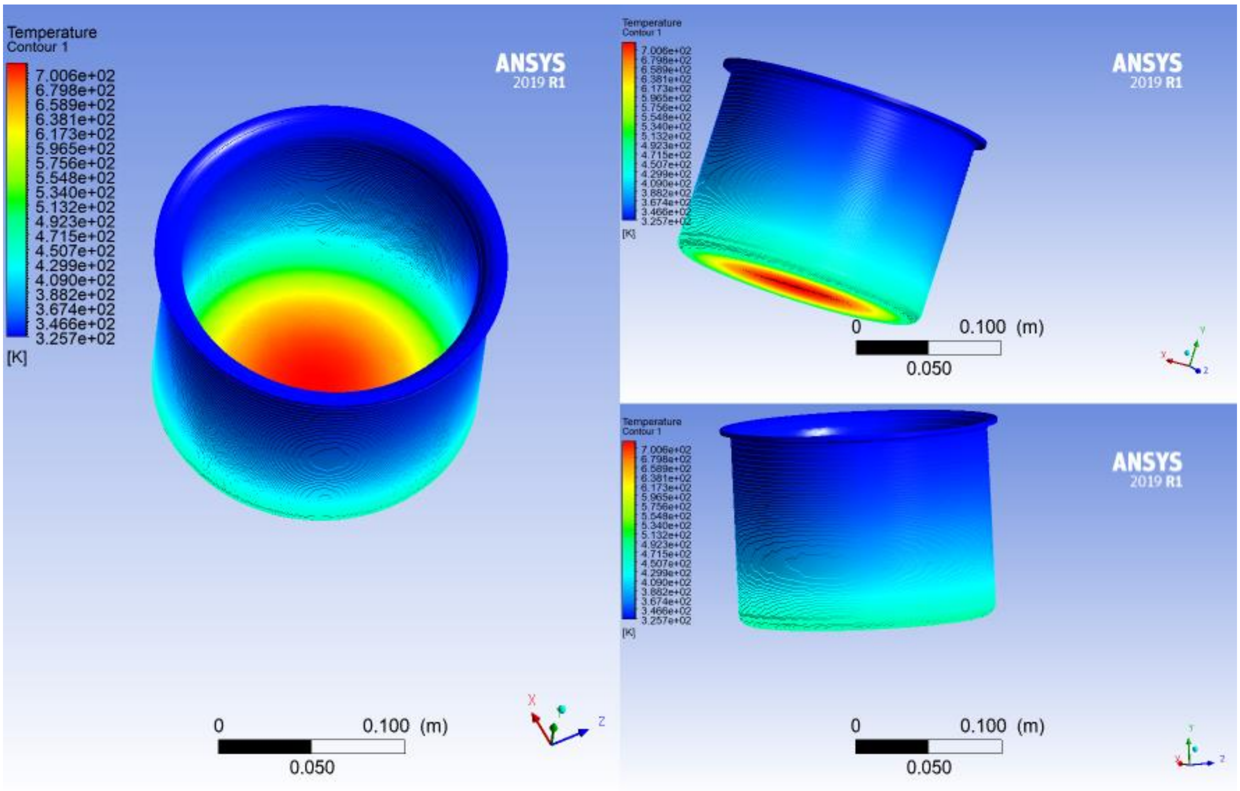


Fig.4.9 Contour temp. distribution of pot.

4.5.5 Analytical and Simulation validation

The constraints to impose or to ensure assurance work or (validation) are: the amount energy gained, the amount of energy loosed by tikikl stove, and other performance indicators. The main constraint is thermal efficiency ($\eta_{th.stove}$) which indicates overall performance 0f stove. According to GTZ SUN ENERGY Project (*Institutional Rocket and Tikikl Stoves (Draft))2010* e.c thermal efficiency ($\eta_{th.stove}$) of single skirt Tikikl stove is about 26% and according to this work it is about 27%[37].

The simulation validation of the stove is validated in terms analytical or (numerical) value respect to CFD simulation data result. The simulation validation based on performance of stove temperature distribution, overall energy distribution, energy losses and surface temperature of Tikikl biomass cook stove. The main validation parameter is thermal efficiency ($\eta_{th.stove}$). Thermal efficiency ($\eta_{th.stove}$) mathematically defined as: The rate of heat utilized (Q_{utilized}) to the total amount heat produced (q_i) from biomass fuel and it analytical value is (27%.) . Thermal efficiency ($\eta_{th.stove}$) in perspective of CFD simulation can be defined as; the amount of thermal energy which reaches bottom part of pot to total energy input in the simulation. Mathematically expressed as follows.

$$(\eta_{th.stove}).\text{CED} = \frac{amount\ of\ energy\ reached\ to\ bottom\ pot}{total\ input\ enrgy} = \frac{157272.35\ J/_{Kg.K}}{540{,}550.89\ J/_{Kg.K}} = 28\%$$

The deviation between analytical value and CFD simulation is .01 and it indicates simulation is validated.

CHAPTER FIVE

5. Thermo-electrical analyzation and simulation in TEG module

5.1 Steady state heat transfer in stove wall and TEG module

In order to get sufficient conversion efficiency of TEG module, the cold side and hot side of the thermo couple are coupled at maximum temperature range between ($30\,^0$C-$300\,^0$C). Therefore, the inner stove wall temperature and the outer stove wall temperature are evaluated as ($598.8\,^0$K or $326\,^0$C) and ($360.8\,^0$K or $88\,^0$C) respectively .In order get to the available temperature for the performance of high electrical power generation, have to assign coupling position of TEG module with perfect heat source temperature. By the following heat transfer relation for any cylindrical circular holes, the thermal conductivity (K_{th}) is constant. So that it is able to get the temperature at arbitrary point in the cylinder [34].

$$T_R = \left(\frac{ln\,(r/r_1)}{ln\,(r_2/r_1)}\right)(T_2 - T_1) + T_1 \quad \text{...} 5.1$$

Refe. Cngel.Y(Heat transfer practical approach. Eq (2-58))[34].

Let

R_1 =75 mm (inner radius of stove wall) and $T_1 = 326\,^0$C

R_2 = 100mm (outer radius of stove wall) an T_2=$88\,^0$C

R = 77.5mm (arbitrary radius where TEG is mounted) and

T_R= 298.9^0_c $298.9\,^0$C or $572\,^0$K

The assumption is the temperature distribution is uniform through out in the location where temperature and radius assigned. That means the areal temperature distribution is uniform.

5.2 Heat transfer analysis TEG module

5.2.1 Steady state heat transfer between heat source and hot side (TEG module)

The thermal and mechanical part is presented in Fig. 5.1 An aluminium plate is mounted in the heat source in order to use as heat exchanger and which helps for uniform temperature distribution and allow heat flow to the next ceramic plate component of the TEG module.

Then the ceramic plate is mounted to the metallic solder (copper plate) of the TEG [26]. The overall heat transfer mechanism between heat source and TEG illustrated in Fig.5.1 as follow:

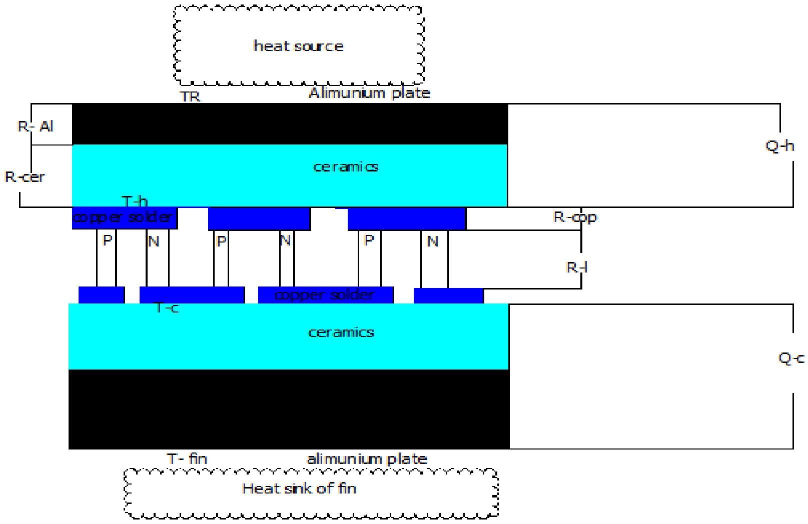


Fig 5.1 Assembly of TEG and its thermal properties

Hot side

Table.5.1 Physical parameters of the TEG assembly (hot side)

Physical parameters	value	unit
Clay material thickness (t_{clay})	5	mm
aluminium plate thickness (t_{al})	1	mm
Ceramic wafer thickness (t_{cer})	1	mm
Copper solders thickness (t_{cu})	.7	mm
Thermal conductivity of clay (K_{clay})	1.3	$\frac{w}{m.k}$
Thermal conductivity of aluminium (K_{al})	237	$\frac{w}{m.k}$

Thermal conductivity of ceramic (K_{cer})	25	$\frac{w}{m.k}$
Thermal conductivity of copper (K_{cu})	401	$\frac{w}{m.k}$
surface Area of clay wall base (A_{clay})	0.056×0.056	m^2
Area of the aluminium interface plate (A_{al})	0.056×0.056	m^2
Area of the ceramic wafer (A_{cer})	0.04×0.04	m^2
Area of the metal solders (A_{cu})	0.04×0.04	m^2

$Q_{hs} = \frac{T_{r1-}T_r}{K_{clay}} = \frac{T_{r-}T_h}{K_{al}+K_{cer}+K_{cu}}$ ……………………………………………………..…………..5.2

$K_{clay} = \frac{t_{clay}}{K_{clay}.A_{clay}}$, $K_{al} = \frac{t_{al}}{K_{al}.A_{al}}$, $K_{cer} = \frac{t_{cer}}{K_{cer}.A_{cer}}$, $K_{cu} = \frac{t_{cu}}{K_{cu}.A_{cu}}$

$$K_{clay} = \frac{t_{clay}}{K_{clay}.A_{clay}} = \frac{0.0025}{1.3(0.003136)} = 0.6132\,\frac{K}{W}$$

$$K_{al} = \frac{t_{al}}{K_{al}.A_{al}} = \frac{0.001}{237(0.003136)} = 0.001345\frac{K}{W}$$

$$K_{cer} = \frac{t_{cer}}{K_{cer}.A_{cer}} = \frac{0.001}{25(0.0016)} = 0.025\frac{K}{w}$$

$$K_{cu} = \frac{t_{cu}}{K_{cu}.A_{cu}} = \frac{0.0007}{401(0.0016)} = 0.001091\frac{K}{W}$$

Therefore:

$Q_{hs} = \frac{T_{r1-}T_r}{K_{clay}} = \frac{(326-298.9)}{0.6132}$ = 44.2 w and

$Q_{hs} = \frac{T_{r-}T_h}{K_{al}+K_{cer}+K_{cu}}$ = 44.2 w and

$T_h = T_{r-}\ Q_{hs}(K_{al} + K_{cer} + K_{cu})$ =298.9 - 44.2 (0.001345 +0.025 +0.001091) =298 ^{0}C

5.2.2 Steady state heat transfer between outer (stove wall) and heat sink (TEG module)

The thermal and mechanical part is presented in Fig.5.1, An aluminium fin is mounted in the cold side or outer wall stove and used as heat exchanger as well as helps to dissipation of thermal energy and facilitate heat transfer between ambient and TEG module. Aluminium plate is connected to fin helps for uniform temperature distribution, and allow heat flow to the next ceramic plate of the TEG module in cold side of the TE modules. The ceramic plate is mounted to the metallic solder (copper plate) of the TEG module.

Then Fourier's law of heat conduction for heat transfer through the cylindrical layer can be expressed as: Refe. Cngel.Y(Heat transfer practical approach. Eq (3-4))[34].

$$Q_{cylinder} = \frac{T_{r1} - T_{r2}}{R_{tot}}$$

Where

T_{r1} =temperature of inner cylinder (598.8 ^{0}K)

T_{r2} = temperature of outer cylinder (360.8 ^{0}K)

$R_{tot} = h_{flame} + R_{cyl}$ and

$h_{flame} = 11.3 \frac{w}{K.m^2}$ is convective heat transfer coefficient flame surface inner wall

$$R_{cyl} = \frac{ln\,(^{r_2}/_{r_1})}{2\pi Lk} = \frac{ln\,(^{.1}/_{.075})}{2\pi.1\times1.3} = 0.82\frac{K}{W}$$

$$R_{conv} = \frac{1}{2\pi r_1 L\,.h_{flame}} = \frac{1}{2\pi.075\times.1\times11.3} = 0.53\,\frac{K}{W}$$

$$R_{tot} = h_{flame} + R_{cyl} = 1.35\,\frac{K}{W}$$

$$Q_{cylinder} = \frac{T_{r1} - T_{r2}}{R_{tot}} = 176.3 \text{ w}$$

Assume that convective heat transfer in the connection area of wall and fin interface is assumed to be negligible. The thermal energy in the outer wall of stove and fins has equal value.

$Q_{cylinder} = Q_{con.fin\ ambient}$ which at mounted location surface area.

When determining the rate of heat transfer from a finned surface, we must consider the *unfinned portion* of the surface as well as the *fins*. Therefore, the rate of heat transfers for a surface containing *N* fins can be expressed as [33].

$Q_{cylinder} = Q_{fin\ base} = Q_{fin.rad} + Q_{fin.conv}$

$Q_{con.fin\ ambient} = Q_{fin.rad} + Q_{fin.conv}$ and

$Q_{fin.rad} = (n_{fin.}-1)\, Q_{fin.space} + [\eta_{fin.}.t(L+2H)+2LH+2t_b\,(L+W)]\, \sigma\, \epsilon_{fin}(T_{fin}^4 - T_{am}^4)$

$= 7Q_{fin.space} + 2.893\times 10^{-11}(T_{fin}^4 - 300^4)$……………………………………5.3

$Q_{fin.space} = \frac{\sigma(S+2H)L(T_{fin}^4 - 300^4)}{(\frac{1-\epsilon_{fin}}{\epsilon_{fin}})(\frac{1}{F_{S-surr}})} = \frac{4.4226\times10^{-10}(T_{fin}^4 - 300^4)}{(\frac{.05}{.95})(\frac{1}{F_{S-surr}})}$ where

$F_{S-surr} = 1- \frac{2\hat{H}[(1+\acute{L}^2)^{.5}-1]}{2\hat{H}\acute{L}+(1+\acute{L}^2)^{.5}-1}$

Where:

$\hat{H} = \frac{\text{height of fin}}{space\ between\ fins} = \frac{H}{S} = \frac{0.035}{0.008} = 4.375$, $\acute{L} = \frac{\text{Length of fin}}{space\ between\ fins} = \frac{L}{S} = \frac{.1}{0.008} = 12.5$

$F_{S-surr} = 1- \frac{2\times4.375\,[(1+12.5^2)^{.5}-1]}{2\times4.375\times12.5+(1+\acute{L}12.5^2)^{.5}-1} = 0.16492$ there fore

$Q_{fin.space} = \frac{4.4226\times10^{-10}(T_{fin}^4 - 300^4)}{(\frac{.05}{.95})(\frac{1}{0.16492})} = \frac{4.4226\times10^{-10}(T_{fin}^4 - 300^4)}{0.3191} = 9.7017\times 10^{-9}(T_{fin}^4 - 300^4)$

$Q_{fin.rad} = 7(9.7017\times 10^{-9}(T_{fin}^4 - 300^4)) + 2.893\times 10^{-11}(T_{fin}^4 - 300^4)$

$= 9.731\times 10^{-9}(T_{fin}^4 - 300^4)$ ………………………………………………. 5.4

To find convective heat transfer in the surface of fins, it can be evaluated by the following equation:

$Q_{fin.conv} = hA_{unfinned}(T_{fin} - T_a) + \eta_{fin.}hA_{fin}(T_{fin} - T_a)$

$= 20\times0.0064(T_{fin} - 300) + .95\times 20\times0.056(T_{fin} - 300)$

$= 1.192\,(T_{fin} - 300)$……………………………………………………………5.5

Therefore, the total heat transfers from fins evaluated as follows:

$Q_{con.fin\ ambient} = Q_{fin.rad} + Q_{fin.conv}$

$= 9.731\times 10^{-9}(T_{fin}^4 - 300^4) + 1.192\ (T_{fin} - 300)$

$= 9.731\times 10^{-9}(T_{fin}^4) + 1.192\ (T_{fin})$ -436.42

and the conduction heat transfer in the outer wall of the stove and the total heat transfer rate in fins are equal. That means $Q_{cylinder} = Q_{con.fin\ ambient}$ .Then by using above two equations, it is possible to obtain the temperature of the fin base.

$Q_{cylinder} = Q_{fin\ base}$

612.72w = $9.731\times 10^{-9}(T_{fin}^4) + 1.192\ (T_{fin})$

62,965,892,508.47=$1\times(T_{fin}^4) + 1.225\times 10^8(T_{fin})$

$T_{fin}(T_{fin}^3 + 1.225\times 10^8)$ - 62,965,892,508.47K= 0 .From this equation the temperature of fin base (T_{fin}) have two solution which are T_{fin}= 62,965,892,508.47^{0}K and $T_{fin}^3 = -1.225\times 10^8\ K$),in this application fin is used to cooling, therefore the negative sign temperature is the value for the solution. $T_{fin} = 496.64\ ^0$K.The rate heat transfer between in the fin base and the rate heat transfer of the cold side TEG modules is assumed to be equal. There fore

$Q_{fin\ base} = Q_{cold\ side\ TEG}$

176.3 w = $\frac{T_C - T_{fin}}{R_{tot}}$ and ……………………………………...………………………….5.6

$R_{tot} = R_{al} + R_{cer} + R_{cu.s}$

$R_{al} = \frac{t_{al}}{K_{al}.A_{al}} = \frac{0.001}{237(0.003136)} = 0.001345\frac{K}{W}$

$R_{cer} = \frac{t_{cer}}{K_{cer}.A_{cer}} = \frac{0.001}{25(0.0016)} = 0.025\frac{K}{w}$

$R_{cu.s} = \frac{t_{cu}}{K_{cu}.A_{cu}} = \frac{0.0007}{401(0.0016)} = 0.001091\frac{K}{W}$

$R_{tot} = R_{al} + R_{cer} + R_{cu.s} = 0.027436\ \frac{K}{W}$ by substituting the value in the above equation cold side temperature (T_C) =501 ^{0}K.

5.2.3 Cold side (heat sink)

Table 5.2_Physical parameters of the heat sink

Input parameters	value	unit
Number of fins (n)	8	
Fin length (L)	0.1	m
Fin High (H)	0.035	m
Width of fin array (W)	0.08	m
Base thickness	5	mm
Fin thickness (t)	2	mm
Spacing between fins (S)	8	mm
Thermal conductivity of aluminium (K_{al})	237	$\frac{w}{m.k}$
Fin emissivity (ε_{fin})	0.05	
Fins surface area (A_{fin})	0.056	m^2
Unfinned surface area (A_{unfin})	0.0064	m^2
Fin efficiency (η_{fin})	95% [38]	
Ambient Temperature (T_{am})	300	K
Stefan Boltzmann constant (σ)	$5.67 \text{ x } 10^{-8}$	$\frac{w}{m^2K^4}$

Convection coefficient outside the stove (h_o) 20 $\frac{W}{m^2K}$

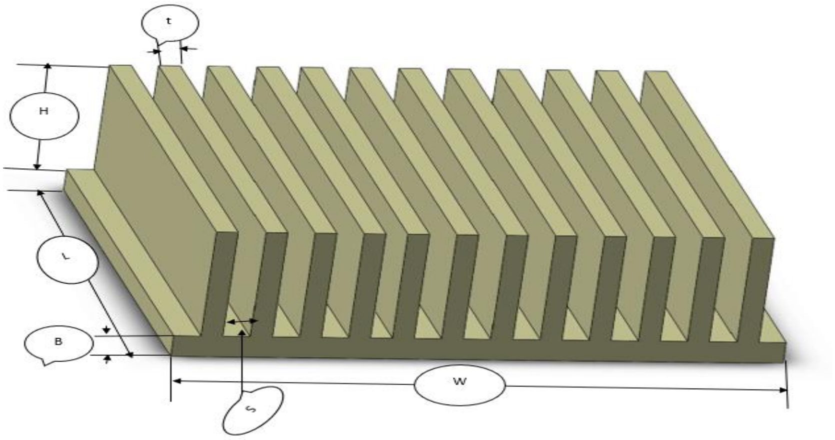


Fig.5.2 Designed fin

5.3 Electrical analyzation of thermoelectric module

5.3.1 Module selection

The selection of proper type thermo electric module from several commercially available modules is taken based on basic performance indicators of the thermoelectric module. Performance indicators for the specific thermoelectric module are [33]

- The relations between open circuit voltage,
- The voltage at maximum power (Vmp), the current at maximum power (Imp) and the maximum power (Pm) are useful indicators of performance,
- The number of couples in the module(N),
- The thermoelement (single leg) area(A) in square centimetre,
- The thermoelement length(L) in centimetre,
- The available temperature difference (ΔT) across the TE module.

The typical area of a commercial TEG is (length× width = 40 mm× 40 mm), and the number of thermoelectric couples, namely, a p-type element and an n-type element, in a TEG are 127 is selected [33]. The selected commercially available module is well known as the AUB design (TEP-AUB and which was manufactured at Thermionic Electronics Co. (Xiamen, China).

Table.5.3 Geometrics characteristics and theoretical performance of module

Geometric characteristics and theoretical performance of modules

Module model/ manufacturer	Leg length (L), cm	Leg area (A), cm^2	Couples (N)	$V_{mp}/\Delta T$, V/K	$I_{mp}/\Delta T$, A/K	Power density $P_m/\Delta T^2/A_s \times 10^6$ W/K^2/cm^2	Cost $/W for ΔT = 150 K
HZ-20/Hi-Z, Inc (USA)	0.50	0.30	71	0.0135	0.036	8.71	15–20
TEP1-12708 Thermanomic Electronics (China)	0.125	0.0196	127	0.024	0.01	15.0	1–2
TEP-AUB	0.14	0.0625	127	0.0241	0.027	20.7	2–5
TEP-12656	0.15	0.0625	126	0.0239	0.025	19.1	2–5

5.3.2 Electric power generation of the module

Power is a function of these parameters. Such as temperature difference applied, the geometry of the thermoelectric module (N, A and L), and the material characteristics (α and ρ). The greater power factor(α^2/ρ) has with the higher power output for a given combination of thermoelectric p and n materials. The maximum power output (P_{mp}) for this module at operating condition, when voltage reads V_{mp} and current reads $I_{mp}$is given by:

$$P_{mp} \cong 0.114\times 10^{-4}\,\frac{A}{L}N\Delta T^2$$

The number of modules affects the amount of power develop from thermoelectric module and the interval of temperature difference or working temperature(ΔT). By consideration of different parameters, the number of modules assigned. These parameters are:

- ✓ High performance low cost TEG unit has been designed and built.
- ✓ Temperature difference mapping between T_h *and* T_c.
- ✓ Open circuit voltage of the module (V_{oc})
- ✓ Maximum power developed of the module p_{mp} .

According of these considerations, the number of modules selected is one and overall description of three thermoelectric modules are given below as follow [33]:

Table.5.4 Steady performance for varied number of modules

Steady state performance for varied number of modules

Number of modules	$\Delta T_{H\infty}$, $K \pm 0.7$	ΔT_{H-C}, $K \pm 0.7$	ΔT_{TEG}, $K \pm 0.2$	$V_{oc,\ exp}$	$V_{oc,\ predicted}$	P_m, $W \pm 0.08$
1	256	152	88	4.1	4.3	4.2
2	250	122	57	5.5	6.3	3.8
3	210	85	41	5.7	6.3	2.7

Therefore, The final power output (P_{mp}) of the thermoelectric modules mathematically:

$I_{mP}=\frac{1}{2}\frac{\alpha}{\rho}\frac{A}{L}\Delta T=1.855\ I$

$V_{mP.}=\alpha N\Delta T=1.6891\ V$

$P_{max.}=\frac{1}{2}\frac{\alpha^2}{\rho}\frac{A}{L}N\Delta T^2=3.133W$

5.4 Simulation of TEG module

5.4.1 Governing equations of module

The governing equations for analysing the thermoelectric system shown in Fig.5.3 include the properties of thermal, electrical, and thermoelectric effects. Therefore, the conservation principles of energy and current are considered simultaneously [39].

The general heat flow and continuity equations of electric charge for the thermoelectric simulation analysis can be expressed as Eqs. (5.7) and (5.8), respectively [40],

$\rho C\frac{\partial T}{\partial t}+\nabla q=\dot{q}$ 5.7

$\nabla(J+\frac{\partial D}{\partial t})=0$ 5.8

where ρ, C, T, t, q, $\dot{q}$, J and D *are* the density, specific heat capacity, absolute temperature, time, heat flux vector, heat generation rate per unit volume, electric current density vector and electric flux density vector, respectively.

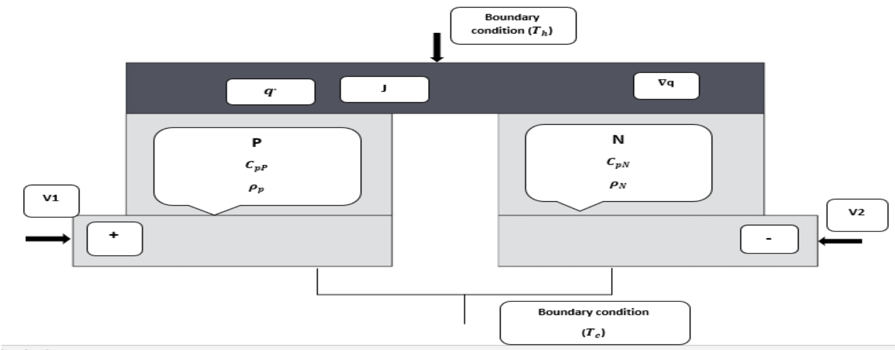


Fig.5.3 Thermal and electromagnetic boundary condition

5.4.2 Boundary conditions

Boundary conditions is taken in two consideration modes. These considerations are named as thermal boundary condition and electromagnetic boundary condition and they are simulated under steady-state conditions. **Thermal boundary condition:** includes heat source (q_h) or temperature of hot side (T_h) and heat sink (q_c) or the temperature of the cold (T_c). the simulation is taken in the following thermal boundary conditions:

T_h= 298 ^{0}C

T_c =228 ^{0}C

The input temperature of hot side (T_h) is coming from the inner or (interior) wall of stove and located or mounted at radius (R = 77.5mm). The cold side temperature (T_c)is mounted by aluminium fin block and fin block used cool down cold side of the thermoelectric module and it absorbs heat from the module. **Electromagnetic boundary condition:** it includes the open circuit voltage (V_{0C}) of the thermoelectric module, voltage developed(V) from module, and short circuit current (I_{sc}) of the module.

5.4.3 Components and material properties

TEG module contains copper plate (includes hot side copper solder and cold side copper solder) and P-N semiconductor material which have the same material properties. CFD simulation includes thermal and electrical properties of the components of the TEG module. Specially the simulation focused on see beck coefficient (S), electrical resistivity (R_{el}), thermal conductivity (K_{th}), and specific heat capacity C_P) of the module. The above-mentioned properties are expressed below in the Table .5.5 as follow:

Table.5.5 Components of module and their properties

component	**Properties**			
	see beck coefficient (S) $^V/_{C^0}$	thermal conductivity (K_{th}), $^w/_{m\,C^0}$	electrical resistivity (R_{el}), Ωm	specific heat capacity C_P) $^J/_{kg\,C^0}$

Hot side copper plate	------------	400	1.7241×10^{-8}	385
P-type semiconductor	.00019	1.5	1.6×10^{-6}	----
N-type semiconductor	.00019	1.5	1.6×10^{-6}	-------
Cold side copper plate	--------------	400	1.7241×10^{-8}	385

5.4.4 The main procedures during the simulation

Geometry of TEG module is modelled on SOLID work 2019 and simulated in ANSYS $19R_1$ **(Discovery AIM)**.

- 3-D part drawing of thermoelectric module, such as Hot side copper plate, P-type semiconductor, N-type semiconductor and Cold side copper plate, and the part are drawn by SOLID work 2019 and assembled.

  Assembled parts are Imported to ANSYS $19R_1$**(Discovery AIM)**. Then the body and its parts have to change in to ANSYS format.

- Assigning and naming of the parts. Then the body meshing in acceptable form that can leads to convergence.

  After the meshing and naming of the parts or components, assigning the boundary conditions is the next procedure. assigning boundary condition in AIM DiscoverR_1 contains three boundary conditions, these are:

  1. selection of material and inserting both thermal and electromagnetic properties for the specified component.
  2. assigning the thermal boundary condition variables like heat source (the rate of heat input or temperature (T_h) and heat sink or cold side temperature (T_c))
  3. assigning electro potential boundary condition variables such open circuit voltage (V_{oc}), voltage developed(V), and short circuit current (I_{sc})

- Inserting the input variables for the boundary condition such as temperature, voltage, and current for the denoted boundary conditions.

- Finally computing the result and evaluating result with related with the respect to analyzed one.

5.4.5 ANSYS and AIM Discovery simulation description

AIM Discovery simulation is undertaken by the following assumptions. The assumptions are:

(1) The internal contact resistance (R_{cO}), is between uni- thermo couple is uniform a negligible and

(2) The internal electrical resistivity (R_{in}), is between uni- thermo couple is uniform or (same). The **AIM Discovery** simulation contains five thermo-couple. Because of one thermo electric module can contain at least more than 110 thermo-couples. The simplest method is taking uni-thermo-couple or more than one is preferable. The reason is those contact resistance (R_{cO}), and internal electrical resistance R_{in} are uniform and the effect in the performance is thermo electric module is negligible. The geometrical description of the thermocouple includes three components, These components are:(1) long copper plate(solder) with dimension (6mm×2.5mm ×.7mm), (2)P-N semiconductor legs with the dimension (2.5mm ×2.5mm ×1.4mm),and lastly (3) short copper plate(solder) with the dimension (3mm×2.5mm ×.7mm).

5.4.6 ANSYS and AIM discovery (2019R1) simulation result

The result expressed in the form of graphical display format or numerical value. In graphical form it displays or (indicates), open circuit voltage (V_{oc}), voltage developed(V), Temperature distribution between (T_h) and (T_c), current density(J) , the magnitude of the current (I_{de}), and also some of basic electrical and thermal features can be evaluated . The numerical reporting is necessary to take and to examine values some basic quantities such as temperature distribution, the amount of voltage, the amount of current developed are computed.

The results of the analysis in **ANSYS and AIM discovery (2019R1) simulation** expressed by using graphical displays and numerical outputs. Both graphical displays and numerical outputs. are illustrated as below in Fig. (5.4- 5.5) [40].

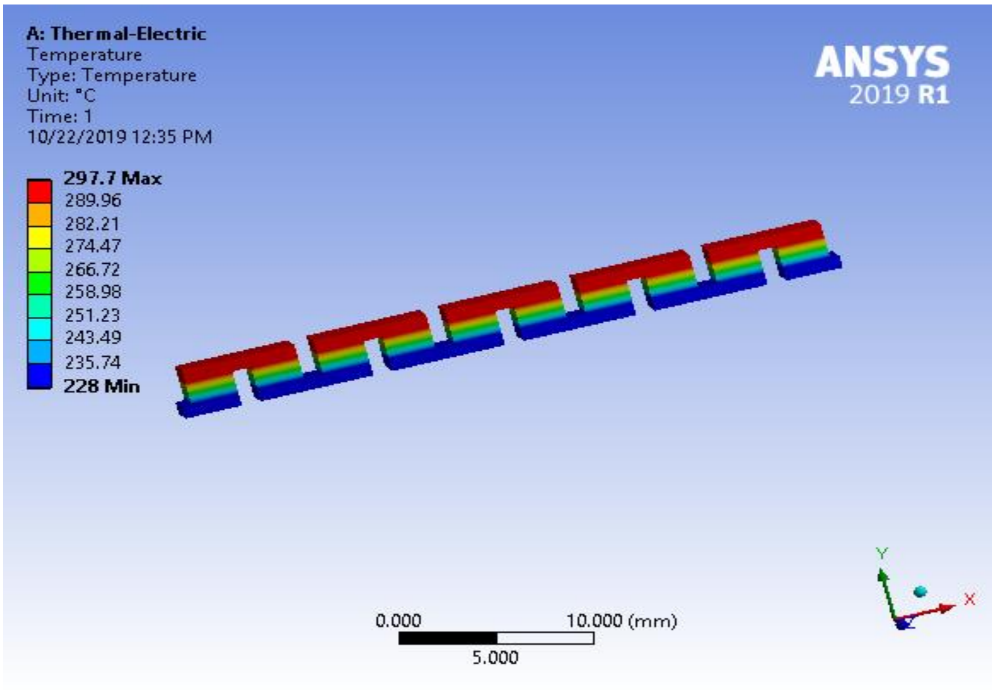


Fig.5.4 Temperature distribution of thermoelectric module

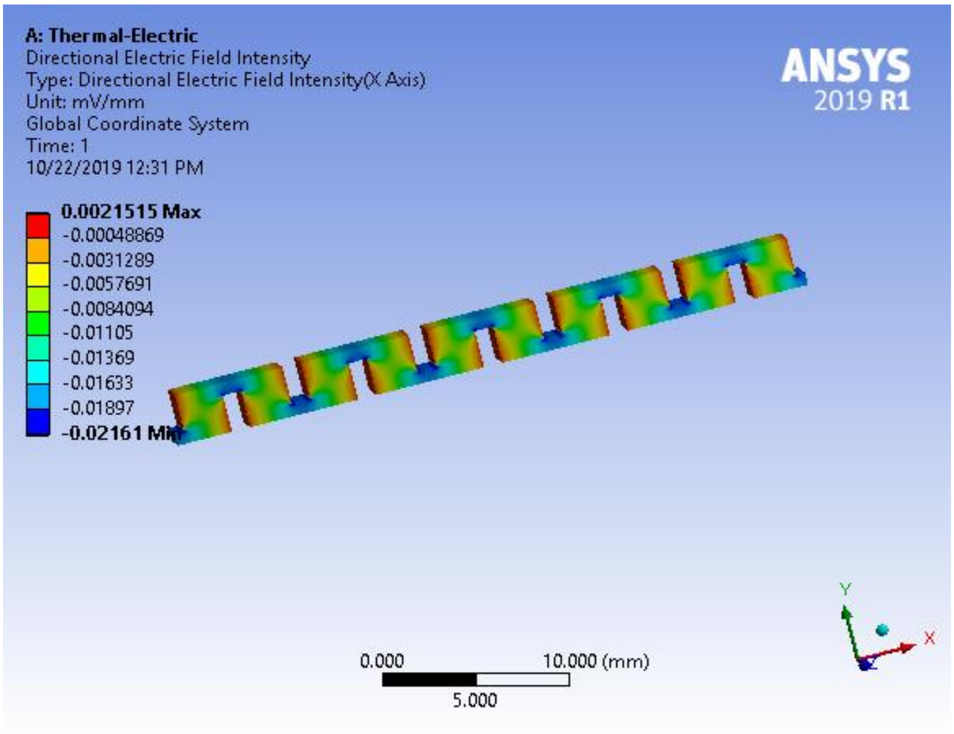


Fig.5.5 Electric field direction

CHAPTER SIX

6. Result and discussion

6.1 Introduction

In this chapter all works have discussed in design, development and performance evaluation of the thermoelectric stove. Especially main focused in sub chapters:

1. Designing and specification (Chap.3),
2. analytical modelling of heat transfers and simulation on non-skirt Tikikl stove (Chap.4), and
3. Steady state heat transfers stove wall and TEG module and Simulation of TEG module (Chap.5),

Design and development addresses method to evaluate input energy and numerical value also calculated. In addition to the involvement Design and development process, method of heat transfer and type of heat transfer mode should also assign, in addition to that also where do these type or mode of heat transfer occurred in stove and its related components such pot and pot holder, and their contributions in overall performance of the stove. These should include the total energy gain and total energy lose in stove to increase thermal efficiency.

6.2 Result and Discussion in analytical modelling of heat transfer

Optimizing performance of heat transfer method in stove design based solely on a technical analysis of thermal performance and material properties. Because the contribution of heat transfer method highly affects the performance and the thermal efficiency of the stove. According to the analytical result radiation heat transfer contribution is higher than other mode of heat transfer mechanisms. For instance, radiative heat transfer contains 50%-63% from overall contributions.

In final evaluation the results have been summarized as follow: The amount of heat energy developed from the biomass fuel during the combustion is about 3.275×10^3 kw.Total energy gain or contribution by the convection heat transfer has been discussed as below; the amount of energy from flame reach to the bottom surface of the pot convection heat transfer is about 283.4W, and the amount energy which is convicted or reflected from pot holder to the bottom surface is about 126W.

Also, radiation heat transfer contribution has discussed and summarised as follow: the amount of energy from flame reach to the bottom surface of the pot by radiation is about 230 W and the amount energy which is radiated or reflected from pot holder to the bottom surface of pot is about 242.4W.The total contribution of energy gain is sum of both convective and radiative heat transfer mode with numerical value of 881.8W,and thermal efficiency **($\eta_{th\ stove}$)** is about ***27*%.** Thermal efficiency **($\eta_{th\ stove}$)** is increased by these factors: (1) increasing flame in-out radiation heat transfer factor ($F_{flame-in\ out}$) between flame and bottom exposed surface of pot, (2) increasing flame into-pot holder radiation heat transfer factor ($F_{flame-into\ potholder}$) between flame and pot holder exposed surfaces, and (3) increasing flame reflection and radiation into-pot holder heat transfer factor ($J_{flame-to\ pot\ holder}$.) between flame reflection radiation pot holder and exposed pot bottom surface area.

6.3 CFD graphical display and numerical value result

The CFD fluent results of the analysis shown in Fig. (6.1-6.4) which is described by graphical displays and numerical outputs illustrated in Tikikl stove show:

1. From Fig. 4.8, The profile of Temperature distribution of flame domain, at the inlet or ignition surface temperature is $800\ ^0$K and it designated as velocity inlet. The temperature decreases to about $775.13\ ^0$K at pressure outlet which indicate that temperature decreases due to heat transfer rate increase to inner surface of the stove wall.
2. The Temperature distribution profile stove in Fig.6.1 shows, temperature distribution decrease uniformly from the inner wall surface to outer wall stove. Temperature is uniformly decreasing $598.8\ ^0$K and $360.75\ ^0$K for inner wall and outer wall of stove respectively. The temperature in bottom of stove is about $330.13\ ^0$K and which shows that heat loss is minimum at the bottom part of stove.
3. Also, Temperature distribution profile pot in Fig.6.4 shows, temperature distribution is maximum at the center of pot bottom surface and decrease to the outer radius pot which indicates the maximum flame energy reaches center of pot bottom.
4. Temperature distribution profile in pot holder shows, temperature distribution is maximum in contacting surface between pot and pot holder which indicates that maximum heat transfer rate occurs pot and pot holder.in *appendix (2&3)*

5. From Fig.6.2, The velocity profile indicate that the inlet air velocity is about (0.2 $m/_s$) as it moves from inlet to the outlet, it increases and with magnitude of (0.209 $m/_s$). Increasing the flow velocity often leads to more turbulence which improves heat transfer efficiency.

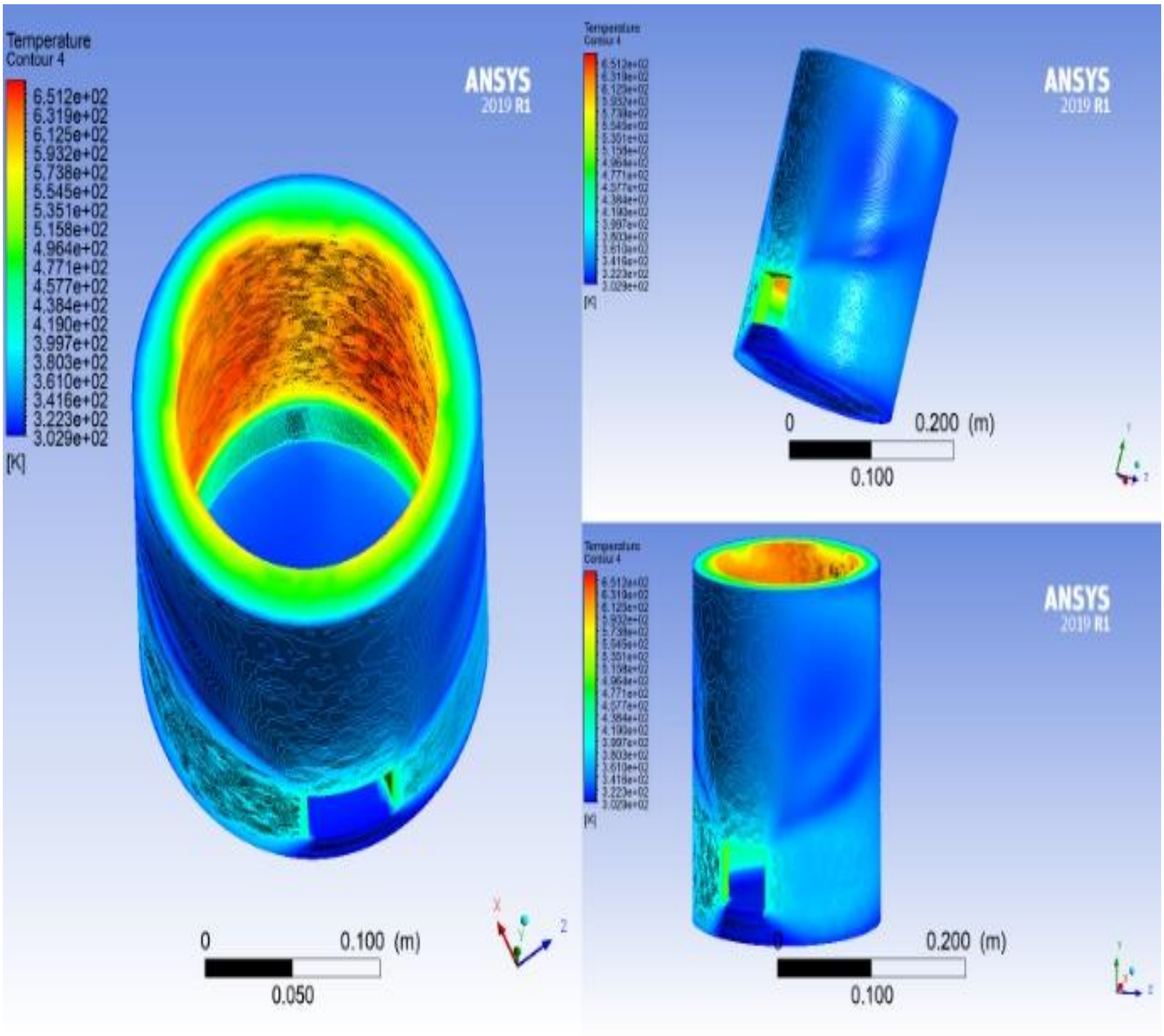


Fig.6.1 Contour temperature distribution of stove.

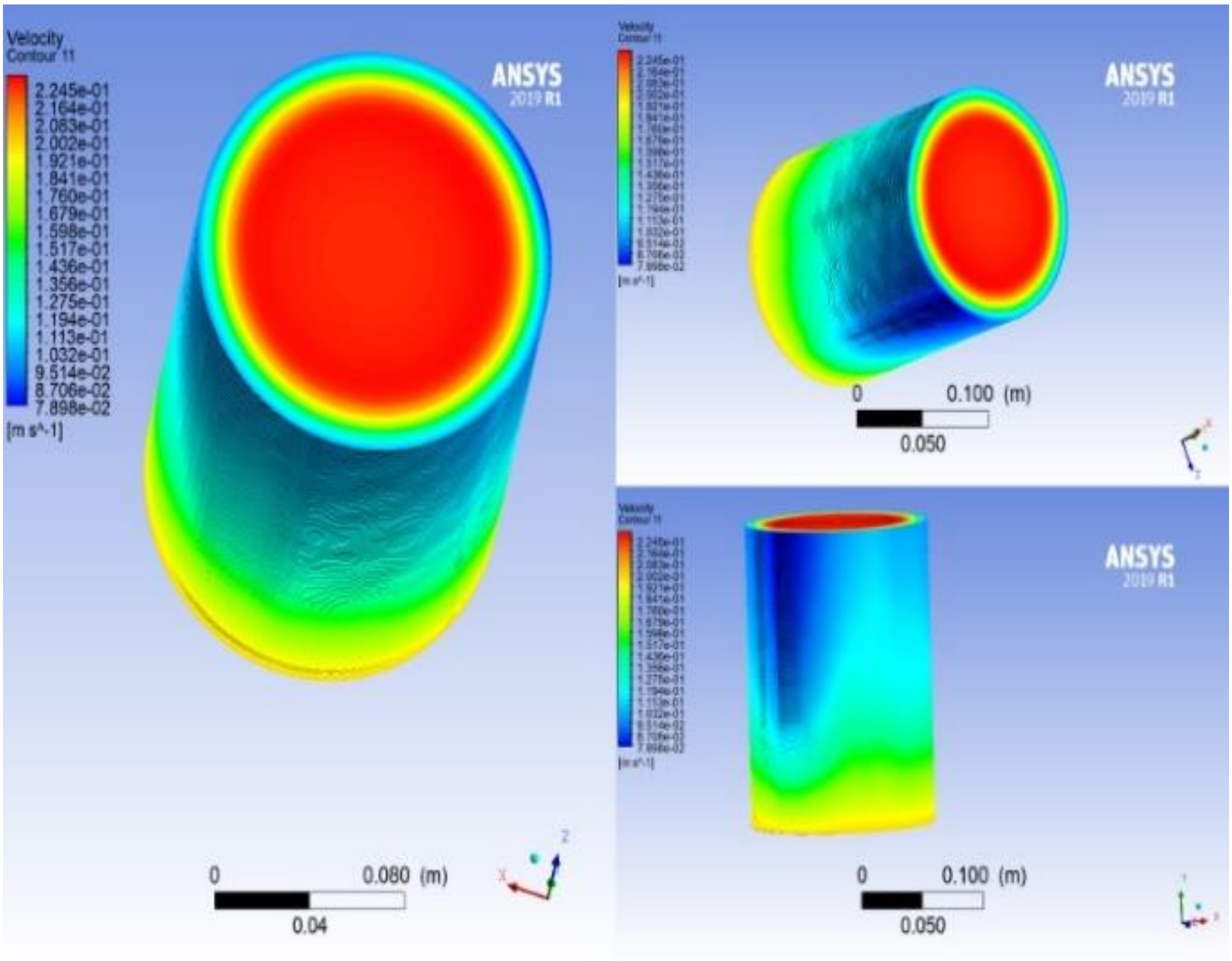


Fig.6.2 Contour of velocity profile flame.

6.4 Thermo electric module steady state heat transfer Analytical results

The configuration of the TEG unit attached to the drilled stove wall, and the position is too enough to generate heat or (temperature) which is capable of generate electrical energy for TEG units. The temperature of stove wall (T_r) in mounting location is about (298.9 ^{0}C), and location of mounting TEG is near to the top of the stove. Temperature of hot side (T_h) thermo-module is (298 ^{0}C***)***, and heat transfer between the stove wall and TEG is direct conduction. The cold side temperature (T_c) of TEG is coupled by fin which is used to cooling process. Cold side temperature of the TEG (T_c) and the fin temperature(T_{fin}) are evaluated as ***(*** 228 ^{0}C***)*** and (223.64 ^{0}C**)** respectively.

6.5 Thermo electric module electrical power Analytical and simulation results

6.5.1 Electrical power result performed

Analytically value on specified Tikikl cooking stoves in case of suggested variables, such as the temperature distribution, open circuit voltage, voltage developed, current and power developed were discussed. These findings were:

- When the module operates at maximum temperature ((T_h) = 298 ^{0}C) and cold side temperature ((T_c) = 228 ^0C) , the open circuit voltage(V_{oc}) is 3.3782V.
- The voltage developed (V_{de}) from the module is 1.6891V, and the amount of current generated (I_{de}) *is 1.855I.*
- Power developed (P_{de}) is product of voltage developed (V_{de}) and current generated (I_{de}) from the module, and it value is 3.133W.
- All evaluated parameters such voltage developed (V_{de}), the amount of current generated (I_{de}), and Power developed (P_{de}) are highly dependent in to hot side temperature(T_h) of module.

6.5.2 Electrical power simulation results

In TEG module simulation for electrical parameters such as the temperature distribution, open circuit voltage, voltage developed, current and power developed were discussed as follow. These findings were:

- The open circuit voltage (V_{oc}) is the voltage which without the load and it indicates the performance of TEG module, also highly dependent in temperature difference between (T_h) and (T_c). Also, it is summation of all individual thermo-couples open circuit voltage (V_{oc}) which are connected electrical in series and illustrated in Fig.6.3 and Fig.6.5.
- In Fig. (6.3,6.4, and 6.6), Beside temperature dependency both open circuit voltage (V_{oc}) and voltage developed (V_{de}) are highly dependent on the number thermo-couple.
- In controversy; The current generated (I_{de}) from the TEG module is highly dependent only on temperature difference between (T_h) and (T_c), and it is the same throughout in TEG module. Because of thermo-couples are connected electrical in series connection and shown in Fig.6.5 below.

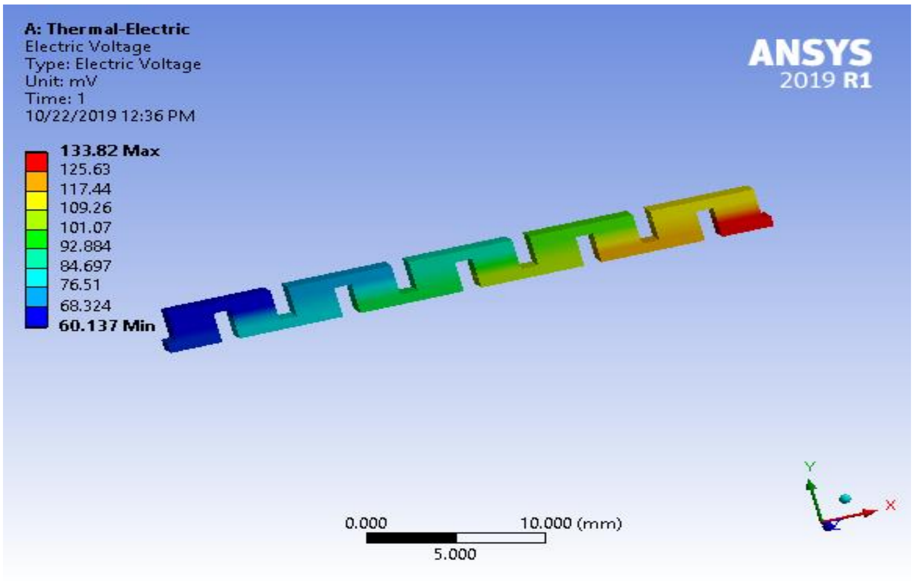
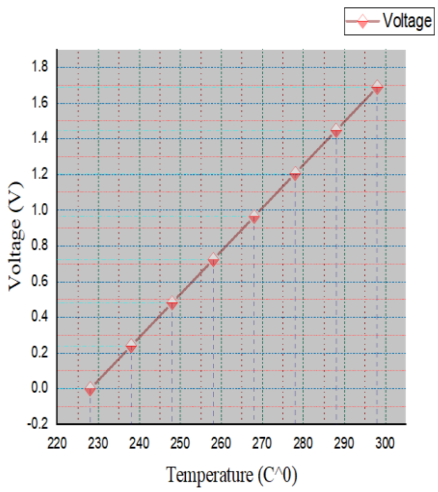


Fig.6.3 Voltage developed.



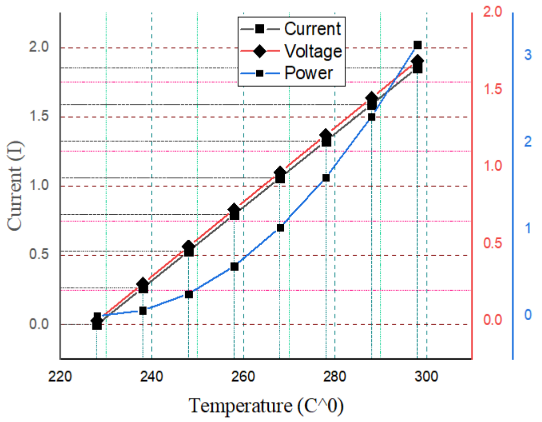


Fig.6.4 Graph for temperature vs voltage.Fig.6.5 Graph of temperature vs current, voltage, and power.

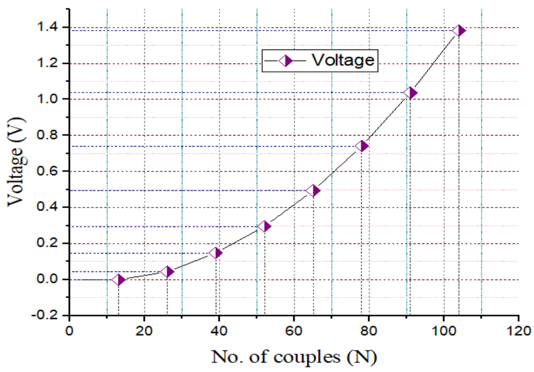


Fig.6.6 Graph for no. of couples' vs voltage.

CHAPTER SEVEN

7. Conclusion

This work focuses on design, development and performance evaluation of the thermoelectric stove using CFD for utilization of waste energy. To achieve the goals of the research; evaluation analysis was conducted to examine the major heat loss and gain area of stove, and to determine and investigate flow characteristic and temperature profile was conducted by using computational fluid dynamics CFD.Thermoelectric module analyses were examined in thermoelectric simulation, as result the temperature effect indicated in both voltage development (V_{de}) and electrical power development (P_{de}).

The important findings and their significances are as follows.

- The total contribution of energy gain is sum of both convective and radiative heat transfer mode with numerical value of 881.8 W**.**
- Thermal efficiency of thermoelectric stove ($\eta_{th\ stove}$) is about *27*%.
- The temperature of outer wall was 360.75 ^{0}K and bottom of stove was 330.13 ^{0}K, which was minimum loss.
- The improved performance of heat transfer rate was done selecting proper air gap and found that the suitable dimension of pot-holder ($he._{air\ gap}$= 25mm, $A_{air\ .gap}$ = 0.01256 m^2).which conducted by CFD.
- CFD shown, Increasing the flow velocity often lead to more turbulence which improved heat transfer efficiency.
- The maximum module operating temperature of thermoelectric stove is 298 ^{0}C.
- Power developed (P_{de}) was product of voltage developed (V_{de}) and current generated (I_{de}) from the module, and its value was 3.133 W.
- Thermoelectric simulation of thermoelectric module, both open circuit voltage (V_{oc}) and voltage developed (V_{de}) are highly dependent on the number thermo-couple.

Recommendation

Looking forward recommendation, substantial thesis work simulation is needed in the following fields:

(1) **CFX simulation in stove:** this simulation contains stove and its related components such as pot and pot-holder. CFX simulation helps you to get how much radiation heat transfer energy reached to the bottom part of stove and as well as helps to get how much energy loosed by radiation heat transfer. Also, and help you how much convective heat transfer energy contribution in overall stove.

(2) The next recommending is to conduct **steady state** or **transient** heat transfer simulation between fins and surrounding to know the contribution of the natural cooling system, is needed for the estimation the amount of energy is needed for the cooling, to select the location of the TE, and to improve the heat sink effectiveness.

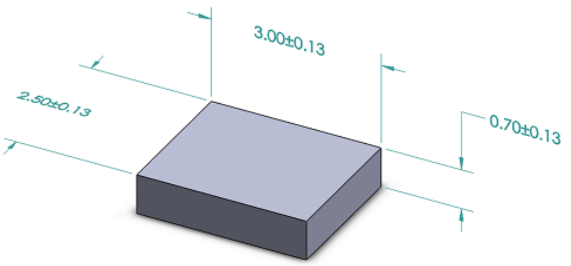
(3) Conducting **CFD fluent simulation** between stove and surrounding or (ambient). Because it able indicate heat loss from stove to the surrounding.

Future work

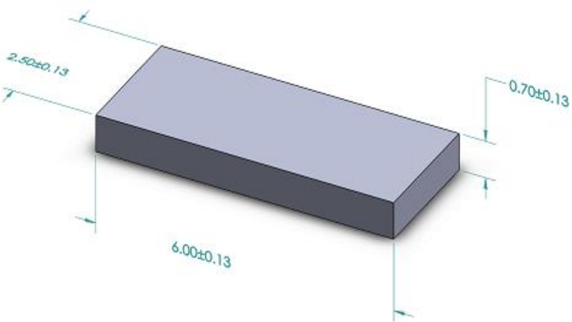
- ✓ Construct the prototype for this thesis by adding some design modification.
- ✓ Conducting the experiment in Tikikl stove by using analyzed result.
- ✓ Increasing electrical power generation by increasing the number of models.
- ✓ Conducting forced cooling mechanism. in order to increase the performance TEG module.

Appendix 1

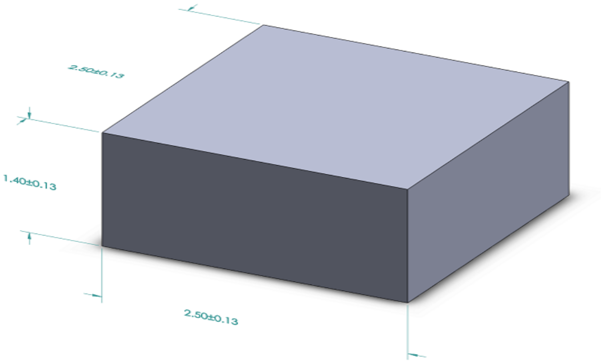
Stove and Thermo-electric module part drawing



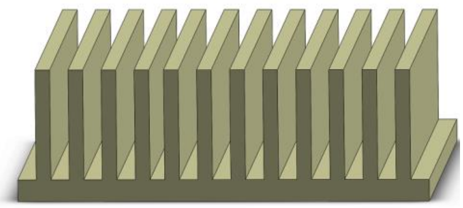
Short copper plate



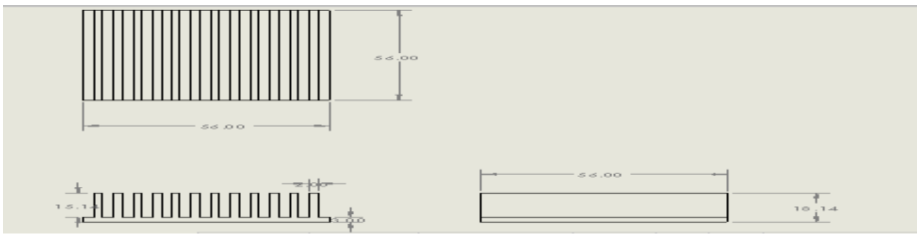
Long copper plate



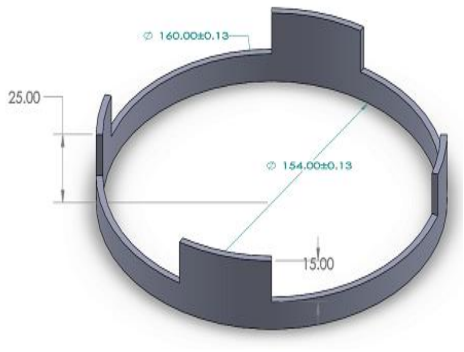
P-N semiconductor

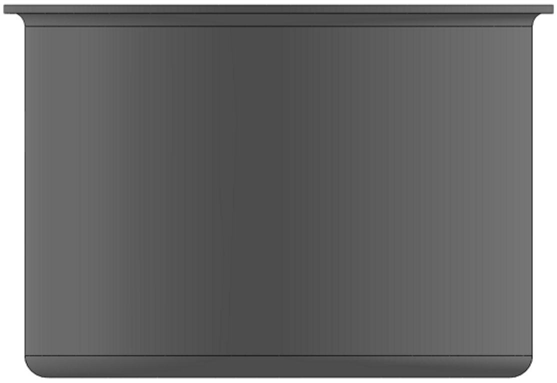


Fins

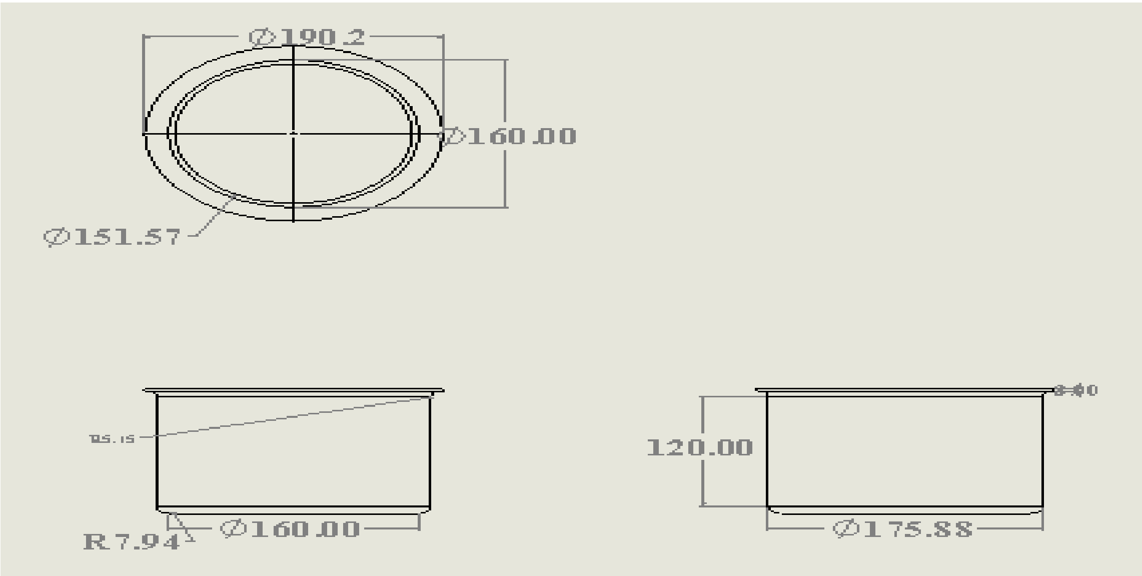


2-D view of fins

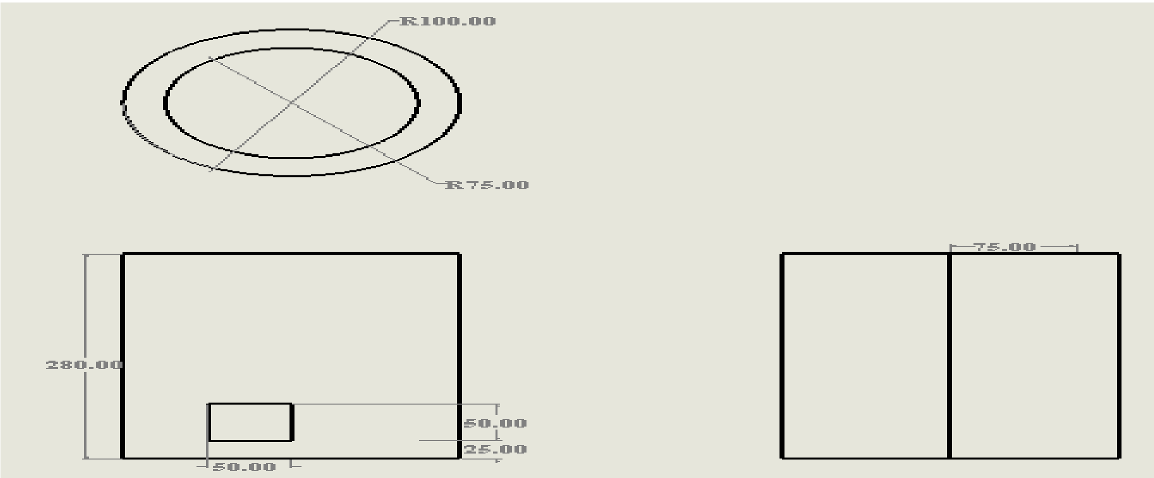




Pot-holder | Pot



2-D view for pot



2-D view for stove

Appendix 2

CFD numerical result in stove

(1) Area-Weighted Average

Total Temperature	***(K°)***
-------------------------------	--------------------
Bottom-pot-cont-region-trg	611.14225
Contact-region-src	479.17135
contact_region_2-src	420.65511
contact_region_3-src	706.5012
contact_region_3-trg	482.59113
contact_region_4-trg	730.97348
inlet	799.22304
inlet-air	499.46549
inner__bott_pot-cot_region_3-tr	625.54487
inner-bottom-stove	329.96513
inner-wall-pot	328.14335
inner_wall_pot-cont_regi_3-trg	375.51257
inner_wall_stove-cont_reg_4-sr	599.00996
interior-35	0
interior-7	0
interior-flame	789.6548
interior-pot	401.86953
interior-pot-holder	455.55454
interior-stove	453.54638
interior-water	735.41786
outer-bottom-stove	330.12941
outer_-wall-pot	372.54442
outer_-wall_-pot-cont_-re.gitrg	469.82469
outer_-wall-_stove	360.75289
outlet	775.12741
top_stove-contt_reg_2-trg	461.69171
wall-pot	326.74424
wall-pot_-holder	456.68654
wall-water	743.26071
----------------	--------------------
Net	575.31066

(2) Area-Weighted Average

Total Energy	***(J/kg)***
-------------------------------	--------------------
bottom_pot-cont_reg-trg	157272.35
contact_region-src	90959.61
contact_region_2-src	61556.366
contact_region_3-src	1707623.2
contact_region_3-trg	92677.98
contact_region_4-trg	352892.25
inlet	421580.66
inlet air	118970.23
inner__bott_pot-cont_reg_3-trg	164509.38

inner_bottom_stove-	51620.027
inner_wall_pot	15071.06
inner_wall_pot-cont_reg_3-trg	38873.145
inner_wal_stove-cont_regi_4-sr	219154.77
interior-35	0
interior-7	0
interior-flame	411950.91
interior-pot	52116.991
interior-pot_holder	79092.635
interior-stove	72755.859
interior-water	1828552.7
outer_bottom_stove	51454.688
outer_wall_pot	37381.708
outer_wall_pot-cont_reg-trg	86263.097
outer_wall_stove	20634.3
outlet	397330.11
top_stove-cont_region_2-trg	80953.554
wall-pot	14368.032
wall-pot_holder	79661.441
wall-water	1861351.5
----------------	--------------------
Net	481095.57

(3)

Mass Flow Rate	***(Kg/s)***
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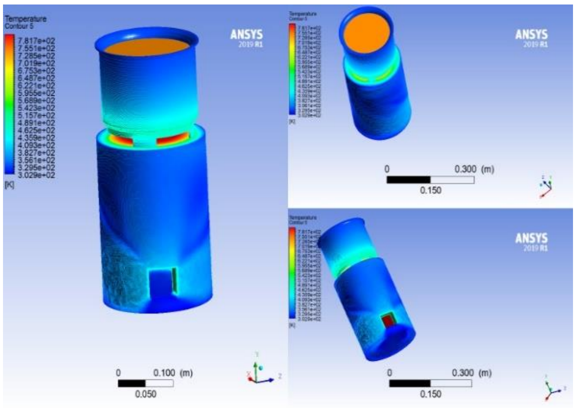
bottom_pot-contact_region-trg	0
contact_region-src	0
contact_region_2-src	0
contact_region_3-src	0
contact_region_3-trg	0
contact_region_4-trg	0
inlet	0.0043262841
inlet-air	0.001009085
inner__bott_pot-contact_region_3-trg	0
inner_bottom_stove	0
inner_wall_pot	0
inner_wall_pot-contact_region_3-trg	0
inner_wall_stove-contact_region_4-src	0
interior-35	0
interior-7	0
interior-flame	0.16986007
interior-pot	0
interior-pot_holder	0
interior-stove	0.0015612707
interior-water	-2.9267496e25
outer_bottom_stove	0
outer_wall_pot	0
outer_wall_pot-contact_region-trg	0

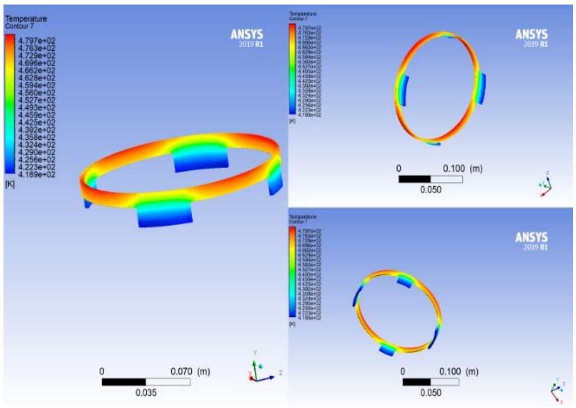
outer_wall_stove	0
outlet	0.0043262841
top_stove-contact_region_2-trg	0
wall-pot	0
wall-pot_holder	0
wall-water	0
----------------	--------------------
Net	0.001009085

Appendix 3

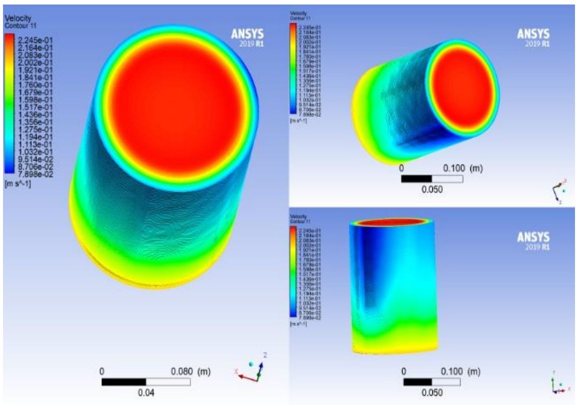
Graphical Simulation Display for stove and TEG module



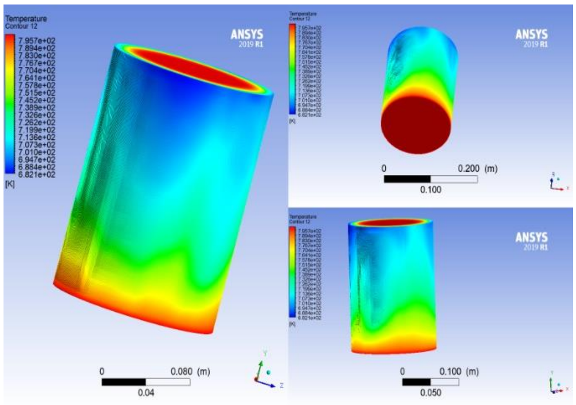
Over all simulation Temp.profile



pot-holder Temp.profile

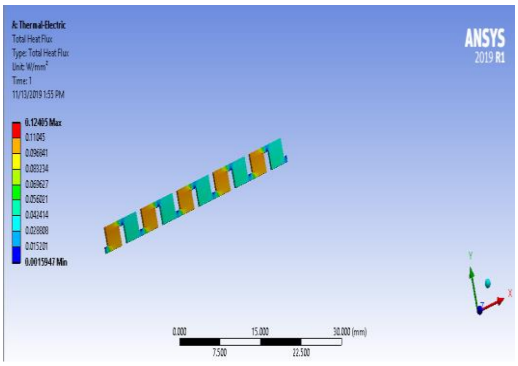


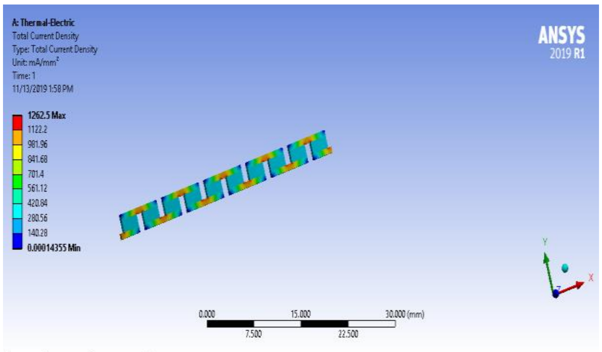
Flame velocity profile

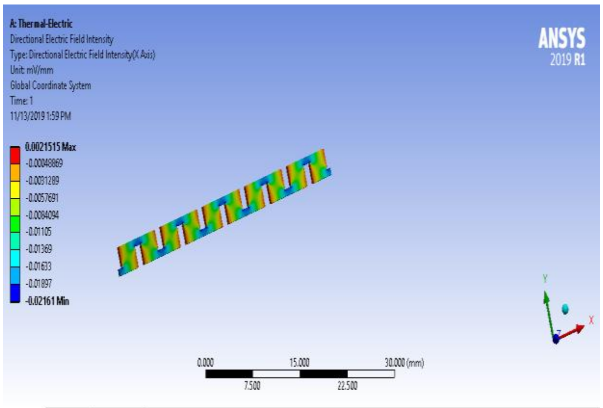


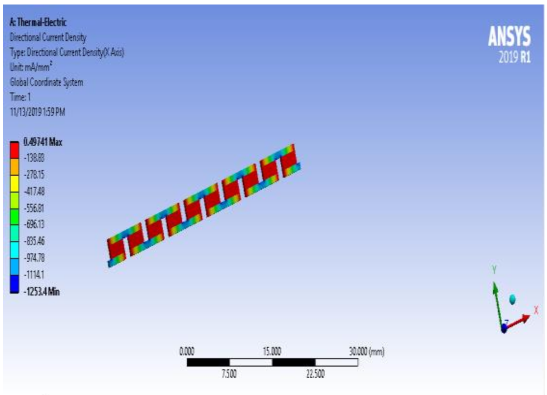
flame Temp. profile

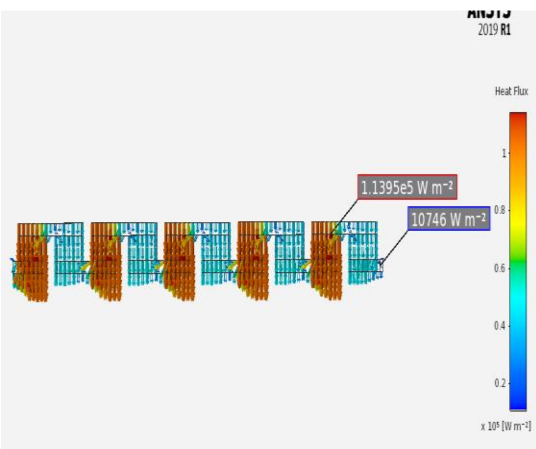
Simulation on TEG (Thermoelectric and AIM Discovery 2019)











Heat flow reaction

Direction of current density

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