

ADDIS ABABA UNIVERSITY



ADDIS ABABA INSTITUTE OF TECHNOLOGY SCHOOL OF GRADUATE STUDIES

**DESIGN, NUMERICAL OPTIMIZATION AND EXPERIMENTAL
INVESTIGATION OF WASTE - HEAT RECOVERY SYSTEM COUPLED
TO ELECTRIC INJERA BAKING PANS (MITADS)**

BY

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ABSTRACT

Electric Injera baking pans (Mitads) are the most prevalent and energy-intensive appliances used in Ethiopia and encounters bulk amounts of heat loss in the systems. However, only few and rarely published research and development were made to improve the thermal efficiency and reduce the heat loss encountered in the system. Therefore, this study aims to make design; numerical optimization and experimental investigation of waste heat recovery system coupled to electric injera baking pans to improve the efficiency of baking pan and reduce the wastage of energy in the baking process. Thus, to verify (quantify) the amount of heat loss accounted in the baking process intensive experimental investigation was made, and data obtained was analytically analyzed and electric Injera baking process was encountered 46.15% heat loss in which bottom insulation encountered 70% of total loss accounted in the process. Therefore, to reduce the major loss accounted in the bottom insulation analytical design and numerical optimization of waste heat recovery system was carried out by using comsol multiphysics software and 6.5mm thick ash insulation at the top and bottom of oil pan and 1.5mm oil pan thickness was obtained as the optimum dimension of heat recovery system. Then, the waste heat recovery system was manufactured as per optimization result and some of the insulation was replaced by simple heat recovery oil pan, with the diameter of 540mm and thickness of 19mm` and coupled to heat recovery tank, to discharge the energy recovered to make coffee and water heating. The performance evaluation of the system was carried out by experimental investigation and the system was recovered 60.66kJ (which account 9.63%) of heat energy at each baking and tested experimentally by boiling water. This study also quantifies the loss accounted in the new system and the system encountered 34.57% heat loss and bottom insulation accounted 22.57%. Compared to the ordinary baking pan the electric injera baking pan coupled with waste heat recovery system will improves the efficiency of baking process by 11.53%. The heat energy recovered by the system is utilized for water heating purpose and for making coffee.

Keywords: waste heat recovery, baking pan, heat loss, saturated porous media.

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NOMENCLATURE

Symbol	Meaning	SI unit
A	Area	[m ²]
D	Diameter	[m]
M	Mass	[kg]
L	Characteristic length	[m]
h_c	Convective heat transfer coefficient	[W/m ² K]
K_{eff}	Effective thermal conductivity	[$\frac{W}{mK}$]
T	Temperature	[K]
C_p	Specific heat capacity	[J/Kg.K]
LH	Latent heat of fusion	[kJ/kg]
\dot{Q}	Heat loss	[J]
K	Thermal conductivity	[$\frac{W}{mK}$]
ν	Kinematic viscosity	[m ² /s]
Pr	Prandtl number	-
β	Expansion coefficient	[K ⁻¹]
ε	Emissivity	-
σ	Stefan Boltzmann constant	[$\frac{W}{m^2K^4}$]
ϕ	Porosity	-
Nu	Nusselt number	-
Ra_L	Rayleigh number	-
Gr_L	Grashof number	-
V_{OP}	Volume of oil pan	[m ³]
V_{HRT}	Volume of heat recovery tank	[m ³]

ΔP	Pressure change	[Pa]
f	Coefficient of friction	-
Re	Reynolds number	-
q_v	Volumetric heat generation	$[\frac{W}{m^3}]$
t	Time	[s]

ABBREVIATIONS

WHRS	Waste heat recovery system
WHRS CEIBP	Waste heat recovery system coupled to electric injera baking pans
GBC	Global boundary conditions

CHAPTER ONE

INTRODUCTION

The electrical form of energy has become virtually important for household human activities like cooking, baking, lighting and water heating [1, 2]. In Ethiopia, over 90% of energy consumed in household level is for cooking and from this injera baking accounts for 50-75% [3]. Indeed, firewood is the primary source of energy used for cooking, even in the absence of a 'stove' in many developing countries like Ethiopia [4]. However, use of such cooking technologies has disadvantages like deforestation, public health risks – primarily related to respiratory illnesses, low efficiency, gender inequality and high fuel consumption [5, 6, and 7]. Therefore, it is long-term plan of the country to reduce adverse environmental and health impacts of using biomass fuels by shifting primarily to electricity for Injera baking [2, 8]. However, each existing electric injera baking stove (mitad) consumes large quantity of electricity nearly about 3.0-3.5 kW for each baking with high-energy wastage encountered in the process [2, 3, 9]. The design of conventional electric mitad suffers many losses due to high resistance, inadequately sized electric wiring, use of poor construction materials and poor insulation, which account large amount of energy dissipation during the baking process, roughly in the range from 40 to 50 percent [3, 10]. Thus, only few researches are developed to minimize the energy wastage and develop energy efficient electric injera baking stove. Therefore, the aim of this research is to design, optimize and made experimental analysis of heat recovery system coupled to electric injera baking stove (mitad) to reduce the major heat loss accounted in bottom insulation by using thermal energy storage systems. The heat recovery system will also be designed in a way to transport and utilize the recovered energy for related cooking activities such as preparation of stew, coffee making etc.

1.1. ADVANTAGES OF USING ELECTIC INJERA BAKING STOVE

Using electric Injera baking stoves has positive advantages in development of the country and in improvement of living standard of the community. Thus, using electric injera baking stove will:

- Mitigate the burden of collecting bio mass fuel for fire wood
- Improve household outcomes - through reduction of health risks and effort in cooking and energy collection

- Reduce deforestation
- Protect the environment (global warming) due to transition to cleaner energy sources [11].

1.2. INJERA BAKING TECHNOLOGY

Depending up on the energy input to the stove, injera baking stove technology is broadly classified in to four:

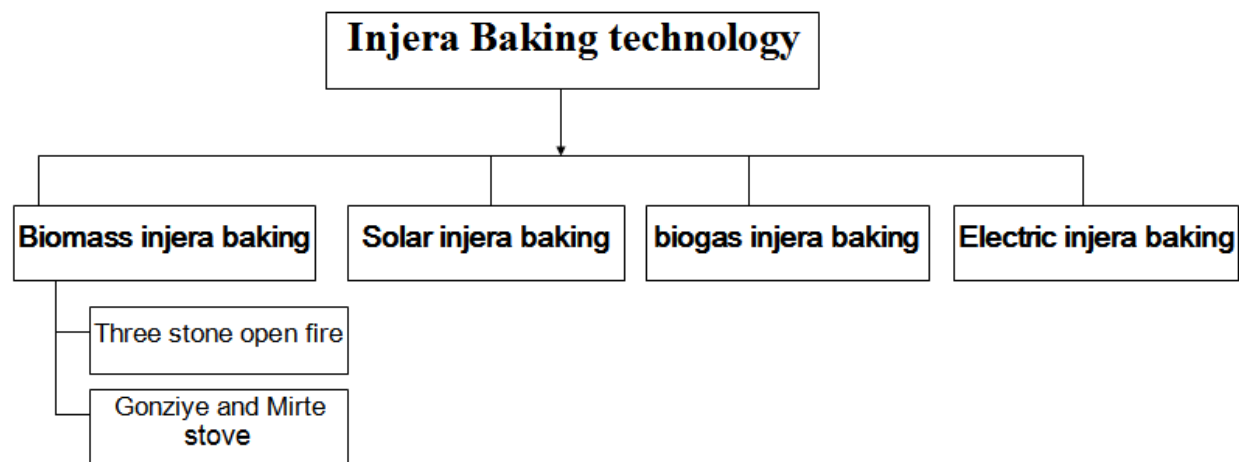


Figure 1.1: Classification of injera baking technology

1.2.1. BIOMASS INJERA BAKING

Biomass is the main energy source of developing countries. Generally, it is considered as renewable source of energy; however, this is a misleading concept for developing countries where deforestation and afforestation actions are not balanced. Many people in Ethiopia, like other developing countries choose biomass as their primary energy supply due to immature technology of other clean energy sources and it is collected for free or cheap. In addition, the rural community of most developing countries lives in scattered villages posing formidable technical and financial challenges to grid-connection, where biomass based energy is a prominent option. Thus, even though Injera baking is energy intensive and time-consuming process, it is carrying out widely by using biomass [12]. Biomass based energies are derived from three sources; agricultural residues, forestry residuals and energy crop [13].

1.2.1.1. Three stone (open fire)

In most of Ethiopian households, Injera baking is carried out using three stone (open fire) in which fires surrounded by three-stone called “*Gulich*”. The heat supplied to the mitad in this system is lost through, the sides, the exhaust gases from the fuel, convection and radiation heat losses from the pan surface. Thus, main drawback of three stone cooking stoves is its inefficiency, unhealthy – causes damage on lungs and eyes and allow excessive deforestation see Figure 1.2 (a) [14]. Generally, only about 9 - 17% of the total energy from open fires burned will be utilized, and reaches the food or water that should be heated [2].

1.2.1.2. Gonziye and Mirte stove

Gonziye and Mirte stoves are an improved design of the *Injera* baking stoves. They are constructed using clay and cement with sand respectively. Mirte stove has a single lower opening for air and fuel (firewood) inlet with single smoke outlet. In most case the smoke heat is recovered for cooking small items like water heating and cooking stew (wote). In some cases, the smoke released through chimney to have smoke free kitchen. Similar to Mirte, Gonziye is made of three to four partial circular walls but Gonziye does have pot or plate-rests. The Mirte stove test has been carried out by the Ministry of Water and energy; they showed its promising energy saving capacity and can achieve fuel efficiency of up to 40% over the open fire stove [2, 15]. Even though, Gonziye and Mirte stove are better and efficient comparing to the open fire baking system; they have disadvantage due to contribution to deforestation, productions of some smoke, which causes damage on lungs and eyes [9, 11].



(a)

(b).

(c).

Figure 1.2: Types of baking technology (a) Three stone injera baking (b) Gonziye stove. (c) Mirte stove [2.9].

1.2.2. SOLAR INJERA BAKING

Solar thermal powered injera baking is the technology used to bake injera by harnessing solar radiation as their energy source. Baking with freely available solar energy is a healthy and environmentally friendly alternative than using wood fuel, gas or electrical energy. The technology is most appropriate in sunny and dry seasons with sufficient levels of solar radiation. However, it has lower efficiency to use during winter seasons and on rainy days. Baking also takes a significantly longer time compared to conventional methods. Users must schedule their cooking time to maximize the use of sunlight. As a result, preparation must start early in the morning so that the food can be placed in the cooker by noon. Therefore, in order to ensure the successful implementation of this technology, local needs, cooking habits and social conditions should also be taken into account. Optimistic assessments assume that the adoption of solar cookers could save more than 35% of fuel wood. Estimations on potential net GHG emission savings vary between 690kt and 140,000kt of CO₂ per year [18, 19].

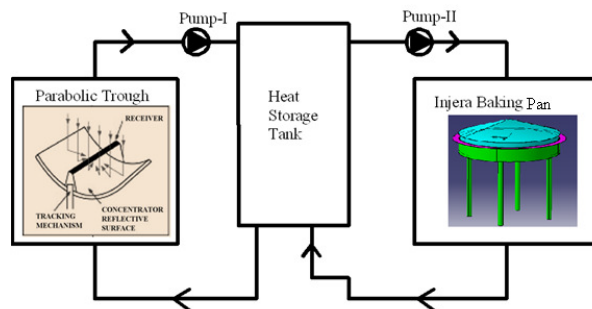


Figure 1.3: solar powered injera baking oven [24]

1.2.3. BIOGAS INJERA BAKING

“Biogas” is a gas produced by anaerobic fermentation of different forms of organic matter and is composed mainly of methane (CH₄) and carbon dioxide (CO₂). Biogas is a flexible energy carrier, suitable for many different applications. One of the simplest applications of biogas is the direct use for cooking and lighting [20]. Matured biogas production technology has led to the development of a number of biogas appliances for lighting, power generation, and cooking. The most promising among them is the biogas stove, to meet the energy requirement for cooking application at domestic as well as at the community level. In Ethiopia, the implemented biogas

gives advantages only for lighting and cooking purposes. However, previously implemented biogas stove used for Injera baking have a problem of consuming a large amount of gas from the plant, loses a large amount of heat out and face unequally distribution of pressures on the holes. Due to, its inefficient size and non-uniform heat distribution throughout the baking pan the quality of injera baked is become lower [21, 22].

1.2.4. ELECTRIC INJERA BAKING

In urban area of Ethiopia, energy shift from biomass fuel to electricity for injera baking occurred in 1960's [3]. However, currently existing electric injera mitad technologies are believed to be in the market for over 40 years [8]. Since then, almost no design improvements have taken place and are highly energy inefficient, have poor design and the product has not been standardized [3, 15]. The causes of energy inefficiency are mainly attributed to the requirement of high amount of electrical energy to heat up the temperature of clay plate to about 200 – 250 °C for baking Injera. This high-energy requirement is due to high heat load (parts of the Mitad to be heated up), heat losses, poor heat insulation, and poor construction materials [3, 23]. Electric injera baking stove (Mitad) is made from steel or Aluminum sheet metal framework having a conical shaped lifting cover, short cylindrical enclosure (body), clay plate, an electric heating element, heat insulator and a support stand [37].

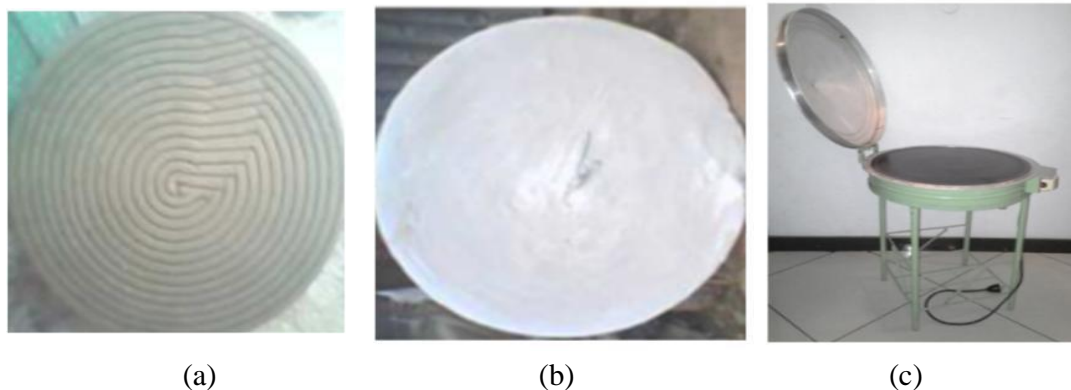


Figure 1.4: (a) Backside of clay plate with groove, (b) Sealed with gypsum and (c) Assembled electric injera stove [9]

Table 1-1: Summary of Gap identified in Review of injera baking technology

Baking technology		Efficiency	Gaps	Ref.
Biomass	Three stone	10-15%	<ul style="list-style-type: none"> ▪ Inefficiency, ▪ Unhealthy; cause damage on lungs and eyes and ▪ Allow excessive deforestation 	[2, 3]
	Mirte & Gonziye	23%		
Solar		-	<ul style="list-style-type: none"> ▪ Difficulty to use in winter seasons and rainy days ▪ Baking will take longer time ▪ Cooker must be scheduled 	[12]
Biogas		51 - 55%	<ul style="list-style-type: none"> ▪ Lower Quality of Injera ▪ Inefficient due to poor design ▪ Face un equal distribution of pressure on the holes 	[21,22]
Electric		50 - 55%	<ul style="list-style-type: none"> ▪ Poor design ▪ Energy inefficiency ▪ High operating cost (Electric Bill) 	[23, 34, 37]

Some of the gaps identified from review of different types of injera baking technologies are summarized in (table 1-1) above. Therefore, depending up on gap presented electric injera baking is preferred due to its clean energy, healthy in operation, save time for baking and collecting firewood. Thus, it will reduce burden on women and children, which will divert their time from education and income generating activities into biomass fuel or wood collection for the firewood injera mitads [16]. However, the electric injera stove currently used is energy inefficient and account higher heat loss in the system, which will increase energy bill on the customer. Thus, this research is aim to design, optimize and make experimental investigation on waste-heat recovery system coupled to injera baking stove and provide for community with optimum cost. Have significant advantages to reduce electric energy bill and help to use waste heat recovered for additional cooking or water heating purposes like cooking stew (wote), coffee and, etc. In addition to that, it will reduce load from national grid and increase the need of community to use clean energy for almost all application of cooking and water heating purpose.

1.3. THERMAL ENERGY STORAGE

Thermal energy storage has been a key technology to store energy in the form of heat for a particular time and provides this energy for later usage [24]. There are mainly three ways of storing heat: sensible heat storage, latent heat storage, and thermo – chemical storage [25].

1.3.1. SENSIBLE THERMAL ENERGY STORAGE

Sensible thermal energy storage technology based on storing thermal energy by raising temperature of a solid or liquid using their heat capacity without changing phases [26]. Sensible thermal energy storage materials are commonly classified as solid and liquid storage materials. Solid storage materials include rocks, stones, brick, iron, soil, concrete etc. and liquid storage materials include mainly water and oils [27].

The amount of thermal energy stored in the form of sensible heat can be determined by [26].

$$Q = \int_{T_1}^{T_2} mx C_p dT = mx C_p x (T_2 - T_1) \quad (1)$$

Where;

Q = is the amount of thermal energy stored or released in form of sensible heat [kJ],

T₁ = is initial temperature [°K], T₂ = is final temperature [°K], m = is mass of material used to store thermal energy (kg), and C_p = is specific heat of the material used to store thermal energy [kJ/Kg.K].

From eqn. (1) it is clear that the amount of thermal energy stored in the form of sensible heat is directly proportional to mass (m), specific heat (C_p) and the temperature change (ΔT) of the material [28, 29].

1.3.2. LATENT THERMAL ENERGY STORAGE

Latent thermal energy storage uses the latent heat of the material to store thermal energy. Latent heat is the amount of heat absorbed or released during the change of the material from one phase to another phase. Materials with this property are called phase change materials (PCMs) [29].

The amount of thermal energy stored in form of latent heat in a material is calculated by;

$$Q = mxLH \quad (2)$$

Where;

Q = is the amount of thermal energy stored or released in form of latent heat [kJ],

m = is the mass of the material used to store thermal energy [kg], and

LH = is the Latent heat of fusion or vaporization [kJ/kg].

From eqn. (2) the amount of thermal energy stored as latent heat depends on the mass and the value of the latent heat of the used material. Materials used to store thermal energy in form of latent heat are called phase change materials. Figure 1.6 gives the storing and discharging process of latent thermal energy storage.

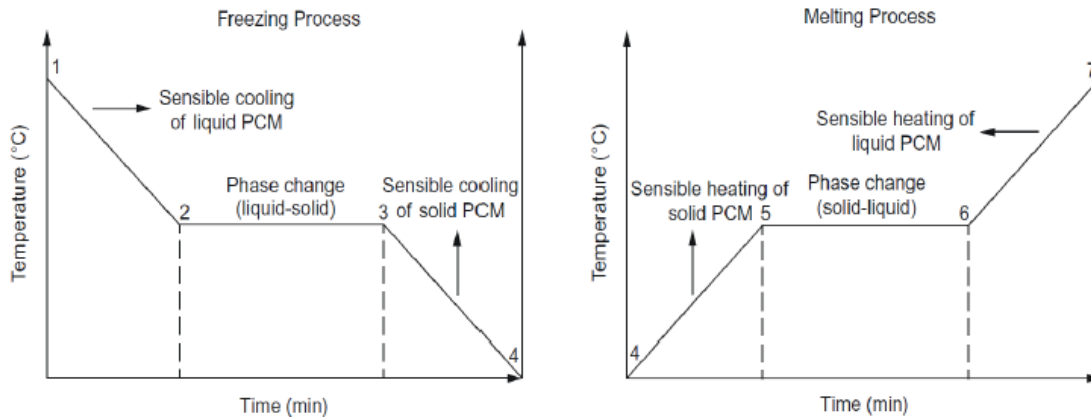


Figure 1.5: Heat storage and discharging processes of the PCM [24]

1.3.2. THERMO – CHEMICAL STORAGE

Thermo – chemical storage uses reversible endothermic/exothermic chemical reactions of reactants to store and release the required heat energy. The supply of heat energy to pairs of chemical material breaks the bonding between them and they separates into individual reactive components. For example, thermochemical reactions of Ca(OH)_2 that can be used for thermochemical heat storage is given by eqn. (3) [24];



Table 1-2: Advantages and disadvantages of thermal energy storage concepts [24]

TES technique	Advantage	Disadvantage
Sensible heat storage	<ul style="list-style-type: none"> Simple 	<ul style="list-style-type: none"> Size of the system Not isothermal storage process
Latent heat storage	<ul style="list-style-type: none"> Isothermal storage process High storage density 	<ul style="list-style-type: none"> Price Low thermal conductivity Almost no convection
Thermo – chemical storage	<ul style="list-style-type: none"> High energy density 	<ul style="list-style-type: none"> Complexity Expensive compound Relatively high temperature required Limited experience with long – term operation

1.4. PROBLEM STATEMENT

Even though Injera baking was energy intensive process, the technology used for baking process was not yet developed. Therefore, still now Injera baking process carried out mostly by using biomass burning. Thus, use of such cooking technologies has disadvantages like deforestation, public health risks – primarily related to respiratory illnesses, low efficiency, gender inequality and high fuel consumption. Therefore, it is long-term plan of the country to reduce the adverse effect caused due to use of biomass burning by shifting to conventional electric Injera baking stove (Mitads). The existing electric injera baking stove is also energy inefficient and cost high electric bill due to major losses accounted in the process such as bottom loss, side loss, infiltration loss and etc. (account 40% - 50% energy loss) [10]. Therefore, recovering the heat loss encountered in the system will improve the efficiency of baking process and reduce electric bill of Injera production process. Hence, heat energy recovered will be used for additional cooking or water heating purposes like cooking stew (wote), coffee and, etc. In addition to that, it will reduce load from national grid.

1.5. OBJECTIVE

The major objective of this research is to design, numerically optimize and make experimental investigation of heat recovery system coupled to electric injera baking stove with thermal energy storage.

1.5.1. SPECIFIC OBJECTIVES

The specific objectives of the research are:

- ❖ To analyze and quantify loss encountered in the electric injera baking pan (mitads)
- ❖ To make conceptual design of heat recovery systems
- ❖ To make mathematical modeling of heat recovery system
- ❖ To make numerical optimization of heat recovery system
- ❖ To manufacture heat recovery system components
- ❖ To experimentally investigate the performance of heat recovery system

1.6. DELIMITATION

This research project is intending to design, make numerical optimization and experimentally investigate the performance of waste-heat recovery system coupled to electric injera baking stove (Mitad) with the objective of reducing energy losses encountered in the process, reduce energy

bill and reduce load from the national electricity grid. Thus, biomass, biogas and solar injera baking technology are not included in this research. However, a detailed comparison of each technology has been presented in the introduction section. The research mainly focuses on energy transfer to the injera baking pan and the problems related to the type of injera and thermo – physical properties of injera will not be investigated and the sizing of electric mitad is not included.

CHAPTER TWO

LITERATURE REVIEW

Numerous types of injera baking stove were designed and developed by various researcher, yielding varying degrees of technical performances. Mainly there are four types of injera baking systems; biomass, biogas, solar and electric stove. Rachsak et al [30] designed waste-heat recovery system for a traditional cooking stove and generate electricity by using thermoelectric module sandwiched between two heat exchangers. The hot side of the thermoelectric module installed under the grate and hot water as a by - product was used for domestic applications. The performance of the cooling system of the thermoelectric generator has enhanced by using a heat pipe with a water-filled box. The amount of electrical power generated and the hot water temperature depends on both the hot-side temperature and the volume of water being heated. The thermal to electrical energy conversion efficiency and hot water production efficiency were calculated. Then, the contact resistances at typical positions have evaluated to improve the waste heat-recovery performances.

Abdulkadir et al [31] designed and manufactured laboratory model solar thermal energy based Injera baking glass pan. In the process Shell thermia oil B was used as a heat transferring medium, due to its better properties to achieve requirement of very high surface temperature (range of 180 °C to 220 °C) for baking injera. To simulate solar heat energy, electrical heating element has been used to raise the temperature of working heat transfer fluid in the storage tank, until the required baking surface temperature is achieved. Thus, heat transfer from the heated oil to the baking glass by convection and to Injera by conduction, heat transfer mechanisms. To transfer heat energy uniformly from the heat transfer oil to batter, fin like structures welded below the pan and this can hinder direct oil flow and increase the contact time between heat transfer oil and increase strength of the gallery. Desta et al [32] presented finite difference modeling of solar thermal powered injera baking oven. The simulation done by varying the pan thickness for 10mm, 8mm and 5mm as well as the temperature of the hot oil in contact with the pan. The results had shown that for 10mm pan thickness, acceptable heat up times has recorded for the hot oil temperature values of 290 °C and 300 °C and for 8mm pan thickness hot oil temperature was lowered to values ranging from 270°C to 300°C. However, comparatively fast

heats up times has recorded for a pan thickness of 5mm and hot oil temperature ranges from 255⁰C to the maximum value of 300⁰C. From the result the researcher proposed baking pan with 5 mm thick and 255⁰C oil temperatures for solar thermal powered injera baking pans.

Abdukadir and Demiss et al [33] presented finite modeling of solar powered injera baking oven for outdoor cooking. In this paper MATLAB software is used to simulate temperature variations on surface of the baking pan during initial heat-up and baking cycle.

Awash et al [23] made experimental investigation on performances characteristics and efficiency of electric injera stove. In this paper, thermo-physical property of injera was determined from the compositional results of batter and injera by using appropriate terms. The researchers also made the comparison between the conventional and improved electric injera baking stove. From experimental result he obtained total time required for baking 15 injera using conventional electric baking stove was around 4260 sec with average power consumption of $12.86 \frac{KW}{m^2}$ while it required 4540 sec and $9.08 \frac{KW}{m^2}$ average power consumption in case of improved baking stoves.

Maximum Energy loss accounted at the bottom side of stove for conventional and improved injera baking pans were determined as 35.08% and 23% with the efficiency of 52% and 75% respectively. Ezana et al. [34] presented finite element heat-balance model for an electric injera cooker and compare the predictions with controlled cooking experiments. Injera cooker efficiency and the major factors affecting the energy intensity and efficiency of injera production were determined. Robin et al. [35] presented the development of energy efficient magic electric mitad for baking injera. He made experimental investigation to enhance the performance of previous design of magic mitad. Magic mitad was developed by a Dutch, start-up company magic venture and used the same heating element as conventional electric mitad, but placed a few centimeters glass sheet underneath (instead of embedded in clay plate). The experimental result showed that energy efficiency of the magic mitad is significantly higher by about 45% and baking time is faster by about 37% compared to the electrical clay mitads. The quality of the injeras baked on the magic mitad perceived by experts as very high, comparable to the quality of injeras baked on clay mitads.

Table 2-1: Summary of the review of various Injera baking stove

S.no.	NAME OF RE-SEARCHER	BAKING TECHNOLOGY USED	SUMMARY OF THE RESEARCH
1.	Rachsak et al	biomass cooking stove	Designed waste heat recovery system for a traditional cooking stove and generate electricity by using thermoelectric module. conversion efficiency from thermal to electrical energy and hot water production efficiency were calculated
2.	Abdulkadir et al	solar thermal baking glass pan	Designed and manufacture laboratory model solar thermal energy based Injera baking glass pan. In the process researcher used shell thermia oil B, as working fluid and electrical heating element to simulate solar heat energy
3.	Desta et al	solar thermal baking oven	Formulate finite difference modeling of solar thermal powered injera baking oven.
4.	Abdukadir&Demiss et al	solar thermal baking oven	Presented finite element modeling of solar powered injera baking oven for outdoor cooking
5.	Awash et al	electric stove	Made experimental investigation on performances characteristics and efficiency of electric injera stove
6.	Ezana et al	electric stove	Presented finite element heat balance modeling for an electric injera cooker and compare its predictions with controlled cooking experiments.
7.	Robin et al.	electric baking stove	Presented the development of energy efficient magic electric mitad for baking injera

Almost in all literature review presented, the researchers expend their effort on the design and modeling of injera baking technologies and to determine thermos – physical properties of injera. However, only few of them deal on the loss encountered on the baking technologies and efficient use of energy in the system. Thus, in this research the researcher aimed to design, optimize and made experimental analysis of waste heat recovery system coupled to electric injera baking stove and provide for community with optimum cost. This will reduce energy bill and help to use waste heat recovered for additional cooking or water heating purposes like cooking stew (wote), coffee and etc. In addition to that it will reduce load from national grid and increase the need of community to use clean energy for almost all application of cooking and water heating purpose

2.1. METHODOLOGY

In order to achieve the main objective of this research the following methodology will be implemented.

▪ Literature Review:

In literature review part of this research the researcher reviews most of previous research done on the injera baking technologies and discusses the gaps present on each of the technologies used for baking injera and finally discusses the alternatives used in this research to solve the gap presented.

▪ Analysis of Loss encountered in the electric stove

In this chapter the researcher analyzes the loss encountered in the electric injera baking stove by making experimental investigation and then by making analytical calculation to quantify the amount of energy lost in the system. Thus, to make experimental investigation the researcher aimed to use temperature measuring instruments i.e. thermometer, K-type thermocouple and infrared thermometer to measure surface temperature of bare plate, enclosure, lifting cover and temperatures at the bottom of clay plate.

▪ Design of heat recovery system and selection of heat storage materials

In this part of the research the design of heat recovery system i.e. Heat recovery oil pan, heat storage tank and selection of material for the system and also type of heat storage oil is carried out.

▪ Mathematical Modeling of heat recovery system

In this portion of the research mathematical modeling represents heat transfer in the heat recovery system is carried out for heat recovery oil pan and heat recovery tank.

▪ Optimization of heat recovery system coupled to injera baking stove by using

✓ COMSOLMULTIPHYSICS

▪ Heat Recovery system assembly to electric stove

▪ Experimental investigation and data collection by using:

✓ K-type thermo couple, Infrared thermometer and glass thermometer

▪ Data analysis

▪ Validation of optimization result with experimental result

▪ **Result and conclusion**

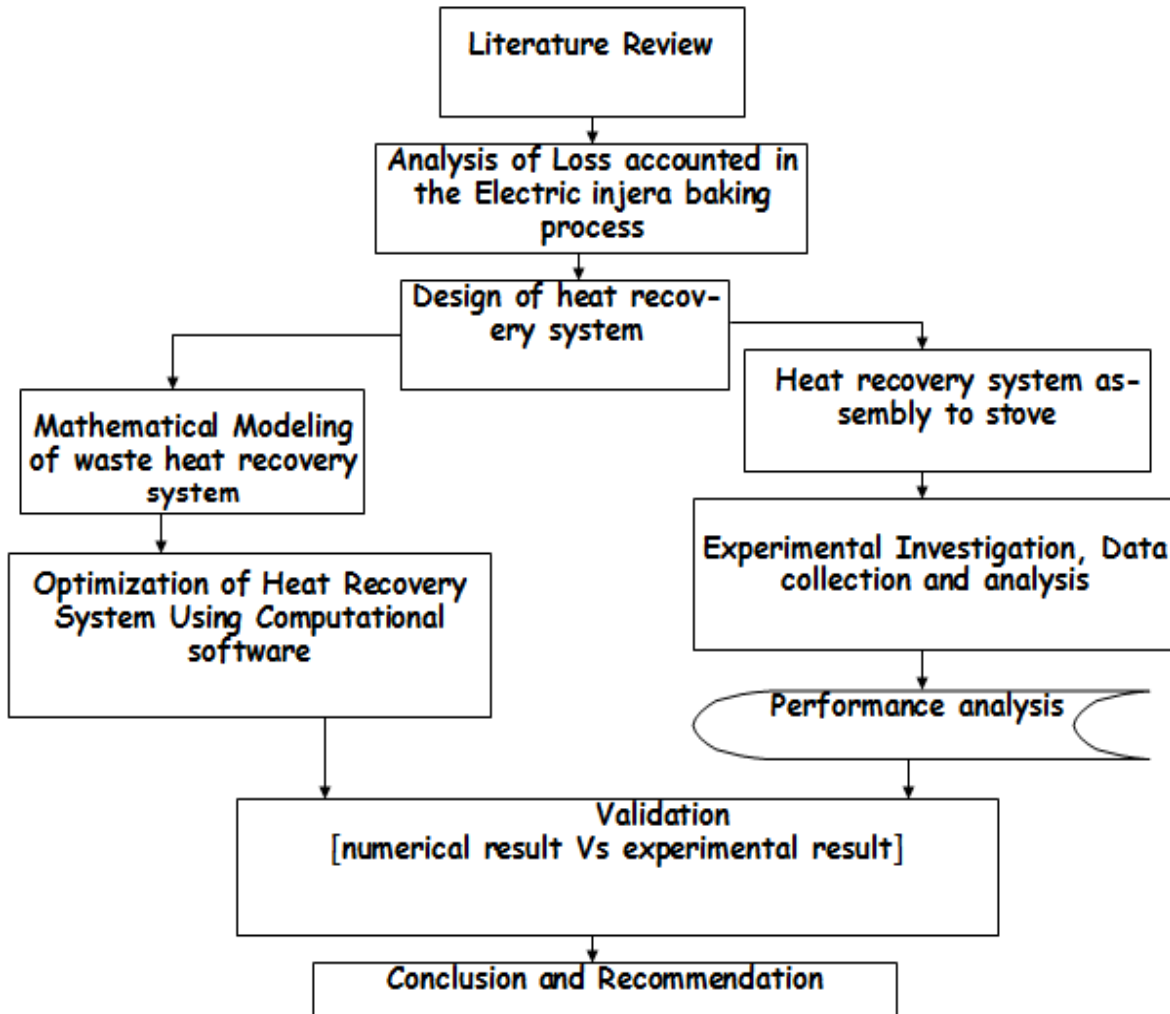


Figure 2.1: Schematic representation of research methodology

CHAPTER THREE

ANALYSIS OF PRINCIPAL LOSS ENCOUNTERED IN INJERA BAKING PROCESS BY ORDINARY ELECTRIC MITAD

In electric Injera baking stove heat energy is lost from top, bottom and side directions of clay plate. Indeed, all three mode of heat transfer; conduction, convection and radiation are involved in the transfer of heat from electric injera baking stove to the environment [36].

In this chapter the researcher analyzed the major heat loss encountered in the Injera baking process and experimentally quantifies the amount of heat lost from the electric injera baking stove. Experimental investigation is carried out by using temperature measuring instrument i.e. K-type thermocouple, glass thermometer and infrared thermometer. Figure 3.1 shows the picture of the actual temperature measuring instruments used for experimental investigation.



Figure 3.1: Temperature measuring instruments (a) Infrared thermometer (b) K- type thermocouple (c) glass thermometer

In the experiment K-type thermocouple is used to measure the temperature at the bottom of clay plate and infrared thermometer is used to measure surface temperature of side enclosure, bottom enclosure, and also surface temperature of clay plate and cover while; glass thermometer is used to measure surrounding temperature. Instrument calibration is made to obtain the correct reading and emissivity of surfaces are adjusted on infrared thermometer to $\varepsilon = 0.11$, 0.95 and 0.98 for cover, side enclosures and baking plate respectively. Figure 3.2 shows the actual pictures of experimental setup and injera texture.



Figure 3.2: Actual picture during experimental investigation (a) & (b) pictures of experimental set up (c). Injera texture

The experiment is carried out for one hour and forty minutes while, fifteen injeras were baked, including initial heating and polishing time of electric injera baking stove. Thus, temperature measurement at each surface was taken within interval of four minutes and presented as shown in Fig (3.3) and finally the average temperature of all measurement at each surface was taken for quantifying the loss accounted in the baking process.

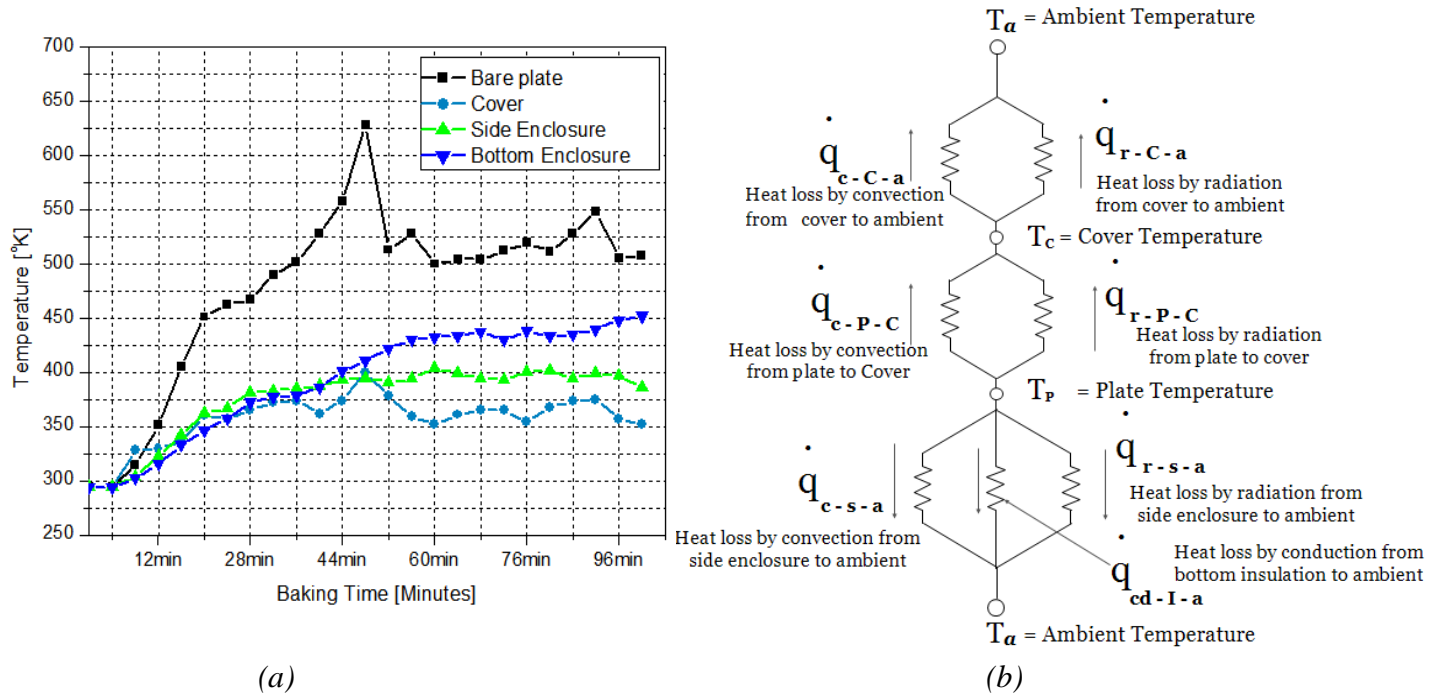


Figure 3.3: (a) Surface temperatures obtained from experimental result (b) Thermal circuit diagram and heat loss in conventional Injera baking pan

3.1. HEAT LOSS FROM THE COVER

Heat loss from the top of clay plate was carried out due to lifting cover which stays closed for over 50% of the baking cycle and gets heated up [37]. Therefore, heat is lost from hot cover to the surrounding by radiation and convection [36, 37].

3.1.1. CONVECTION HEAT LOSS FROM THE COVER

In this case thermal energy is lost due to transfer of heat to the cold environment by the bulk movement of the air.

Data obtained from experiment

- Average temperature of cover $T_c = 356^{\circ}\text{K}$
- Surrounding temperature $T_{\infty} = 299^{\circ}\text{K}$
- Film temperature, $T_f = \frac{T_p + T_{\infty}}{2} = \frac{356 + 299}{2} = 327.5^{\circ}\text{K}$

Properties of air at film temperature

$$v = 18.66 \times 10^{-6} \text{ m}^2/\text{s} \quad P_r = 0.703$$
$$k = 28.34 \times 10^{-3} \text{ W}/\text{mk} \quad \beta = 3.05 \times 10^{-3} \text{ K}^{-1}$$

Cover data

- Characteristic length of cover is $L_c = s = 32.3\text{cm} = 0.323\text{m}$
- Surface area $A_s = \pi r s + \pi r^2 + 2\pi r h = 0.674\text{m}^2$
- Emissivity of lifting cover $\varepsilon = 0.11$
- Stefan- Boltzmann constant $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}$

Rate of convection heat loss from the cover is observed to be proportional to the temperature difference and is conveniently expressed by newton's law of cooling as shown in eqn. (3.1) [38, 39 & 40].

$$\dot{Q}_{conv} = hA_s(T_c - T_{\infty}) \quad (3.1)$$

Where,

h = convection heat transfer coefficient, $\text{W}/\text{m}^2 \times ^{\circ}\text{K}$

A_c = cover heat transfer surface area, m^2

T_c = temperature of the cover surface, $^{\circ}\text{K}$

T_{∞} = temperature of the air sufficiently far from the surface, $^{\circ}\text{K}$

Convective heat transfer coefficient over horizontal enclosure can be calculated by using eqn. (3.2) [38 &39].

$$h_c = \frac{Nu K}{L} \quad (3.2)$$

Where,

$$h_c = \text{convection heat transfer coefficient, } \left[\frac{W}{m^2 \cdot K}\right]$$

Nu = nusselt number

$$k = \text{thermal conductivity of the fluid (air)} \left[\frac{W}{m \cdot K}\right]$$

L = characteristic length [m]

The empirical correlation for the average nusselt number (Nu) in natural convection was shown in eqn. (3.3) [33, 34].

$$Nu = C(Gr_L Pr)^n = C Ra_L^n \quad (3.3)$$

The values of the constants *C* and *n* depend on the geometry of the surface and the flow regime, which is characterized by the range of the Rayleigh number.

Where; (*Ra_L*) is the Rayleigh number, which is the product of the Grashof (*Gr_L*) and Prandtl (*Pr*) numbers:

$$\begin{aligned} Ra_L = Gr_L Pr &= \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} Pr \\ &= \frac{9.8 \times (3.05 \times 10^{-3} K^{-1}) \times (83-26)K \times (0.323)^3}{(18.66 \times 10^{-6} m^2/s)^2} \times 0.703 \end{aligned} \quad (3.4)$$

$$Ra_L = 1.16 \times 10^8$$

Hence, average nusselt number for natural convection over the horizontal enclosure (cover) heated from below is determined from correlation proposed by Globe and Dropkin [38];

$$Nu = 0.069 Ra_L^{1/3} Pr^{0.074} \quad \text{for } 3 \times 10^7 \leq Gr_L Pr \leq 7 \times 10^{11} \quad (3.5)$$

$$Nu = 32.78$$

$$\text{Therefore; } h_c = \frac{Nu K}{L} = \frac{32.78 \times 0.02834}{0.323} = 2.876 \frac{W}{m^2 K}$$

At each baking (180se) heat energy lost from the cover by convection heat loss can be obtained as;

$$\begin{aligned} \dot{Q}_{conv} &= hA_c(T_c - T_\infty) \times 180 \text{sec} \\ &= 2.876 \frac{W}{m^2 K} \times 0.674 m^2 \times (356 - 299)K \times 180 \text{sec} \end{aligned}$$

$$\dot{Q}_{\text{conv}} = 19.9\text{kJ}$$

3.1.2. RADIATION HEAT LOSS FROM THE COVER

Thermal radiation is the transfer of energy due to electromagnetic waves. It is continuously emitted by all matter whose temperature is above absolute zero and increases with increasing temperature of the body [39].

The net energy emitted at each baking (180s) from cover surface at temperature (T_s) to the surrounding (T_{sur}) will be given by Stefan-Boltzmann law [38].

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s(T_c^4 - T_{\text{sur}}^4) \times 180\text{sec} \quad (3.6)$$

$$\dot{Q}_{\text{rad}} = 0.11 \times 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4} \times 0.674\text{m}^2 \times (356^4 - 299^4) \times 180\text{sec}$$

$$\dot{Q}_{\text{rad}} = 6.11\text{kJ}$$

Where:

ε = is emissivity of surface (Aluminum, $\varepsilon = 0.11$)

σ = is stefan – Boltzmann constant = $5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}$

A_s = is surface area of cover

T_c = is temperature of cover surface

T_{sur} = is surrounding temperature

From experimental investigation it is recorded that cover was kept open for 25 percent of baking process (45 seconds) to remove the injera baked and pour the dough, from the total of 180 seconds needed for Injera to be well baked. Therefore, considering cover can be closed for 75 percent of baking process, the total rate of heat energy lost from the top of cover is defined as;

$$Q_t = 0.75(Q_{\text{conv}} + Q_{\text{rad}}) \quad (3.8)$$

$$= 0.75 \times (19.9\text{kJ} + 6.11\text{kJ})$$

$$Q_{\text{tLc}} = 19.51\text{kJ}$$

3.2. HEAT LOSS FROM THE BARE PLATE

Heat energy is lost from the bare plate of electric injera baking mitads through convection and radiation heat transfer modes to the surrounding.

3.2.1. CONVECTION HEAT LOSS FROM BARE PLATE

Data obtained from experiment

- Average temperature of bare plate $T_p = 477.5^{\circ}K$
- Surrounding temperature $T_{\infty} = 299^{\circ}K$
- Film temperature, $T_f = \frac{T_p + T_{\infty}}{2} = \frac{477.5 + 299}{2} = 388.25^{\circ}K$

Properties of air at film temperature

$$\nu = 25.12 \times 10^{-6} \text{ m}^2/\text{s} \quad k = 32.91 \times 10^{-3} \text{ W/mk}$$

$$Pr = 0.6924 \quad \beta = 2.57 \times 10^{-3} \text{ K}^{-1}$$

Plate Data

- Characteristic length of plate; $L_c = D = 58\text{cm} = 0.58\text{m}$
- Surface area; $A_s = \pi r^2 = 0.264\text{m}^2$
- Emissivity of plate; $\varepsilon = 0.98$
- Stefan- Boltzmann constant; $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}$

Convection heat loss from flat plate can be defined as [32, 33].

$$\dot{Q}_{\text{conv}} = hA_p(T_p - T_{\infty}) \quad (3.9)$$

Where,

h = convection heat transfer coefficient, $\text{W/m}^2 \times ^{\circ}\text{K}$

A_p = heat transfer surface area of plate, m^2

T_p = temperature of the plate surface, $^{\circ}\text{K}$

T_{∞} = temperature of the air sufficiently far from the surface, $^{\circ}\text{K}$

Convective heat transfer coefficient over flat plate can be calculated by eqn. (3.2) [38 &39].

$$h_c = \frac{\text{Nu K}}{L}$$

Where,

h_c = convection heat transfer coefficient, $[\frac{\text{W}}{\text{m}^2\text{oK}}]$

Nu = nusselt number

k = thermal conductivity of the fluid (air) $[\frac{\text{W}}{\text{mK}}]$

L = characteristic length [m]

The recommended correlations for the average nusselt number over upper surface of hot plate are [38].

$$Nu = 0.54Ra_L^{1/4} \quad (10^4 \leq Ra_L \leq 10^7), Pr \geq 0.7 \quad (3.10)$$

$$Nu = 0.15Ra_L^{1/3} \quad (10^7 \leq Ra_L \leq 10^{11}), \text{ all } Pr$$

Where; (Ra_L) is the Rayleigh number, which is the product of the Grashof (Gr_L) and Prandtl (Pr) numbers:

$$Ra_L = Gr_L Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} Pr$$

$$Ra_L = \frac{9.8 \times (2.57 \times 10^{-3} \text{ K}^{-1}) \times (204.5 - 26) \text{ K} \times (0.58)^3}{(25.12 \times 10^{-6} \text{ m}^2/\text{s})^2} \times 0.6924$$

$$Ra_L = 9.62 \times 10^8$$

Therefore; average nusselt number is calculated as;

$$Nu = 0.15Ra_L^{1/3} = 0.15 (9.62 \times 10^8)^{1/3}$$

$$\mathbf{Nu = 148.07}$$

$$\text{Hence ; } h_c = \frac{Nu K}{L} = \frac{148.07 \times 0.03319}{0.58} = \mathbf{8.47 \frac{W}{m^2K}}$$

Therefore, at each baking (180sec) heat energy lost from the flat plate by convection heat transfer can be obtained as;

$$\dot{Q}_{conv} = hA_p(T_p - T_\infty) \times 180 \text{ sec}$$

$$\dot{Q}_{conv} = 8.47 \frac{W}{m^2K} \times 0.264 \text{ m}^2 (477.5 - 299) \text{ K} \times 180 \text{ sec}$$

$$\dot{Q}_{conv} = \mathbf{71.8 \text{ kJ}}$$

3.2.2. RADIATION HEAT LOSS FROM BARE PLATE

At each baking of injera (180sec) heat energy lost from the bare plate by radiation heat loss is determined as;

$$\dot{Q}_{rad} = \epsilon \sigma A_s (T_c^4 - T_{sur}^4) \times 180 \text{ sec} \quad (3.11)$$

$$\dot{Q}_{rad} = 0.98 \times 5.67 \times 10^{-8} \frac{W}{m^2K^4} \times 0.264 \text{ m}^2 (477.5^4 - 299^4) \text{ K}^4 \times 180 \text{ sec}$$

$$\dot{Q}_{\text{rad}} = 116.2\text{kJ}$$

From experimental investigation it's recorded that lifting cover was kept open for 25 percent of baking process (45 seconds) to remove the injera baked and pour the dough, from the total 180 seconds needed for Injera to be well baked. Therefore, considering lifting cover to be open for 25 percent of baking process, the total heat energy lost from the top of clay plate is defined by eqn. (3.12).

$$\dot{Q}_{\text{tp}} = 0.25x(Q_{\text{conv}} + Q_{\text{rad}}) \quad (3.12)$$

$$= 0.25 \times (71.8\text{kJ} + 116.2\text{kJ})$$

$$\dot{Q}_{\text{tp}} = 47\text{kJ}$$

3.3. HEAT LOSS FROM THE SIDE

Heat is transferred from the sides of clay plate to the supporting ring by conduction and then lost from the enclosure surface by convection (Q_{conv}) and radiation (Q_{rad}) heat transfer mechanisms [29, 31].

3.3.1. CONVECTION HEAT LOSS FROM THE SIDE ENCLOSURE

Data obtained from experiment

- Average temperature of side enclosure $T_e = 374.5^{\circ}\text{K}$
- Surrounding temperature $T_{\infty} = 299^{\circ}\text{K}$
- Film temperature, $T_f = \frac{T_p + T_{\infty}}{2} = \frac{374.5 + 299}{2} = 336.75^{\circ}\text{K} \approx 337^{\circ}\text{K}$

Properties of air at film temperature

$$v = 19.61 \times 10^{-6} \text{ m}^2/\text{s} \quad k = 29.03 \times 10^{-3} \text{ W/mk}$$

$$Pr = 0.702 \quad \beta = 2.97 \times 10^{-3} \text{ K}^{-1}$$

Side enclosure Data

- Characteristic length of side enclosure; $L_c = 10\text{cm} = 0.1\text{m}$
- Surface area enclosure; $A_s = (2\pi r) x h = 0.094\text{m}^2$
- Emissivity of plate; (Gray painted) $\varepsilon = 0.95$
- Stefan- Boltzmann constant; $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}$

Convection heat loss from side enclosure can be defined as [38, 39];

$$\dot{Q}_{conv} = hA_e(T_e - T_\infty) \quad (3.13)$$

Where,

h = convection heat transfer coefficient, $W/m^2 \times ^\circ K$

A_e = heat transfer surface area of side enclosure, m^2

T_e = temperature of the side enclosure, $^\circ K$

T_∞ = temperature of the air sufficiently far from the surface, $^\circ K$

Convective heat transfer coefficient from side enclosure can be calculated by

$$h_c = \frac{Nu K}{L}$$

Where,

h_c = convection heat transfer coefficient, $[\frac{W}{m^2 oK}]$

Nu = nusselt number

k = thermal conductivity of the fluid (air) $[\frac{W}{mK}]$

L = characteristic length [m]

Empirical correlations for the average nusselt number for natural convection over side enclosure are defined by eqn. (3.14)[38, 39].

$$Nu = 0.59Ra_L^{1/4} \quad (10^4 \leq Ra_L \leq 10^9) \quad (3.14)$$

$$Nu = 0.1Ra_L^{1/3} \quad (10^9 \leq Ra_L \leq 10^{13})$$

Where; (Ra_L) is the Rayleigh number, which is the product of the Grashof (Gr_L) and Prandtl (Pr) numbers:

$$Ra_L = Gr_L Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} Pr$$

$$Ra_L = \frac{9.8 \times (2.97 \times 10^{-3} K^{-1}) \times (374.5 - 299) K \times (0.1)^3}{(19.61 \times 10^{-6} m^2/s)^2} \times 0.702$$

$$Ra_L = 4.01 \times 10^6$$

Therefore; average nusselt number is calculated as;

$$Nu = 0.59Ra_L^{1/4} = 0.59 (4.01 \times 10^6)^{1/4}$$

$$Nu = 26.40$$

$$\text{Hence ; } h_c = \frac{Nu K}{L} = \frac{26.40 \times 0.02903}{0.1} = \mathbf{7.664 \frac{W}{m^2K}}$$

At each baking of injera (180sec), heat energy lost from the side enclosure by convection heat transfer can be obtained as;

$$\dot{Q}_{conv} = hA_p(T_p - T_\infty) \times 180sec$$

$$\dot{Q}_{conv} = 7.664 \frac{W}{m^2K} \times 0.094m^2(374.5 - 299)K \times 180sec$$

$$\dot{Q}_{conv} = \mathbf{9.7kJ}$$

3.3.2. RADIATION HEAT LOSS FROM SIDE ENCLOSURE

At each baking of injera heat energy lost from the side enclosure by radiation, is determined as;

$$\dot{Q}_{rad} = \varepsilon\sigma A_e(T_e^4 - T_{sur}^4) \times 180sec \quad (3.15)$$

$$\dot{Q}_{rad} = 0.95 \times 5.67 \times 10^{-8} \frac{W}{m^2K^4} \times 0.094m^2(374.5^4 - 299^4)K^4 \times 180sec$$

$$\dot{Q}_{rad} = \mathbf{10.6kJ}$$

Expressing each of the terms using the appropriate rate equations, total heat energy lost from the side will be defined as;

$$Q_{Te} = \dot{Q}_{conv} + \dot{Q}_{rad} \quad (3.16)$$

$$Q_{Te} = 9.7kJ + 10.6kJ$$

$$Q_{Te} = \mathbf{20.3kJ}$$

3.4. HEAT LOSS FROM THE BOTTOM

Thermal Insulation commonly used to reduce heat loss at the bottom of electric injera baking mitads are Sandstone and Gypsum which has high thermal conductivity and increase the amount of heat loosed via the bottom of clay plate [36, 38]. At the bottom of clay plate heat loss is carried out through saturated *porous media* that are combinations of stationary sandstone (solid)

and air (fluid). Considering saturated porous medium that is subjected to surface temperatures T_1 and T_2 at $x = 0$ and $x = L$ respectively, rate of heat loss after steady state may be expressed by eqn. (3.17)[38].

$$q_x = \frac{K_{eff}A}{L}(T_1 - T_2) \tag{3.17}$$

Where: K_{eff} is an effective thermal conductivity and Eqn. (3.17) is valid if fluid motion, as well as radiation heat transfer within the medium is negligible. The effective thermal conductivity varies with the porosity or void fraction of the medium ϕ which is defined as the volume of fluid relative to the total volume (solid and fluid). In addition, k_{eff} depends on the thermal conductivities of each of the phases and, it is assumed that $K_s > K_f$. For detailed solid phase geometry, the size distribution, packing arrangement of individual powder particles and contact resistances that might evolve at interfaces between adjacent solid particles can impact the value of k_{eff} . Hence, prediction of k_{eff} can be difficult and, in general, requires detailed knowledge of parameters that might not be readily available.

Despite the complexity of the situation, the value of the effective thermal conductivity can be bounded by considering fluid region of length ϕL and a solid region of length $(1 - \phi)L$.

Considering only two conduction terms in the model with no convection ($h_1 = h_2 = 0$) maximum effective thermal conductivity can be obtained as follows by using eqn. (3.18) [38].

$$K_{eff} = \phi K_f + (1 - \phi)K_s \tag{3.18}$$

Table 3-1: Experimental and property data

Parameter	Unit	Quantity	Reference
Temperature at the top of insulation [T_1]	K	437	
Temperature at the bottom of insulation [T_2]	K	391.9	
Porosity [ϕ]	-	0.30	[41]
Thermal conductivity of solid (sandstone) [K_s]	$\frac{W}{mK}$	1.83	[42]
Thermal conductivity of fluid (air) [K_f]	$\frac{W}{mK}$	0.03542	[38, 39, 43]
Thickness of insulation [L]	m	0.030	
Surface area [$A_s = 2\pi r^2 + 2\pi r h$]	m^2	0.5831	

Therefore; effective thermal conductivity was calculated by using eqn. (3.18) [42].

$$K_{eff} = \phi K_f + (1 - \phi)K_s$$

$$K_{eff} = 1.29163 \frac{W}{mK}$$

At each baking of injera heat energy lost from the bottom insulation is determined as;

$$q_x = \frac{K_{eff}A}{L}(T_1 - T_2) \times 180sec = \mathbf{203.8kJ}$$

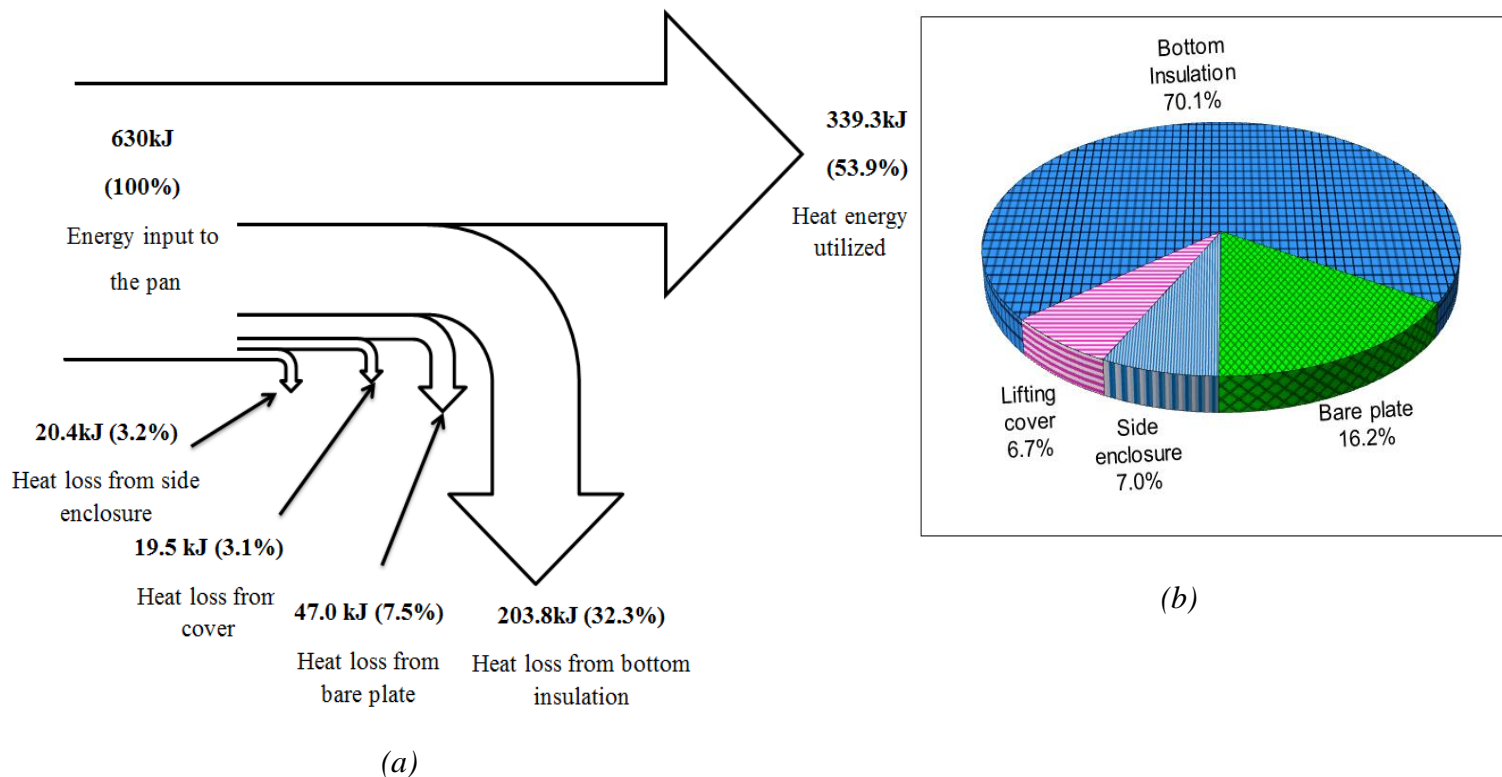


Figure 3.4: Result obtained from analytical analysis (a) Energy flow (Sankey) diagram of electric injera baking stove (b) Percentage description of total heat loss accounted in the electric injera baking Mitads

The result from analytical analysis of the loss accounted in the baking process shows, heat loss of electric mitads was 46.15 percent with bottom insulation accounts major loss (70.1% of total loss) from the system were, bare plate, cover and side enclosure account 16.2%, 6.7% and 7.0% respectively. Thus, useful energy (the amount of energy utilized for baking injera) (339.3kJ, 53.85%) was obtained by subtracting all loss encountered in the system from input (630kJ) electrical energy for each baking of injera.

CHAPTER FOUR

DESIGN OF HEAT RECOVERY SYSTEM AND SELECTION OF HEAT STORAGE MATERIALS

4.1. HEAT RECOVERY OIL PAN SIZING AND SELECTION

To recover bottom heat loss some of the insulation in the bottom of clay plate will be replaced by oil pan. In right side of oil pan inlet and outlet ports were drilled with ½ inch diameter size and piped with ½ inch diameter pipes welded to the drilled inlet and outlet ports. To reduce heat loss from the sides, oil pan will be insulated by 20mm thick ash and also, bottom and top of heat recovery oil pan will be insulated by 6.5mm thick ash to reduce bottom heat loss of electric injera baking pan.

The volume of the heat recovery oil pan was determined by using eqn. (4.1) [44].

$$V_{op} = \frac{\pi}{4} D^2 h \quad (4.1)$$

Where; D is diameter of oil pan (540mm) and h, is height of oil pan (19mm), therefore using eqn. (4.1) volume of oil pan was determined as $(0.0043m^{-3}$ or 4.3litre)

Table 4-1: Oil pan Material selection and design parameter

Oil pan Material selection and design parameter	Selected
Material	Carbon steel
Thickness	1.5mm
Diameter	540mm

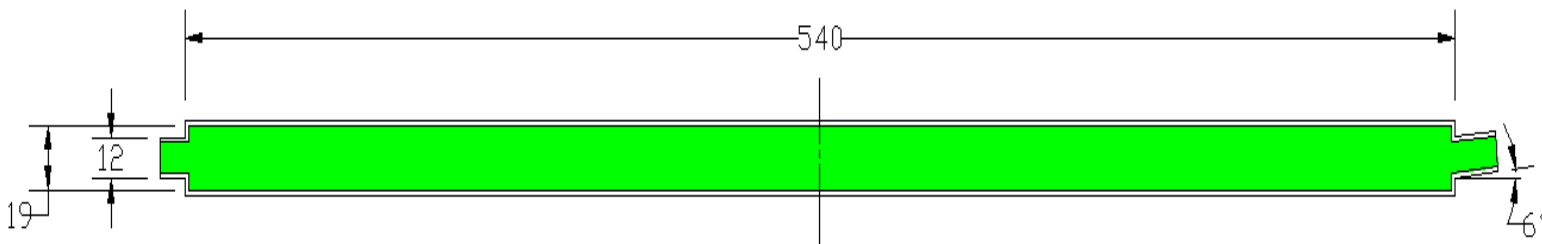


Figure 4.1: Heat recovery oil pan (all dimensions are in mm)

4.2.PROPERTIES AND BENEFITS OF ASH FOR INSULATION

Ash is a by-product from the combustion of fuel wood especially in the preparation of foods by using biomass fuel. In some cases ash from fuel wood is used as nutrient for plants because it improves the fertility of soil. Properties of ash and the benefit to use wood ash for insulation system are discussed as follows:

Benefits of ash

- Ash is completely burned material and have very low thermal conductivity (K which varies from 0.092 to 0.17)
- Ash is a waste material and pays no cost for it and also available everywhere locally
- It does not cause fire hazard and not toxic, so there is no problem of safety

Properties of ash

- It is fire resistant,
- It does not conduct electricity,
- It is lightweight,
- It repels bugs,
- Retains heat.

Table 4-2: Comparison of thermo – physical properties and relative cost of various insulation materials used in the baking pan

Name of material	Thermal conductivity (K) [W/mK]	Specific heat capacity (C_p) [$J/kg K$]	Relative Cost
Sandstone	1.83 – 2.90	710	Medium
Wood ash	0.092 – 0.17	840	Low
Gypsum	0.17	1090	High

4.3.PIPING SYSTEM

Piping of heat recovery system can be designed to meet natural circulation of the heat transferring fluid from oil pan to the heat recovery tank and then back to the oil pan. The

advantage of natural circulation systems is the elimination of the circulating pumps which will reduce capital, operating and maintenance costs and also eliminates all safety issues associated with the failure of the circulating pumps. To minimize pressure losses and enhance flow rates, natural circulation systems should eliminate all unnecessary pipe bends, elbows, etc. and finally come with simple piping layout which can be factory fabricated [45].

Thus, in this research the inlet pipe from oil pan to the heat recovery system can be lined straight horizontal and the flow of hot oil from heat recovery oil pan to the heat recovery system can be enhanced by the volume expansion of oil caused in the heating process and the return pipe can be lined at 6° angle (slope) to allow the flow of cold oil back to the oil pan (see Fig: 4.3).

Table 4-3: Pipe line Material selection and design parameters

Piping system material selection and design parameter	Selected
Material	Carbon steel
Diameter	12mm (1/2 inch)
Angle (inlet pipe, outlet pipe)	(180°, 6°)

4.3.1. PRESSURE DROP IN PIPELINE

Pressure drop in the piping of heat recovery system will be calculated to evaluate the effect of friction inside pipes which will occur due to viscosity of the oil. Pressure drop for all types of fully developed internal flows (laminar or turbulent flows, circular or noncircular pipes, smooth or rough surfaces, horizontal or inclined pipes) was computed by eqn. (4.4).

$$\Delta P = f \frac{L}{d} \frac{\rho v^2}{2} \tag{4.4}$$

Where; f = coefficient of friction v = considering average velocity of oil [0.4 $\frac{m}{s}$]

ρ = density of oil [888 $\frac{kg}{m^3}$] d = pipe diameter [0.0125m]

L = total effective flow length [2.5m]

The coefficient of friction for smooth carbon steel pipe is 0.042 and the corresponding Reynolds number is in the order of 2×10^3 i.e., 1524 as evaluated by eqn. (4.5) [12].

$$f = \frac{64}{Re} \tag{4.5}$$

Pressure drop in the pipeline is determined as; $\Delta P = 596.7Pa$ or $5.68bar$ hence, natural circulation of fluid is accompanied by compensating this pressure drop by volume expansion of oil and hydraulic head between oil pan and heat recovery tank.

4.4.THERMAL ENERGY STORAGE MATERIAL SELECTION

The two main thermal storage material for domestic scale TES applications are sensible heat TES (SHTES) and latent heat TES (LHTES). SHTES is cheaper than LHTES for small storage volumes but its energy storage density is lower. STES materials are commonly classified as solid and liquid storage materials. Solid storage materials include rocks, stones, brick, iron, soil, concrete etc. and liquid storage materials include mainly water and oils [24].

Solid STESs are common for space heating and high temperature heating applications. It is usually operated in temperature ranges of 313 to 348 °K for rock beds/concrete and over 423 °K for metals. Solid STES has the advantage to reduced risks of leakage at elevated temperatures and feasible to store very high temperatures.

However, solid STES have also the following limitations:

- Relatively low specific heat capacity (~1200 kJ /m³/K)
- Reduced energy storage density compared to liquid storage materials
- Increased risks of self-discharge (heat losses) in long-term storage systems
- Stratification of storage unit [24].

On the other hand, liquid STES have been widely preferred for low and medium temperature application ranges. From liquid STES Oil; sunflower oil, therminol 55, therminol 66 and used engine oil are commonly used and comparatively studied as SHM oil for solar cookers from which it was shown that sunflower oil performed better. However, used engine oil is observed as better choice due to its better thermal conductivity value which helps to transfer heat energy more efficiently and its freely available (low cost) as well [46]. Therefore, due to above advantages used engine oil was used in this research, as thermal energy storage medium of heat recovery system.

Table 4-4: Properties of some sensible thermal energy storage oils [47]

Medium	Fluid Type	Temp. Range [°K]	Density [Kg/ m ³]	Heat capacity [J/Kg.K]	Thermal conductivity [W/m.K]
Caloria HT43	Oil	263 to 588	-	2300	-
Therminol 55	Oil	255 to 588	-	2400	-
Therminol 66	Oil	264 to 616	750	2100	0.106 at 616 ^o K
Used engine oil	Oil	Up to 433	888	1880	0.145

Table 4-5: Density of engine oil with function of temperatures (SAE 30)

Temp [⁰ K]	273	283	293	303	313	323	333	343	353	363	373
Density [kg/l]	0.894	0.888	0.882	0.875	0.869	0.863	0.857	0.851	0.844	0.838	0.832

4.4.1. BENEFIT OF USED ENGINE OIL

In this research used engine oil was used as thermal energy storage medium by considering the properties of the fluid, environmental benefit, availability and cost. The use of used engine oil for heat storage medium has the following benefits;

- ✓ Preferable to disposal and provide great environmental benefit
- ✓ In expensive, freely available
- ✓ Comparatively high thermal conductivity to promote high heat transfer
- ✓ Operating temperature range up to 433°K.
- ✓ Good viscosity/temperature characteristics

4.4.2. VOLUME EXPANSION OF USED ENGINE OIL

When heated, thermal oil expands in volume and this should be considered when designing the system. Therefore, the volume of oil pan ought to be designed by considering the amount the oil expands at the operating temperature and the fluid’s coefficient of thermal expansion. Since, thermal oils expand at different rates; the oil pan capacity should be verified against the oil properties prior to filling the system [44 & 48].

Density of oil changes with change in temperature and hence, final density (ρ_f) of the fluid can be expressed by eqn. (4.2) [44].

$$\rho_f = \frac{\rho_o}{[1+\beta(T_f-T_o)]} \tag{4.2}$$

Where;

$$\rho_f = \text{Final density [Kg/m}^3\text{]}$$

$$\rho_o = \text{Initial density oil is equal to } 882 \text{ [Kg/m}^3\text{] at } (T = 293^{\circ}\text{K)}$$

$$\beta = \text{Volumetric temperature expansion coefficient} = 0.0007 \text{ [}^1\text{/}^{\circ}\text{K]}$$

$$T_f = \text{Final oil operating temperature [}^{\circ}\text{K]} = 433^{\circ}\text{K}$$

$$T_o = \text{Intial oil temperature [}^{\circ}\text{C]} = 293^{\circ}\text{K}$$

Assuming initial fluid temperature will be equal to ambient temperature (293⁰K), final density (ρ_f) of thermal oil will be determined by using eqn. (4.2).

$$\rho_f = 803.28 \text{ Kg}/\text{m}^3$$

Since the mass of the fluid does not change with temperature (conservation of mass), the volume of the fluid at 433⁰K can be calculated by using eqn. (4.3).

$$m_f = m_o = V_o\rho_o = V_f\rho_f \tag{4.3}$$

Considering the volume of oil pan (4.3litre) will be equal with initial volume of heat transfer oil, final volume of oil expanded will be determined by using eqn. (4.3).

$$V_f = \frac{V_o\rho_o}{\rho_f} = \frac{0.0043 \times 882}{803.28} = 0.0047 \text{ m}^3 = 4.7L$$

From the result it's seen that thermal oil was expanded by 0.0004m³ volumes, and this will enhance the flow of hot oil from oil pan to heat recovery tank.

4.5.HEAT STORAGE (RECOVERY) TANK SIZING

Heat storage tank is used to allow discharging of heat recovered by the system. Due to viscosity of oil and piping layout for enhancing natural circulation, only 50% of oil inside heat recovery oil pan will be considered to flow to heat recovery tank. Therefore, volume of heat recovery tank will be determined as;

$$V_{HRT} = 0.5V_f = 2.35 \times 10^{-3} \text{ m}^3 = \mathbf{2.35L}$$

Therefore, heat recovery tank has the dimension of; diameter D = 220mm and height of 100mm as shown in the Figure (4.2) below.

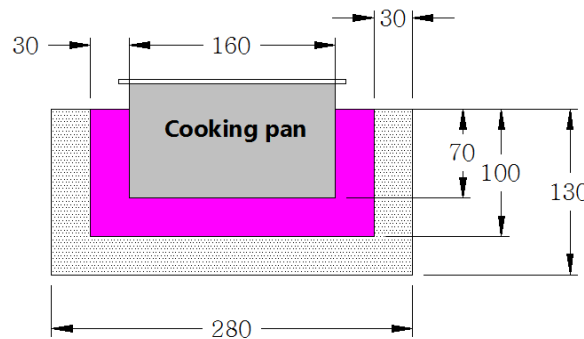


Figure 4.2: Heat storage tank

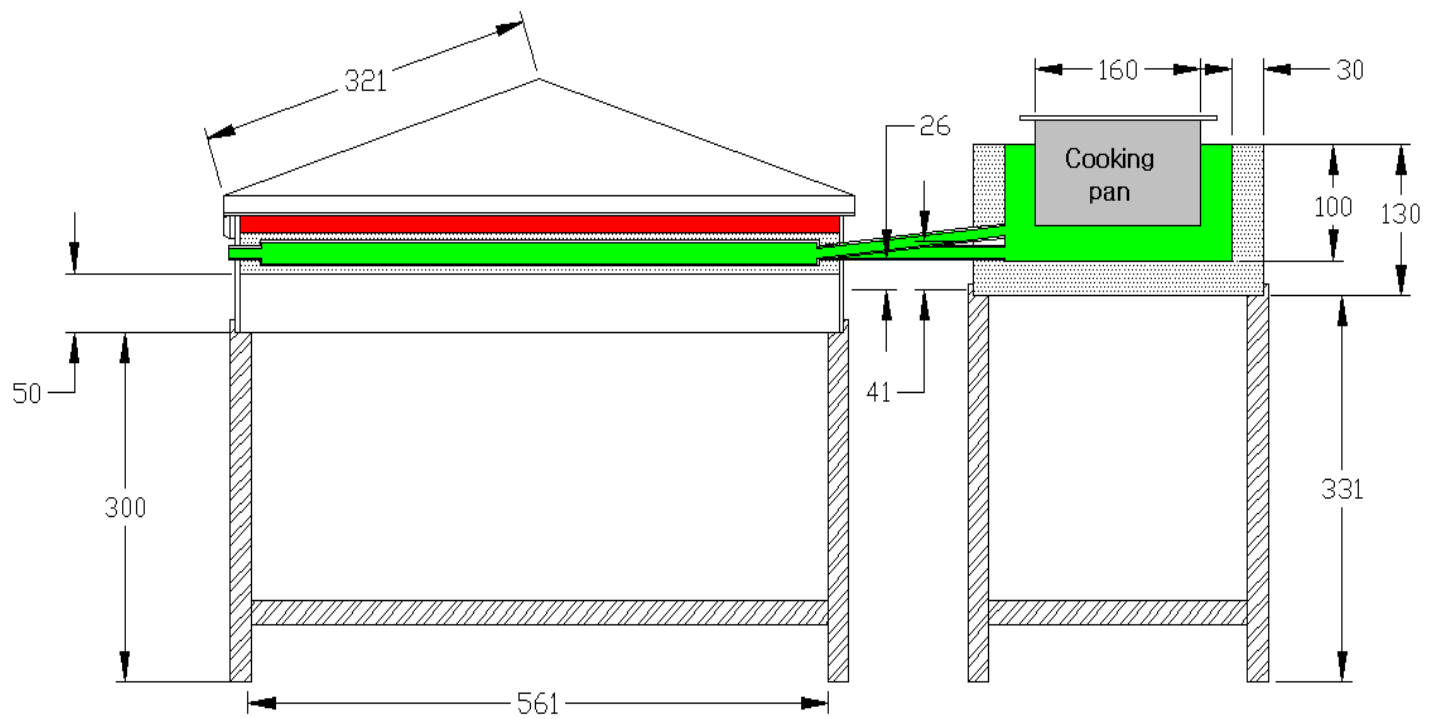


Figure 4.3: Heat recovery system assembly

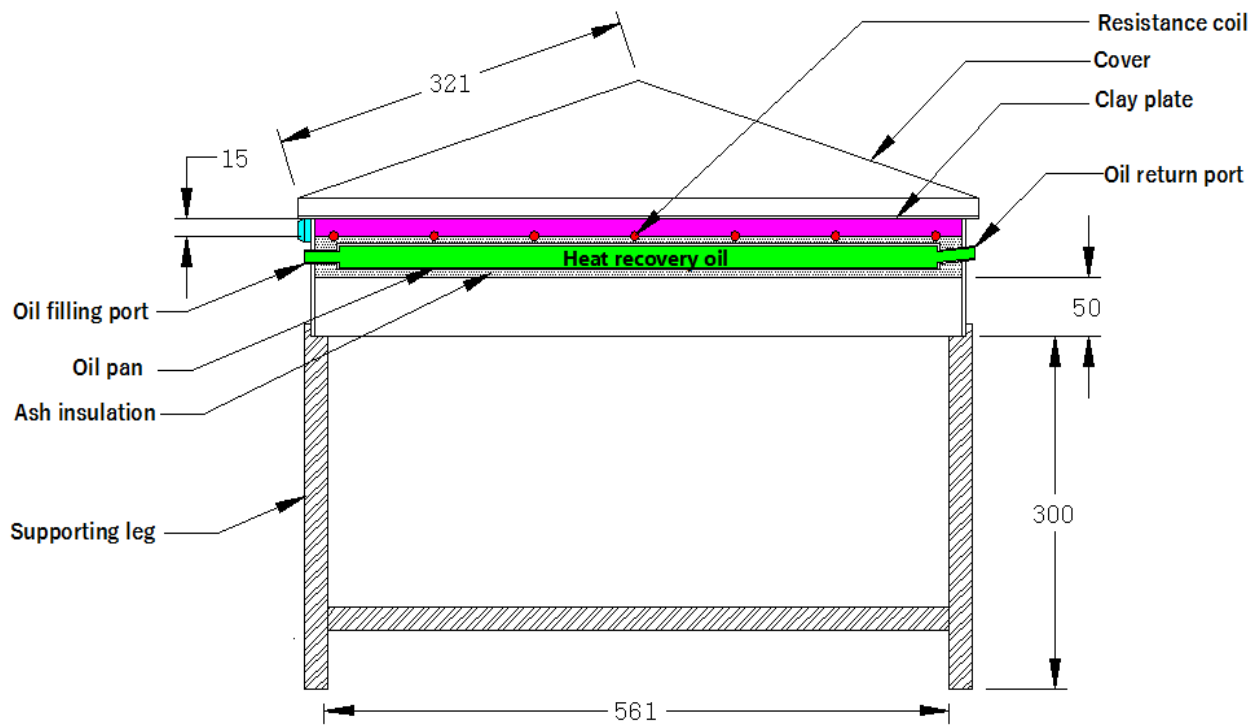


Figure 4.4: Component description of baking pan with heat recovery oil pan

CHAPTER FIVE

MATHEMATICAL MODELING OF HEAT RECOVERY SYSTEM

Mathematical modeling represent heat transfer in the heat recovery system is made in this section by considering the transient 2D model. In the process heat transfer involves the transfer of energy through materials (solid & stationery fluid) due to temperature difference.

5.1.ASSUMPTIONS

The following assumptions are used to simplify mathematical modeling of heat transfer in oil pan and heat storage tank;

- Heat transfer is assumed to be two dimensional (radial and axial direction)
- Transient (unsteady state) heat transfer
- Homogeneous medium within which there is no bulk motion of oil(advection)
- Constant properties

5.2.MATHEMATICAL MODELING OF OIL PAN

Heat is transferred from the bottom insulation to the heat recovery oil pan through transient heat conduction mechanism. Energy balance for heat conduction through an infinitesimal non-moving volume can be expressed by eqn. (5.1) [38, 39].

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T + q_v \quad (5.1)$$

Where;

ρ =density [$\frac{Kg}{m^3}$], C_p = specific heat capacity [$\frac{Kj}{kg K}$], T = temperature [K], t = time (s) and k =

Thermal conductivity [$\frac{W}{mK}$], and q_v = volumetric heat generation [$\frac{W}{m^3}$]

Considering 2D heat transfer, with no heat generation and constant thermal conductivity, energy balance can be defined in cylindrical coordinate system as shown in eqn. (5.2) [39].

$$\rho C_p \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + k \frac{\partial^2 T}{\partial z^2} \quad (5.2)$$

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right)$$

Where,

$$\alpha = \frac{k}{\rho C_p} \text{ is thermal diffussivity}$$

5.2.1. BOUNDARY AND INITIAL CONDITIONS

To describe a 2D conduction heat transfer problem completely there should be four boundary conditions along which heat transfer is significant. For heat transfer in heat recovery oil pan boundary condition i.e. Initial boundary condition, generalized BC, Symmetry BC and Insulated boundary condition is defined as follows [39].

5.2.1.1. Boundary conditions

Generalized boundary condition at the sides of oil pan

$$-\left(k \frac{\partial T}{\partial n}\right)_{(r,z,t)} = h_{s1}(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_\infty^4) \quad \text{on } \Gamma_{qcr} \quad (5.3)$$

Where,

h_{s1} = convective heat transfer coefficient T_s = surface temperature of oil pan and

ε = emissivity of side surface

Insulated boundary condition at the bottom of oil pan

The oil pan is well insulated on the bottom thus heat loss through the bottom of oil pan can be assumed to be negligible. Then the boundary condition at bottom can be expressed as insulated boundary conditions [39].

$$-\left(k \frac{\partial T}{\partial n}\right)_{(r,z,t)} = 0 \quad \text{on } \Gamma_I \quad (5.4)$$

Thermal Symmetry boundary condition

Since, oil pan has cylindrical shape thermal symmetry of pan is about the center line (or midpoint). The thermal symmetry boundary condition requires that the first derivative of temperature with respect to r (the radial variable) be zero at the centerline.

$$-\left(k \frac{\partial T(0,t)}{\partial r}\right) = 0 \quad \text{on } \Gamma_s \quad (5.5)$$

5.2.1.2. Initial boundary condition

Oil pan is initially at the uniform temperature (room temperature) $T_i = 294^0K$. In cylindrical coordinates, the initial condition for the oil pan can be specified in the form as;

$$T(r, z)_{t=0} = T_i = 294^0K \quad \text{on } \Gamma_T \quad (5.6)$$

5.3.AMOUNT OF SENSIBLE HEAT STORED

The amount of heat energy stored in the heat storage oil depends on the specific heat of the medium, the temperature change and the amount of storage material and can be expressed by Eqn. (5.7) [24 & 47].

$$Q = \int_{T_1}^{T_2} mC_p dT = mC_p(T_2 - T_1) \quad (5.7)$$

Where;

Q is the amount of thermal energy stored or released in form of sensible heat [kJ],

T₁ is the initial temperature [^oK], T₂ is the final temperature [^oK], m is the mass of material used to store thermal energy [kg], and

C_p is the specific heat of the material used to store thermal energy [kJ/kg.^o K].

5.4. MATHEMATICAL MODELING OF HEAT STORAGE TANK

Heat energy was transferred from heat storage oil tank to the cooking pan through steady state 2D conduction heat transfer mechanism. In the process heat energy is transferred in the radial and axial direction from cylindrical shaped oil storage tank to the stew cooking pan. Energy balance model on differential control volume of oil storage tank can be expressed as shown in eqn. (5.8) [38, 39].

$$k\nabla^2 T = 0 \quad (5.8)$$

Where;

ρ =density [$\frac{Kg}{m^3}$], C_p = specific heat capacity [$\frac{Kj}{Kg K}$], T= temperature [K], and k =Thermal

conductivity [$\frac{W}{mK}$], t= time (s)

Considering 2D heat transfer, and constant thermal conductivity, energy balance can be defined in cylindrical coordinate system as shown in eqn. (5.9).

$$\frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + k \frac{\partial^2 T}{\partial z^2} = 0 \quad (5.9)$$

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = 0$$

5.4.1. BOUNDARY AND INITIAL CONDITIONS

5.4.1.1. Boundary conditions

Symmetry boundary condition

Heat storage tank has cylindrical shape thus; thermal symmetry of pan passes about the center line (or midpoint). The thermal symmetry boundary condition requires that the first derivative of temperature with respect to r (the radial variable) be zero at the centerline.

$$-\left(k \frac{\partial T(0,t)}{\partial r}\right) = 0 \quad \text{on } \Gamma_s \quad (5.10)$$

Insulated boundary condition

Heat storage tank is well insulated on the outer surface and Bottom side thus heat loss through the outer surface and bottom side of heat storage tank can be assumed to be negligible. Then the boundary condition at the outer surface and bottom side can be expressed as insulated boundary conditions.

$$-\left(k \frac{\partial T}{\partial n}\right)_{(r,z,t)} = 0 \quad \text{on } \Gamma_l \quad (5.11)$$

Generalized boundary condition at Top of storage tank

$$-\left(k \frac{\partial T}{\partial n}\right)_{(r,z,t)} = h_{s1}(T_{st} - T_{\infty}) + \varepsilon\sigma(T_{st}^4 - T_{\infty}^4) \quad \text{on } \Gamma_{qcr} \quad (5.12)$$

Where,

h_{s1} = convective heat transfer coefficient T_{st} = surface temperature of tank

ε = emissivity of top surface And, σ = stefan – boltzmann constant = $5.67 \times 10^{-8} \left[\frac{W}{m^2 K^4}\right]$

5.4.1.2. Initial boundary condition

Heat storage tank is initial available at the surrounding temperature $T_i = 294^{\circ}K$. In cylindrical coordinates system, the initial condition for the heat storage tank can be specified by eqn. (5.13).

$$T(r, z)_{t=0} = T_i = 294^{\circ}K \quad \text{on } \Gamma_T \quad (5.13)$$

CHAPTER SIX

NUMERICAL OPTIMIZATION OF HEAT RECOVERY SYSTEM

In this chapter numerical optimization of heat recovery oil pan is made by using COMSOL Multiphysics software for the analysis and AUTOCAD software for modeling geometry of the system. For the analysis transient two dimensional solid – heat transfer was considered by assuming the oil as stationery and convection and surface to surface radiation boundary condition (heat loss) at the top of clay plate and side enclosure. In the optimization process thickness of the heat recovery oil pan and thickness of the insulation at top and bottom of oil pan are used as the variable under consideration.

6.1. COMSOL MULTIPHYSICS SOFTWARE

COMSOL multiphysics software was a finite element analysis, solver and simulation software package for solving various physics and engineering applications. COMSOL multiphysics simulation environment facilitates all steps in the modeling process i.e. defining geometry, specifying physics, meshing, solving and then post-processing the result [49].

In this research COMSOL multiphysics software was used to make numerical analysis of the heat recovery system due to its capability to solve all kinds of scientific and engineering problems [50]. COMSOL multiphysics software analysis have been utilized by the number of researchers worldwide where, Dede et al [51] conducted multiphysics topology optimization of heat transfer and fluid flow systems by using COMSOL multiphysics with a method of moving asymptotes (MMA) optimizer in custom MATLAB scrip. In his research gradient based topology optimization within COMSOL multiphysics via a MMA optimizer was presented. Initially as benchmark single physics with pure heat conduction problem was selected both in 2-D and 3-D to evaluate a custom MATLAB script and self-similar branching structures were obtained. The method was then extended to multiple physical processes including convection, diffusion and Navier-stokes flow with corresponding objectives. Carrizales et al [52] made two dimensional COMSOL simulation of heavy-oil recovery by electromagnetic heating and validated the numerical solutions obtained from COMSOL with analytical solutions for a 1-D radial electro – magnetic heating model by neglecting conduction heat transfer. Kylili et al [53] conducted numerical heat transfer analysis of phase change material (PCM) - enhanced plasters. For

validation COMSOL simulation results for the REFPLASTER and the PCM PLASTER5 were compared with experimental results and the simulation results for both cases were found in good agreement with the experimental results.

6.2. GLOBAL BOUNDARY CONDITIONS AND MATERIAL PROPERTIES

Global boundary conditions used in the simulation are defined as it is shown in **Table (6.1)**.

Table 6- 1: Global boundary condition and material properties (GBC Data, taken from experimental result obtained in chapter 3)

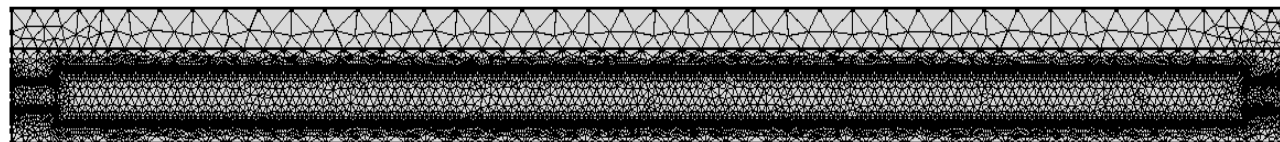
Boundary condition	Values
Baking plate surface temperature	477.5K
Convection heat transfer coefficient at the top of baking plate	$8.47 \frac{W}{m^2K}$
Emissivity of baking plate	0.98
Convection heat transfer coefficient at the side enclosure	$7.664 \frac{W}{m^2K}$
Surface temperature of side enclosure	374.5K
Surrounding temperature	299K
Emissivity of side enclosure	0.95

6.3. GEOMETRY AND MATERIAL

Figure 6.1 represent two - dimensional (2D) geometry that was employed in COMSOL Multiphysics software for simulation of heat transfer in the heat recovery system. The system has six layers i.e. clay plate with thickness of 20mm, oil pan with thickness of 1.5mm, ash insulation with the thickness of 6.5mm at the top and bottom of oil pan and stationery engine oil with thickness of 19mm.



(a)



(b)

Figure 6. 1 (a). Two – dimensional geometry of heat recovery system (b) Mesh generated in COMSOL multiphysics software

Table 6- 2: Thermo – physical properties of materials employed for the numerical simulation of heat recovery system

Material	ρ [kg/m^3]	C_p [$J/kg K$]	K [W/mK]	σ [s/m]
Clay plate	1900	1381	1.1	
Wood ash	640	840	0.092 - 0.17	
Carbon steel	8,050	502.46	43	5.9×10^6 s/m
Used engine oil	888	1880	0.145	

Table 6- 3: List of varied parameter

Thickness of ash insulation	Thickness of oil pan
8mm	No
7mm	1mm
6.5mm	1.5mm
5mm	3mm

For optimization of heat recovery system consol simulation was made for time interval of 100minutes by varying the parameters listed in the Table 6-3.

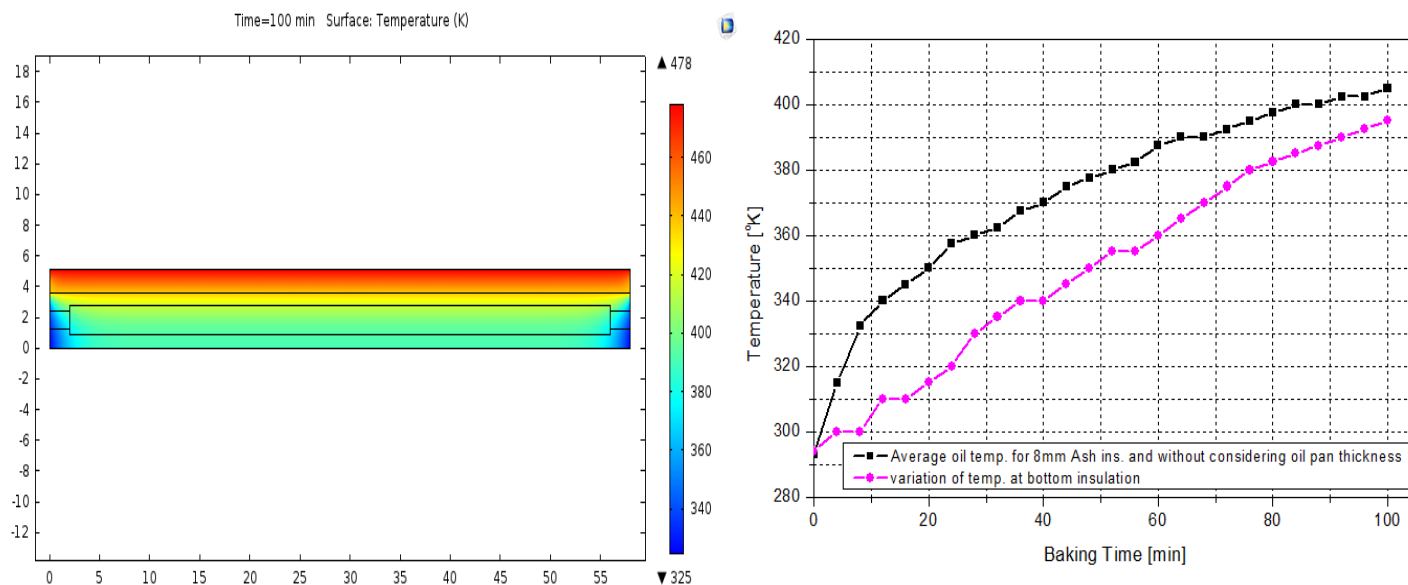


Figure 6. 2: COMSOL simulation result with 8mm thickness insulation and without considering thickness of the oil pan

Figure 6.2 depicts average temperature variation of heat recovery oil and bottom insulation, by considering 8mm thickness insulation and without considering thickness of the oil pan. The simulation result shows the average temperature of heat recovery oil was obtained as 405K and the maximum temperature at the bottom insulation is obtained as 395K. The average oil temperature obtained in this simulation result was enough for water heating and for cooking stew. However, the bottom insulation temperature obtained was much higher which indicates the bottom loss was still higher.

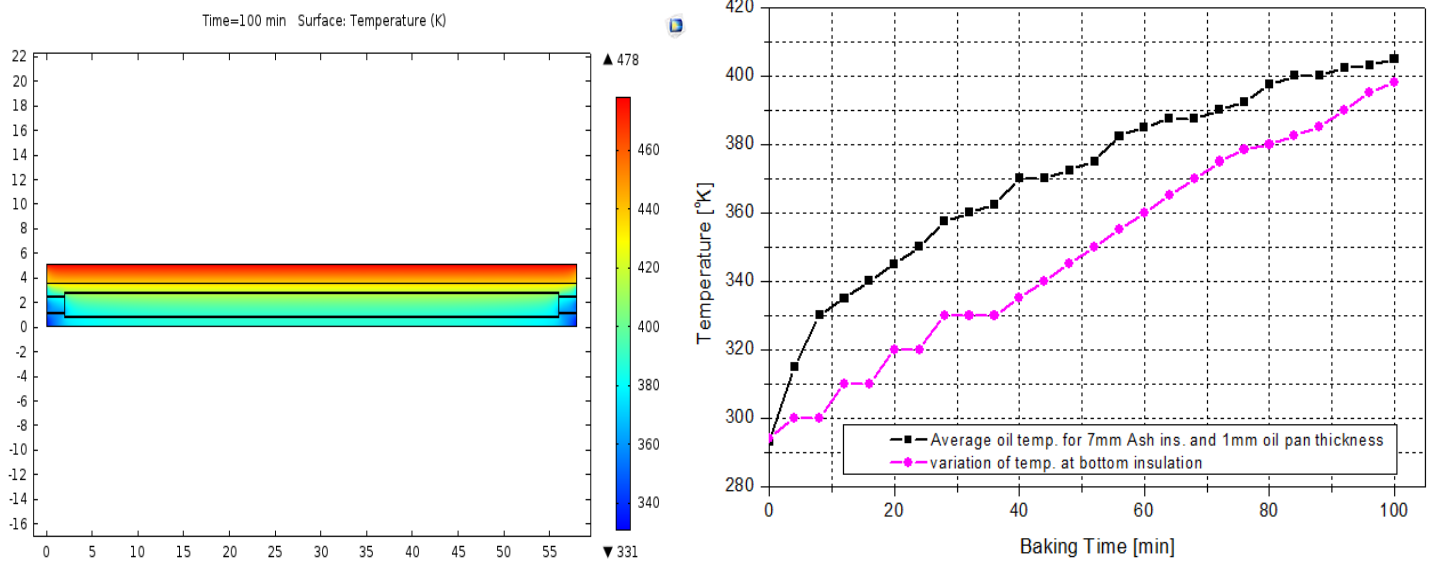


Figure 6. 3: COMSOL simulation result with 7 mm thickness insulation and 1mm thickness of oil pan

Figure 6.3 present the temperature distribution in the heat recovery system and temperature variation in the heat recovery oil and bottom insulation, by considering 7mm thickness insulation and 1mm thickness of oil pan. The simulation result shows the average temperature of heat recovery oil was obtained as 405K and the maximum temperature at the bottom of insulation was obtained to be 394K. This simulation result shows considering very thin oil pan thickness will improve only few amount of bottom heat loss. However, it does not affect the average oil temperature due to fast heat transfer carried out in the thin layer of carbon steel.

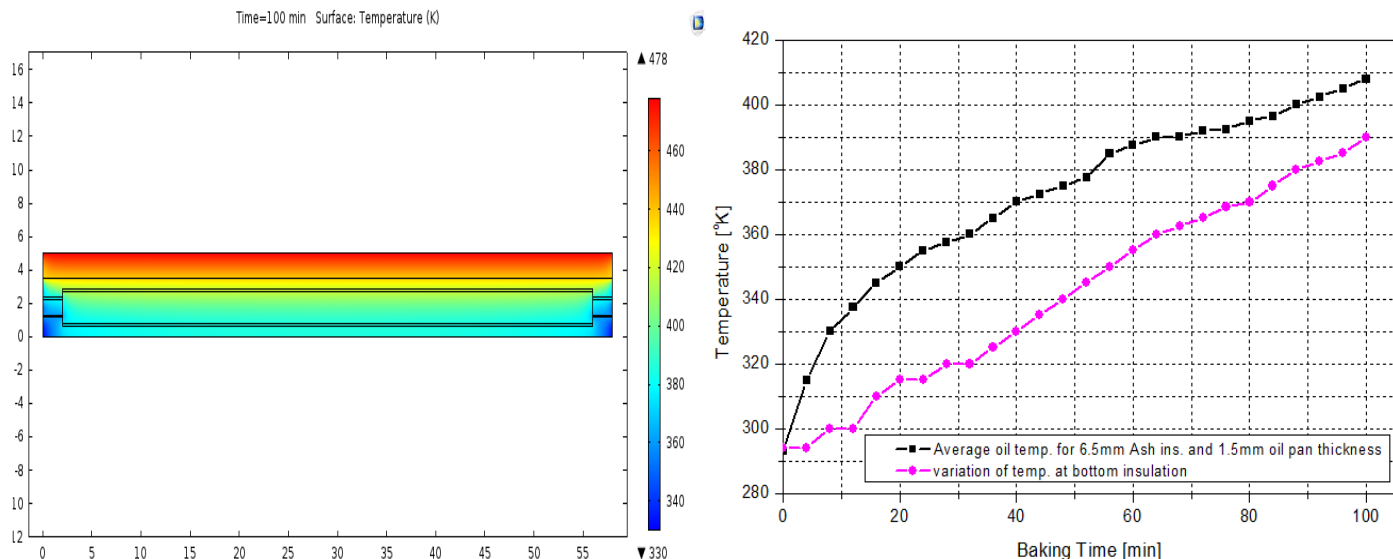


Figure 6. 4: COMSOL simulation result with 6.5 mm thickness insulation and 1.5mm thickness of oil pan

Figure 6.4 shows the temperature distribution in the heat recovery system, oil temperature variation and bottom insulation variation with the function of time, by considering 6.5 mm thickness insulation and 1.5mm oil pan thickness. The simulation result shows the average temperature of heat recovery oil is obtained as 408K and the maximum temperature at the bottom of the insulation was 390K. This simulation result depicts reducing ash insulation thickness and increasing thickness of oil pan by 0.5mm will improve the amount of heat recovered as well as it will reduce bottom heat loss, by improving heat retaining capacity of ash insulation.

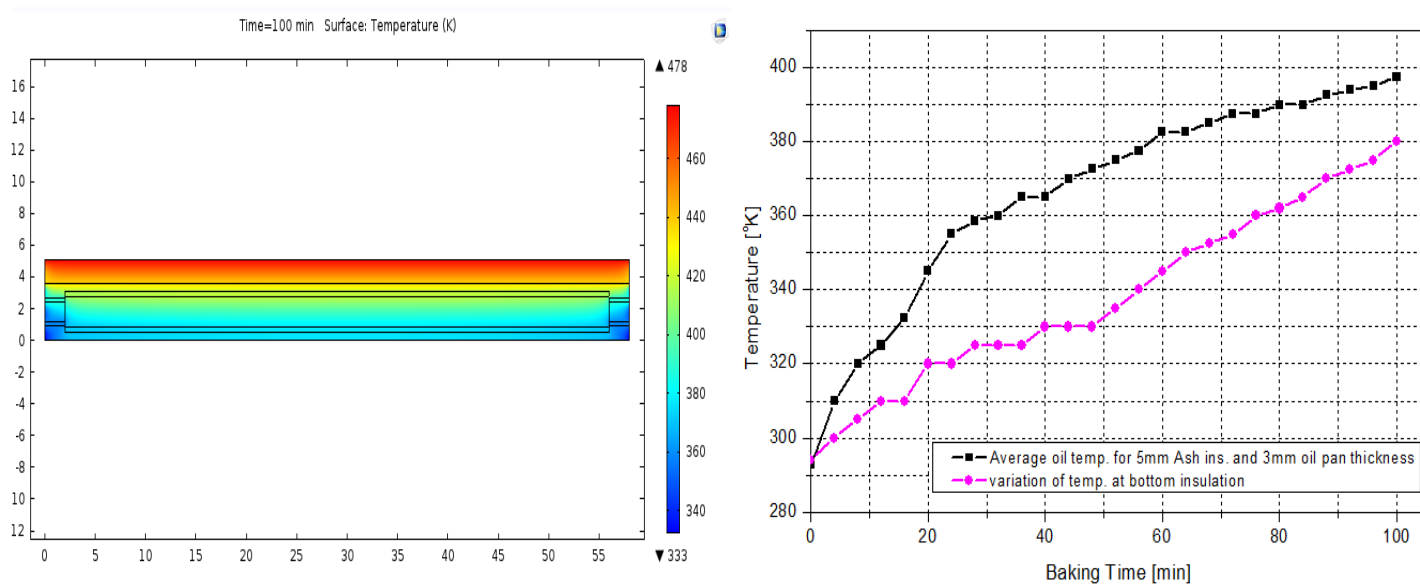


Figure 6. 5: Comsol simulation result with 5mm thickness insulation and 3mm thickness of oil pan

Figure 6.5 shows the temperature distribution in the heat recovery system, oil temperature variation and bottom insulation variation with the function of time, by considering 5mm thickness insulation and 3mm oil pan thickness. The simulation result shows the average temperature of heat recovery oil was obtained as 397.5K and the maximum temperature at the bottom of the insulation was 385K. This result shows further reducing thickness of ash insulation and increasing thickness of oil pan will reduce amount of heat recovered by the system. However, it will have positive advantages to reduce bottom heat loss accounted in the system.

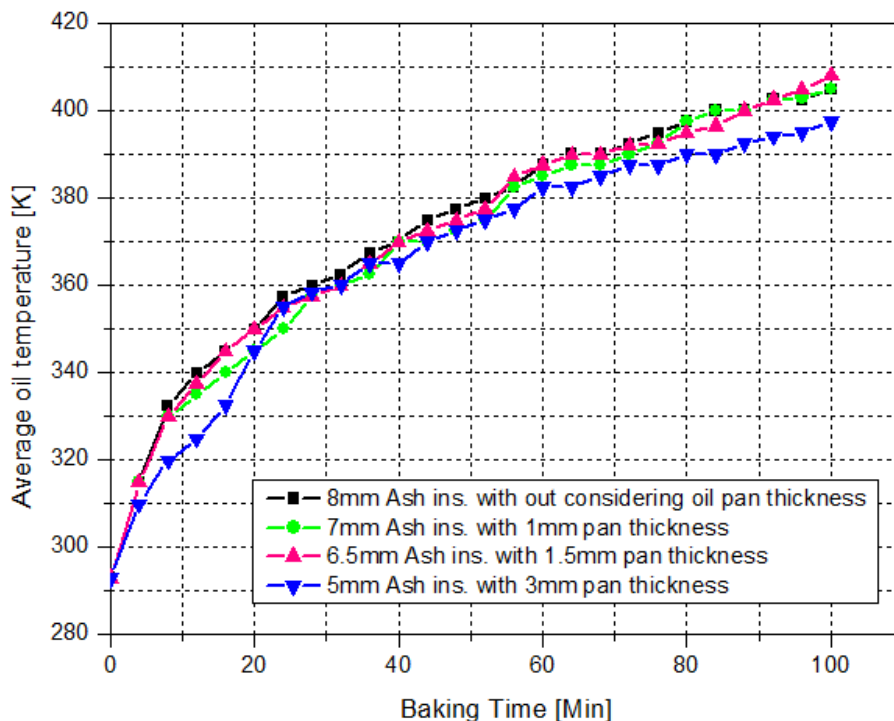


Figure 6. 6: Average oil temperature variation with the function of time

Depending up on the average oil temperature and bottom insulation temperature obtained from the optimization result, it was obtained that 6.5 mm thickness insulation and 1.5mm oil pan thickness was optimum dimension of heat recovery system. The ash insulation used in heat recovery system enhances effective insulation and achieve better improvement in the thermal efficiency of injera baking pans. The system was recovered significant amount of heat energy 57.15kJ (857.28kJ of energy during baking fifteen injera) at each baking of injera and enhances the efficiency of the injera baking pans by reducing the major heat energy lost from bottom insulation through porous media. The heat energy recovered by system during fifteen injera baking process was good enough to use for water heating and also for cooking stew as well.

CHAPTER SEVEN

EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF HEAT RECOVERY SYSTEM

In this chapter the result obtained from experimental investigation will be presented. Experimental investigation was carried out to analyze the performance of heat recovery system as well as to examine performance of the baking pan and finally to make analyses on the thermal efficiency of the system. Then comparison on thermal efficiency of the system was made with the actual baking pan used for injera baking.

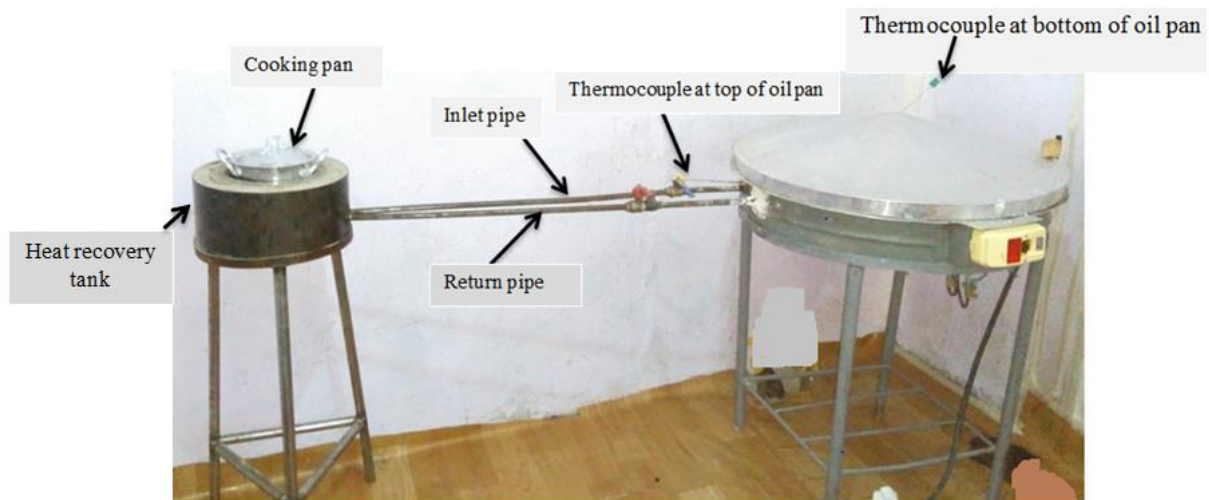


Figure 7. 1: Actual picture of heat recovery system assembly and positions of thermocouple during experimental setup

7.1. EXPERIMENTAL SETUP



Figure 7. 2: Experimental setup and injera texture

In the experimental investigation temperature measuring equipment i.e. infrared thermometer, k – type thermocouple and glass thermometer were used for data collection.

7.1.1. INFRARED THERMOMETER

Infrared Thermometer is a non-contact, fast responding temperature measuring device. Its sensor works by measuring the infrared radiation emitted by objects at temperatures above absolute zero, ($^{\circ}\text{K}$) and converts the energy factor into temperature reading [44]. A non-contact infrared thermometer is useful for measuring temperature under circumstances where thermocouples or other probe-type sensors cannot be used or do not produce accurate data for a variety of reasons.

In this experimental investigation Infrared thermometer was used to measure surface temperature of bare plate, lifting cover, bottom and side enclosure and surface temperature of heat recovery tank.

7.1.2. K – TYPE THERMOCOUPLE

A thermocouple is an electrical device consisting of two dissimilar electrical conductors forming electrical junctions at differing temperatures. K – type (Chromel – alumel) thermocouple is the most common general purpose thermocouple with sensitivity of approximately $41 \mu\text{V}/^{\circ}\text{K}$ and temperature measuring capacity range from 73°K to 1623°K . In this experiment k – type thermocouple was used to measure temperature at the top and bottom of oil pan.

7.1.3. GLASS THERMOMETER

Mercury in glass thermometer is used for measurement of room temperatures. In this experiment it was used to measure the surrounding temperatures during experimental investigations.

7.2. RESULT AND DISCUSSIONS

Experimental investigation is made for one hour and forty minutes, while fifteen injeras were baked, including initial heating and polishing time of electric injera baking pan. In the experimental investigation the temperature variation in bare plate, side and bottom enclosures and heat recovery tank were measured by using Infrared thermometer. K – Type thermocouple was used to measure temperature variation at the top and bottom of oil pan while, Glass thermometer was used to measure the variation of temperature in the room during experimental investigations. Hence, temperature measurement at each surface was taken with in interval of four minutes and presented as shown in the fig (7.3) and finally, average temperature at each surface was used for quantifying the loss accounted in the system.

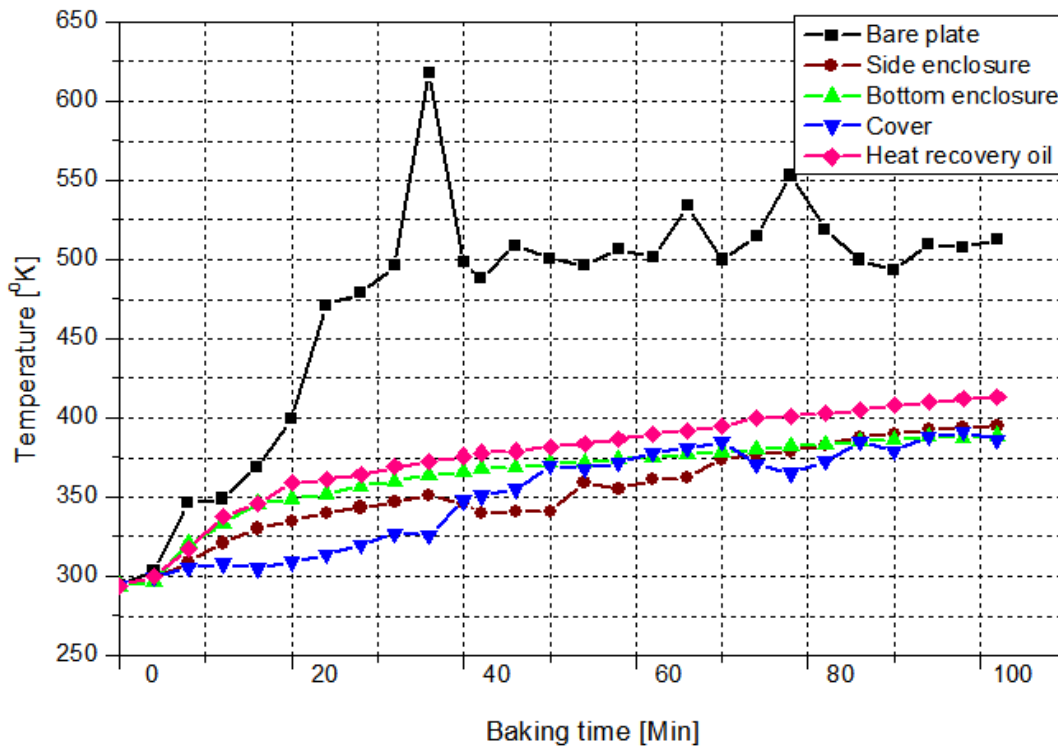


Figure 7. 3: Temperatures variations obtained from experimental result

7.2.2. AMOUNT OF HEAT ENERGY RECOVERED

The amount of heat energy recovered by heat recovery oil at each baking of injera was calculated by using eqn. (5.7). By considering 4kg mass of used engine oil, $1880 \frac{J}{Kg K}$ specific heat capacity (C_p) and 294°K initial and 415°K final temperature of used engine oil. From calculation result it was obtained that the system recovered 909.9kJ of heat energy during baking fifteen injera, including heating and polishing time of pans which means, 60.66kJ (9.63%) of energy at each baking.

For quantifying the heat loss accounted in the baking process average temperature of all measurement at each surface was used. The average temperature at bare plate, side enclosure, cover and bottom enclosure were obtained as 473°K, 354°K, 350°K and 363°K respectively. Hence, analytical calculation was made by applying eqn. (3.12), eqn. (3.16) and eqn. (3.8) for bare plate, side enclosure and lifting cover respectively, and bottom heat loss was carried out through conduction in the ash insulation and then by convection and radiation heat transfer to the surrounding.

The result of analytical calculation of loss accounted in baking process shows electric injera baking pan coupled with heat recovery system was accounted 217.8kJ (34.57%) heat loss with bottom insulation accounts 142.19kJ (22.57%) from the system were, bare plate, cover and side enclosure account 45.0kJ (7.1%), 16.94kJ (2.7%) and 13.68kJ (2.2%), respectively. Compared to the ordinary injera baking pan, baking pan coupled to WHRS improves the efficiency of baking process by 11.53%, from which 9.63% of heat energy was recovered by heat recovery system.

7.2.1. ENERGY UTILIZED FOR BAKING

Energy utilized is the amount of energy used for each baking of injera without including the loss accounted during baking process. It is the sum of energy required for raising the temperature of the dough to the boiling point of water, plus the energy required to vaporize the major part of the water in the dough. Therefore, the amount energy utilized can be obtained from the following equation [36, 40].

$$E_u = m_i C_{pi}(T_b - T_o) + h_{fg}(m_d - m_i) + (m_d - m_i) C_{pw}(T_b - T_o) \quad (7.1)$$

Where,

E_u = Energy utilized [kJ]

m_d = average mass of dough [0.4995kg]

m_i = average mass of baked injera [0.4135kg]

T_b = Boiling temperature of water in dough [366K]

T_o = initial temperature of dough [294K]

C_{pi} = Average specific heat capacity of injera [3440.7 $\frac{J}{kgK}$]

h_{fg} = latent heat of evaporation of water [$2.6 \times 10^6 \frac{J}{kg}$]

Hence, the amount of energy utilized for each baking of injera was obtained as 352.04kJ energy which account 55.8% of total energy supplied to the system.

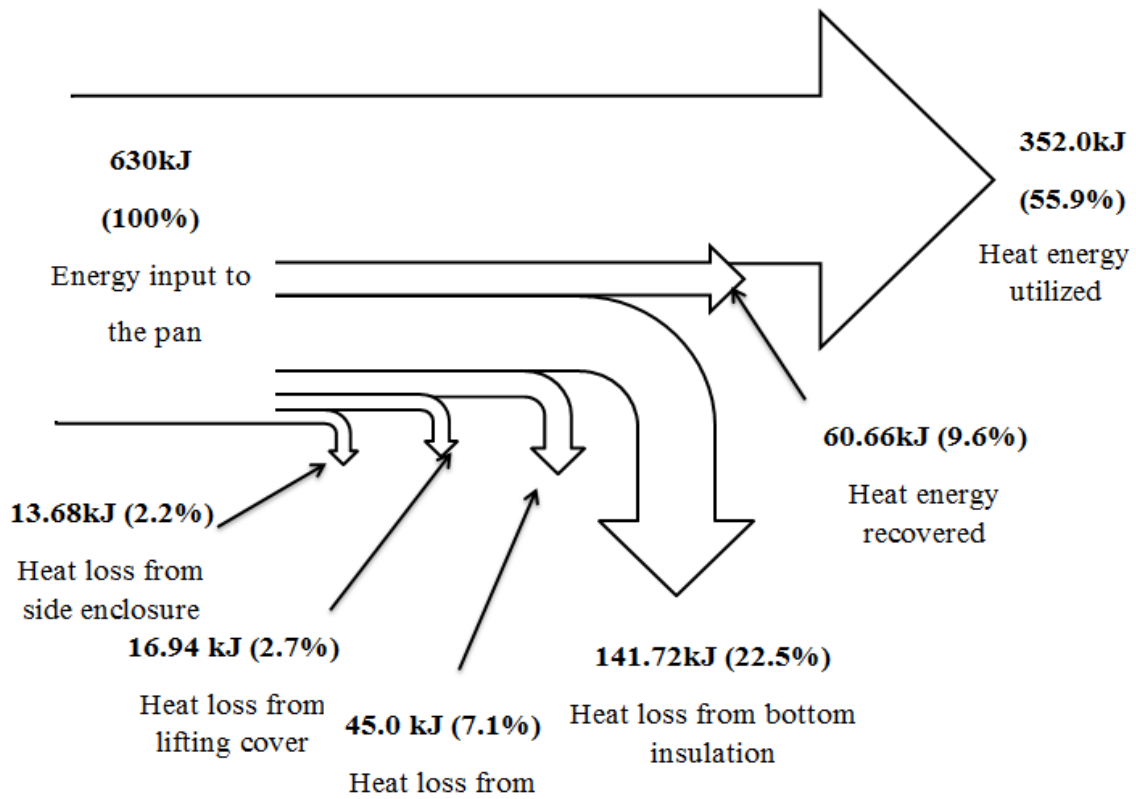


Figure 7.4: Energy flow (Sankey) diagram of electric injera baking pan coupled with WHRS

7.3. VALIDATION OF NUMERICAL RESULT

The numerical result obtained from comsol multiphysics software was validated using the data obtained by experimental investigation. Figure (7.4) shows the used engine oil temperature variation during injera baking process. It could be seen that, the temperature obtained by numerical simulation was in a reasonable agreement with those measured during experimental investigation. Where, the maximum temperature of used engine oil obtained from numerical simulation was 408°K while, it was obtained as 215°K during experimental investigation.

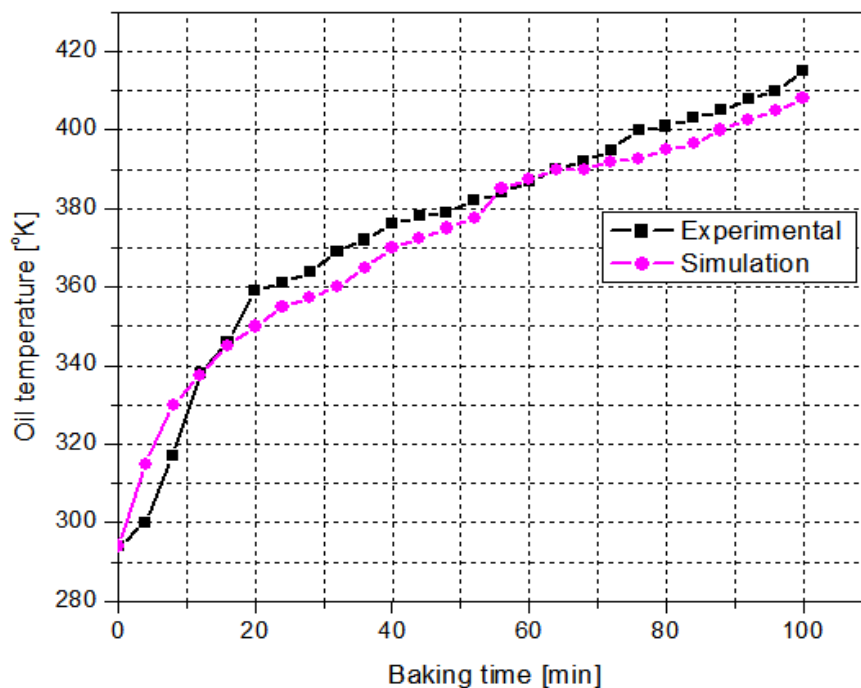


Figure 7. 5: Comparison of simulation and experimental oil Temperature variations

7.4. SURFACE TEMPERATURE OF WASTE HEAT RECOVERY

Surface temperature of heat recovery tank is recorded during experimental investigation, to show temperature variation during discharging of heat energy for water heating purpose.

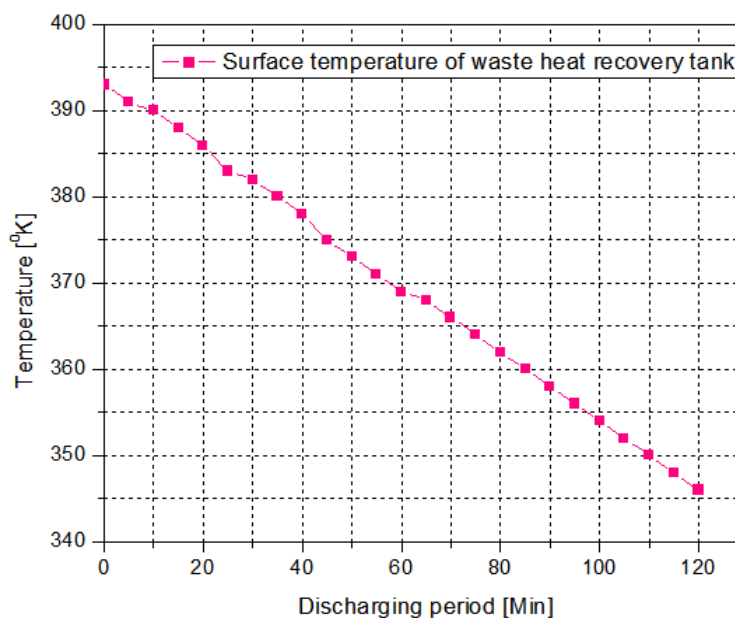


Fig 7.6: surface temperature of waste heat recovery during discharging period

CHAPTER EIGHT

CONCLUSION AND RECOMMENDATION

8.1. CONCLUSION

In this work design, optimization and experimental investigation of WHRS CEIBP has been carried out (performed). First, for quantifying the loss accounted in the electric injera baking pan intensive experimental investigation was made, and electric Injera baking mitads accounts 46.15% heat loss and from total heat loss accounted in the system bottom insulation accounts the major loss, which was 70.1% where, bare plate, cover and side enclosure account 16.2%, 6.7% and 7.0% respectively. The value obtained from the analysis lies between the ranges (40 - 50%) of prediction made in previous studies. Next, design, and numerical optimization of heat recovery system was carried out and heat recovery system with 1.5mm oil pan thickness and 6.5mm ash insulation thickness at the top and bottom of oil pan was obtained as the optimum parameter. From the simulation result the maximum average oil temperature was obtained as 408°K, with this value the system will recover 57.15kJ of heat energy at each baking of injera. Then, heat recovery system was manufactured and coupled to the electric mitads as per design parameter and finally, experimental investigation was carried out. From experimental investigation heat recovery system was recovered 60.66kJ (9.63%) of heat energy at each baking of injera. The loss accounted in system was also quantified and the system encountered 217.8kJ (34.57%) heat loss. Compared to the ordinary pans the electric injera baking pan coupled with WHRS will improves the efficiency of baking process by 11.53%. The simulation result was also validated with data obtained from experimental investigation.

8.2. RECOMMENDATION

The following points can be recommended for the future work

- In the comsol simulation made for the optimization of WHRS 2D solid heat transfer is used but, it is better to make optimization of heat recovery system by using 3D Joule heating methods in order to consider electric heat supplied to the system.
- In this paper economic analysis of the system is not made due to shortage of time, however, it is better to make economic analysis of the system.
- The maximum temperature of used engine oil used as heat transferring fluid is 433⁰K which will restrict amount of heat recovered by the system, therefore, it is better to check feasibility of the heat recovery system by using other types of oil i.e. thermia oil and sunflower oil.

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APPENDIX

Appendix –A: Heat loss from 1/2" to 6" steel pipes at various temperature differences [44].

Heat loss from fluid inside pipe (W/m)													
Normal bore		Temperature difference ($^{\circ}C$)											
mm	inch	50	60	75	100	110	125	140	150	165	195	225	280
15	1/2	30	40	60	90	130	155	180	205	235	280	375	575
20	3/4	35	50	70	110	160	190	220	255	290	370	465	660
25	1	40	60	90	130	200	235	275	305	355	455	565	815
32	1 1/4	50	70	110	160	240	290	330	375	435	555	700	1000
40	1 1/2	55	80	120	180	270	320	375	420	485	625	790	1120
50	2	65	95	150	220	330	395	465	520	600	770	975	1390
65	2 1/2	80	120	170	260	390	465	540	645	715	910	1150	1650
80	3	100	140	210	300	470	560	650	740	860	1090	1380	1980
100	4	120	170	260	380	585	700	820	925	1065	1370	1740	2520
150	6	170	250	370	540	815	970	1130	1290	1470	1910	2430	3500

Appendix –B: Thermophysical properties of Selected Materials [38].

Materials	Density (ρ) [Kg/m ³]	Specific heat capacity [J/Kg.K]	Thermal conductivity (K) [W/m.K]
Selected Metals			
Aluminum	2702	903	237
Copper	8933	385	401
Iron	7870	447	80.2
Carbon steel			
Plain carbon	7854	434	60.5
AISI 1010	7832	434	63.9
Stainless steel	8055	480	15.1
AISI 302	7900	477	14.9
AISI 304			
Silver	10500	235	429
Tin	7310	227	66.6
Insulation material used in pans (Mitads)			
Sand stone	2150	710	1.83 – 2.90
Wood Ash	-	840	0.092 – 0.17
Gypsum	-	1090	0.17
Selected oils			
CaloriaHT43	-	2300	-
Therminol55	-	2400	-
Therminol66	750	2100	0.106 at 343 ^o C
Used engine oil	888	1880	0.145

Appendix - C: Table of Emissivity Values of various surfaces

Material	Emissivity (ϵ)
Aluminum	
Polished	0.095
Oxidized	0.11
Bronze, polished	0.10
Cast Iron	
Oxidized	0.64 – 0.78
Polished	0.210
Stainless steel 18-8	
Polished	0.16 – 0.19
Oxidized	0.83
Paper, Any color	0.94
Paint,	
Alum. Paint	0.55
Green paint	0.95
Gray paint	0.95
Oil paints	0.920 – 0.960
Blackened plate	0.920 – 0.940
Baking plate	0.98

Appendix - D: Thermophysical properties of air at atmospheric pressure [38]

T [K]	$\nu \cdot 10^{-6}$ [m²/s]	$k \cdot 10^{-3}$ [W/m.k]	$\beta \cdot 10^{-3}$ [k⁻¹]	pr
150	4.425	13.8	6.67	0.758
200	7.590	18.1	5.0	0.737
250	11.44	22.3	4.0	0.720
300	15.89	26.3	3.33	0.707
327.5	18.66	28.34	3.05	0.703
337	19.61	29.03	2.97	0.702
350	20.92	30.0	2.86	0.700
388.25	25.12	32.91	2.57	0.6924
400	26.41	33.8	2.5	0.690