INVESTIGATING THE PERFORMANCE IMPROVEMENT OF AN ELECTRIC INJERA BAKING MITAD USING COPPER POWDER AS ADDITIVE MATERIAL

By

Hiwot Berhanu Bayu

A Thesis Submitted to Department of Thermal and Aerospace Engineering

School of Mechanical Chemical and Materials Engineering

Office of Graduate Studies

Adama Science and Technology University

July 2020

Adama, Ethiopia

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Advisor: Dr. Addisu Bekele

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APPROVAL PAGE

We, the undersigned, members of the Board of Examiners of the final open defense by Hiwot Berhanu have read and evaluated his thesis entitled "Investigating the Performance Improvement of an Electric Injera Baking Mitad using Copper Powder as Additive Material" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the degree of Master of Science in Thermal Engineering.

Name	Signature	Date
Hiwot Berhanu Boru Name of Student		28/07/20
Dr. Addisu Bekele Advisor		July 28, 2020
Samson Mekbib Atnaw (PhD) External Examiner		27/07/20
Dr. Daniel Gudeta Internal Examiner		1/08/20
Bekele Gadissa Chairperson		Aug 07, 2020
Bekele Gadissa Hordofa Thermal and Aerospace Engineering Department Head Head of Department		Aug 07, 2020
Dr. Tatek Temesgen Terfasa School of Mechanical Chemical & Materials Engineering Dean School Dean		Aug 10, 2020
Post Graduate Dean		

Declaration

I hereby declare that this MSc. Thesis **"Investigating the Performance Improvement of an Electric Injera Baking Mitad using Copper Powder as Additive Material"** in partial fulfillment of the requirements for the Award of the Degree of Master of Science in Thermal Engineering is an authentic record of my own work carried out from July 2019 to July 2020 under supervision of Dr. Addisu Bekele, Assistant Professor of Thermal Engineering, Adama Science and Technology University.

The matter embedded in this thesis has not been submitted for the Award of degree or diploma in any other university. All relevant resource information used in this paper has been duly acknowledged.

Hiwot Berhanu

Student Signature

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This has been submitted for examination with my approval.

Dr. Addisu Bekele

Advisor Signature

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ABSTRACT

In this research work, the improvement of an electric Injera baking Mitad using copper powder as additive material was experimentally studied. The improvement required due to the inaccuracies in the manufacturing of the conventional electric Injera baking Mitad. These inaccuracies leads for requirement range of 1.23−1.41 kWh energy for initial heating with uneven temperature distribution on the baking surface. The objective of the study was reducing the time required for initial heating, maintaining uniform temperature distribution on the baking surface and enhancing the thermal efficiency. Using standard sampling and guidelines four different samples with different ratios of the clay soil and copper powder the composite material was developed, and experimentally studied. The experimental result shows that the composite material property is improved due to the additive material and it fulfills the objective with the composition of 20% copper powder and 80% clay soil.

Using similar composition ratio with the selected sample, the electric Injera baking Mitad is constructed and experimentally studied for initial heating time, uniform heat distribution and energy consumption.

Initial heating time and baking surface temperature profile of the baking Mitad are studied and the time it takes to reach the baking temperature is 11 minutes with 200 ℃ baking surface temperature at heating rate of 15.6 ℃/min. The experimental results of an improved baking Mitad is compared with that of conventional baking Mitad available in the market. The comparison shows it reduces the initial heating time for more than 10 minutes. Then, the uniformity of the baking surface temperature is studied after recording the temperature at the center, 13 cm and 26 cm away from the center of baking surface. The result shows the variation of temperature for improved electric Injera baking machine on the baking surface during the baking process is uniformly distributed.

Finally, the energy consumption analyses is performed for both improved and conventional baking Mitads for 13 Injera baking per cycle. The gross energy consumed is 2.13 and 3.54 kWh respectively for improved and conventional baking Mitads with maximum losses through bottom surface. The average thermal efficiencies of improved and conventional electric baking Mitad are 87.51% and 52.91%, respectively.

Key Words: *Baking Mitad, Injera, Heating time, Uniform heat, Thermal efficiency*

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ACRONYMS AND ABBREVIATIONS

Symbol	Definition	SI Unit
h_{cv}	Convective heat transfer coefficient	*(W/m^2.K)*
h_{fg}	Heat of vaporization of water	*(J/kg)*
h_r	Radiative heat transfer coefficient	*(W/m^2.K)*
F_{pr}	Overall coefficient for radiation heat transfer	---
Q_F	Heat transferred by convection	*(W)*
Q_c	Heat transfer due to conduction	*(W)*
T_b	Boiling temperature of water in the given environment	*(K)*
T_{bs}	Baking surface temperature	*(K)*
T_{lc}	Temperature of the lid cover	*(K)*
c_p	Specific heat capacity	*(J/kg.K)*
m_t	Total mass	*(kg)*
ΔT	Change in temperature	*(K)*
A	Area	*(m^2)*
E	Energy	*(J)*
g	Gravitational constant	*(m/s^2)*
h	Convective heat transfer coefficient	*(W/m^2.K)*
I	Electric Current	*(A)*
k	Thermal conductivity of material	*(W/m.K)*
m	Mass	*(kg)*
P	Power	*(W*
q	Rate of heat input	*(W)*
R	Resistance	*(Ω)*
Re	Reynolds Number	----
t	Time	*(sec)*
V	Voltage	*(V)*
v	Kinematic viscosity	*(m^2/s)*
x_i	Mass fraction of ith component	---

β	Volumetric expansion coefficient	*(1/K)*
ρ	Density of material	kg/m^3
Nu	Nusselt Number	---
Pr	Prandtl Number	---
Ra	Rayleigh Number	---
δ	Stefan Boltzmann constant	$(W/m^2.\ K^4)$
ε	Emissivity of the surface	---

Subscripts and Superscripts

Subscripts or Superscripts	**Definition**
∞	Surrounding
a	Ash
ap	Apparent
bak	Baking
bat	Batter
bs	Baking surface
bm	Baking Mitad
c	Carbohydrate
f	Fat
gyp	Gypsum insulation material
inh	Initial heating
inj	Injera
p	Protein
S	Solid
t	Total
T	True
w	Water

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

In Ethiopia, the domestic sector accounts for about 89% of the total energy consumption and this sector shares from biomass, petroleum and electric energy sources [1]. Studies showed that the household energy requirements are primarily for baking and cooking purposes; accounting for about 60% of households' energy consumption [2]. Based on the type of energy supplied to baking Mitad, different types of baking Mitads were developed for baking Injera. The heat supplied to the baking Mitad comes from either burning of firewood, cattle dung or agricultural residue in biomass, solar energy and electrical power.

The three stone open fire system uses three separate stones to support the baking plate. Then, firewood is inserted into the openings between the stands for burning. While burning is taking place below the Mitad, Injera is baked on it [3]. Because of the heat is allowed to escape into the open air rather than heating the baking Mitad, three stone fires have a low thermal efficiency of around 10%. Where as in the case of, biomass Injera baking Mitad, there is no direct supply of the biomass energy sources. There is a process called biomass gasification, which converts solid biomass energy sources into a fuel gas. The gas phase is a combustible gas and can be used for heating the Mitad for baking Injera [4]. When it is compared with a three-stone open fire Injera baking system the thermal efficiency, CO emission and particulate matter reductions were improved during the gasifier Mitad Injera baking system. Additionally, heat losses in the components of the biomass gasifier Mitad is reduced. Still there is problem of heat losses from the Mitad, and resulting longer heating up time between consecutive baked Injera.

In the case of solar powered Injera baking system, there is no direct supply of the heat to baking Mitad, rather its works by using energy storage like phase change material and pressurized water vessel with auxiliary heating components. After the solar system collects heat from the solar radiation the heat is transferred to the working fluid or storage, finally it reaches to the Mitad for baking Injera [5, 6]. The problem here is the system is efficient during the sunshine hours only. Additionally, it takes longer time to heat the baking Mitad, and the idle time between the baking is longer when it is compared with other system.

Finally, the conventional electric Injera baking system uses resistance-heating system, which involves passing line frequency of current through high resistance heating elements. The resistance to the current flow generates heat in the coil by using the electric power source; and then the heat transferred to the baking Mitad through conduction. Based on the number of clay used, single clay, the double clay and the rotating type electric Injera baking Mitads are available in the market. The conventional electric Injera baking Mitads are rated at 3.7 to 4.0 kW power. It is customary to see the dimming of light bulbs, lessening of power level during baking. Other electrical devices like cooking Mitads and water heaters will not be turned on once Injera baking Mitads are in operation. Electric Injera baking Mitads contribute to the bulk of the electric power demand and consumption of a typical residential household and the nation [7].

In conventional electric baking Mitad, non-uniformity of heat distribution is likely to occurs because of the inaccuracy of the manufacturing process of the Mitad itself. Such manufacturing error includes the difference in the depth of the groove the electrical resistor is embedded and the difference in density of the resistor rolling across its length. In addition to that, the time it takes for initial heat up is more than 20 minutes.

The common features of all types of Injera baking Mitad is the requirement of heat energy for heating the Mitad for baking Injera. During the development from three stone open-fire to electric Injera baking system there are technological problems or challenges. This is the implication for the requirement of improvement for efficient utilization of energy supplied in all type of Mitads.

Electricity consumption of electric Injera baking Mitads depends on the power rating of the set, voltage level, thickness of the batter to be baked, and experience of the baker. The estimated electric Injera baking Mitad consumption in Ethiopia for the last three years, from 2017-2019 were 625GWh, 681GWh, and 742 GWh with the losses of 128 GWh, 119 GWh and 119 GWh, respectively [8]. From the report, it observed that, as there is large amount of energy losses. Since these losses are related with baking Mitads, improvement on the baking plate will reduces the energy consumptions and bill cost.

The challenges for the improvement of Injera baking Mitad are low awareness of energy saving on both manufactures and customers, lack of improved baking plate material instead of conventional clay, and lack of standard production materials. Additionally, there is no standard of labelling and governmental policy on manufacturing of the electric Injera baking Mitad.

1.2 Statement of Problem

There are inaccuracies in the manufacturing of the conventional electric Injera baking Mitad. Moreover, there is requirement of energy in a range of 1.23−1.41 kWh for initial heating only with uneven heat distribution on the baking surface. This leads to high electric power consumptions with high bill cost in range of 0.82−0.90 Birr per each Injera, and hotspots on the baking surface. This is due to lack of extensive work carried out in order to improve the thermal property of the Injera baking Mitad material. Additionally, few works only have been carried out to reduce the initial heating time and for maintaining uniform temperature distribution on the baking surface of baking Mitad using other options rather than improving the plate property.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this study is to improve the performance of a conventional electric Injera baking Mitad using copper powder as additive material.

1.3.2 Specific Objectives

- ✓ Study the thermo-physical properties of Injera baking plate and Injera
- ✓ Reduce the time required for initial heating
- ✓ Maintain uniform heat distribution on the baking surface of the baking Mitad
- ✓ Improve the efficiency of baking Mitad by minimizing the side and bottom losses
- ✓ Compare the performance of the conventional and improved electric Injera baking Mitad

1.4 Scope and Significances of the Study

1.4.1 Scope of the Study

The scope includes:

- ✓ Thermo-physical properties enhancement with additive material
- ✓ Selection of proper type of insulating material to prevent bottom and side loss
- ✓ Selection of proper type of thickness of baking plate
- ✓ Developing the prototype using the composite material
- ✓ Testing the prototype for initial heating-up time; uniform temperature distribution on the baking surface; energy consumption and utilization of baking Mitad
- ✓ Conducting performance test of both improved and conventional electric Injera baking Mitad

1.4.2 Significances of the Study

Construction of the improved electric Injera baking Mitad has the following significance:

- ✓ It reduce high-energy consumption
- ✓ It reduce the weight of the baking Mitad, since the plate thickness is reduced

1.5 Limitation of the Study

During the thesis work, the following limitation makes the study hard.

- ✓ Lack of accessibility of measuring equipment like data logger, energy meter and others
- ✓ Lack of heating element composite material like stainless steel foil (SS 304), Nicrome heating element in form of sheet and others

1.6 Methodology

The methodology followed in this research work is based on the objectives formulated in section 1.3. The methodology followed for this study starts with extensive literatures review on baking Mitad and the baking system inaccuracies. Additionally, finding the difficulty for the improvement of an eclectic Injera baking Mitad. Then, after finding the difficulty solution is proposed and the electric Injera baking machine was manufactured and experimental analysis is conducted. Based on the experiment conducted the results and discussions developed. Finally, conclusions and recommendations are derived.

The full detailed flow chart of research methodology is as shown in the figure 1.1 below

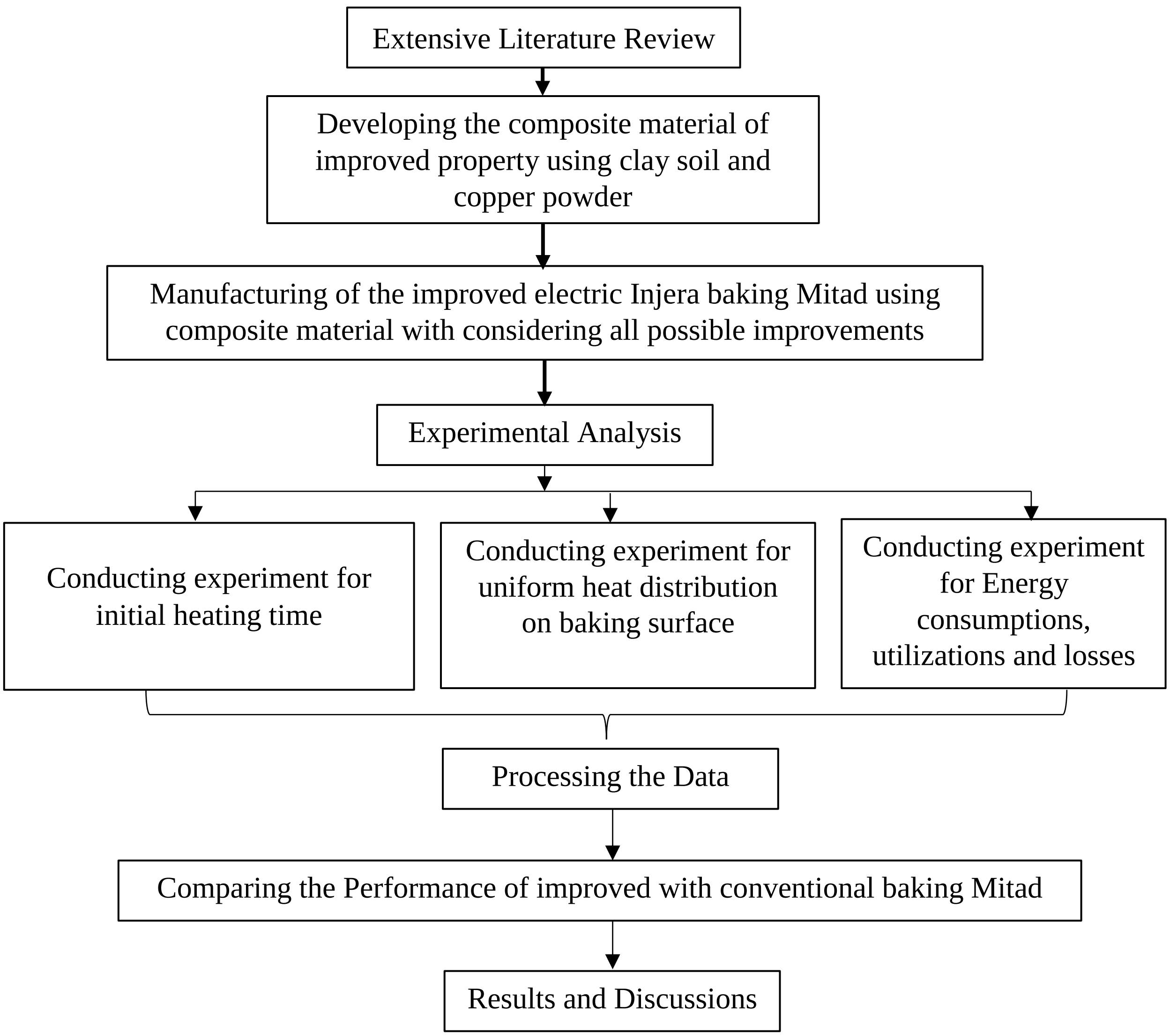

Figure 1.1 Research Methodology Flow Chart

CHAPTER TWO

LITERATURE REVIEW

In this chapter description of the firewood, biomass gasifier, and solar powered and conventional electric Injera baking systems are reviewed. Additionally, researches and inventions of electric Injera baking Mitad, materials for baking applications, and heat and mass transfer of Injera baking process are reviewed.

2.1 Firewood Injera Baking System

2.1.1 Three-stone Open Fire Baking System

As the name implies, three-stone open fire Mitad uses three separate stones to support Mitad for baking. The types and sizes of stones used varies according to the availability of the stones. Usually three 10-15 cm high stones were used for supporting. The three stones were placed in a triangle to support or carry the baking Mitad with a diameter of 60 cm and thickness of 20 cm on average. Then, firewood was inserted into the openings between the stands for burning. While burning was taking place below the Mitad, Injera was baked on it. In the process, 90% of the energy supplied was lost to the environment [3].

Figure 2.1 Three Stone Open Fire Baking System [9]

2.1.2 Mirt Injera Baking Mitad

Mirt Mitad was an enclosed Injera baking Mitad designed by the Ethiopian Energy Studies and Research Center of the Ministry of Mines and Energy under the cooking efficiency improvement and new fuels marketing project (CEINFMP). The basic design of Mirt Mitad was adopted from the Ambo and Burayu enclosed Injera Mitads and further optimized so that it can handle different types of fuels. The raw materials for the production of Mirt Mitad were cement and pumice (sometimes known as volcanic ash). Pumice binds well with cement and was used as a good insulator. Since it was formed at high temperature, it resists heat quite comfortably. In areas where pumice was not available scoria (red ash) or pure river, sand can be used alternatively. Pumice was pounded and sifted to remove large particles and then mixed together with cement. The pumice to be mixed with two particle sizes. The fine grain size was 3 mm and the course grain in 5 mm. These two-grain sizes will be mixed in three parts fine and one-part coarse grains. Four part of this pumice will again be mixed with one part of cement and water. When the mixture was dump wet, it will be molded to different Mitad parts using metal molds. The mixture will be compacted inside the mold by hand tamping or using a vibrator. Then the molded Mitad part will be immediately removed from the mold and will be left for about 7 days for drying. It needs watering at least twice a day until the seventh day. The Mitad has six parts; four arcs fit together to form the circular combustion chamber. Producing this section of the Mitad in four parts avoids formation of cracks due to thermal stresses. It also eases the problems of handling, transportation and storage of Mitads. The U-shaped part and the circular pot rest placed on top of it will form the chimney part. The total weight of the Mitad was about 45 kg [10].

Figure 2.2 Mirt Injera Baking Mitad [10]

2.1.3 Summary of Open Fire Injera Baking System

These traditional wood fires imply a high risk of burns and scalds especially on children. Mirt Mitad was better and efficient compared to the open fire baking system. Furthermore, since the heat was allowed to escape into the open air rather than heating the cooking vessel, three stone fires have a low thermal efficiency of around 10 %. This implies a high fuel consumption, which results in an increase of the amount of wood harvested and related deforestation. A number of efforts were performed to improve the performance of traditional open fire cooking Mitads.

2.2 Biomass Gasifier Injera Baking System

Biomass gasification was used as the partial oxidation thermochemical conversion process of biomass energy sources, like cattle dung or agricultural residue, into a gas and solid phases. The solid phase includes char and the inert material present in the biomass (ash). The gas phase was a combustible gas and used for power generation or biofuel production. The combustible gas produced, when using air as gasifying agent, consists mainly of CO, H_2, CH_4, CO_2 and N_2 [12]

However, the actual gas composition may vary considerably depending on fuel type and gasifier design. People living in rural areas of developing countries cannot afford buying forced draft or advanced biomass gasifier Mitads, therefore research on natural draft gasifier Mitads was prioritized. Small-scale gasifier Mitads were getting popular and considered the future clean cooking Mitads due to their benefits in terms of smoke and soot free clean combustion [4]. Biomass gasification based cooking systems have also some other attractive advantages like high efficiency, uniform and steady flame, ease of flame control, and possible attention-free operation over extended duration. The working principle of biomass gasifier Mitad will be as follows:

The feed hopper was located above the reactor and conically shaped to facilitate the movement of woodchips down to the reactor. It was closed with a lid for easy loading of biomass and has a water seal to avoid gas leakage during the operation. The feed hopper was connected to the upper part of the reactor and the fuel moves down to the reactor by gravity. The reactor was a cylindrical body 2.5 mm thick, 400 mm diameter and 350 mm height. A grid placed in the reactor holds the biomass but allows the ashes to fall free through it. The ashes accumulated can be removed by opening a steel door located under the grate. The primary air inlet was an inverted 'L' shaped unit attached to the side of the reactor. The amount of primary air supplied to the reactor was controlled by a butterfly valve. Perforated steel sheets were used at the primary air inlet and exit areas to keep the fuel inside the reactor. A flange connects the producer gas outlet and the combustion chamber. The combustion chamber has a cylindrical shape and then it opens up in a conical structure to accommodate the Mitad. The cylindrical burner was equipped with a secondary air inlet sieve-like structure with a diameter of 150 mm. The reactor, feed hopper, gasholder, combustion unit and secondary air inlet sections were insulated using 50 mm thick fiberglass and covered with aluminum sheets. The Injera baking cover was a standard item made of aluminum with a wooden holder at the edge [13]

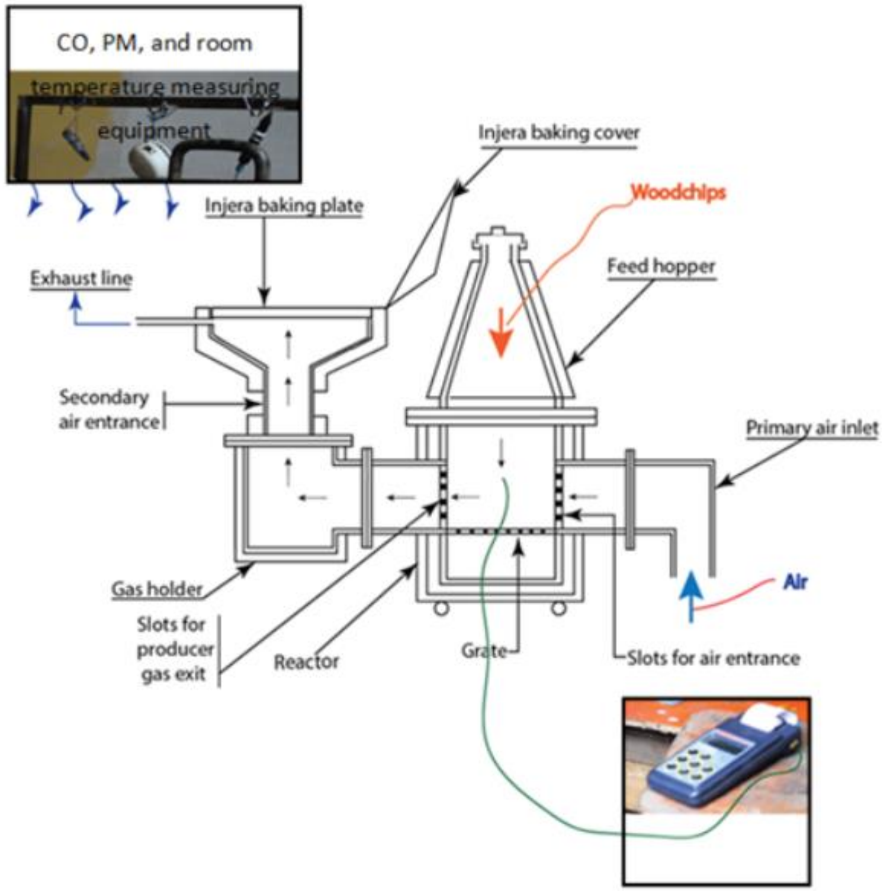

Figure 2.3 Biomass Gasifier Mitad for Injera Baking [13]

2.2.1 Summary of Biomass Gasifier Mitad

When it is compared with a three-stone fire Injera baking system the thermal efficiency, CO emission and particulate matter reductions were improved during the gasifier Mitad Injera baking system. Additionally, heat losses in the components of the biomass gasifier Mitad was reduced. Still there is opportunity for improvement for further reducing the heat losses from the Mitad, initial heat up time baking system.

2.3 Solar Powered Injera Baking System

Many designs exist for solar cooking purposes; relatively few exist for frying [12]. The existing systems were also limited to direct cooking technologies by illuminating the Mitads on the sides as well as the bottom. Whereas, for Injera baking, the heating must be directed to the bottom of the baking Mitad. Solar baking works by using energy storage like phase change material, pressurized water vessel, box type solar cooker with auxiliary heating and pebble bed thermal energy storage have been proposed [6]. The majority of these systems work below the baking temperature required for baking Injera (180-220 ℃). Besides, they do not satisfy the general requirements for baking Injera.

Gallagher (2010) developed the solar fryer, which was specifically designed for cooking Injera. He used a 460 mm diameter Mitad and 1200 mm diameter mirror for his prototype, which was designed for cooking 420 mm diameter slices of Injera. A mirror below the Mitad directs the radiation to the Mitad bottom, which was coated with a low-emissivity black absorber. The mirror uses flat, hexagonal panels of aluminized-Mylar to provide uniform illumination across most of the Mitad bottom. This system was mainly designed for cooking outdoors [15]. Devos (2006) developed the other well-known solar fryer by arranging an array of 0.15 m square glass mirrors in a 1.54 m^2 rectangle, with each mirror tilted to fit an off-axis parabola. The array was placed near the ground just beyond a table that supports the fry Mitad, which sits at an opening in the table. Reflected sunlight was brought to a quasi-focus on the bottom of the Mitad, and a metal vane below the table was used to block part or all of the incident sunlight. The mirror angle was adjusted through the day and the seasons to direct focused sunlight to the Mitad [16] Jorgen Lovseth (1997) proposed a concentrating solar thermal system with pebble-bed heat storage using air as heat transfer medium [17].

Abdulkadir Hassen et al. (2007) was proposed the following design, the block diagram of the proposed solar powered Injera baking system is shown in figure 2.4. The system consists: parabolic trough, pumps, heat storage tank and the Injera baking Mitad. The parabolic trough was used to collect solar energy and increase the temperature of the fluid.
The heat transfer fluid coming from the trough gives up its heat to the fluid coming from the baking Mitad, within the heat exchanger. The baking Mitad consists of a ceramic Mitad with steel plate underneath. Fin structures were welded at the bottom of the steel plate to facilitate heat transfer and to hinder direct oil flow from oil gallery.

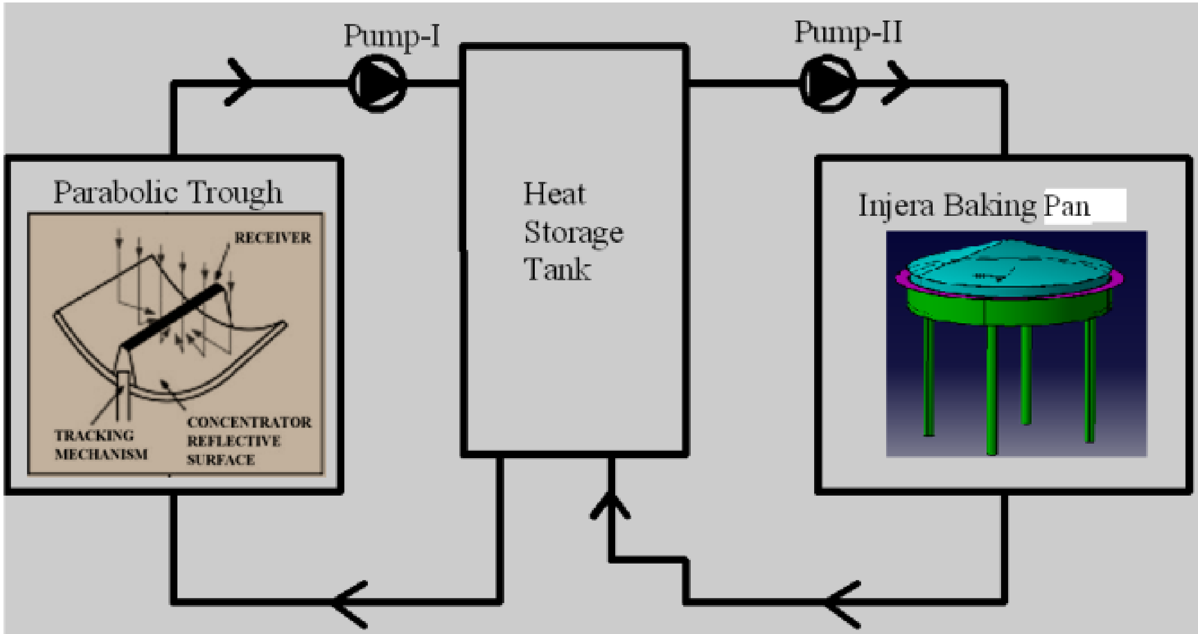

Figure 2.4 Block Diagram of Solar Powered Injera Baking Mitad [5]

Heat was transferred from the working fluid to the steel plate then to clay Mitad and finally to Injera during baking. The baking plate was placed in the kitchen where the baking was done. All other components were placed at intermediate levels according to the building requirements. Pump-I was used to Pump the heat transfer fluid between the parabolic trough and the heat storage tank (heat exchanger). The energy extracted from the sun was used to heat up the oil to the required temperature. Once the required temperature was reached 300 ℃, the heat energy transferred to the baking Mitad using Pump-II. Oil was partly stored below the baking Mitad, in order to overcome sudden drop of surface temperature of the baking Mitad during baking [5].

2.3.1 Summary of Solar Powered Injera Baking System

Most of the solar powered Injera baking system do not directly heat the Mitad, rather the system leads for the usage of phase change material, pressurized water vessel, box type solar cooker with auxiliary heating and pebble bed thermal energy storage. For instance, from the experimental result of the above literature [5]. It was observed that it took approximately 1 hour for heating oil to 300 ℃ and 40 minutes to reach the optimum baking surface temperature. Injera was removed from the baking Mitad every two minutes and it takes an idle time of three minutes between each Injera to recover to optimum baking temperature. Based on average family size, 20 Injera can be baked per day in approximately three hour and 28 minutes. This was time consuming and many component-integrated system. Additionally, the system works during the sunshine hours and requires high initial investment.

2.4 Conventional Electric Injera Baking System

Conventional electric Injera baking Mitad uses resistance-heating system, which involves passing line frequency of current through high resistance heating elements. The resistance to the current flow generates heat in the Nickel-Chromium (Ni-Cr) coil; and the heat is transferred to the baking Mitad through conduction. Nickel-Chromium or Nicrome is a nonmagnetic alloy that is commonly made up of 80% nickel and 20% chromium [18].

The power source of the electric Mitad is an electrical power. This electrical power is converted to heat energy by using an electric flow resistance wire inserted on the backside of the grooved baking Mitad. In general, mathematical power dissipated in an electric resistance wire can be expressed as Ohmic heating; occurs when a resistor is heated as current flows through it.

$$P = I^2R = V^2/R \qquad 2.1$$

Where: P = Power (W)

R= Resistance *(Ω)* and

I = Current (A)

2.4.1 Types of Conventional Electric Injera Baking Mitad

Depending on the number of clay used, there are three type of electric Injera baking Mitad. These are single clay, the double clay and the rotating type, as described in figure 2.6. The single clay Mitad comprises only one baking clay with the top surface used as baking surface and the electrical resistor was inserted at the bottom side of the clay. In the double clay Mitad, there are two layers of clay placed one on top of the other. The upper clay was used as the baking clay and the second clay was used to insert the electrical resistor. The rotating type Mitad was comprised of two layers of clay. Both clays were placed back-to-back and the front side of both clays was used as baking surface as shown in figure 2.5. The electrical resistor was inserted in the bottom side of either of the two clay. The clay embedded with the electrical resistor was called the heating clay while the other clay is called the dependent clay. The baking process was conducted by rotating the one after the other.

The single clay-baking Mitad takes more than 20 minutes for initial heating, whereas the double clay-baking Mitad takes more than 24 minutes during the experimental investigation. This implies single clay-baking Mitads reaches the baking temperature faster than double clay-baking Mitads. Furthermore, heating non-uniformity and temperature increment during baking process shows similar behavior for both the single and double clay-baking Mitads. Whereas, the initial heating time for the rotating baking Mitad is about 15 minutes, which is lower when compared with single and double clay type baking plate. The reason is the rotating type is the improved one with its limitations [7].

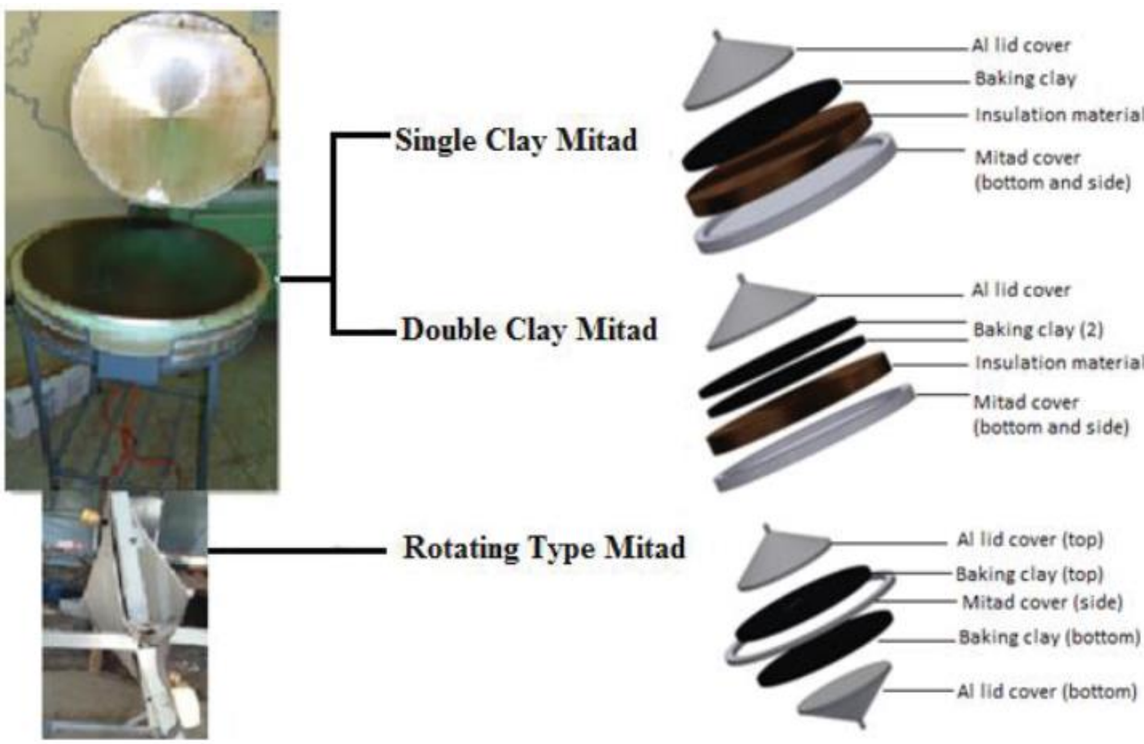

Figure 2.5 Description of the Three Type of Electric Injera Baking Mitad [7]

The widely available Injera baking electrical Mitad in urban are the single clay and double clay type. The clay diameter was similar for both type, in the range of 550 to 580 mm. The conventional electric Injera baking Mitads are rated at 3.7 to 4.0 kW power.

The common parameters of conventional electric Injera baking Mitad is tabulated in the table

2.1. It is all about the baking plate parameters like dimensions of grooves, embedding and insulating materials.

Table 2.1 Physical Dimension of the Conventional Electric Injera Baking Mitads [7, 19]

Parameters	**Dimensions**
Number of grooves	10-11 patterns
Groove depth	7- 8.5 mm
Groove diameter	8 mm
Pitch distance	17.5 mm
Resistor coil diameter	6 mm
Resistor wire diameter	0.9 mm
Resistor coil length-before stretching	650 mm
Resistor coil length-after stretching	9600 mm
Circuit connection type	Parallel
Average clay thickness	20 mm
Average clay diameter	550 to 580 mm
Bottom insulation thickness	30 to 35 mm

Figure 2.6 shows the assembly procedure of the electric Injera baking Mitad. It starts with grooving the baking plate and embedding the heating element. Then, sealing with the gypsum and assembling the other components.

a) Back side before sealing

Backside sealed with gypsum

Electric Injera baking Mitad

Figure 2.6 Conventional Electric Injera Baking Mitad [7]

2.4.2 Researches and Inventions of Electric Injera Baking Mitad

Electric Injera baking Mitads have wider use in urban areas where grid electricity is available. Many researchers have conducted numerical and experimental investigations on electric Injera baking Mitad. Some of these are briefed in the table 2.2.

Table 2.2 Electric Injera Baking Mitads Research Output

No.	Authors	Tittle of Research	Major Output	Major Limitations
1	Mekonnen Mesele (2011) [19]	Design and Manufacturing of Laboratory Model for Solar Powered Injera Baking Oven	✓ Design and manufacturing a laboratory model for solar powered Injera baking pan system consisting of oil storage and heating tank, pumping and piping system, baking Mitad assembly ✓ The system uses electrical heater to heat the thermic fluid to be used for baking. ✓ A temperature of 215℃ is achieved on baking Mitad and baked Injera.	✓ Requirement of extensive initial heating and baking time ✓ Lack of using proper pump for the purpose of pumping heat transfer fluid in the system ✓ Leakage of oil during circulating in the system
2	Gashaw Getenet (2011) [20]	Heat Transfer Analysis during the Process of Injera Baking by Finite Element Method	✓ Developed mathematical models and finite element formulations for baking pan and Injera during baking. ✓ Simulation was done in terms of temperature profile during heat-up and cyclic Injera baking	✓ Only simulation work performed for thickness other than 0.02m ✓ Requirement of wide initial heating time
3	Garedew Ambaw (2015) [21]	Performance Analysis and Reliability Testing of a Ceramic Bake Ware for an Electric Injera Baking Pan	✓ The FE model validated by using experimental data obtained from field testing of the performance ✓ The simulation shows about 82% efficiency can be realizable by reducing the thickness to 8mm for 20 cycles of Injera baking	✓ Non uniform heating of baking plate ✓ Lack of sufficient insulation ✓ Requirement of extensive initial heating and baking time.

Table 2.3 Invention Regarding Injera Baking Mitad and Their Major Outputs

No.	Inventor	Title of the invention	Major inventions
1	Mengistu Kindie (2003) [22]	Method and Apparatus for Making Bread	A device used to bake Injera and bread by making use of a distributer. The distributer pours the batter in the baking surface, which is heated by an electric power supply from the bottom. The device is automated for continuous Injera baking operation
2	Emiru Dessalegn (2005) [23]	Method of and Apparatus for Making Ethiopian Bread	A measured amount of batter dispensed into a horizontal moving conveyor where Injera is baked and transported to a cooling zone. The machine is automated to bake Injera continuously with the help of electric power.
3	Wundeh Mulugeta (2006) [24]	Injera Manufacturing System	A continuous Injera baking machine consisting of storage, dispensing, baking and cooling stages. The machine is capable of producing Injera in mass continuously.
4	Yoseph Temesgen (2008) [25]	Injera Baking Machine	Automated Injera baking machine starting from polishing the surface of baking plate, dispensing and removing using spatula attached to a reciprocating conveyor. The batter dispensing mechanism can rotate and reciprocate simultaneously.
5	Wassie Mulugeta (2011) [26]	Rotary Baking System and Method	An automatic rotary Injera baking machine, which consists of a movable dispensing unit with a rotary system for baking using a gas burner. The gas will be fed to each baking surface from the gas cylinder.

2.4.3 Summary of the Conventional Electric Injera Baking System

Non-uniformity of heat distribution likely occurs because of the inaccuracy of the manufacturing process of the Mitad. Such manufacturing error includes the difference in the depth of the grooves, the electrical resistor embedding and the difference in density of the resistor rolling across its length. In addition to that, the time it takes for initial heating is more than 20 minutes. Even though the baking surface has reached the required baking temperature at early period of the heating up process, the temperature of the heating element is increasing which means the system were consuming additional power from the source irrelevantly.

It was also reviewed from literatures; the improvement of the electric Injera baking Mitad would be attained from the reduction of the thickness of the baking clay, thermal conductivity improvement of the clay, the insulation thickness increment and proper dimensioning of the electrical resistor.

2.5 Alternative Energy Sources for Baking

The above classification of the Injera baking Mitad is classified based on the sources of energy for baking. In the case of the electric Injera baking Mitad, the electric line is bought from the Ethiopian Electric Utility (EEU) and consumers were charged monthly consumption fee. The price for consumption depends on the energy used in kWh per month.

Alternative energy sources such as biomass, solar and electric energies are summarized in figure 2.7.

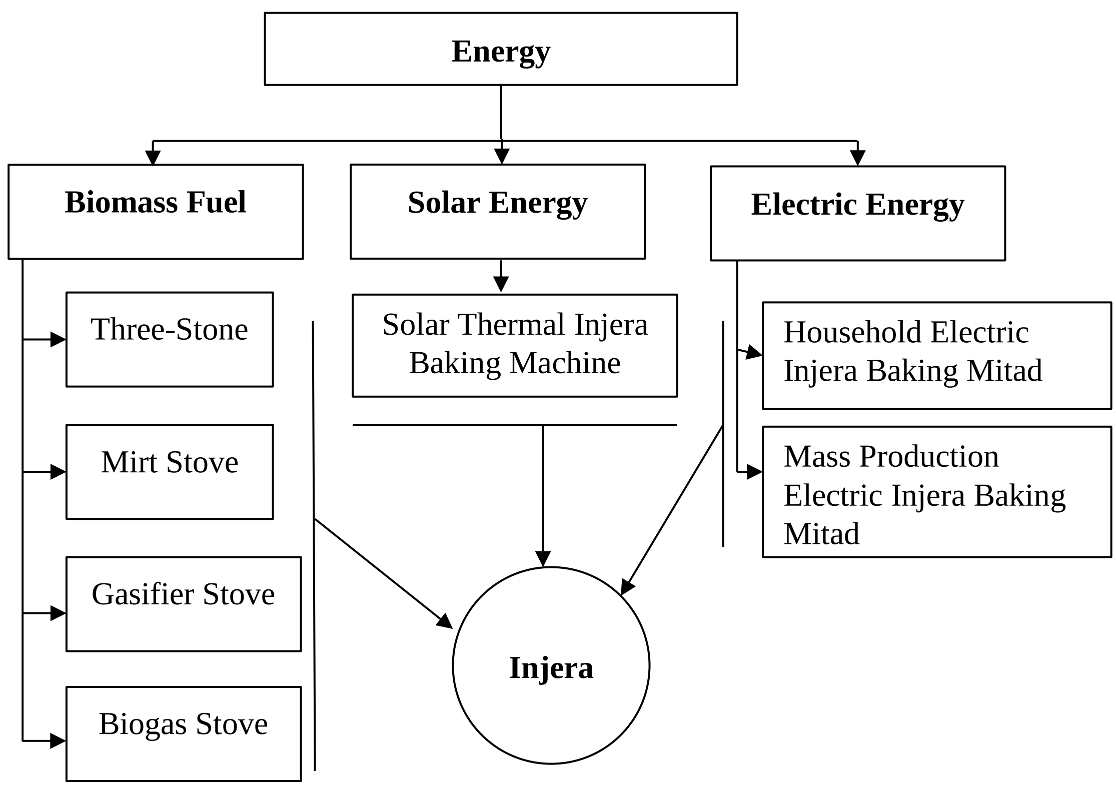

Figure 2.7 Alternative Energy Sources for Baking Injera

2.6 Methodology Used by Different Researchers

Different researchers used different types of research methodology to improve the efficiency of an electric Injera baking Mitad. Most of the research methodology starts with literature review and ends with conclusions and recommendations. Two researcher's research methodology displayed in figure 2.8 and 2.9.

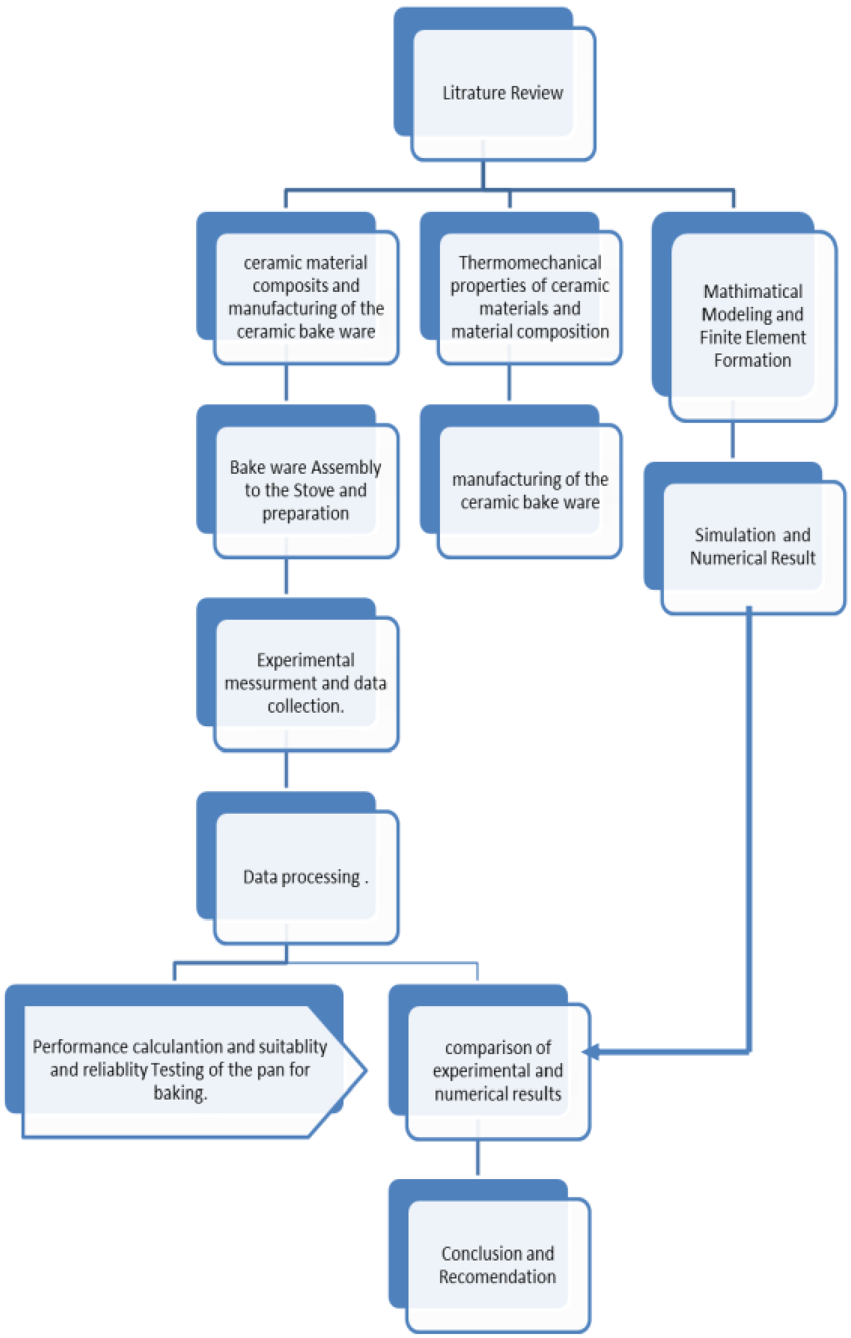

Figure 2.8 Flow Chart for Methodological Approach [21]

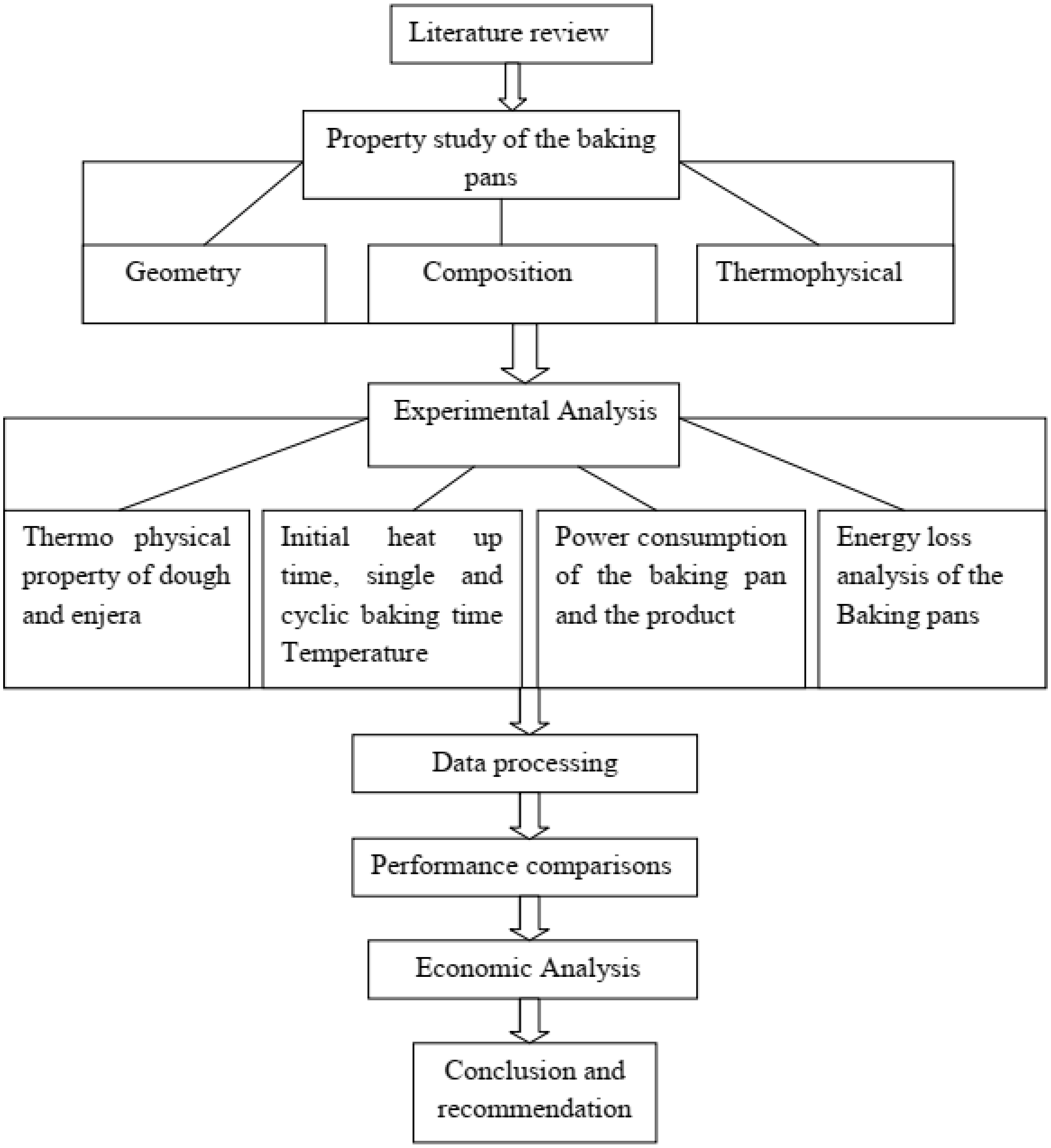

Figure 2.9 Flow Chart for Methodological Approach [27]

2.7 Heat Transfer of the Injera Baking Mitad

Heat transfer from the baking surface to the Injera and other parts of the baking Mitad is briefly described.

Generally, heat flows from the baking plate to the different Mitad components and the product Injera. The primary paths of heat flows are the following [32]:

- ✓ Heat transferred from the heating element through conduction to the plate surface, then, in similar fashion to the Injera batter.
- ✓ Heat transferred from the baking plate to the sides of the baking Mitad through conduction, and then lost through convection and radiation to the surrounding.
- ✓ Heat transferred from the baking Mitad through primitive dried insulation to the galvanized iron sheet metal bottom surface, and then lost through radiation and convention from the bottom.
- ✓ A minor heat-flow transferred from the baking Mitad surface to the lid cover, and then lost to the surrounding through convection and radiation.

2.7.1 Mechanisms of Heat transfer in the Injera Baking Mitad

The second law of thermodynamics states that heat always flows from the higher temperature to the lower temperature direction. Heat transfer occurs mainly via three fundamental mechanisms: conduction, convection and radiation [33]

2.7.1.1 Conductive Heat Transfer

Conduction heat transfer is defined as the transfer of energy from one point of a medium to another under the influence of temperature differences. A distinguishing characteristic of conduction is that it takes place within the boundary of a medium, or across the boundary of a medium into another medium in contact with the first, without an appreciable displacement of the matter. Heat conduction is important in Mitad top cooking, where heat is conducted from the heat source, gas flame or electric coils directly to the bottom side of the Mitad. Conduction continues as heat passes through the Mitad to the food from the baking Mitad. Even after the Mitad is removed from the heat, conduction continues until the Mitad and the food reach the same temperature.

The equation of heat transfer mode by conduction is given by [33]:

$$Q_c = {}^{kA(T_{bs} - T_{ls})}\!/_{x} \qquad 2.2$$

Where: Q_c= Heat transfer due to conduction *(W)*

k = Thermal conductivity of baking plate *(W/m.K)*

A= Surface are of heat flow *(m^2)*

T_{bs}= Baking surface temperature *(K)*

T_{ls}= Lower surface temperature *(K)* and

x = Average thickness of the Mitad *(m)*

The rate of heat input to the Mitad (Q_i) is not equal to the rate of heat output (Q_o). The difference is the accumulation of heat Q_a (which can be positive or negative). If there is no heat generation in the slab, heat balance requires that [33]:

$$Q_i - Q_o = Q_a \qquad 2.3$$

2.7.1.2 Convective Heat Transfer

Convection aids heat transfer through liquids and gases, which otherwise conduct heat slowly. It involves the constant movement of cold currents of air or liquid toward warmer currents. Because warmer liquids and gases are less dense and rise up while colder liquids and gases are denser and they sink. Heat and mass transfer in fluids occur, usually, simultaneously with bulk movement of the medium. This system is called convection heat transfer [45].

$$Q_F = hA_p(T_{bs} - T_{lc}) \qquad 2.4$$

Where: Q_F = Heat transferred by convection *(W)*

h = Convective heat transfer coefficient *($W/m^2 \cdot K$)*

A_p = Surface area of the product *(m^2)*

T_{lc} = Temperature of the lid cover *(K)*

T_{bs}= Baking surface temperature *(K)*

The movement is caused by heat or mass transfer itself, usually by virtue of density differences is known as natural (free) convention heat transfer. Air in contact with the Mitad surface is heated, expands, becomes less dense, moves upwards and is replaced by colder, heavier air.

Empirical correlations for convection heat and mass transfer for natural (free) convection, which is essentially based on differences in density, hence on thermal expansion of the fluid, the correlations contain the Grasshof number (Gr). This dimensionless group contains the term, $\Delta\rho$ the difference in the density of the fluid, which in turn is related to the differences in temperature

(ΔT) and the coefficient of thermal expansion β. The following correlations are taken from Kreith et.al. [45].

The recommended correlation for the calculation of natural convection heat transfer from vertical surfaces:

$$Nu = 0.59 Gr^{0.25} Pr^{0.25} \quad 2.5$$

For a sphere immersed in fluid, the following equation is proposed:

$$Nu = 2 + 0.6 Gr^{0.25} Pr^{0.33} \quad 2.6$$

For horizontal plate and uniform surface temperature, the recommended correlation for the heated upper surface:

$$Nu = 0.54(Ra)^{0.25}, for\ 10^5 < Ra < 2 * 10^7 \quad 2.7$$

$$Nu = 0.14(Ra)^{1/3}, for\ 2 * 10^7 < Ra < 3 * 10^{10} \quad 2.8$$

Where: Ra =Rayleigh number, and

Pr = Prandtl number

2.7.1.3 Radiation Heat Transfer

The term radiation covers a vast array of phenomena that involve energy transport in the form of waves. Above the absolute temperature of zero degree Kevin, all substances emit electromagnetic radiation. In contrast with conduction and convection, heat transfer by radiation does not require the presence of a material medium. Hot Mitads radiate heat; to prove this, place a hand over not on the surface of the baking Mitad and feel the heat radiating from its surface. Dark surfaces typically radiate more heat than lighter ones because dark surfaces absorb more heat energy to begin with. Radiation is the transfer of heat energy from surface of the Mitad to the ambient or to the product [33].

$$Q_r = \varepsilon A_p \sigma \left({T_{bs}}^4 - {T_{lc}}^4 \right) \quad 2.9$$

Where: Q_r=Heat transferred by radiation *(W)*

ε =Emissivity of the surface

A_p= Surface area of the Mitad *(m^2)*

σ = Stefan-Boltzmann constant *($W/m^2.K^4$)*

T_{bs}= Baking surface temperature *(K)*

T_{lc} = Temperature of the lid cover *(K)* and

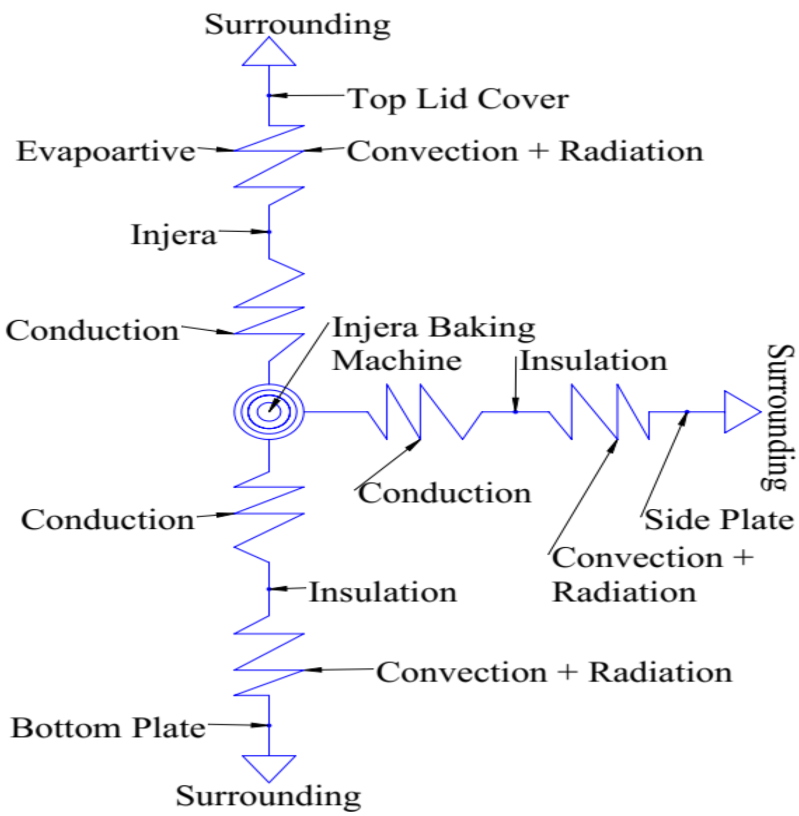

Figure 2.10 Heat Transfer Mechanism of Injera Baking Mitad with Electric Power Source

2.8 Insulation and Insulating Materials

Using insulation helps for energy conservation, personnel protection and comfort, maintaining process temperature, reducing temperature variation and fluctuations, fire protection, reducing noise and vibration. There are wide varieties of insulation materials available in the market, but most are primarily made of fiberglass, mineral wool, polyethylene, foam, or calcium silicate. The values of conductivity of gypsum plasterboard at very high temperatures and specific heat have been modified to some extent in the calibration of the heat transfer model. Conductivity was increased substantially at higher temperatures to allow for ablation. The 1947 Guide lists a thermal conductivity of 0.20 *W/m.K* for gypsum board at a density of 1005 kg/m^3, based on tests at the Armour Institute of Technology, provides a correlation for the conductivity of gypsum as a function of density ρ [34]:

$$k = 0.025 \exp\left(0.08\rho^{1/2}\right) \qquad 2.10$$

Where: ρ = Density of the insulation in (kg/m^3)

k = Thermal conductivity of the insulation in *(W/m.K)*

Generally, a substance, which has lower thermal conductivity than the other, can be used as insulation of the system. For instance, fired clay, primitive dried clay and clay brick can be used as good insulation for high thermal conductivity of metals for 50-250 *kW/m.K*.

2.9 Summary of the Literatures Review

On reviewing the literature, to gain an insight to the area of interest, background, influencing regulations and research. The Injera baking Mitad has been improved over the decades from the open fire to the electric Injera baking Mitad with improving its efficiency of energy utilization. That means the conversion efficiency of the supplied energy source to heat energy for baking is increased. In order to do that, improvement is started from three-stone open fire to Mirt Injera baking Mitad by enclosing the heat-supplying area, and by using the insulating material. For conserving the environment, the open fire Injera baking Mitad is improved to biomass type Injera baking Mitad, which replaces the firewood by biomass energy sources with more energy utilization efficiency. Additionally, the solar and electric powered Injera baking Mitad were used by harnessing the solar energy and electric power, respectively. In the case of the conventional electric baking Mitad, non-uniformity of heat distribution likely occurs because of the inaccuracy of the manufacturing process and heating element embedded to the Mitad. Additionally there is no improvement on the material property of the Injera baking Mitad, which is clay type. Generally, there is requirement of improving the thermal property of the material, uniform temperature distribution and the time it takes for initial heating.

CHAPTER THREE

THERMO-PHYSICAL PROPERTIES OF INJERA

This chapter gives brief description on the thermo-physical properties of Injera and Injera making process.

3.1 Thermo-physical Properties of Injera

Knowing the thermal and physical (thermo-physical) properties of foods are important for modeling and optimization of processes involving heating or cooling. The properties used in a mathematical model of heat transfer are usually thermal conductivity, specific heat, and density. An improved knowledge of these thermo-physical properties of foods is essential for accurate predicting of temperature changes, process duration, and energy consumption during processing. Among these properties, specific heat and density are significant in analyzing mass energy balances. Thermal conductivity is the key property in determining the rate of thermal energy transfer within a material by conduction. The combination of these three properties, thermal conductivity, specific heat, and density gives thermal diffusivity, is a key property in the analysis of transient heat transfer. In the past years, much research have been involved to determine thermo-physical property of different foodstuffs: soybean [35], chickpea [36], bread dough [37, 39], and Indian flat bread (chapatti) [40], are some of them.

The thermo-physical properties of a food depends on the temperature, the material chemical composition i.e. carbohydrate, fat, protein, ash, fiber and water contents, and physical structure. Since foodstuffs are composite materials, it is apparent that the relevant information is the average value.

Moreover, thermo-physical properties of foodstuffs can be obtain experimentally or using analytical methods based on composition. The analytical method uses composition data in conjunction with temperature dependent mathematical models of the thermal properties of individual components. The percentage composition of the major components of fermented cereals is given in the FAO Report [41]. The percentage composition of Teff Injera taken from the FAO Report is shown in figure 3.1.

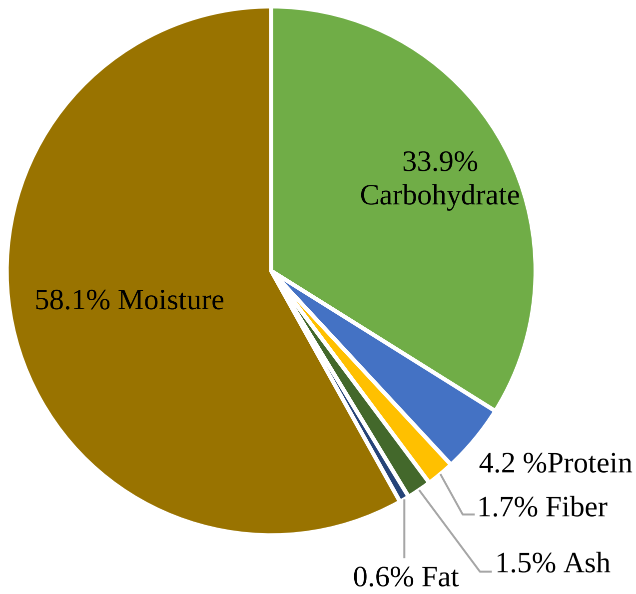

Figure 3.1 Percentage Composition of Injera [41]

3.1.1 Specific Heat Capacity

The specific heat of foodstuff is defined as the quantity of thermal energy associated with a unit mass of the food and a unit of change in temperature. This thermo-physical property is often referred to as heat capacity and is an essential component of a thermal energy analysis on a food product, a thermal process, or processing equipment used for heating or cooling of a food. Specific heat capacity depends on the nature of the heat addition process in terms of either at constant pressure or at constant volume. However, since pressure change in heat transfer problems of food materials are usually very small, the specific heat at constant pressure is most often considered [42−43].

Specific heat is the ratio of heat lost or gained to temperature change for a unit mass.

$$c_p = \frac{Q}{m\Delta T} \qquad 3.1$$

Where: c_p = Specific heat capacity *(J/kg.K)*

Q = Heat loss or gained *(J)*

ΔT = Temperature change *(K)*, and

m = Mass of the food *(kg)*

Previously, different empirical equations have been proposed by different researchers to determine specific heat.

Choi and Okos (1986) [44] gave a more generalized equation for specific heat, which takes into account the composition of food as [42, 45]:

$$c_p = 4180x_w + 1711x_p + 1928x_f + 1547x_c + 0.908x_a \qquad 3.2$$

Where: *x*=mass fraction of each component, and the subscripts are, *w=water, p=protein, f=fat, c=carbohydrate, and a=ash.*

Iradyarai (2002) [46] suggested an additional dimension of the dependence of the specific heat on composition:

$$c_p = 4187x_w + 1549x_p + 1675x_f + 1424x_c + 0.837x_a \qquad 3.3$$

Gupta suggested the following equation to determine the specific heat of food products as a function of temperature and water content in a range of 303−336 K and in a moisture content range of 0.1−80 % [40].

$$c_p = 2477 + 2356\, x_w + 3.7\, T \qquad 3.4$$

Choi and Okos [44] published a more comprehensive model for the prediction of specific heat of food.

$$c_p = \sum_{j=1}^{n} x_j\, c_{pj} \qquad 3.5$$

$$= x_w c_{pw} + x_p c_p + x_f c_{pf} + x_c c_{pc} + x_a c_{pa} + x_{fib} c_{pfib}$$

Where: c_p= Specific heat capacity *(J/kg.K)*

c_{pj}= Specific heat capacity of the components of the food *(J/kg.K),* and

x_j= Percentage composition of the components

Empirical equations used for the determination of the specific heat of the major components of a food c_{pj} are given in Table 3.1, which is taken from [42, 46−47].

Table 3.1 Models of Specific Heat for Major Components of Foods [42, 46−47]

Components	Equations
Fiber	$c_p = 1.8459 + 1.8306\times10^{-3}\,T - 4.6509\times10^{-6}\,T^2$
Fat	$c_p = 1.9842 + 1.4733\times10^{-3}\,T - 4.8008\times10^{-6}\,T^2$
Carbohydrate	$c_p = 1.5488 + 1.9625\times10^{-3}\,T - 9.399\times10^{-6}\,T^2$
Protein	$c_p = 2.0082 + 1.2089\times10^{-3}\,T - 1.3129\times10^{-6}\,T^2$
Ash	$c_p = 1.0926 + 1.8896\times10^{-3}\,T - 3.6817\times10^{-6}\,T^2$
Water/moisture	$c_p = 4.1762 - 9.0864\times10^{-5}\,T + 5.4731\times10^{-6}\,T^2$

Based on the above model the specific heat capacity of Injera batter as function of temperature will be determined by taking the individual composition with the specific heat of compositions model:

$$c_p = \sum_{j=1}^{n} x_j\, c_{pj} = 3095.4 + 7.3158 * 10^{-4}\, T + 9.4806 * 10^{-7}\, T^2$$

This equation implies the specific heat capacity value depends on the average Injera baking temperature. The variation with baking temperature shown below in figure 3.2 and for average Injera baking temperature the specific heat capacity becomes 3095.96 $J/kg.K$.

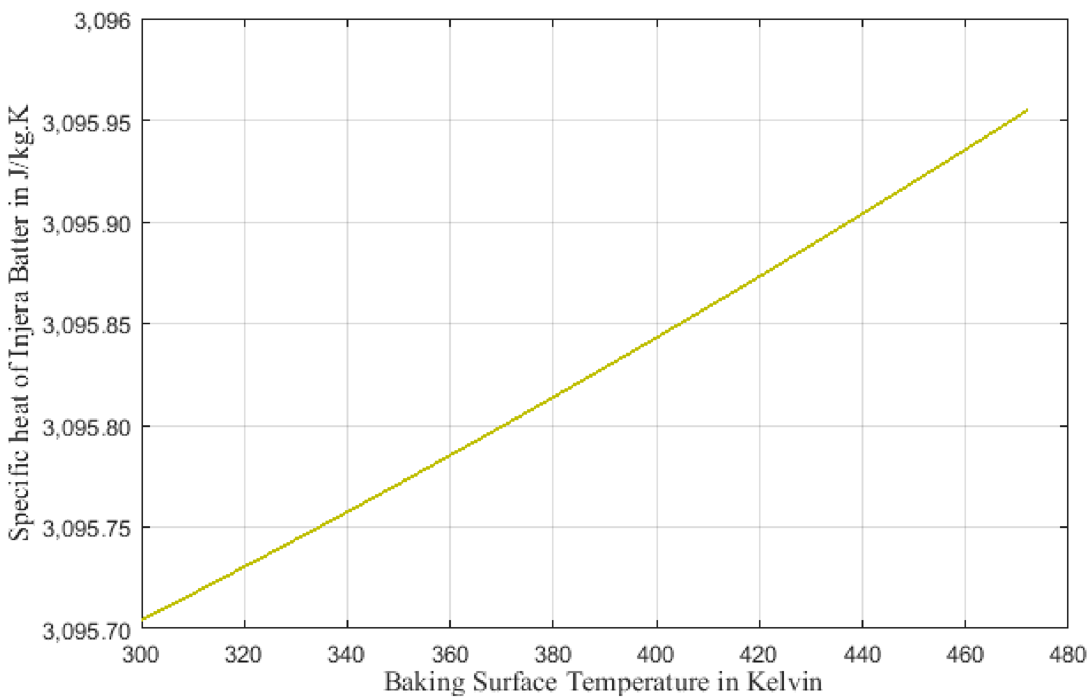

Figure 3.2 Specific Heat of Injera Batter with Baking Surface Temperature Variation

3.1.2 Thermal Conductivity

Thermal conductivity of a food is the quantity of heat that flows per unit time through a food of unit thickness and unit area having unit temperature difference. Thermal conductivity can be either determined experimentally or through mathematical estimation. A simplified approximation for thermal conductivity is given as [42, 48−50]:

$$k = \frac{\dot{Q}x}{A\Delta T} \tag{3.6}$$

Where: k= Thermal conductivity *(W/m.K)*

$\dot{Q}$= Rate of heat input *(W)*

x = Material thickness parallel to heat flow *(m)*

ΔT= Temperature change (*K*), and

A= Contact area normal to direction of heat flow *(m^2)*

A number of physical models have been proposed to predict thermal conductivity of foods. The most common models are those assuming that different components are arranged in layers either parallel or normal to the heat flow, resulting in the following expressions based on the electric analogy of heat transmission [47].

Series model:− in this model, layers of components placed normal to the heat flow, in a series arrangement of resistances and the effective thermal conductivity can be calculated as follows:

$$k = \frac{1}{\sum_{i=1}^{n} \varepsilon_i / k_i} \tag{3.7}$$

Where: k= Thermal conductivity (*W/m.K)*

ε_i= Volume fraction of i^{th} component phase *(m^3)*, and

k_i= Thermal conductivity of i^{th} phase *(W/m.K)*

Parallel model: − in this model, layers of components are placed in the direction of the heat flow, in parallel arrangements of resistances. The effective thermal conductivity is given by:

$$k = \sum_{i=1}^{n} k_i \varepsilon_i \tag{3.8}$$

The volume fractions can be calculated from the mass fractions x_i and intrinsic densities ρ_i as:

$$\varepsilon_i = \frac{x_i/\rho_i}{\sum_{i=1}^{n} x_i/\rho_i} \tag{3.9}$$

Where: ε_i= Volume fraction of each food composition *(m^3)*

ρ_i= Density of each food composition *(kg/m³)*, and

x_i= Mass or weight fraction of each food composition

An empirical relation for the determination of thermal conductivity of major components of foods is given in Table 3.2.

Table 3.2 Models for Thermal Conductivity of Major Components of Foods [47]

Components	Equations
Carbohydrate	k = 0.20141+1.3874×10^{-3} T−4.3312×10^{-6} T^2
Ash	k = 0.32962+1.4011×10^{-3} T−2.9069×10^{-6} T^2
Fiber	k = 0.18331+1.2497×10^{-3} T−3.1683×10^{-6} T^2
Fat	k = 0.18071+2.7604×10^{-3} T−1.7749×10^{-6} T^2
Protein	k = 0.17881+1.1958×10^{-3} T−2.7178×10^{-6} T^2
Water	k = 0.57109x_w+1.7625×10^{-3} x_wT−6.7036×10^{-6} x_wT^2

Table 3.3 Estimation of Volume Fraction of Major Components of Injera

Components	Composition (%), x_i	Density (kg/m^3), ρ_i	x_i/ρ_i	$\varepsilon_i = \frac{x_i/\rho_i}{\sum_{i=1}^{n} x_i/\rho_i}$
Carbohydrate	0.339	1582.025	2.14×10^{-4}	0.248
Ash	0.015	2408.365	6.23×10^{-6}	0.00723
Fiber	0.017	1291.376	1.32×10^{-5}	0.015
Fat	0.006	902.624	6.65×10^{-6}	0.00772
Protein	0.042	1301.388	3.23×10^{-5}	0.03748
Moisture	0.581	985.987	5.89×10^{-4}	0.68353
$\sum$			8.617x10^{-4}	

By using the parallel model and applying temperature dependent empirical equations as shown in table 3.2. It is simple to evaluate thermal conductivity of the major components as shown in table 3.4.

Determination of thermal conductivity of major components for the parallel model, the sum of individual component thermal conductivity is about:

$$k = \sum_{i=1}^{n} k_i \varepsilon_i = 0.0631 + 0.57109\, x_w + 4.299\text{x}10^{-3}\,\text{T} + 1.7625\text{x}10^{-3}\, x_w T - 1.2459\text{x}10^{-6}\,\text{T}^2 + 6.7036\text{x}10^{-6}\,\text{T}^2\, x_w$$

This implies the thermal conductivity depends on the average baking temperature and moisture content, up on substituting the average values the thermal conductivity is 0.7610 *W/m.K.*

By following the same procedure, the thermal conductivity for the series model can be calculated using the average baking temperature and average moisture content.

Table 3.4 Estimation of Thermal Conductivity of Major Components of Injera

Components	Composition (%) x_i	$\varepsilon_i = \frac{x_i/\rho_i}{\sum_{i=1}^{n} x_i/\rho_i}$	k_i	$\frac{\varepsilon_i}{k_i}$ *(m.K/W)*
Carbohydrate	0.339	0.24800	0.38466	0.6447
Ash	0.015	0.00723	0.49789	0.0145
Fiber	0.017	0.01500	0.36346	0.0413
Fat	0.006	0.00772	0.29636	0.026
Protein	0.042	0.03748	0.35358	0.106
Moisture	0.581	0.68353	0.69775	0.9796
$\sum$				1.7794

Therefore, thermal conductivity for the series model is about 0.562 *W/m.K.*

According to the literatures, any value between the series and the parallel model can be used as the thermal conductivity of the food, i.e**.** *0.562 <k< 0.7610 W/m.K.*

3.1.3 Density

Density is the ratio of mass to volume of a material. Density of food products is an important property in analyzing food-processing operations. Density is closely related to porosity and moisture content of food. The structure of food materials can be characterized by density (apparent and true), porosity, specific volume, particle density shrinkage and so on. Among these, density and porosity are the most common structural properties.

Apparent density (ρ_{ap}): concerns powdered and porous materials and it is determined by the mass of the sample and its apparent volume.

$$\rho_{ap} = \frac{m_t}{v_t} \quad 3.10$$

Where: m_t = Total mass *(kg)* and

v_t = Total volume of the sample including the pores *(m^3)*

True density (ρ_T), is the density excluding all pores and it is determined by the mass of the sample and its true volume.

$$\rho_T = \frac{m_t}{v_p} \quad 3.11$$

Where: $v_p = v_s + v_w$ *(m^3)*, is the total volume of the sample excluding pores (volume of dry solids and water).

Density is an intensive property it depends directly on the mass fractions of the major components of the food and can be found from [47, 51−52].

$$\rho = \frac{1}{\sum_{i=1}^{n} x_i/\rho_i} \quad 3.12$$

Where: ρ = Density of the product *(kg/m^3)*

ρ_i = Density of each food composition *(kg/m^3)* and

x_i = Mass or weight fraction of each food composition

An empirical relation for the determination of density of major food components as a function of temperature is given in Table 3.5.

Table 3.5 Models for Density of Major Components of Foods [47, 51−52]

Components	Equations
Carbohydrate	$\rho = 1.5991\times10^{3} - 0.31046\ T$
Ash	$\rho = 2.4238\times10^{3} - 2.8063\ T$
Fiber	$\rho = 1.3115\times10^{3} - 0.36589\ T$
Fat	$\rho = 9.2559\times10^{2} - 0.41757\ T$
Protein	$\rho = 1.3299\times10^{3} - 0.51840\ T$
Water	$\rho = 997.18 + 3.1439\times10^{-3}\ T - 3.7574\times10^{-3}\ T^{2}$

Table 3.6 Estimation of Density of Major Components of Injera

Components	Composition (%), x_i	Density *(kg/m³)*, ρ_i	$\frac{x_i}{\rho_i}$
Carbohydrate	0.339	1582.025	2.14×10^{-4}
Ash	0.015	2408.365	6.23×10^{-6}
Fiber	0.017	1291.376	1.32×10^{-5}
Fat	0.006	902.624	6.65×10^{-6}
Protein	0.042	1301.388	3.23×10^{-5}
Moisture	0.581	985.987	5.89×10^{-4}
Σ			8.617×10^{-4}

Therefore, the density of Injera at the average baking temperature is about 1160.55 *kg/m³*.

3.1.4 Thermal Diffusivity

Thermal diffusivity indicates how fast heat propagates through a sample while heating or cooling. Thermal diffusivity is a parameter used in the heat transfer calculation by conduction. The rate at which heat diffuses by conduction through a material depends on the thermal diffusivity and can be defined as [30]:

$$\alpha = \frac{k}{\rho c_p} \tag{3.13}$$

Where: α = Thermal diffusivity *(m²/s)*

ρ = Density (*kg/m³*)

c_p = Specific heat capacity *(J/kg.K)*, and

k = Thermal conductivity *(W/m.K)*

Thermal diffusivity either can be determined by direct experiment or estimated from the thermal conductivity, specific heat, and density data. Based on the estimated values of the thermal conductivity, specific heat capacity, and density, the thermal diffusivity is about $1.53\text{x}10^{-7}$ *m²/s*.

3.2 Injera Making Processes

Injera is one of the most delicate food items to automate due to its characteristics that includes; "bubbly eye", circular flat geometry, very elastic, smooth back surface and a fluffy texture. Preparation of Injera is rather a long process relative to Ethiopian food preparation; it usually takes two to four days from mixing to baking. Injera can be produced from almost any staple grain, such as teff, sorghum, and millet being the most common in Ethiopia, Eritrea, and part of Somalia and Sudan. Simple Injera making process is described by using flow chart in figure 3.3.

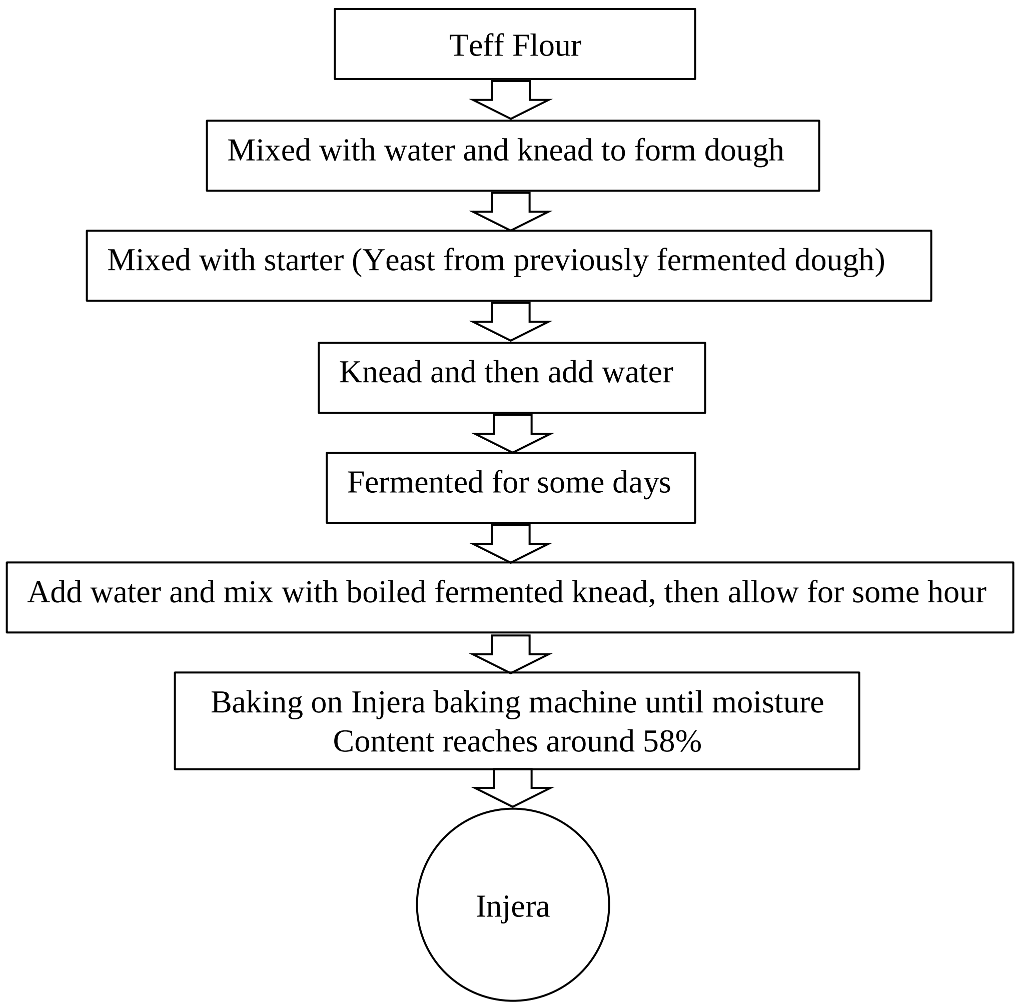

Figure 3.3 Flow Chart for "Teff" Injera Making Process

CHAPTER FOUR

DEVELOPMENT OF COMPOSITE MATERIAL

This chapter briefly describes the development of the composite material using clay soil and copper powder. The first part deals with the materials and methods of sample of the study and the second part deals with characterization and equipment used for testing the composite material.

The first experimental test performed for this study was to measure the thermo-physical properties of the composite material. The thermo-physical properties of composite material experiment were done in materials engineering department laboratory of ASTU.

4.1 Raw Materials

The raw materials used for preparation of baking plate are clay soil and copper powder. The clay soil was obtained from Gewassa Lege Tafo, in Oromia State. The copper powder were prepared from copper wire after grinding by using grinding Mitad. The reason why copper was selected is due to its good thermal conductivity characteristic and availability that distinguishes it from other metals; small amount of copper enhances the thermal property.

4.2 Methods

4.2.1 Preparation of the Clay Soil

To eliminate any traces of organic fiber, clay soil was placed in the drying oven until traces of organic fiber burns. Then, extracted from the oven and allowed to cool down. Finally, powdering it to increase the contact surface area during mixing with additive material, copper powder. The powdered clay soil and the copper powder is shown in the figure 4.1.

a) Prepared Clay Soil b) Copper Powder

Figure 4.1 Prepared Raw Materials

4.2.2 Preparation of the Composite Materials

The composite materials were prepared by mixing different weight concentrations of copper powder (20, 40, 50 g) with clay soil (160 g) at a rate of 60 ± 5 rpm for 10 minutes. Then, water was added (90 g) and mixed at a rate of 85 ± 10 rpm for 10 minutes. The mixture obtained were poured into standard sampling mold of 100 mm× 50 mm × 20 mm metallic mold.

Similarly, to study the thermal conductivity of clay without additive material, mixture of clay with water poured in to similar mold. The composite materials composition used to create a sample matrix is shown in Table 4.1.

Table 4.1 Composition of Composite Material

Sample Naming	Copper Powder (g)	Clay Soil (g)	Water (g)	Description
S_0	0	200	90	Clay
S_1	20	160	90	Composite
S_2	40	160	90	Composite
S_3	50	160	90	Composite

The molds containing the mixtures were left to dry at room temperature until it dry. Then, the composite materials extracted from the molds for characterization. The extracted samples displayed in figure 4.2.

Figure 4.2 Samples of Composite Material

4.3 Equipment

The following equipment are used for composite material property testing.

4.3.1 Quick Thermal Conductivity Meter

Quick thermal conductivity meter, QTM-500, does quick and easy measurement of all kinds and types of sample materials.

Principle of Measurement

The probe consists of single heater wire and thermocouple. When constant electric power is given to the heater, the temperature of the wire will rise in exponential progression. Temperature rising curve is plotted in linear line with time axis scaled in logarithm, as shown on display of figure 4.3. The angle of this line increases if the sample has less thermal conductivity, and decreases if it has higher thermal conductivity. Therefore, thermal conductivity of a sample can be determined from the angle of the rising temperature graphic line.

Figure 4.3 Principle of Measurement

4.3.2 Characterization

For this study, hot wire method for steady state heat flux measurement property was used. Figure 4.4 shows the experimental setup for measuring thermal conductivity, which consists of the following elements: Constantan heater wire and chromel-alumel thermocouple, three reference plates, samples of the composite materials, aluminum-cooling plate, mounting system, and the necessary mechanisms for tuning and measurement. The reference palates are Polyethylene, silicone rubber and clear quartz. Some of the most important specifications in the guideline of the equipment are as follows: the method must be applied to materials with thermal conductivities of up to 12 W/m.K and the temperature during the test must be kept between -100 to 1000 ℃. The other specifications in the guideline of the equipment are shown in Appendix H.

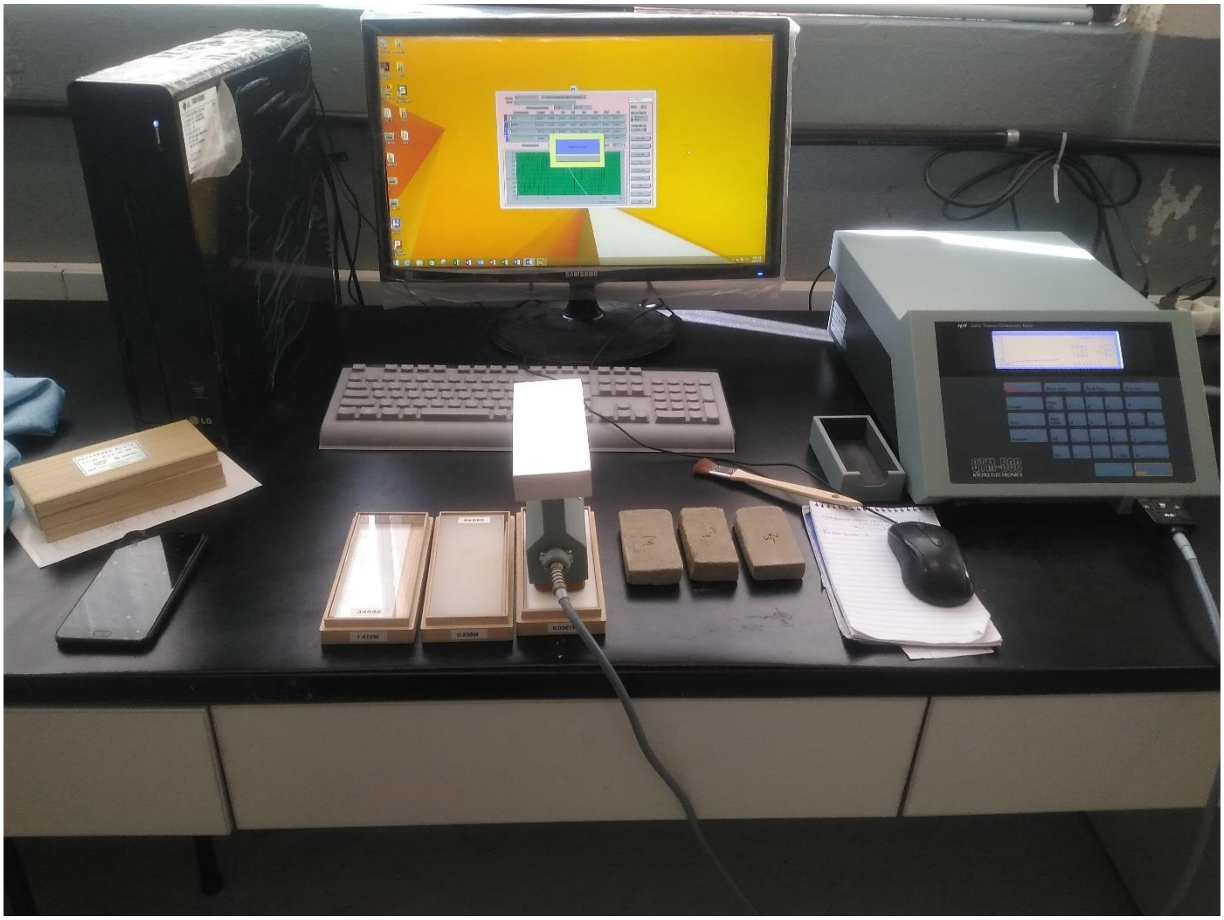

Figure 4.4 Experimental Set-up for Measuring the Thermal Conductivity

4.3.3 Results and Discussion for the Thermal Conductivity Measured

Table 4.2 Experimental Results of the Composite Material

Sample Naming	Thermal Conductivity *(W/m.K)*
S_0	0.5172 ± 0.02586
S_1	0.7204 ± 0.03602
S_2	1.0450 ± 0.05225
S_3	1.3760 ± 0.0688

At the testing temperature interval, all of the composite materials tested have higher thermal conductivities than the pure clay; the average values were in range of $0.7204 - 1.376$ W/m.K. It is known that thermal conductivity is the ability to transfer heat while the specific heat capacity is the ability to hold a particular amount of heat. Increasing the thermal conductivity of the composite material will decrease the specific heat capacity and for baking purpose, it is required having optimum specific heat capacity material. For this reason, 20% copper powder with 80% clay composition suits both thermal property requirement and it increases the clay thermal conductivity for more than 50%. Therefore, sample S_2 selected and used to prepare the electric Injera baking Mitad material.

CHAPTER FIVE

DESIGN MANUFACTURING AND RELIABILITY TESTING OF AN ELECTRIC INJERA BAKING MITAD

This chapter briefly describes the manufacturing process of an electric Injera baking Mitad with the respective parts design. It also compresses the reliability testing of the baking Mitad.

5.1 Design and Manufacturing of a Baking Plate

5.1.1 Design of a Baking Plate

A baking plate is a flat and circular plate commonly about 550 to 600 mm in diameter and traditionally used over large clay hearths to bake Injera [55]. The baking plate used in this case was 10 mm thick and 580 mm diameter of composite material with similar ratio of selected sample. In addition to additive material used thickness of plate is reduced, which gives high thermal conductivity than the one, which is available in the local market.

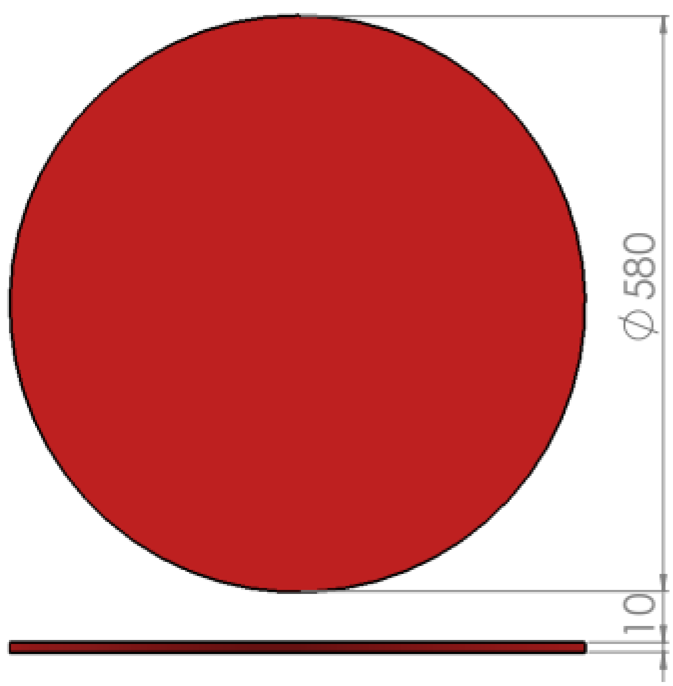

Figure 5.1 Dimensions of Baking Plate

5.1.2 Manufacturing of a Baking Plate

The manufacturing process of baking plate briefly described with the following steps.

Step 1: Developing the Composite Material and Mixing

Using similar ratio with the selected sample, mixing the clay with the copper powder in order to develop the composite material. Then, mixing the composite material with water and allowing it until it develops plastic property.

Step 2: Shaping

The excess water is squeezed out to make a moisture content for about 20%, then shaping to desired dimension follows, 580 mm diameter with effective diameter of 550 mm and 10 mm thickness.

Step 3: Drying, Smoothing and Painting

Then allow it to dry slowly, during the stage it will lose all of the water except that which is bound up in crystal lattices. Using iron sheet and emery-paper smoothing the baking, sides and bottom surfaces, and shaping the effective baking diameter. Then, painting follows by using the locally named "Wole'lla Mineral", which is a type of colored clay dye. The purpose of this clay mineral is to develop smooth and no-stick surface. Its effect of developing smooth surface is observed after heating the painted composite mineral plate in high temperature as shown in figure 5.2b.

Step 4: Heating the Plate in High Temperature

Finally, firing the dried composite material plate in high temperatures. Firing at high temperature serves to substantially reduce the number of pores, to increase the density, and to bond together.

a) Shaping of the Composite Material b) Baking Surface After Firing

Figure 5.2 Shaping, Smoothing, Painting and Firing of the Composite Material

5.1.3 Design and Manufacturing of Lid Cover

Lid cover helps to protect heat loss from Injera during baking process. Lid cove manufactured from aluminum with the following dimensions. The material selection criterial is depending on the suitability of aluminum for food preparation utility.

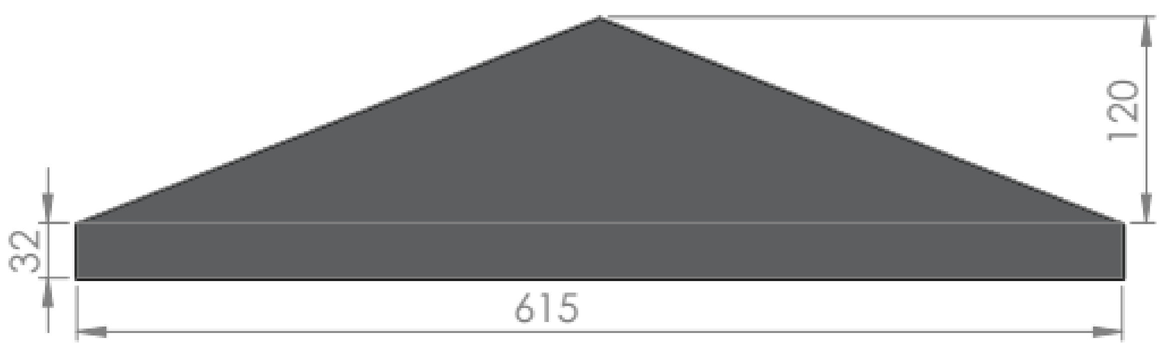

Figure 5.3 Dimensions of Lid Cover

5.1.4 Design and Manufacturing of Casing

The casing of the Mitad used to support the insulated baking plate after emending of the heating element with insulating material gypsum and fiberglass.

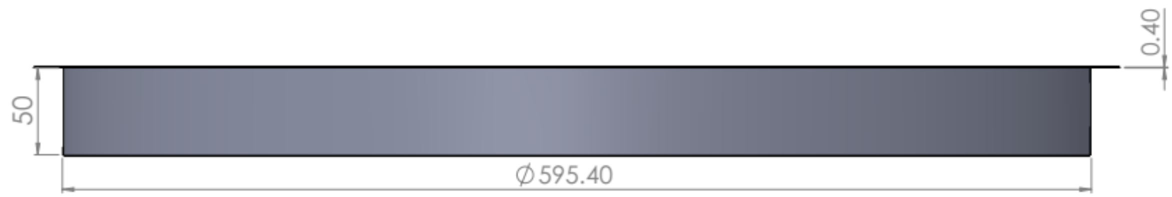

Figure 5.4 Dimensions of Casing

5.1.5 Design and Manufacturing of Supporting Stand

For supporting the whole weight of Mitad, four supporting stands were welded to support ring of the baking Mitad assembly as shown in the figure bellow.

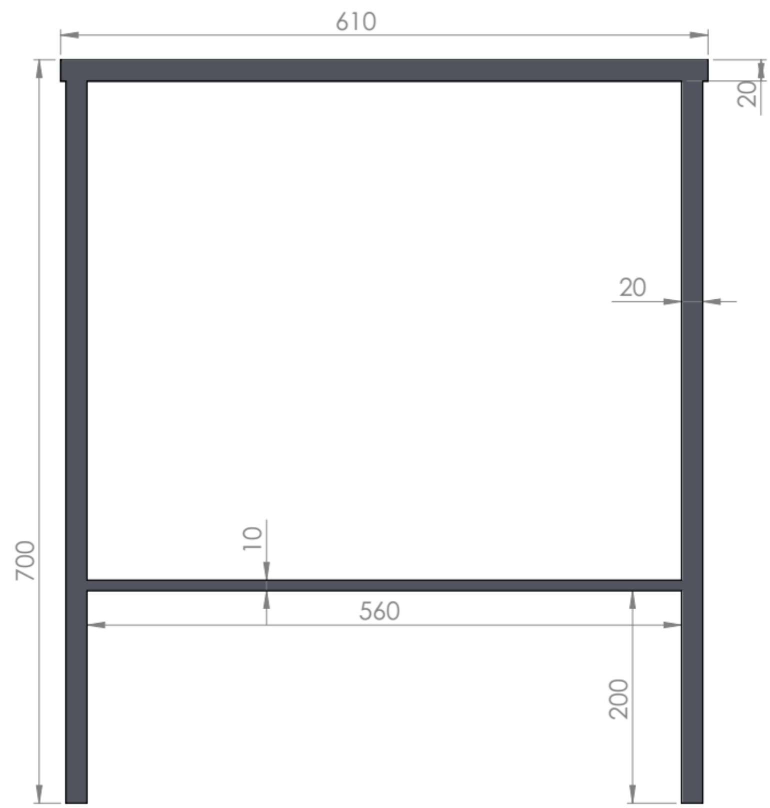

Figure 5.5 Dimensions of Supporting Stand

5.2 Assembly of an Electric Injera Baking Mitad

An assembly of an electric Injera baking Mitad carried using the following steps.

Step 1: Grooving the Bottom Surface of the Baking Plate for Embedding the Heater

In order to input power to the baking Mitad R09 (thickness of Nicrome wire = 0.9 mm) type Nicrome resistance wire is used, which is commonly used for Injera baking Mitad. For this research work two R09 of each rated with 1500W capacity and 700 mm length was used. Then, it tightly connected at one end and then the wire is uniformly stretched to a length that fit in the grove space provided at the bottom surface of the composite material. This type of arrangement uniformly distribute 3000 W power over the groove space provided.

Step 2: Insulating the Baking Mitad

The Nicrome coil wire as heating element embedded in the grooved space at backside of the composite material and sealed with composite material, gypsum, and fiberglass. The gypsum and fiberglass are used as insulating material to prevent bottom and side losses. Then, allowed to dry before assembling to the casing.

a) Grooving and Embedding Nicrome wire b) Insulating with Gypsum

Figure 5.6 Grooving, Embedding Nicrome wire and Insulating of the Composite Material

Step 3: Assembly of the Baking Mitad

Using the manufactured supporting stand and the casing the insulating gypsum and fiberglass placed on their positions as shown in figure 5.7. Then, the baking plate placed over the insulation with prepared ring and mounting the lid cover. Finally, using the switches and electric wire the final assembly of an electric Injera baking Mitad carried out. The three dimensional assembly also given in appendix I.

a) Casing

b) Fiber Glass Insulation in the Casing

c) Assembling

d) Final Assembly

Figure 5.7 Assembly of the Baking Mitad

Step 3: Surface Preparation of the Baking Mitad

Surface preparation of baking Mitad was required to create a smooth, no-stick and thermal stress free baking surface. Primarily a layer of vegetable oil was lay on the baking surface of baking Mitad and heated until the vegetable oil was burned and creating a black organic blacktop. During these process, the thermal stress relief by filling the gaps and porosity, which helps to prevent cracking. Then, after the surface was, smoothed and hardened, the traditional crushed oil seed “Gomenzer”, was burnt on the heated surface, and the burning seeds are rubbed into the surface to create the final smooth no-stick coating.

5.3 Reliability Test of the Baking Mitad and Quality of Injera

The reliability of the improved baking Mitad was checked by baking Injera using the prepared batter. The temperature of baking surface is about 200 ℃ to start baking process. Commonly mothers use “Gomenzer” on the baking surface to check whether it is ready or not for baking. If the “Gomenzer” on the baking surface starts burning, they start baking. The concept of baking surface temperature may be observed from their conception. Once the baking started, the temperature of the baking surface starts varying with pouring the batter and removing the Injera. The average time it takes for baking each Injera was about 100 seconds with 50 seconds gap between successive Injera. The gap time between successive Injera is related with accessibility of batter and utilities. The electrical shock test was checked during the baking process; because of the additive material used, and it was free from any shocking. Since thick painting was used before heating at high temperature during manufacturing of the baking Mitad.

The quality of Injera baked on the improved baking Mitad was the same as the conventional baking Mitad.

5.4 Thermo-Physical Property of Injera Baking Mitad Parts

The thermo-physical property of Injera baking Mitad plate: thermal conductivity, specific heat capacity and density were determined by using different laboratory equipment and tabulated in table 5.1. The dimensions of the baking plate, thickness of insulating materials and others were measured using different instruments like tap-meter, caliper and digital mass balance and others. Other parameters and properties are taken from literatures [18−19]. Most of the dimensions of the baking plate are similar with the conventional electric Injera baking machines which available in the market.

These properties and parameters are used for energy analyses calculations.

Table 5.1 Thermo-Physical Property of Injera Baking Mitad

Baking Mitad Parts	**Numerical Values**	**SI Unit**
Baking Mitad plate thickness	0.010	*(m)*
Baking Mitad plate diameter	0.580	*(m)*
Baking Mitad plate effective diameter	0.550	*(m)*
Entire diameter of the baking Mitad	0.640	*(m)*
Thermal conductivity of baking Mitad plate	1.045	*(W/m.K)*
Specific heat capacity of baking Mitad plate	790	*(J/kg.K)*
Density of baking Mitad plate	3304	(kg/m^3)
Thermal conductivity of supporting plate	43	*(W/m.K)*
Thickness of supporting plate sheet	0.0006	*(m)*
Emissivity of baking surface of the plate	0.94-0.97	
Emissivity of each sides	0.240	
Emissivity of the lid cover	0.300	
Specific heat capacity of lid cover	756	*(J/kg.K)*
Thickness of fiberglass used for insulation	0.0025	*(m)*
Thermal conductivity of fiberglass used for insulation	0.046	*(W/m.K)*
Thickness of gypsum used for insulation	0.030	*(m)*
Thermal conductivity of gypsum used for insulation	0.15	*(W/m.K)*
Mass of the baking Mitad plate	6.4	*(kg)*

CHAPTER SIX

EXPERIMENTAL TEST AND ENERGY ANALYSIS OF ELECTRIC INJERA BAKING MITAD

This chapter deals with the experimental set-up of two conditions with no load and with load, i.e. without baking and during baking, respectively and energy analysis. The first section deals with experimental testing and equipment used. The second section deals on the energy analysis including consumptions, utilizations and losses.

6.1 Experimental Test

The experimental testing of an electric Injera baking Mitad was performed in thermo-fluid laboratory of ASTU. The following equipment were used for experimental testing of the Injera baking Mitad, for collecting data's during the initial heating and baking processes.

6.1.1 Infrared Thermometer, Thermocouple and Multi meter

Infrared thermometer was used to measure the baking surface temperatures of Injera baking Mitad and room temperature. Additionally, 'K' type thermocouples were used to measure the temperatures of top lid cover, bottom casing surface and side of the baking Mitad. Whereas, the multi meter was used to measure the current flow, and voltage. These parameters help for energy analysis of the baking Mitad.

*6.1.1.1 Positions of Infrared Thermometer and Thermocouple*s

The temperature profile was taken in two conditions: with no load and with load condition. It will be located at the:

- ✓ Center of the baking surface
- ✓ 13 cm away from the center of the baking surface
- ✓ 26 cm away from the center of the baking surface

The upper surface positions for with no load condition helps to analyze the initial required time for heating up, heating rate and temperature distribution. Whereas, the lower surface positions with a load and with no load helps for energy consumption analysis.

For energy consumption analysis additional positions are required, these are:

- ✓ At the center tip of the Aluminum lid cover
- ✓ At the sides of the baking Mitad

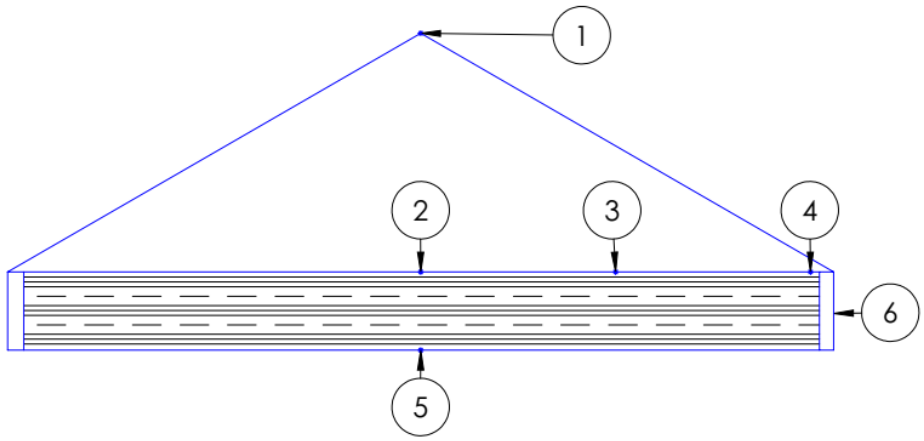

Figure 6.1 Positions of Thermocouple and Infrared Thermometer on Baking Mitad

Thermocouples were used for position 1, 5 and 6 to measure the temperatures of lid cover, bottom casing surface and side of the baking Mitad respectively. Additionally, infrared thermometer were used for position 2, 3 and 4 to measure the temperature of the baking surface at the center, 13 cm and 26 cm away from the center of the baking Mitad respectively.

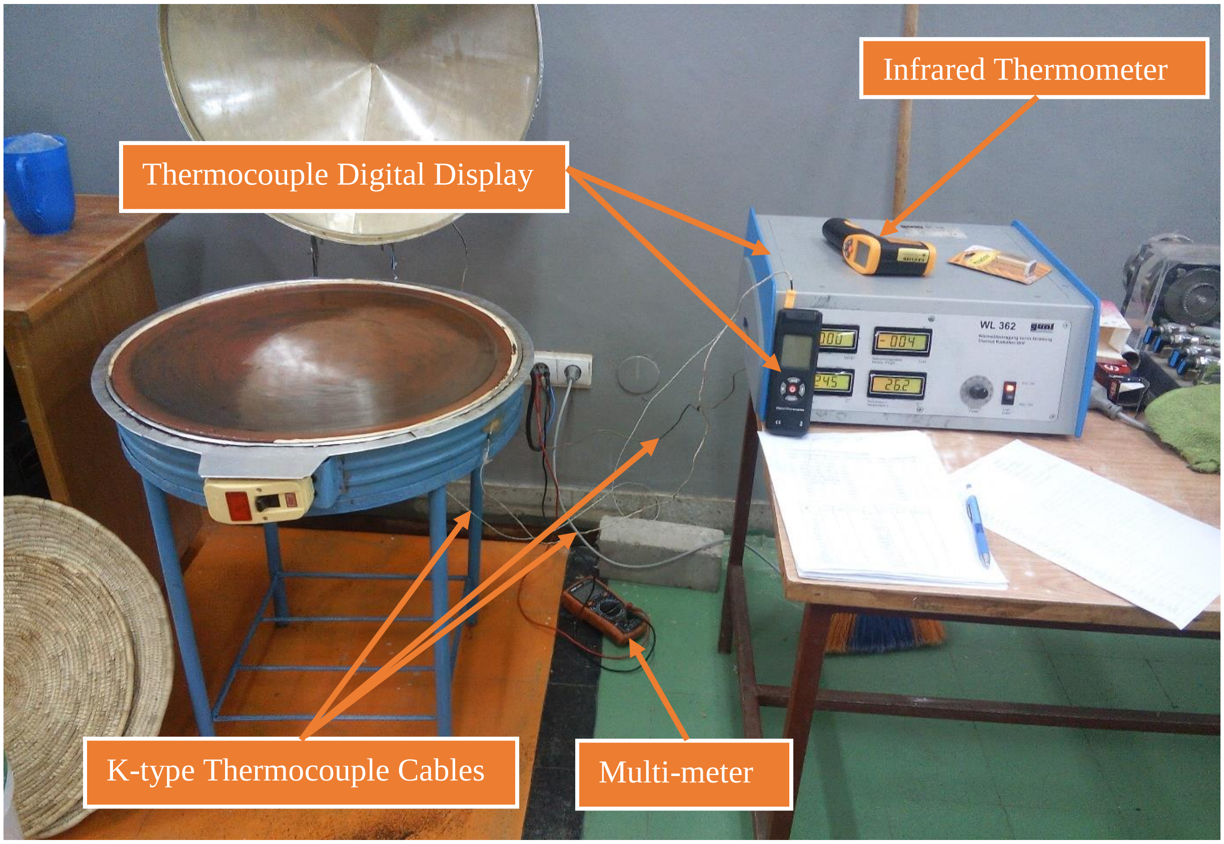

Figure 6.2 Infrared Thermometer, Thermocouples and Multi-meter in Experimental Set-up

6.1.2 Digital Mass Balance

Digital mass balance was used for measuring the mass of batter ready for baking and baked Injera. Objects to be weighed are placed on the balance pan and the mass noted from the digital display. Zero key used to reset the readouts before weighing an object. The measured values of the batter and Injera is tabulated in table 7.1. The average weigh of the batter was about 0.6 kg and the product, Injera obtained was 0.45 kg, about 0.15 kg of water evaporated during the baking.

6.2 Heat Transfer Features of Injera Baking Mitad

Heat can be transferred in three different modes: conduction, convection, and radiation. All modes of heat transfer require the existence of a temperature difference, and all modes transfer heat from the high-temperature medium to a lower-temperature one. In the case of Injera baking

Mitad, all modes of heat transfers are there in all directions of the Mitad. Those are through top surface, bottom surface and sideways of the baking Mitad, which energy dissipates to the environment. During baking, the bottom surface of Injera is heated by conduction through the baking surface of baking Mitad and heat is given off from Injera at the top surface to the surrounding by convection and radiation. Therefore, the energy transferred to Injera is the only useful energy used to bake the Injera and the other energy transfer is lost energy.

6.2.1 Heat Transfer Analysis for Injera Baking Mitad

The heat source of electric Injera baking Mitad is the current flow through Nicrome coil wire that inserted at bottom surface of the baking Mitad as heating element.

6.2.1.1 Heat Transfer from Baking Surface

During the baking process heat transferred from baking surface of the baking Mitad to the lid cover and surrounding through convection and radiation, respectively. The transferred heat through convection and radiation is lost heat. To determine the lost energy it required to know their heat transfer coefficients.

Heat Transfer from Baking Surface of the Baking Mitad to the Lid Cover:

For free convection heat transfer the Nusselt number relates the Rayleigh number and other parameters. In addition to that, the Nusselt number is defined as function of Rayleigh number, prandtl number, geometric shape and boundary condition. The air properties are used at film temperature in order to determine the convective heat transfer coefficient between baking surfaces of the baking Mitad to the lid cover, air properties are tabulated at Appendix C:.

Rayleigh number (Ra) given as follows [18−19, 30, 52−53]:]:

$$R_a = \frac{\beta \Delta T g l^3}{v^2} Pr \qquad 6.1$$

Where, β = Volumetric expansion coefficient *(1/K)*

ΔT = Change in temperature between T_{bs} and T_{∞} *(℃)*

g = Gravitational constant *(m/s²)*

l = Characteristic length *(m)* and given by l = 0.9D, D= Diameter of baking Mitad plate

Pr= Prandtl number

v = Kinematic viscosity *(m^2/s)*

The Nusselt number for horizontal plate and uniform surface temperature for the calculated interval, the recommended correlation for the heated top surface is given as follows [30, 52−53]:

$$N_u = 0.14(R_a)^{1/3} \text{ for } 2*10^7 < R_a < 3*10^{10} \quad 6.2$$

Convective heat transfer coefficient from the baking surface to the lid cover is given by [30, 52−53]:

$$h_{cvbc} = N_u \frac{k}{l} \quad 6.3$$

Where, Nu = Nusselt number

k = Thermal conductivity of evaporated water *(W/m.K))*

Using similar procedure the convective heat transfer coefficient from the lid cover the surrounding, h_{cvbc} calculated.

The radiative heat transfer coefficient from the baking surface to lid cover is given by [30, 52−53]:

$$h_{rbc} = \varepsilon\delta \frac{{T_b}^4 - {T_{tc}}^4}{T_b - T_{tc}} = \varepsilon\delta({T_{bs}}^2 + {T_{lc}}^2)(T_{bs} - T_{lc}) \quad 6.4$$

Where; ε =Emissivity of the surface

δ =Stefan Boltzmann constant *($W/m^2.\ K^4$)*

T_{bs} = Baking surface temperature *(K)*

T_{lc} = Lid cover temperature taken from the measured data *(K)*

Using similar procedure, the radiative heat transfer coefficient from lid cover to the surrounding, h_{rcs} calculated.

6.2.1.2 Heat Transfer from Bottom Surface

Heat transfer through this surface is by conduction through the insulation to the plate casing and consequently by convection and radiation from the bottom casing surface to the surrounding. Overall heat transfer coefficient could be simply calculated by using thermal resistance concept:

$$U_{bt} = \left[\frac{t_{gyp}}{k_{gyp}} + \frac{t_{fg}}{k_{fg}} + \frac{t_p}{k_p} + \frac{1}{h_{bt}}\right]^{-1} \quad 6.5$$

Where, U_{bt} = Overall heat transfer coefficient from bottom surface to surrounding *(W/m²·K)*

k = Thermal conductivity of material *(W/m.K)*

h_{bt} = Sum of convective and radiative heat transfer coefficient from bottom surface to surrounding ($W/m^2.K$)

t = Thickness of materials *(m)* with subscript *gyp*, *fg* and *p*, gypsum, fiberglass insulation material and casing surface plate, respectively.

The convective and radiative heat transfer coefficients are calculated in similar way as baking surface.

6.2.1.3 Heat Transfer from Side

The energy lost from the side of the baking Mitad may be calculated using similar procedure with the bottom surface. The overall heat transfer coefficient could be simply calculated by using thermal resistance concept:

$$U_s = \left[\frac{t_{bm}}{k_{bm}} + \frac{t_{fg}}{k_{fg}} + \frac{t_p}{k_p} + \frac{1}{h_s}\right]^{-1} \quad 6.6$$

Where, U_s= Overall heat transfer coefficient from side to the surrounding *($W/m^2.K$)*

k = Thermal conductivity of material *(W/m.K)*

h_s= Sum of convective and radiative heat transfer coefficient from side to surrounding ($W/m^2.K$)

t = Thickness of materials *(m)* with subscript *bm*, *fg* and *p*, baking Mitad plate, fiberglass insulation material and casing surface plate, respectively.

Using the above heat transfer coefficients the energy lost during the baking process calculated and the result tabulated in table 5.3. The calculation part shown in Appendix E.

6.2.2 Heat Losses from the Baking Mitad

The heat transfer mechanism of the Injera baking Mitad model is shown in figure 2.10. Considering an overall energy balance on the baking Mitad, the heat losses is given as follows [7, 18−19].

$$Q_{losses} = Q_{conv,top} + Q_{rad,top} + Q_{conv,bottom} + Q_{rad,bottom} + Q_{conv,side} + Q_{rad,side} = Q_{top,loss} + Q_{bottom,loss} + Q_{side,loss} \quad 6.7$$

6.3 Energy Consumption and Utilization

For this study, total energy is the amount of energy used to bake a fixed quantity of Injera; it includes both the energy utilized and lost during baking process. Whereas, the utilized energy is the amount of energy, which is used during baking Injera, not including any of the losses during the baking process. The average energy required for Injera baking implies the energy that is necessary to raise the temperature of batter from room temperature to boiling point and evaporate the required amount of water during the baking process. This useful baking energy it could be estimated in the form of sensible heat for heating of the batter from room temperature to water boiling temperature and latent heat responsible for evaporating some of the water content of the batter.

The following assumptions are made in order to calculate the amount of utilized energy by a baking Mitad:

- ✓ The average mass of Injera and moisture loss for every single Injera is constant
- ✓ The difference in mass between the baked Injera and the initial batter is equal to the mass of moisture loss during baking.

Based up on the above assumptions the total amount of utilized energy by a baking Mitad calculated as [7, 18−19].

$$E_{utl} = n\left(m_{ba}c_{pba}(T_b - T_\infty) + \left(m_{ba} - m_{inj}\right)h_{fg}\right) \quad 6.8$$

Where: E_{utl} = Energy utilized *(kJ)*

n = Total Injera baked per cycle

m_{ba} = Mass of batter for each Injera *(kg)*

c_{pba} = Specific heat capacity of batter *(kJ/kg.K)*

T_b = Boiling temperature of water in the given environment *(K)*

T_∞ = Surrounding temperature *(K)*

m_{inj} = Mass of each Injera *(kg)*, and

h_{fg} = Heat of vaporization of water at the T_b *(kJ/kg)*

The heat energy required for initial heating or to reach the temperature of baking is given by the following equation [19]:

$$Q_{inh} = m_{bm}c_{pbm}(T_{bs} - T_\infty) \qquad 6.9$$

Where: Q_{inh} = heat energy required for initial heating *(kJ)*

m_{bm} = Mass of Injera baking Mitad plate *(kg)*

T_{bs} = Baking surface temperature *(K)*

T_∞ = Surrounding temperature *(K)*

c_{pbm}= Specific heat capacity of Injera baking Mitad *(kJ/kg.K)*

The heat loss from the baking Mitad during initial heating-up is the difference between the electrical energy supplied to the baking Mitad during initial heating period and the heat energy required for initial heating-up. Actually, their difference could not be consider as the loss because of it is stored in the baking Mitad for the baking process in the form of stored energy.

The total time required during the baking cycle is the sum of time taken for initial heating, baking and the gap between successive Injera.

By assuming in the household an average of n Injera baked per cycle, the total time required could be determined by using the following equation [40].

$$t_t = t_{inh} + n * t_{bak} + (n-1)t_{gap} \qquad 6.10$$

Where: t_{inh} = Time taken for initial heating-up *(sec)*

t_{bak} = Time taken for baking each Injera *(sec)*

t_{gap} = Time take between two successive Injera *(sec)*

n = Total Injera baked per cycle

The gross energy consumption per cycle will be calculated using the electric power flow throughout the baking process. This electrical power is the product of the current flow variation with the terminal voltage supply at the given interval; the equation is given as [40].

$$Q_t = Q_{int} + n * Q_{bak} + (n-1)Q_{gap} \quad 6.11$$

Where: Q_{int}= Energy consumed during initial heating-up *(kWh)*

Q_{bak}= Energy consumed during baking each Injera *(kWh)*

Q_{gap}= Energy consumed between two successive Injera *(kWh)*

6.3.1 Thermal Efficiency of Injera Baking Mitad

The efficiency of Injera baking Mitad is simply the ratio of total utilized energy to the total energy input for baking process [7, 18−19].

$$\eta_{th} = \frac{Total\ Energy\ Utlized}{Totla\ Energy\ Input} * 100\% \quad 6.12$$

$$= \frac{n\big(m_{ba}c_p(T_b - T_\infty) + \big(m_{ba} - m_{inj}\big)h_{fg}\big)}{Q_t} * 100\%$$

Where: Q_t = Total energy input to the system *(kJ)*

CHAPTER SEVEN

RESULTS AND DISCUSSIONS

This chapter comprises the results and discussions of the thesis work. The initial heating time, temperature profile of baking surface during the initial heating and baking process, baking Mitad energy requirement, useful energy consumption, energy loss, and thermal efficiency results are briefly discussed below.

7.1 Initial Heating Time and Baking Surface Temperature Profile

In order to determine the initial heating time, heating rate and energy requirements for initial heating a no load temperature measurement condition was used. In addition, using of a no load condition helps to check uniformity of temperature distribution on the baking surface of the Mitad. An investigation of the baking temperature of the electrical Injera baking Mitad is an important indicator about the energy consumption behavior of the equipment. This temperature reading was taken from the baking surface of the baking Mitad.

Using the data collected on the baking surface of the baking Mitad during conducting experiment, the temperature profile variation with time has been developed and shown in figure 7.1 and 7.2. Figure 7.1 shows the average variations of the baking surface temperatures during the initial heating process for both improved and conventional an electric Injera baking Mitad. The average baking surface temperature in sense, the average surface measured temperature values taken at center, 13 cm and 26 cm away from the center of the baking surface.

The experimental result shown in figure 7.1 shows the time taken for initial heating, i.e. the temperature required to start baking in range of 200−220 ℃, are about 11 and 21 minutes for the improved and conventional electric Injera baking Mitads, respectively. Additionally, it has the heating rate of 15.6 and 8.2 ℃/min during the initial heating period for improved and conventional electric Injera baking Mitads, respectively.

It can be observed that the surface temperature of the baking Mitad before the start of baking is around 200−220 ℃. The readings recorded with infrared thermometer are given in appendix A.

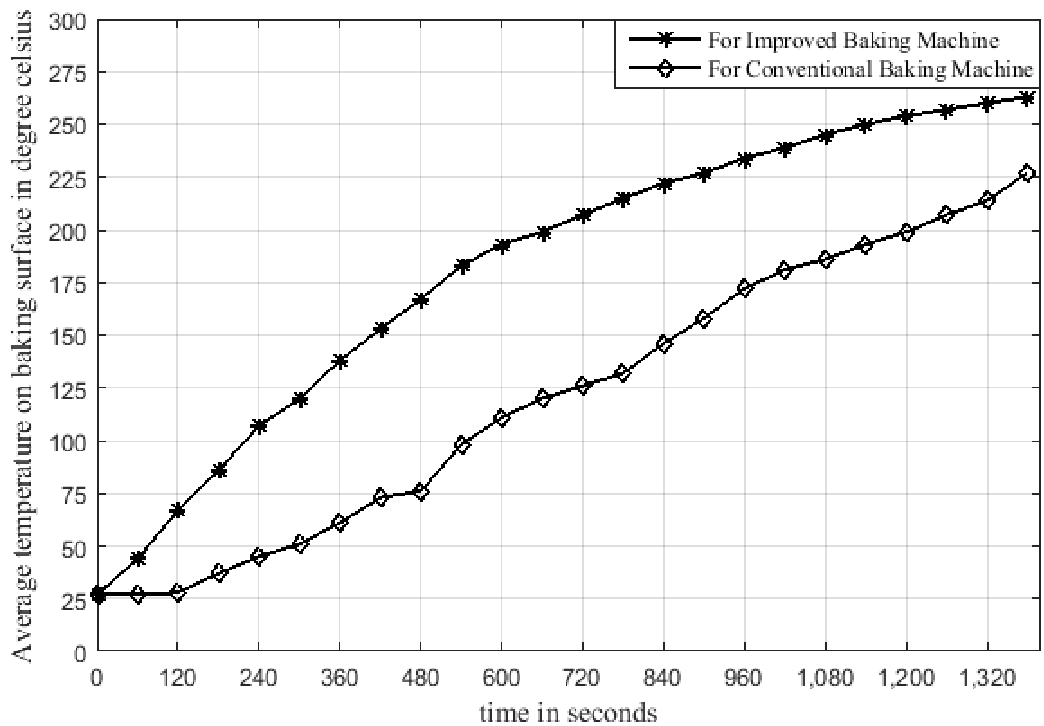

Figure 7.1 Initial Heating Time Vs Baking Surface Temperature Profiles Comparison

Figure 7.2 shows initial heating temperature variations of the three point temperatures were taken at the center, 13 cm and 26 cm away from the center of the baking surface, during experimental testing with no load condition. The recorded temperatures are starting from ambient temperature to the maximum of up to 294 ℃ and 304 ℃ for improved and conventional baking Mitads, respectively. It can also be noted that the improved baking Mitad is heated non-uniformly during the initial heating with temperature variation greater than 10 ℃ then it became uniform with temperature variation less than 5 ℃ during the baking process, as shown in figure 7.2. This is due to inaccuracy during grooving the plate; the center point has higher pitch than others do. This results lowering of the temperatures at the center as compared with 13 cm and 26 cm away from the center, during initial heating. This can be overcome by equal pith grooving. However, during the baking session heat gained distributed uniformly i.e. at higher temperature.

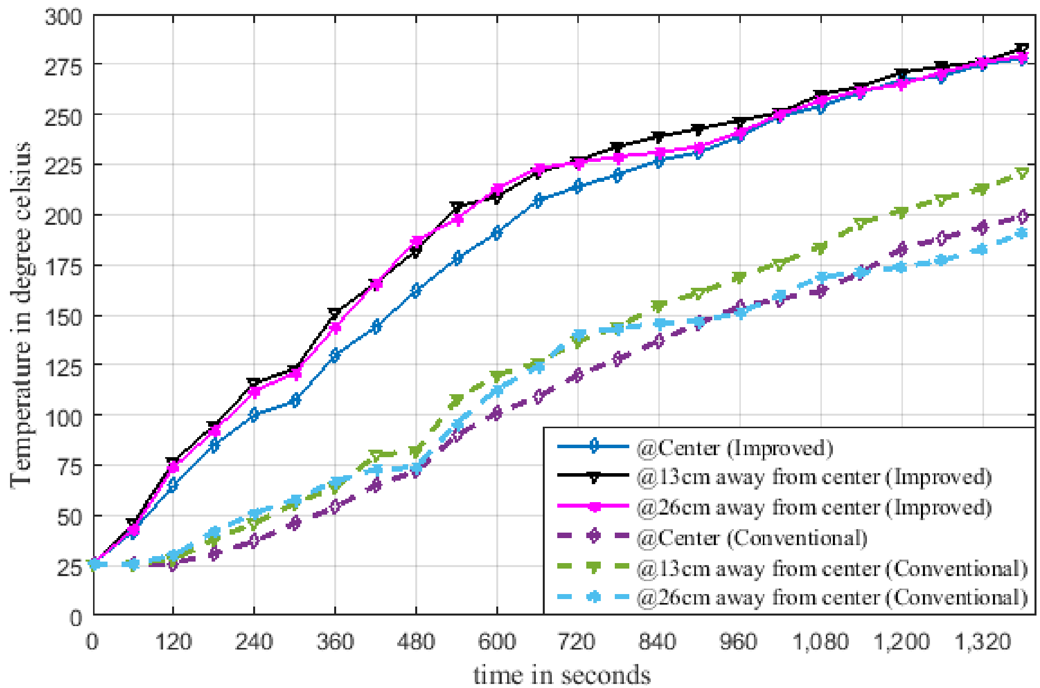

Figure 7.2 Temperature Distribution on Baking Surfaces Comparison

Additionally, it indicates that even though the baking surface temperature has reached the required baking temperature at early period of the heating up process; the temperature of the heating element is increasing. This means the system is consuming additional power from the source; out of this, some power will be consumed for increasing the temperature of the batter during the baking process. Whereas, the remaining consumed energy dissipated in the form of different losses such as top loss, bottom loss and lateral or side losses.

7.2 Temperature Profile during Baking Process

The temperature profile during baking process is another important indicator for energy analyses of the Injera baking Mitad. In order to determine the energy consumption and utilization behavior of the Injera baking Mitad, a load temperature measurement condition was used.

Figure 7.3 shows the temperature profile of an improved electric Injera baking Mitad during the baking period. The temperature variation of the baking surface reaches low point during batter pouring on the baking surface and reaches high point by gaining heat after the Injera is removed and oscillates in those intervals with some variation. The average time it takes to bake each Injera is about 100 seconds with 50 seconds idle time between successive Injera. The temperature of the batter in conversion to Injera starts from ambient temperature and reaches to 93 ℃, whereas the temperature of the baking surface reduces from baking temperature to 93 ℃. This is the implication of heat transfer from high temperature to low temperature and reaching to thermal equilibrium. After the Injera removed, the baking surface retains to its baking temperature because of there is continues supply of electric power. During the cyclic baking process similar values observed with small variations.

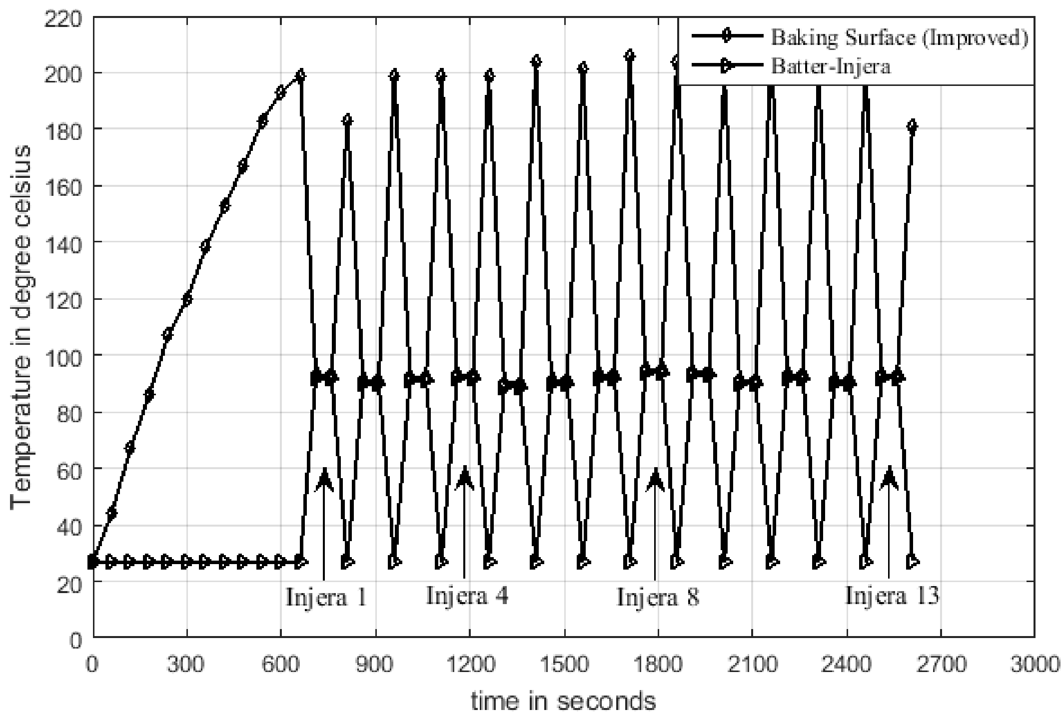

Figure 7.3 Temperature Profile of Improved Baking Mitad during Baking Process

Similarly, the temperature profile of a conventional electric Injera baking Mitad during the baking period is shown in figure 7.4. The temperature variation of the baking surface reaches low point during batter pouring on the baking surface and reaches high point by gaining heat after the Injera is removed and oscillates in those intervals with some variation. The average time it takes to bake each Injera is about 120 seconds with 60 seconds idle time between successive Injera. The temperature of the batter in conversion to Injera starts from ambient temperature and reaches to 91 ℃, which is the back surface temperature of the Injera before fully removing from the baking surface. After the Injera removed the baking surface retains to its baking temperature because of there is continues supply of electric power.

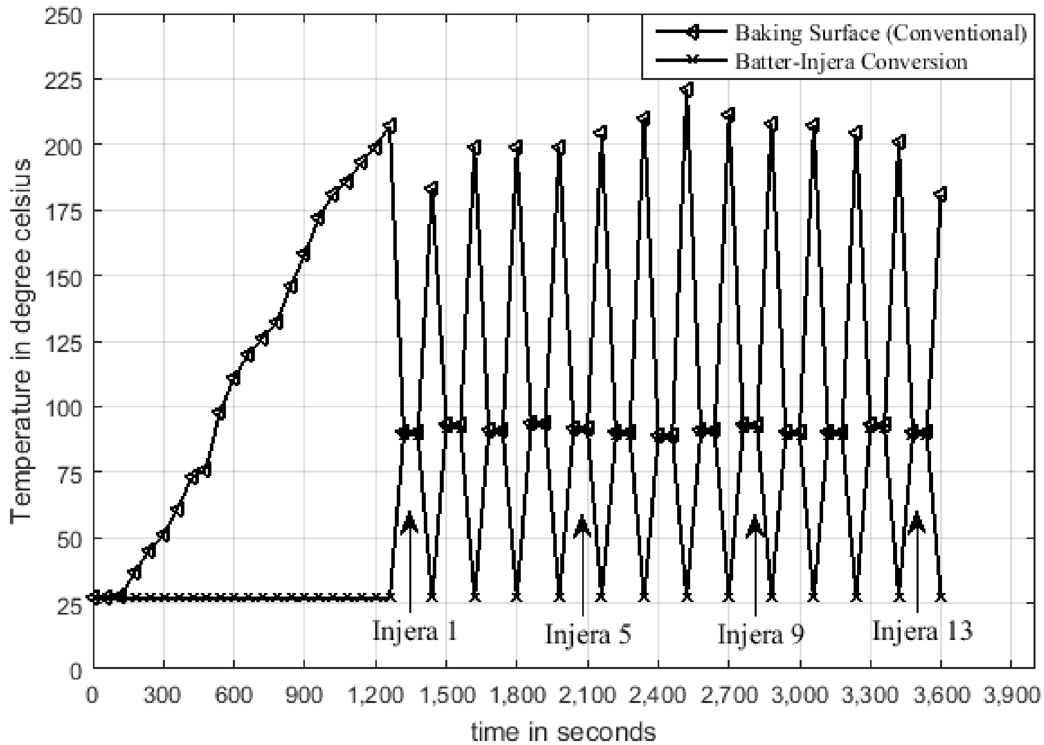

Figure 7.4 Temperature Profile of Conventional Baking Mitad during Baking Process

The loss of heat energy from the system uses different parts of the baking Mitad such as the lid cover, bottom and lateral plates. To visualize these losses, surface temperature profiles during initial heating and baking process are shown in figure 7.5 and 7.6 for improved and conventional baking Mitads, respectively. From the figure 7.5 when the parts temperature profile compared with baking surface temperature it can visualize the baking surface temperature is lower for the entire baking process. Whereas, for the conventional baking Mitad this cannot work, especially the bottom plate temperature is above the baking surface temperatures at some points after 1700 seconds onward, as shown in figure 7.6. This is due to lack of using good insulation material in conventional baking Mitad and implication of maximum losses occurrence in the bottom surface. These parts temperature profile values are used to determine the energy losses with their respective surfaces.

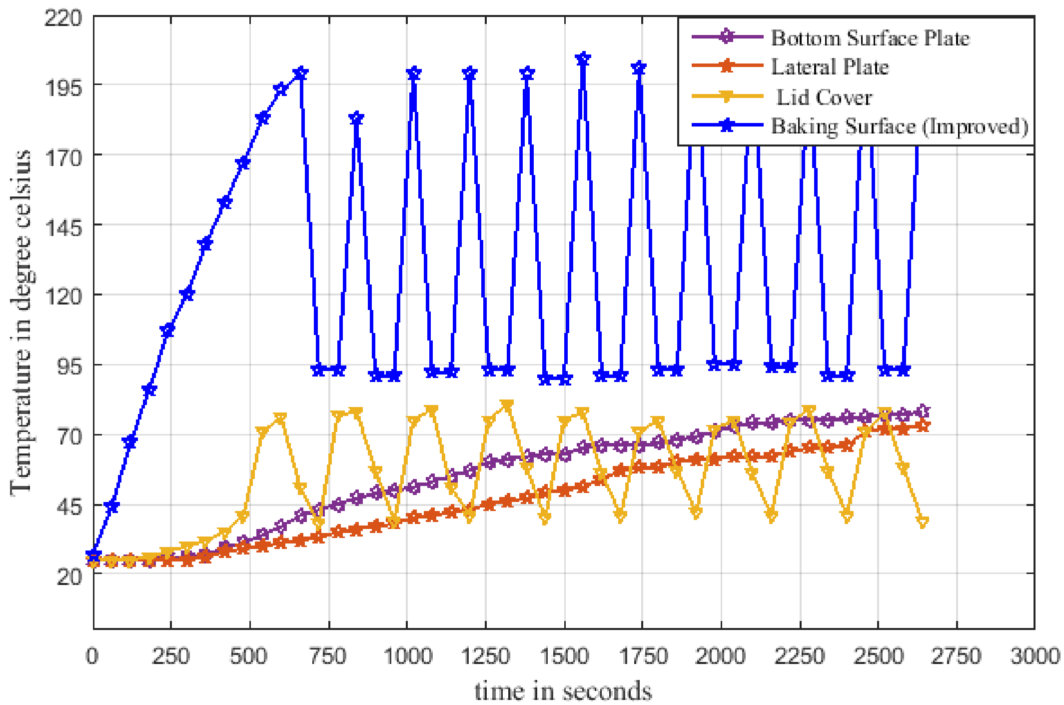

Figure 7.5 Temperature Profiles of the Improved Baking Mitad Parts

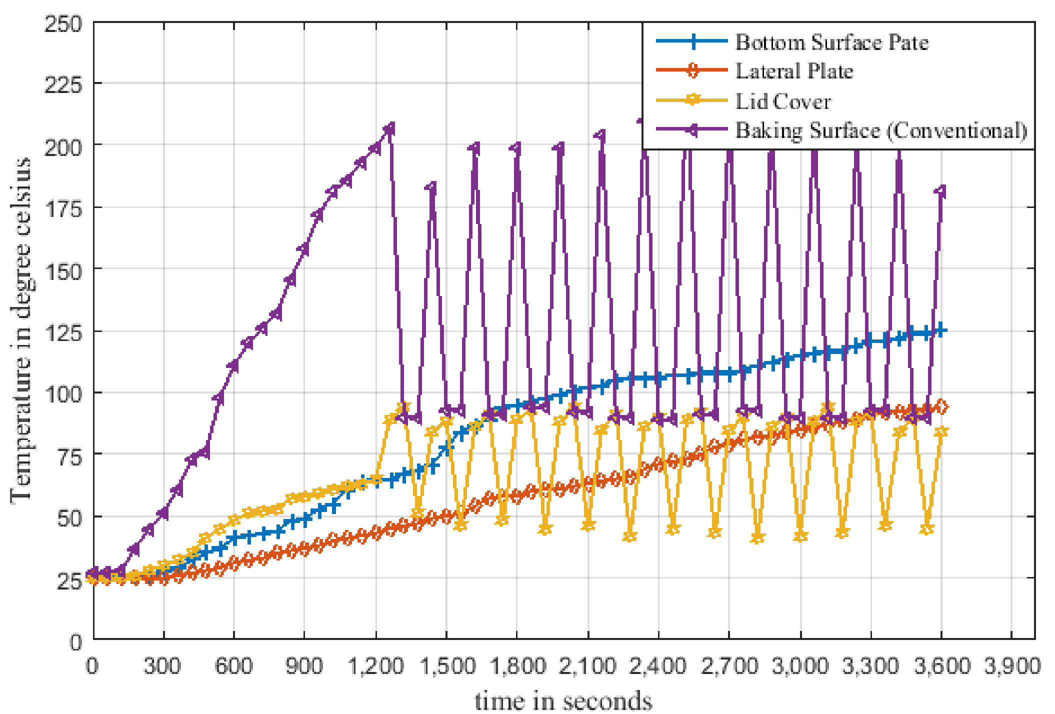

Figure 7.6 Temperature Profiles of the Conventional Baking Mitad Parts

Figure 7.7 shows a magnified view of the temperature profile of the baking plate surface and Injera surface. The baking surface temperature reduced from 200 ℃ to 93 ℃, whereas the temperature of batter in conversion to Injera increased from ambient temperature to 93 ℃. This is the implication of heat transfer from baking plate to Injera through conduction and reaching thermal equilibrium.

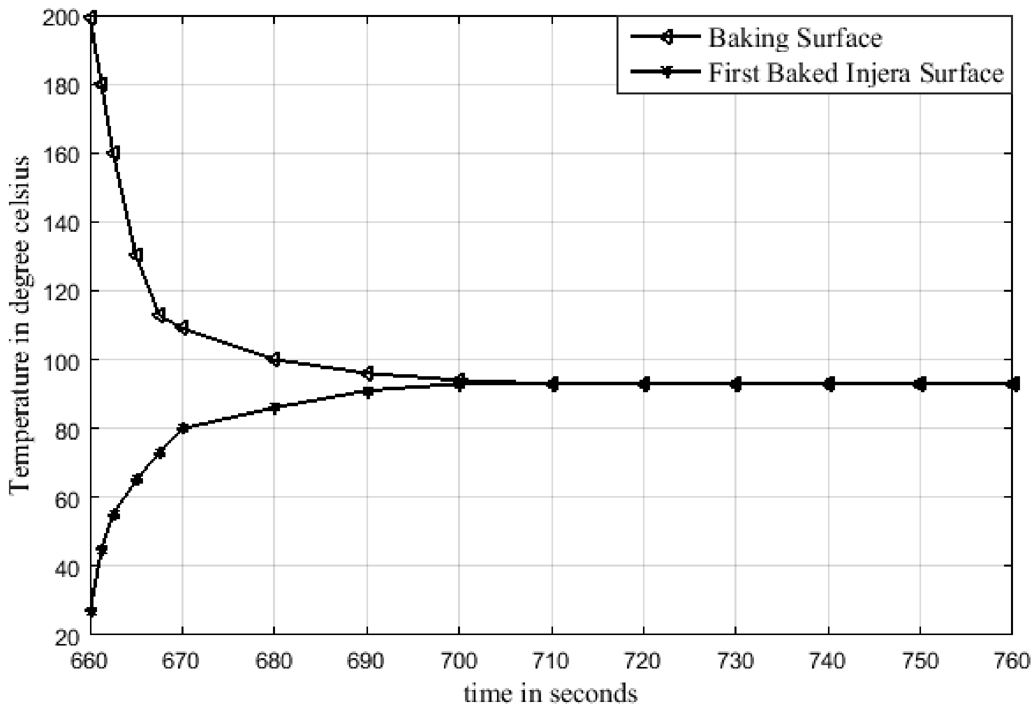

Figure 7.7 Temperature Profile of Baking Surface and First Baked Injera Surface

7.3 Energy Consumption and Utilization Results

In order to determine the energy consumption of the baking Mitad during initial heating and baking process the current flow measurement was taken during experimental investigation and the resulting values plotted in figure 7.8. The terminal voltage supplied to the heating element average value was 213 V and using the current variation, the power dissipation in the heater calculated. The resulting values of power supply plotted in figure 7.9. The energy consumption of the baking Mitads are numerically integrated using trapezoidal numerical integration from the power time curve for the time it takes. As shown in the figure 7.8 the current variation observed during the initial heating and oscillates at the same point after baking Injera started. This is due to the system changes its phase from continuous heating to baking process; in the case of baking process there is continuous utilization of the supplied power.

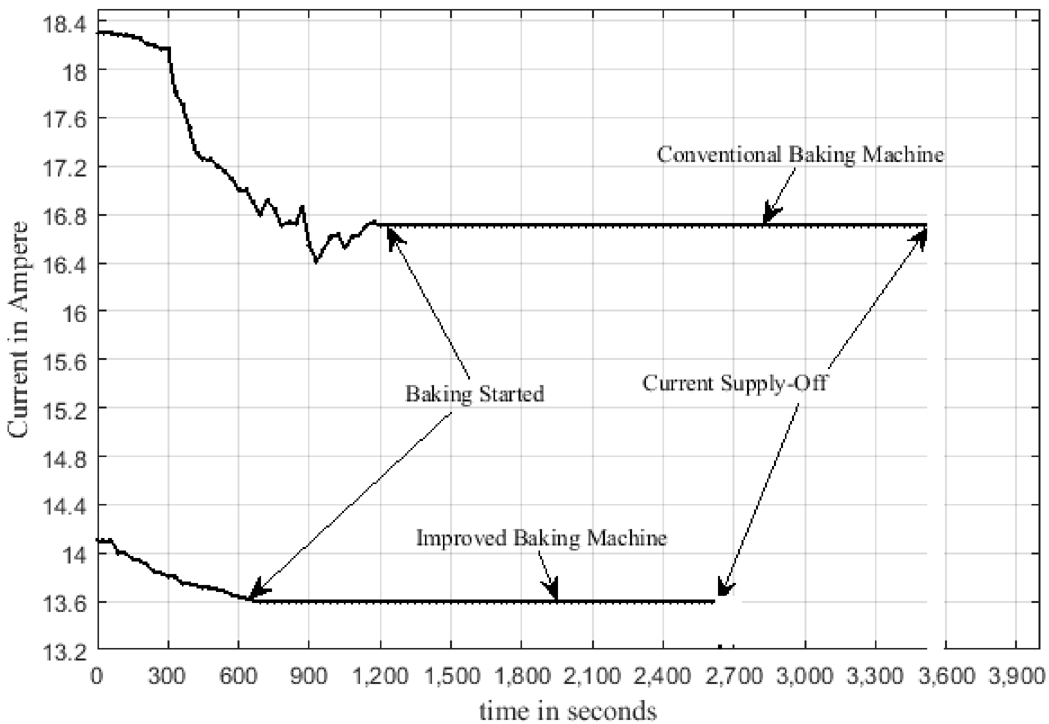

Figure 7.8 Current Flow Variation of Improved and Conventional Baking Mitads

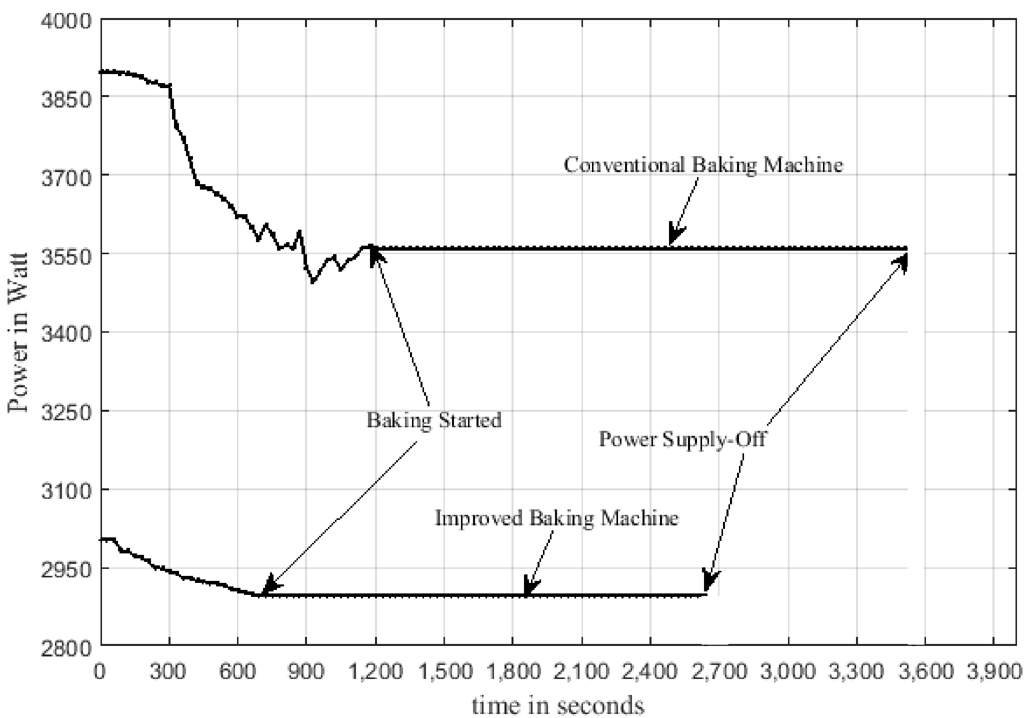

Figure 7.9 Power Flow Variation of Improved and Conventional Baking Mitads

During the initial heating and baking process, the following data's were collected using the equipment described in section 6.1 and tabulated in table 7.1. The tabulated values are used to analyze the energy consumption, energy utilization, losses and time series of the improved and conventional electric Injera baking Mitads. From the table it is possible to compare the total time taken in order to bake 13 Injera per cycle. It takes about 2560 second or 42.67 minute and 3540 second or 59 minute for improved and conventional Injera baking Mitad, respectively. This implies when it is compared with the conventional, the improved baking Mitad reduces the baking time with 980 second or 16.33 minute to bake 13 Injera. This reduced time saves 5064.384 kJ amount of energy.

Table 7.1 Data Collected During Experimental Investigation

Description	**Baking Mitad Type**	
	Improved	**Conventional**
Input Voltage *(V)*	213	213
Input Current *(A)*	14.1	18.3
Total Injera baked per cycle *(n)*	13	13
Total Injera baked per cycle *(kg)*	5.85 (0.450*13)	5.85
Total mass of batter per cycle *(kg)*	7.80 (0.60*13)	7.80
Total mass of water evaporated *(kg)*	1.95	1.95
Time taken for initial heating-up *(sec)*	660	1,260
Time taken for baking each Injera *(sec)*	100	120
Time take between two successive Injera *(sec)*	50	60
Total time taken *(sec)*	2560 (42.67 minute)	3540 (59 minute)

The total electrical energy supplied to the baking Mitad during initial heating and baking process for improved and conventional baking tabulated in table 7.2. Based on the equations developed in sections 6.2 and 6.3 input, output and lost energies are analyzed and tabulated in table 7.2 and 7.3.

Table 7.2 Energy Consumption Analysis of Injera Baking Mitads Comparison

Description	**Baking Mitad Type**	
	Improved	**Conventional**
Baking Mitad power requirement *(kW)*	3.003	3.898
Energy required for initial heating-up *(kJ)*	869.632	1,784.500
Energy required for initial heating-up *(kWh)*	0.242	0.496
Comparison for 13 Injera Baking Per Cycle		
Gross Energy Consumption (Input Energy)		
➢ Energy consumed during initial heating-up *(kJ)*	1,943.427	4,628.431
➢ Energy consumed during initial heating-up *(kWh)*	0.540	1.286
➢ Energy consumption for baking only *(kJ)*	5,735.664	8,115.044
➢ Energy consumption for baking only *(kWh)*	1.593	2.254
➢ ***Gross energy consumption (kJ)***	***7,679.091***	***12,743.475***
➢ ***Gross energy consumption (MJ)***	***7.679***	***12.743***
➢ ***Gross energy consumption (kWh)***	***2.133***	***3.540***
Specific Energy Consumption (Input Energy)		
Energy for baking only, without heating up *(kWh/Injera)*	0.123	0.173
Energy for baking only, without heating up *(kWh/kg of Injera)*	0.272	0.385
Useful energy of the Injera baking process (Output Energy)		
➢ Latent heat of water *(kJ)*	4,399.200	4,399.200
➢ Sensible heat present in Injera *(kJ)*	2,400.420	2,400.420
➢ ***Total useful energy for the baking process (kJ)***	***6,799.620***	***6,799.620***
➢ ***Total useful energy for the baking process (MJ)***	***6.800***	***6.800***
➢ Total useful energy for the baking process (kWh)	1.889	1.889
➢ Specific useful energy *(kJ/Injera)*	523.047	523.047
➢ Specific useful energy *(kJ/kg of Injera)*	1,162.328	1,162.328

Table 7.3 Energy Loss Analysis of Injera Baking Mitads Comparison

Description	**Baking Mitad Type**	
	Improved	**Conventional**
Energy loss		
➢ Top loss (kJ)	237.340	1,325.196
➢ Bottom loss (kJ)	527.626	3,565.930
➢ Lateral or Side loss (kJ)	114.505	1,052.729
Total energy loss (kJ)	***879.471***	***5,943.855***

Table 7.4 Thermal Efficiency Comparison of the Baking Mitads

Description	**Baking Mitad Type**	
	Improved	**Conventional**
Useful energy of Injera baking process (Output Energy) (kJ)	6,799.620	6,799.620
Gross Energy Consumption (Input Energy) (kJ)	7,679.091	12,743.475
Average thermal efficiency (%)	***87.509***	***52.905***

7.3.1 Sankey Diagram for Electric Injera Baking Mitads

Based on the experimental result obtained, the Sankey diagram drawn for 13 Injera baked per cycle and it shows that the thermal efficiency of the Injera baking Mitad is about 88.55 % and 53.36 % for the improved and conventional baking Mitad, respectively. The highest energy loss occur at the bottom surface of the system with 6.87 % and 27.98 % losses for the improved and conventional baking Mitad, respectively. Even if the efficiency of improved one is higher than the conventional still there is considerable energy loss due to insulation material used. During the baking process, the 14th Injera is baked without electric power supply, which helps to reduce the energy loss if it encountered in energy analysis.

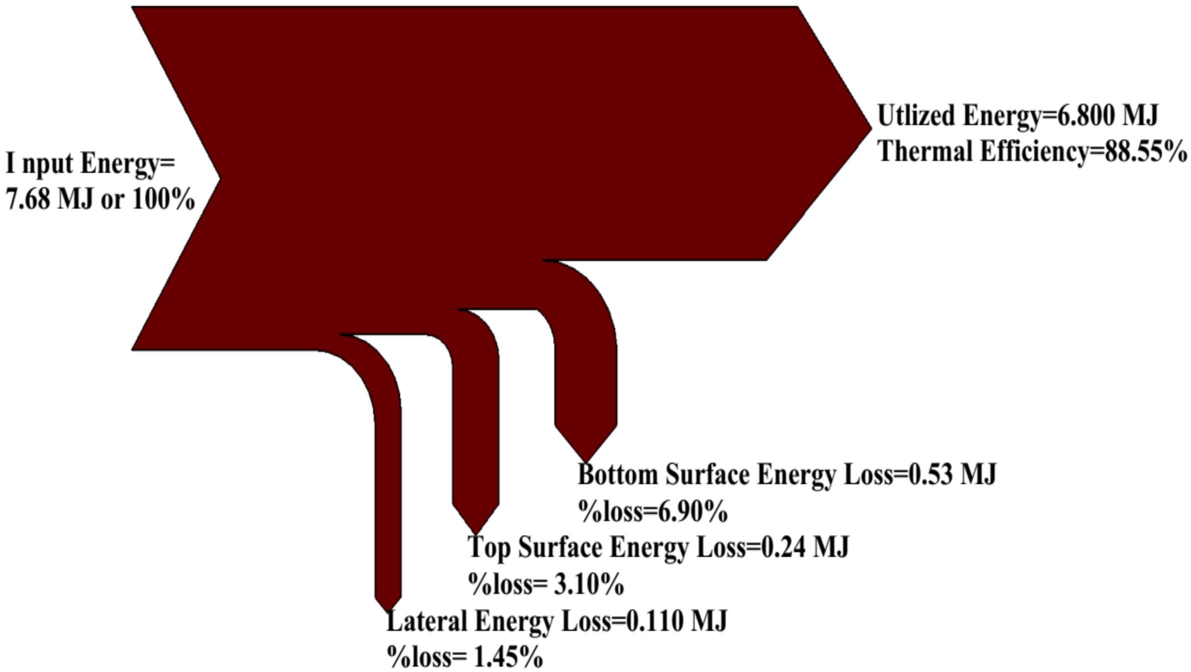

Figure 7.10 Sankey Diagram for Improved Baking Mitad for 13 Injera per Cycle

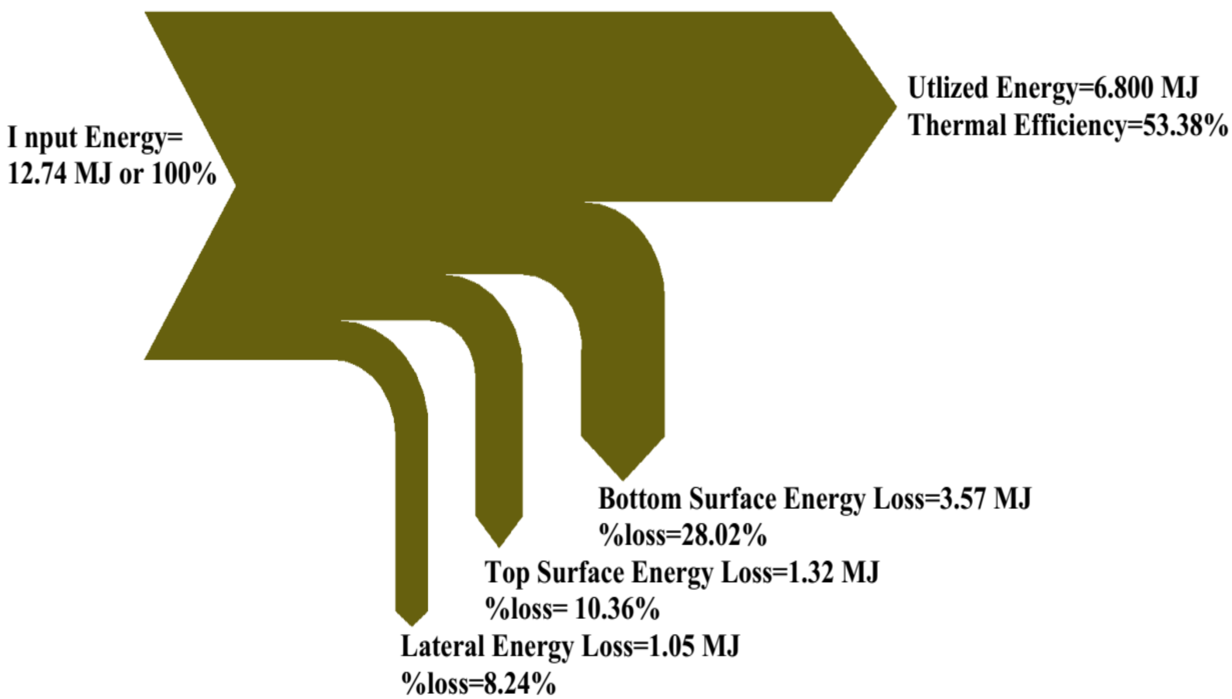

Figure 7.11 Sankey Diagram for Conventional Baking Mitad for 13 Injera per Cycle

7.4 Cost and Energy Saving of Improved Baking Machine

Using the improved electric Injera baking Mitad for baking Injera, it is possible to save both energy and energy bill cost. It saves about 0.304 kWh of energy per each Injera. For the current charging fee of electric energy in average consumption range of 1.275 Birr per kWh it saves about Birr 0.3876 per Injera i.e. (0.304 kWh×1.275 Birr/kWh).

7.5 Comparison of Present Work with Previous Works

The present work, investigating the performance improvement of an electric Injera baking Mitad using copper powder as additive material is compared with previous research works. The parameters used for comparisons are initial heating time, baking time for each Injera, idle time between successive Injera and baking energy consumption per kg of Injera. Efficiency comparison neglected because of it depends on the number of Injera baking per cycle and different number of Injera baking per cycle used in research works.

Table 7.5 Comparison of Present Work with Previous Works

Research Works	**Comparing Parameters**			
	Initial heating time (sec)	Baking time for each Injera (sec)	Idle time between successive Baking (sec)	Baking Energy Consumption (kWh/kg of Injera)
Present Work (Source: Electric Power)	660	100	50	0.272
Conventional (Source: Electric Power)	1260	120	60	0.385
Abdulkadir Hassen et al. [5] (Source: Solar Energy)	2400	120	180	-
Mekonnen Mesele [17] (Source: Solar Energy)	6300	120	-	-
Gashaw Getenet [18] (Source: Electric Power)	845	120	100	-
Garedew Ambaw [19] (Source: Electric Power)	1200	120	120	0.554

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

From the experimental results obtained, the following points concluded:

- ✓ The thermo-physical properties of composite materials used for construction of baking plate are better than that of conventional clay material.
- ✓ The initial heating time required to reach the baking surface temperature, 200℃ is about 11 and 21 minutes for the improved and conventional baking Mitads, respectively. Using the composite materials instead of clay reduces the initial heating time, i.e. it reduces the energy consumptions and increases the efficiency.
- ✓ The heating rate of the baking Mitad is about 15.6 ℃/min and 8.2 ℃/min for the improved and conventional baking Mitads, respectively.
- ✓ Uniform temperature distribution on the baking surface is achieved with variation less than 5℃.
- ✓ The average specific baking energy required is about 0.123 and 0.173 kWh/Injera or 0.272 and 0.385 kWh/kg of Injera for improved and conventional baking Mitads, respectively.
- ✓ The gross energy consumed is 7.7 MJ and 12.7 MJ for 13 Injera baking per cycle for improved and conventional baking Mitads, respectively
- ✓ The maximum energy losses of improved and conventional baking Mitads occurred through the bottom surface of the baking Mitad with 6.90 % and 28.02 % with the average thermal efficiency of 87.51% and 52.91%, respectively.
- ✓ The electrical shock test is checked during the baking process; because of the additive material used, it is free from any shocking. Since thick painting is used before heating at high temperature during manufacturing of the baking Mitad.
- ✓ The quality of Injera baked on the improved baking Mitad is the same as the conventional baking Mitad.

8.2 Recommendations

Recommendations for further work to enhance efficiency concentrate on the following:

- ✓ Awareness for energy saving is low at all level, from the baking Mitad manufacturers to end user. This needs to be addressed with implementation of appropriate policies and standardization for more efficient baking Mitad.
- ✓ Finding of alternative heating material instead of using only Nicrome coil wire
- ✓ According to the experimental result obtained, the efficiency for 10 mm thickness of the baking Mitad for 13 Injera baked per cycle is about 87.51%. Therefore, it is important to investigate the efficiency improvement of the improved baking Mitad by finding suitable insulation material to reduce the losses.
- ✓ Finding other additive materials to develop composite material, which may improve the baking Mitads efficiency.

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APPENDICES

Annex A: Experimental Collected Temperature Records from the Baking Surface

Annex A$_1$: Experimental Collected Temperature Records from the Baking Surface of Improved Electric Injera Baking Mitad

Time (sec)	Temperature (℃)	Time (sec)	Temperature (℃)	Time (sec)	Temperature (℃)
0	27	900	93	1800	94
60	44	960	93	1860	94
120	67	1020	199	1920	199
180	86	1080	90	1980	91
240	107	1140	90	2040	91
300	120	1200	204	2100	207
360	138	1260	91	2160	93
420	153	1320	91	2220	93
480	167	1380	201	2280	200
540	183	1440	93	2340	91
600	193	1500	93	2400	91
660	199	1560	206	2460	201
720	92	1620	95	2520	93
780	92	1680	95	2580	93
840	199	1740	204	2640	181

Annex A_2: Experimental Collected Temperature Records from the Baking Surface of Conventional Electric Injera Baking Mitad

Time (sec)	Temperature (℃)	Time (sec)	Temperature (℃)	Time (sec)	Temperature (℃)
0	27	1200	199	2400	89
60	27	1260	90	2460	221
120	28	1320	90	2520	91
180	37	1380	183	2580	91
240	45	1440	93	2640	211
300	51	1500	93	2700	93
360	61	1560	199	2760	93
420	73	1620	91	2820	208
480	76	1680	91	2880	90
540	98	1740	199	2940	90
600	111	1800	94	3000	207
660	120	1860	94	3060	90
720	126	1920	199	3120	90
780	132	1980	92	3180	204
840	146	2040	92	3240	93
900	158	2100	204	3300	93
960	172	2160	90	3360	201
1020	181	2220	90	3420	90
1080	186	2280	210	3480	90
1140	193	2340	89	3540	181

Annex B: Experimental Collected Temperature Data from Parts

Parameters	Average Temperature Value (℃)	
	Improved	Conventional
Baking surface temperature	196	202
Bottom plate surface temperature	63.5	120.3
Side temperature	47	61
Top lid cover temperature	57	64

Annex C: Thermo-Physical Properties of Air at Atmospheric Pressure [57]

T *(℃)*	ρ *(kg/m³)*	c_p *(J/kg.K)*	v (m²/s)*10⁻⁵	k *(W/m.K)*	α (m²/s)*10⁴	Pr	β*10⁻³(1/K)
27	1.1774	1.0057	1.568	0.02624	0.22160	0.7282	0.301
40	1.127	1.007	1.702	0.02662	0.2346	0.7251	0.385
45	1.109	1.007	1.750	0.02699	0.2416	0.7241	
77	0.9980	1.009	2.076	0.03003	0.2983	0.7154	0.630
127	0.8826	1.014	2.590	0.03365	0.3760	0.7051	0.860

Annex D: Thermo-Physical Properties of Water at Atmospheric Pressure [57]

T *(℃)*	ρ *(kg/m³)*	c_p *(J/kg.K)*	v (m²/s)*10⁶	k *(W/m.K)*	α (m²/s)*10⁴	Pr	β
100	960.63	4216.1	0.294	0.680	1.680	1.74	0.000751
120	945.25	4250	0.247	0.685	1.708	1.446	0.000858
140	928.27	4283	0.214	0.684	1.724	1.241	0.000895
160	909.69	4342	0.190	0.680	1.729	1.099	

Annex E: Energy Loss Analysis

Annex E$_{1}$: Energy Loss Analysis for Improved Electric Injera Baking Mitad

Heat Transfer from Baking Surface

- ✓ Convective heat transfer coefficient from the baking surface of the baking Mitad to the lid cover: Film or average temperature=$\frac{57+196}{2} = 126.5$ °C≅127 ℃

Using the film temperature thermo-physical properties taken from Appendix C for calculation:

β = Volumetric expansion coefficient (1/K) = 0.860

ΔT = Change in temperature between T_{bs} and T_{∞} (℃) (196−57=139

g = Gravitational constant (m/s^2) = 9.81

l = Characteristic length (m) and given by l =0.9D=0.522m, D= Diameter of baking Mitad

Pr= Prandtl number = 0.689

v = Kinematic viscosity (m^2/s) = 2.590 *10^{-5}

Rayleigh number (Ra) given as follows: $R_a = \frac{\beta \Delta T g l^3}{v^2} Pr = 2.486*10^8$ and the Nusselt number: $N_u = 0.14(R_a)^{1/3}$=88.029

Therefore, convective heat transfer coefficient from the baking surface of the baking Mitad to the lid cover: $\mathbf{h_{cvbc} = N_u \frac{k}{l}}$ **= 5.67 W/m^2.K**

- ✓ Using the similar procedure, convective heat transfer coefficient from lid cover to surrounding: using film or average temperature=$\frac{57+27}{2} = 42$ ℃ : $\mathbf{h_{cvcs}}$ **= 3.777 W/m^2.K**
- ✓ The radiative heat transfer coefficient from the baking surface of the baking Mitad to lid cover is given by:

$$h_{rbc} = \varepsilon\delta \frac{{T_b}^4 - {T_{tc}}^4}{T_b - T_{tc}} = \varepsilon\delta({T_{bs}}^2 + {T_{lc}}^2)(T_{bs} - T_{lc}) \quad 0$$

Where; ε =Emissivity of the surface = 0.95

δ =Stefan Boltzmann constant =5.67×10^{-8} W/m^2.K^4

T_{bs} = Baking surface temperature (K) =196 ℃

T_{lc} = Lid cover temperature taken from the measured data (K) =57℃

$$\mathbf{h_{rbc}} = \boldsymbol{\varepsilon\delta}\frac{\mathbf{T_b}^4 - \mathbf{T_{tc}}^4}{\mathbf{T_b} - \mathbf{T_{tc}}} = \boldsymbol{\varepsilon\delta}(\mathbf{T_{bs}}^2 + \mathbf{T_{lc}}^2)(\mathbf{T_{bs}} - \mathbf{T_{lc}}) = \mathbf{2.462\ W/m^2.K}$$

- ✓ Using the similar procedure the radiative heat transfer coefficient from lid cover to the surrounding calculated: the only difference is considering the sky temperature with the following relation. The sky temperature given by: $T_s = T_\infty - 6$=27−6=21

$$\mathbf{h_{rcs}} = \boldsymbol{\varepsilon\delta}(\mathbf{T_{lc}}^2 + \mathbf{T_s}^2)(\mathbf{T_{lc}} - \mathbf{T_s}) = \mathbf{0.379\ W/m^2.K} \qquad \mathbf{0}$$

In order to calculate the effective heat transfer coefficient from baking surface to surrounding: Taking their respective sums: $h_1 = h_{cvbc} + h_{rbc} = \mathbf{8.137\ \ W/m^2.K}$

$$h_2 = h_{rbc} + h_{rcs} = \mathbf{4.156\ W/m^2.K}$$

- ✓ The effective heat transfer coefficient from baking surface to surrounding:

$$\mathbf{U_{bs}} = \left[\frac{\mathbf{1}}{\mathbf{h_1}} + \frac{\mathbf{1}}{\mathbf{h_2}}\right]^{-\mathbf{1}} = \mathbf{2.751\ W/m^2.K}$$

The losses from the baking surface to surrounding could be determined using the diameter of baking Mitad (0.58m) and temperature changes. $Q_{top,lost} = AU_{bs}(T_{bs} - T_\infty) = \mathbf{124.92W}$

To converting to energy form, multiplying the lost power by the time it takes for baking (2560−660=1900 second). $\mathbf{E_{top,lost}} = \mathbf{1900s * 124.92J/s = 237.34kJ}$

Heat Transfer from Bottom Surface

Heat transfer through this surface is by conduction through the insulation to the plate casing and consequently by convection and radiation from the bottom casing surface to the surrounding.

- ✓ Convective heat transfer coefficient from the bottom surface to the surrounding, h_{cvbt}: Film or average temperature=$\frac{63.5+27}{2} = 45.25 \cong 45$℃. Using the film temperature properties taken from Appendix C and calculated with similar procedure with baking surface heat transfer.

$$\mathbf{h_{cvbt} = 9.61W/\ W/m^2.K}$$

- ✓ The radiative heat transfer coefficient from the bottom surface of the baking Mitad surrounding, h_{rbt} calculated using similar procedure with baking surface heat transfer.

$$\mathbf{h_{rcs} = 4.57\ W/m^2.K}$$

Sum of convective and radiative heat transfer coefficient from bottom surface to surrounding, $\mathbf{h_{bt}} = \mathbf{h_{cvbt}} + \mathbf{h_{rcs}} = \mathbf{14.18\ W/m^2.K}$

Then, the overall heat transfer coefficient through the bottom surface to surrounding used to calculate the lost heat energy through this surface. Overall heat transfer coefficient could be simply calculated by using thermal resistance concept:

$$U_{bt} = \left[\frac{t_{gyp}}{k_{gyp}} + \frac{t_{fg}}{k_{fg}} + \frac{t_p}{k_p} + \frac{1}{h_{bt}}\right]^{-1}$$

Where, U_{bt} = Overall heat transfer coefficient from bottom surface to surrounding (W/m^2.K)

k = Thermal conductivity of material (W/m.K)

h_{bt} = Sum of convective and radiative heat transfer coefficient from bottom surface to surrounding (W/m^2.K)

t = Thickness of materials (m) with subscript gyp, fg and p, gypsum, fiberglass insulation material and casing surface plate, respectively.

- ✓ Using table 3.7, thickness and thermal conductivity of materials taken and the overall heat transfer coefficient through the bottom surface to surrounding calculated.

$$\mathbf{U_{bt} = \left[\frac{t_{gyp}}{k_{gyp}} + \frac{t_{fg}}{k_{fg}} + \frac{t_p}{k_p} + \frac{1}{h_{bt}}\right]^{-1} = 15.52\ W/m^2.K}$$

The losses from the bottom surface to surrounding could be determined using the diameter of baking Mitad (0.58m) and temperature changes. $Q_{bottom,lost} = AU_{bt}(T_{bt} - T_\infty) = \mathbf{277.70W}$
To converting to energy form, multiplying the lost power by the time it takes for baking.

$$\mathbf{E_{bottom,lost} = 1900s * 277.70J/s = 527.63kJ}$$

Heat Transfer from Side

The energy lost from the side of the baking Mitad may be calculated using similar procedure with the bottom surface. The overall heat transfer coefficient could be simply calculated by using thermal resistance concept:

$$U_s = \left[\frac{t_{bm}}{k_{bm}} + \frac{t_{fg}}{k_{fg}} + \frac{t_p}{k_p} + \frac{1}{h_s}\right]^{-1}$$

Where, U_s= Overall heat transfer coefficient from side to the surrounding (W/m^2.K)

k = Thermal conductivity of material (W/m.K)

h_s= Sum of convective and radiative heat transfer coefficient from side to surrounding (W/m^2.K)

t = Thickness of materials (m) with subscript bm, fg and p, baking Mitad plate, fiberglass insulation material and casing surface plate, respectively.

- ✓ Using the similar procedures with the baking and bottom surface heat transfer analysis, the heat lost through the side calculated.

$$\mathbf{E_{side,lost} = 1900s * 60.27J/s = 114.505kJ}$$

Annex E2: Energy Loss Analysis for Conventional Electric Injera Baking Mitad

Similar procedures used to calculate the heat transfer coefficients and heat losses.
The losses from the baking surface to surrounding could be determined using the diameter of baking Mitad (0.58m) and temperature changes. $Q_{top,lost} = AU_{bs}(T_{bs} - T_{\infty}) = \mathbf{581.23\ W}$
To converting to energy form, multiplying the lost power by the time it takes for baking (3540−1260=2280 second). $\mathbf{E_{top,lost} = 2280 * 581.23\ J/s = 1,325.196kJ}$

The losses from the bottom surface to surrounding could be determined using the diameter of baking Mitad (0.58m) and temperature changes. $Q_{bottom,lost} = AU_{bt}(T_{bt} - T_{\infty}) = \mathbf{1564W}$
To converting to energy form, multiplying the lost power by the time it takes for baking.

$$\mathbf{E_{bottom,lost} = 2280s * 1564J/s = 3,565.930kJ}$$

Using the similar procedures with the baking and bottom surface heat transfer analysis, the heat lost through the side calculated.

$$\mathbf{E_{side,lost} = 2280s * 461.72J/s = 1052.729kJ}$$

Annex F: Thermal Properties of Some Selected Materials [57]

Materials	**Density, ρ *(kg/m³)***	**Specific heat, c_p *(J/kg.K)***	**Thermal conductivity, *k* *(W/m.K)***
Aluminum	2700	903	237
Asbestos	580	1050	0.16
Blanket (fiberglass)	16	800	0.046
Brick, common	1600	840	0.72
Concrete (stone mix)	2240	880	1.13
Copper	8930	385	388
Cork	160	1680	0.043
Glass, plate	2500	750	1.4
Gypsum			0.15
Hard board	840	1170	0.094
Iron	7870	447	80.2
Mercury	13,529	139	8.54
Soil	2050	1840	0.52
Steel, AISI302	8060	480	15.1
Steel, Carbon 1%	7830	460	43
Tin	227	7310	66.6
Vermiculite fill (flaks)	80	835	0.068
Water	996.5	4179	0.613

Annex G: Emissivity Values of Common Materials [56]

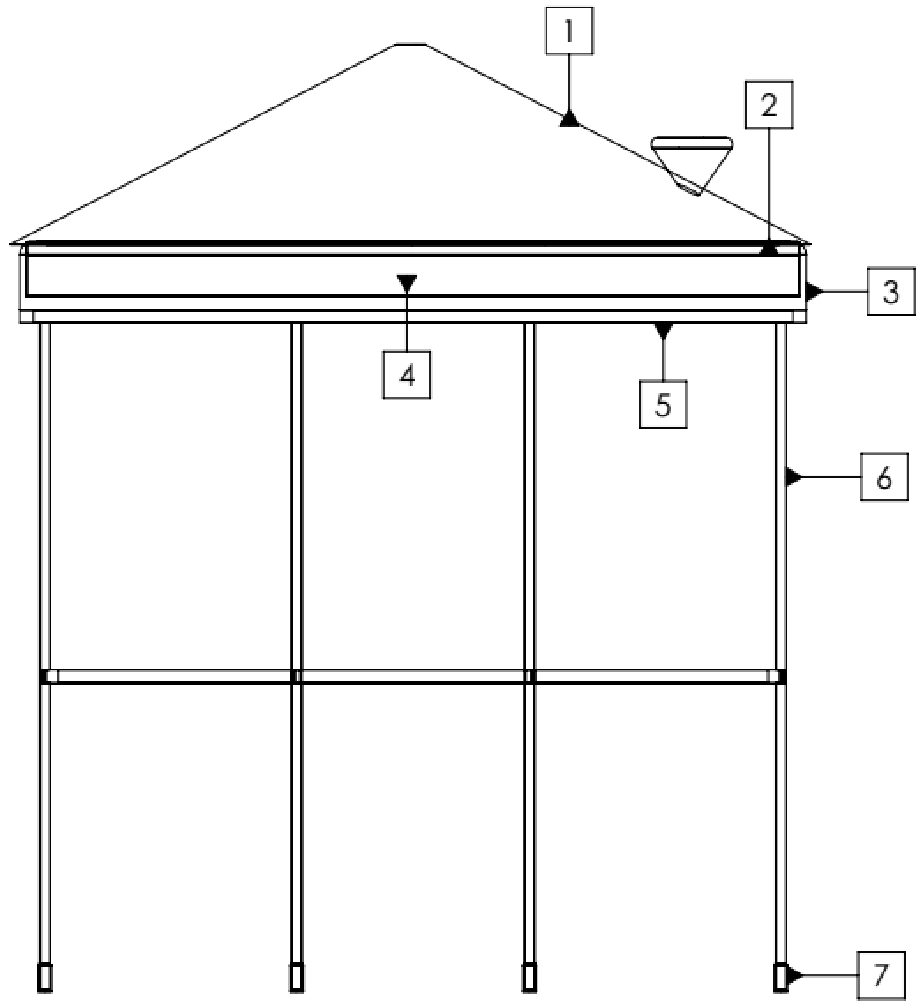
Material	Emissivity
Aluminum*	0.30
Copper*	0.95
Glass (plate)	0.85
Iron*	0.70
Lead*	0.50
Limestone	0.98
Oil	0.94
Paint	0.93
Paper	0.95
Plastic**	0.95
Rubber	0.95
Sand	0.90
Skin	0.98
Snow	0.90
Steel*	0.80
Textiles	0.94
Water	0.93
Wood***	0.94
* Oxidized ** Opaque *** Natural	

Annex H: Specification QTM-500 Quick Thermal Conductivity Meter

Type and model name	QTM-500 Quick Thermal Conductivity Meter
Precision	±5% reading value per reference plate
Reproducibility	±3% reading value per reference plate
Temperature	−10 to 200˚C (Thermal bath is necessary for measurement at different room temperature)
Measuring time	Standard 60sec (specimen must be in temperature equilibrium)
Sensor	PD-11 Box Probe Constantan heater wire and chromel-alumel thermocouple
Heater current precision	±0.1% of setup value
Display	30 digits ╳ 7 lines LCD with back light Display: Thermal conductivity: 0. ╳╳╳╳~╳╳╳. ╳W/m.K Measuring temperature: −100 to 1000 ℃ Guiding message for measurement
External communication	RS-232C 1 channel
Minimum sample required	Approx. 100(W)╳50(L)╳20(Thickness) (mm)
Measuring method	Hot Wire method
Measuring range	0.023 to 12W/m.K

Ambient condition	Temperature: 5 to 35˚C Humidity: Below 85%RH (No condensation)
Power source	100 to 240VAC, 50/60Hz
Power consumption	Approx. 60W
Dimension	Main unit: 300(W)╳475(D)╳175(H) (mm) Box probe: 100(W)╳50(D)╳100(H) (mm)
Weight	Approx. 9kg
Supplied parts	1. PD-11 Box probe 2. Probe constant card 3. Power cord with ground wire 4. Power fuse 5. Reference plate: R1-2 Clear quartz in box R2-2-silicone rubber in box R3-2-polyethylene form in box 6. Cooling plate (aluminum) 7. Brush 8. Operating manual

Annex I: 3D of Electric Injera Baking Mitad



ITEM NO.	PART NAME	DESCRIPTION	QTY.
1	ALUMINIUM LID COVER		1
2	COMPOSITE MATERIAL		1
3	SIDE COVER		1
4	INSULATION	FIBER GLASS & GYPSUM	1
5	CASING OR BODY		1
6	SUPPORTING LEG		1
7	STANDFOOT		4

Annex J: Specifications of HT-822 Non-Contact Infrared Thermometer

1. Measurement Range: −50~380℃.
2. Resolution: 0.1°C / 0.1°F
3. Emissivity: Fixed at 0.95
4. Distance Factor: Distance to Target Ratio 8:1
5. Basic Accuracy: +2% of reading or +2C/+4F
6. Response time: <1 second
7. Diode laser: Output <1mW at 630−670mm class II laser produce
8. Spectral Response: 6−14um
9. Power Supply: 9V battery, NEDA 1604A or IEC 6LR61, or equivalent