

Experimental Performance Analysis of Multi Electric Mitad Injera Baking System



Kalkidan Mekonnen Meshesha

A Thesis Submitted to the Department of Mechanical Engineering

School of Mechanical, Chemical, and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree
of Master of Science in Thermal Engineering

Office of Graduate Studies

Adama Science and Technology University

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DECLARATION

I hereby declare that this MSc. thesis entitled “Experimental Performance Analysis of Multi Electric Mitad Injera Baking System” in partial fulfillment of the requirement for the award of the degree of Master of Science in thermal engineering is my original work under the supervision of Dr. Gezahegn Habtamu.

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

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candidate

Signature

Date

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

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Date

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ACKNOWLEDGEMENT

First of all, I would like to give special thanks to God and Saint Mary for giving me patience, courage, and strength during my life. I would like to express my sincere gratitude to my advisor Dr. Gezahegn Habtamu for his valuable guidance, encouragement, and constructive comments from the beginning until the completion of this thesis. I would also like to thank Dr. Addisu Bekele for sharing his academic experience, knowledge, and guidance during my Master's study. I express my sincere thanks to Mr. Mekonen Yalelet and Mr. Dessie Tadele of the Thermal and Aerospace Engineering staff, for their outstanding suggestions and continuous inspiration during this thesis. I extend my deep gratitude to Adama Science and Technology University for allowing me to join a master's program with a full scholarship.

I express my sincere thanks to my best friend Mr. Engdaye Mersha for his encouragement, advice, and suggestion, I also like to express my special thanks to the thermo fluid lab assistant Mr. Sentayehu Shifera. I would also like to thank Mrs. Tirugenzeb Getahun for her more than expected contribution to experimental work. I also express my sincere thanks to chemical engineering department head and lab assistant Mr. Hunegnaw Baylie and Mr. Bundi Roba.

Finally, I would like to express my deep feeling of happiness to all my family especially my dad Mr. Mekonnen Meshesha, who encourages me to finish this study with full of commitment, and everyone who helped me to finish this thesis.

ABSTRACT

In Ethiopia, single clay electric injera mitad which uses 3.5 kW electric power is extensively used for baking injera by almost all urban households and it is reported to have 50 – 60% energy loss from which 35.08% is bottom loss. This single clay mitad is also time and energy-consuming for mass production. The major objective of this thesis is to design and experimentally investigate the performance of locally constructed multi mitad injera baking electric system consisting of four mitads arranged vertically in a single column stand but can be retracted horizontally in and out of the stand to do the baking processes. Numerical simulation and experimental performance investigations were done to study the performance of each mitads and when all the multi mitad were operated together. Initial heating up time, cyclic injera baking time, power consumption, heat losses of the system, energy efficiency, and effects of mitad gaps variation between consecutive mitads and varying power input were studied experimentally and numerically during the baking test (with Injera and Ambasha baking) and no-load test (no batter as load) were studied with and without lid cover cases of operation. The numerical performance was studied by deriving governing equation using conservation of energy equation and solving the resulting nonlinear coupled algebraic-ordinary differential equation using numerical iteration solution scheme for simulating closed mitad temperature responses at three different power inputs. Experimental performance test was conducted under open and closed baking doors within constant power source. Good agreement was also observed between the numerical and experimental results. The numerical result showed that the temperature for mitads 1, 2, 3, and 4 at 11 minutes of run were found to be 194,238,242 and 217 °C respectively. From the experimental studies conducted, it was observed that the temperature distribution of the mitad is uniform and the use of lid cover on each mitad reduce the heating up time by about 1 minute compared to results obtained without lid cover. The average time it takes to bake each Injera was found to be about 90 seconds with 40 seconds idle time between successive Injera. The overall efficiency of multi mitad was found to be 85.3%. In the present multi mitad injera baking system, side loss contributes about 6.44% of total loss due to larger surface area than both the top and bottom of the system, and the system can also save time consumption for injera baking for instance it takes 20 minutes to bake 20 injera with the present system, whereas the conventional system takes 78 minutes.

Keywords: Multi mitad, injera, baking temperature, heating time, load test.

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ABBREVIATIONS

T_a	Ambient temperature
T_{LC_1}	Temperature of lid cover one
T_{p_1}	Temperature of plate one
T_{LC_2}	Temperature of lid cover two
T_{p_2}	Temperature of plate two
T_{LC_3}	Temperature of lid cover three
T_{p_3}	Temperature of plate three
T_{LC_4}	Temperature of lid cover four
T_{p_4}	Temperature of plate four
m_f	Mass fraction of fat
m_s	Mass fraction of nonfat solids
m_w	Mass fraction of water
ρ_{ap}	Apparent density
ρ_t	True density

NOMENCLATURE

A	Area [m^2]
c	Heat capacity of liquid [kJ/kg.k]
D	Diameter [m]
E	Energy [kJ]
g	Acceleration due to gravity [m/s^2]
h	Convection heat transfer coefficient
h_{fg}	Heat of vaporization [kJ/kg]
I	current through the resistor (A),
k	Thermal conductivity [W/m.k]
k_i	Thermal conductivity of i^{th} phase (W/m.K)
L	Length [m]
m_t	Total mass (kg)
m	Mass [kg]
Nu	Nusselt number
P	Power [kW]
Pr	Prandtl number
Q	Heat flow [watt]
$\dot{Q}$	Rate of heat input (W)
Ra	Rayleigh number
Re	Reynolds number
R	Resistance of the resistor (Ω).
T	Temperature [$^{\circ}\text{C}$ or $^{\circ}\text{K}$]
T_{∞}	Temperature of the environment
ΔT	Temperature gradient (change in temperature) [$^{\circ}\text{C}$ or $^{\circ}\text{K}$]
V_t	Total volume of the sample including the pores (m^3)
x	Material thickness parallel to heat flow (m)
x_i	Mass or weight fraction of each food composition
β	Volumetric thermal expansion coefficient

σ	Stefan-Boltzman constant [$\text{W}/\text{m}^2.\text{K}^4$]
ε	Emissivity of a material
ρ_i	Density of each food composition (kg/m^3)
ε_i	Volume fraction of i^{th} component phase (m^3)
η	Efficiency
α	Absorbance

*All measurements indicated on the drawings are in mm.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Injera, a large pancake-like bread, is the staple food of most Ethiopian households which is served at least twice a day. Mostly Injera baking is performed traditionally by women which makes it a labor and time-consuming work. Most of the people living in Ethiopia bake injera using biomass on open-fire stoves. The inefficient open-fire stove consumes large amounts of firewood and produces high indoor air pollution and CO₂ emission (Adem and Ambie, 2017). Based on the type of energy it uses, different types of injera baking systems are found. The first type of baking method which is widely used by most of rural areas is the three stone open fire system that 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 (Byene and Koch, 2013). Because the heat is allowed to escape into the open air, three stone open fire baking have a low thermal efficiency of around 10%.

The next type of injera baking method is biomass baking system at which the heat source for baking is supplied indirectly. Unlike three stone open fire method biomass baking method uses biomass gasification process which converts solid biomass energy sources into a fuel gas. The gas phase is a combustible gas and can be used for heating source for the mitad in the injera baking process (Sutar *et al.*, 2015). Compared with a three-stone open fire Injera baking system, biomass baking system has relatively improved thermal efficiency, lesser CO emission lower heat loss and reduced particulate matter. Beside such comparable improvement, there is still a problem of heat losses from the either side of mitad resulting longer heating up time between consecutive Injera baking steps.

Solar powered Injera baking system is another type of baking method where there is no direct heat supply to baking mitad, rather the heat obtained from the sun is converted into useful heat using heat transfer fluid and uses thermal energy storage for later operation. 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 (Hassen, 2011). The drawback of such system is intermittent nature of sun which makes 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 (Tafere, 2011). The domestic tariff group (Residential households and non-commercial premises) customers of the Ethiopian electric power, which are primarily residential households, are about 2,369,619 in the year 2013. The energy consumed by the domestic customers in the same year is 2,374.6 Giga watt-hour (draft data). This constitutes about 34% of the total national energy consumption and is more than the energy sold to the commercial or the industries tariff group. Based on the Ethiopian power system expansion master plan study high case forecast, the energy consumption of the domestic tariff group increases nearly at an average rate of 9% per year (Danas, 2015).

Electric Injera mitads are the most prevalent and energy-intensive appliances used in Ethiopia and contribute to the bulk of the electrical energy consumption and power demand of the domestic tariff group. The product is believed to be in the market for over 40 years. The problems behind the use of conventional electric mitad includes overloading and frequent power interruptions, outages, and voltage drops. Its excessive energy consumption has forced the consumer and the power provider to pay for the wasted energy. The causes of the low energy efficiency of such systems are excessive heat loss from the set during operation, high heat loads, lack of standard on the product, and the traditional methods of production. The core problem of the existing electric Injera mitad is that it is energy inefficient and it takes more time for mass production of Injera. Most Ethiopian women use baking and selling Injera as a business for exporting and selling for hotels, restaurants, and shops. The injera demand for such huge business is fulfilled by using single electric mitad system as shown in figure 1.1 which is both energy and time-consuming work.



Figure 1.1 Single electrical injera baking method (Mekonnen, 2011).

Automatic Injera Lumpia Spring Roll Wrapper Machine is developed and used for mass production of injera as indicated in figure 1.2. The whole machine is made of 304 stainless steels, easy to clean and safe, with a capacity range from 500pcs/h to 9000pcs/h but it is huge, expensive and difficult to adapt for microbusiness owners (Ali, 2018).



Figure 1.2 Automatic injera baking system (Ali, 2018).

In order to solve stated problems, the present work aims to design injera baking system which consists of four different mitads arranged vertically which can minimize the amount of energy used for baking injera. The system uses the energy lost by radiation and convection from the heating of other consecutive mitads which will result a reduced time of baking and lesser human effort in Injera baking process with relatively reduced cost and overall size.

1.2 Statements of the Problem

Heat loss plays a major factor in the efficiency of electric cooking appliances. Conventional injera baking system uses single clay mitad which uses 3.5 kW electric power as input for

baking and it is reported to have 50- 60 % energy loss (Mesele *et al.*, 2017) out of it 35.08% is bottom loss (Tafere, 2011). This heat loss is considerable and could be utilized as useful heat input if another baking mitad is placed underneath the top mitad. Thus, the present work introduces a multi-electric mitad injera baking system that can minimize the amount of energy required for baking, and energy losses by radiation and convection. In addition, the system reduces human effort in the injera baking process as well as it can reduce the cost and size of baking electric mitad. In this work numerical and experimental heat transfer performance of four electric mitads arranged on top of each other are studied during baking and without baking processes.

1.3 Objective of the Study

1.3.1 General Objective

The general objective of this thesis is to develop and investigate the performance of electric-powered multi mitad injera baking system with baking mitads arranged vertically on top of each other in a single column.

1.3.2 Specific Objectives

The specific objectives of the present work are

- Analyze the theoretical performance of the multi mitad injera baking system numerically.
- To design and develop prototype of electric-powered injera baking system that can accommodate four mitads in a single column.
- Evaluating the performance of a multi mitad injera baking system with an experiment in terms of thermal efficiency, baking time, energy consumption, heat losses, and mass transfer during baking (load test) and no-load test (or without baking).
- Comparative performance analysis of single mitad with that of multi mitad system.

1.4 Significance of the Study

The present multi-electric mitad injera baking system has a number of advantages namely it can minimize the electric consumption by using the bottom loss form one of the mitad as an energy input for the other mitad underneath it. As it uses a number of mitad at a time, it can also minimize the heating up time and the time consumption for baking injera. It is made from locally available materials which makes it cost effective. Moreover, it paves a way for the design, development and improvement of multi electric mitad injera baking system.

1.5. Scope and Limitations

This study mainly focuses on experimental performance investigation of multi electric mitad injera baking system by designing each multi–electric mitad system components. The study also establishes the theoretical or numerical procedure for the design of system components. Governing equations for temperature distribution of each mitads with and without lid cover also included. In addition, experimentation to identify initial heating up time, surface temperature distribution and thermal efficiency tests were conducted. Furthermore, comparison on the multi electric system performance with and without lid cover was done. Finally, baking test or load test (and also no-load) and economic analysis for the developed prototype of the multi electric mitad injera baking system were performed. The major limitation of the present study is absence of temperature sensor to automatically sense and give alarm to guide the baking process and the self-switching of the breaker during long time operation.

1.6 Organization of the Study

This thesis is composed of seven chapters. After the previous chapter introduces the concept of Injera, Injera baking systems, and source of energy for Injera baking, a literature survey, thermo-physical properties of Injera and Injera baking mitad was presented in chapter two with its summary. The third chapter presents the material and methodology section of the work followed by chapter four which presents the Heat transfer analysis and theoretical design and sizing of system components for individual performance investigation. Then, the fifth chapter describes the conceptual design, construction process, and the experimental setup of the prototype. Chapter six presents the major findings and results of the experimental analysis conducted with their implication. The last chapter includes the conclusion of the whole work and recommendations for further study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This section presents the thermophysical properties of injera, detail description of different types of injera baking methods such as firewood, biomass gasifier, solar-powered and electric Injera baking systems. The chapter also includes the mechanisms of heat transfer in

to the baking mitad and method insulating and insulating material types. Finally, previous related research works on electric Injera baking mitad and summary of all the literature and its gap is also included.

2.2 Thermophysical Properties of Injera

Thermo-physical properties of foods are important for modeling and optimization of processes involving heating and cooling. The properties used in a mathematical model of heat transfer are usually thermal conductivity, specific heat, and density. Improved knowledge of these thermophysical properties of foods is essential in accurately predicting 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; and the combination of these three properties, thermal diffusivity, is a key property in the analysis of transient heat transfer. In the past years, much researches have been involved to determine the thermophysical property of different food kinds like: soybean (Shahin *et al.*, 2008), chickpea (Nalaini, 2005), bread dough (Tong and Lund, 1993), Indian flatbread (Gupta, 2001) and cereal flours (Gonul, 2007).

Generally, the thermo-physical properties of food depend 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. This value is clearly some function of those of the components (Shaifur, 1995). The percentage composition of the major components of fermented cereals is given in the FAO report (1982). Figure 2.1 depicts the percentage composition of teff Injera.

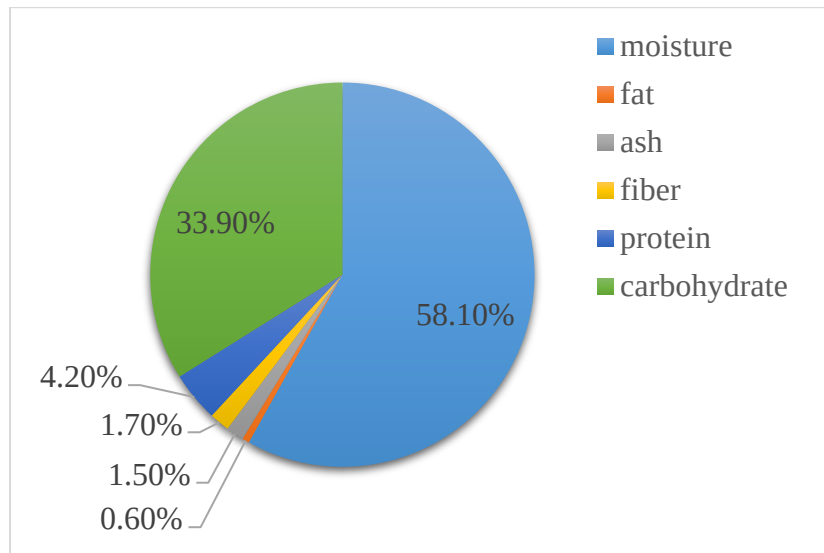


Figure 2.1 Percentage composition of injera (FAO, 1982)

Thermo-physical properties of foodstuffs can either be obtained experimentally or using analytical methods based on composition. In this study, the analytical method based on composition will be used for the determination of the thermo-physical property of Injera. The analytical method uses composition data in conjunction with temperature-dependent mathematical models of the thermal properties of individual components.

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

$$c_p = \frac{Q}{m\Delta T} \quad 2.1$$

The empirical expression is based on experimental data for high moisture foods, and it is anticipated that the coefficient within the expression vary with temperature. This relationship expanding on the dependence of the specific heat of a food composition was suggested by Leninger and Beverloo (1975) as follows:

$$C_p = (0.5m_f + 0.3m_s + m_w) \times 4.18 \quad 2.2$$

Where; m_f =mass fraction of fat, m_s = mass fraction of nonfat solids and m_w = mass fraction of water and references the specific heat of water 4.18kJ/kg at 20°C; and a very similar relationship was suggested by Charm (1978)

$$C_p = 1.094m_f + 1.256m_s + 4.187m_w \quad 2.3$$

The charm equation uses the specific heat of water at 75°C and the coefficient for the fat and non-fat solids are the same as with the above equation, when the temperature is adjusted. Batter and Injera are a multi-phase and multi component system, mainly composed of proteins, lipids, carbohydrates, water and ash. The specific heat of the food can be predicted in most cases accurately from the chemical composition of the major food components weighted by the mass fractions (Choi and Okos, 1986).

$$c_p = \sum_{j=1}^n x_j c_{pj} = x_w c_{pw} + x_p c_{pp} + x_f c_{pf} + x_c c_{pc} + x_a c_{pa} + x_{fib} c_{pfib} \quad 2.4$$

Table 2.1 Determination of specific heat of major components of injera

Constituents	Composition % (x_j)	Specific heat J/kg.k ($x_j c_{pj}$)
Carbohydrate	0.339	$0.339(1.5488+1.9625 \times 10^{-3}T-5.9399 \times 10^{-6}T^2)$
Protein	0.042	$0.042(2.0082+1.2089 \times 10^{-3}T-1.3129 \times 10^{-6}T^2)$
Fat	0.006	$0.006(1.9842+1.4733 \times 10^{-3}T-4.8008 \times 10^{-6}T^2)$
Fiber	0.017	$0.017(1.8459+1.8306 \times 10^{-3}T-4.6509 \times 10^{-6}T^2)$
Ash	0.015	$0.015(1.0926+1.8896 \times 10^{-3}T-3.6817 \times 10^{-6}T^2)$
Moisture	0.581	$0.581(4.1762-9.0864 \times 10^{-5}T+5.4731 \times 10^{-6}T^2)$

Based on the model in table 2.1 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:

$$c_p = \sum_{j=1}^n x_j c_{pj} = 3095.4 + 7.3158 \times 10^{-4} T + 9.4806 \times 10^{-7} T^2 \quad 2.5$$

Equation 2.5 implies the specific heat capacity value depends on the average Injera baking temperature. The variation of specific heat with baking temperature is presented in figure 2.2.

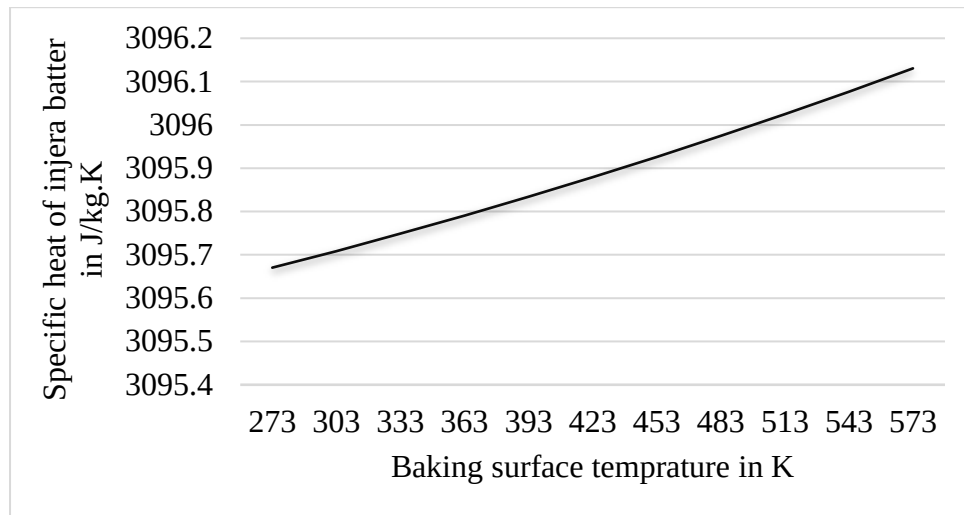


Figure 2.2 Specific heat of injera batter with baking surface temperature variation

2.2.2 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.

$$\rho_{ap} = \frac{m_t}{v_t} \quad 2.6$$

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

$$\rho_T = \frac{m_t}{v_p} \quad 2.7$$

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.

$$\rho = \frac{1}{\sum_{i=1}^n \frac{x_i}{\rho_i}} \quad 2.8$$

An empirical relation for the determination of density of major food components as a function of temperature is given in table 2.2.

Table 2.2 Density of major components of injera

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

Therefore, the density of Injera at the average baking temperature can be expressed as;

$$\rho = \frac{1}{\sum_{i=1}^n \frac{x_i}{\rho_i}} = 1160.55 \text{ kg/m}^3 \quad 2.9$$

2.2.3 Thermal Conductivity (k)

Thermal conductivity is a basic thermophysical property of any material. It represents the quantity of heat” Q” that flows per unit time through a unit thickness and unit area having unit temperature difference between faces; and its SI unit is [W/m. K].

$$k = \frac{\dot{Q}x}{A\Delta T} \quad 2.10$$

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 (Rahman, 2005).

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:

$$k = \frac{1}{\sum_{i=1}^n \frac{\varepsilon_i}{k_i}} \quad 2.11$$

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:

$$k = \sum_{i=1}^n \varepsilon_i k_i \quad 2.12$$

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

$$\varepsilon_i = \frac{\frac{x_i}{\rho_i}}{\sum_{i=1}^n \frac{x_i}{\rho_i}} \quad 2.13$$

Table 2.3 and 2.4 shows an empirical relation for the determination of thermal conductivity and volume fraction of major components of Injera respectively. Determination of thermal conductivity of major components for the parallel model, the sum of individual component thermal conductivity as shown in table 2.5.

Table 2.3 Models for thermal conductivity of major components of foods

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

Table 2.4 Volume fraction of major components of injera

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

Table 2.5 Determination of thermal conductivity of major components for the parallel model

Constituents	ε_i	$\varepsilon_i k_i$
Carbohydrate	0.24800	$0.0499 + 3.4408 \times 10^{-4}T - 1.0741 \times 10^{-6}T^2$
Ash	0.00723	$2.3828 \times 10^{-3} + 1.0129 \times 10^{-5}T - 2.1014 \times 10^{-8}T^2$
Fiber	0.01500	$2.7649 \times 10^{-3} + 1.8746 \times 10^{-5}T - 4.7525 \times 10^{-8}T^2$
Fat	0.00772	$1.3806 \times 10^{-3} + 2.1302 \times 10^{-6}T - 1.3697 \times 10^{-9}T^2$
Protein	0.03748	$6.7018 \times 10^{-3} + 4.4819 \times 10^{-5}T - 1.0186 \times 10^{-7}T^2$
Moisture	0.68353	$0.57109x_w + 1.7625 \times 10^{-3}Tx_w + 6.7036 \times 10^{-6}T^2x_w$
$k = \sum_{i=1}^n \varepsilon_i k_i = 0.0631 + 0.57109x_w + 4.2999 \times 10^{-3}T + 1.7625 \times 10^{-3}Tx_w$ $- 1.2459 \times 10^{-6}T^2 + 6.7036 \times 10^{-6}T^2x_w$		

The final equation of K 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 as indicated in table 2.6.

Table 2.6 Determination of thermal conductivity of major components for the series model

Constituents	Composition% x_i	ε_i	k_i	ε_i/k_i
Carbohydrate	0.339	0.24800	0.38466	0.6447
Protein	0.042	0.03748	0.35358	0.106
Fat	0.006	0.00772	0.29636	0.026
Fiber	0.017	0.01500	0.36346	0.0413
Ash	0.015	0.00723	0.49789	0.0145
Moisture	0.581	0.68353	0.69775	0.9796
$\sum_{i=1}^n \frac{\varepsilon_i}{k_i} = 1.8122 \text{ W/m.K}$				

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.

2.2.4 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 (Vincenzini, 1991):

$$\alpha = \frac{k}{\rho c_p} \quad 2.14$$

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 $1.53 \times 10^{-7} \text{ m}^2/\text{s}$. The thermo-physical property of baking pans: thermal conductivity, specific heat, and density are obtained from literatures.

✓ Property of clay baking pan:

$$k = 0.5 \frac{\text{W}}{\text{m}} \cdot k \quad c_p = 830 \frac{\text{J}}{\text{kg}} \cdot k \quad \rho = 1900 \frac{\text{kg}}{\text{m}^3}$$

2.3 Injera Baking Method

Injera will continue to be the staple food for Ethiopians and Eritreans and some parts of east Africa in years to come. To efficiently bake, Injera using various types of stoves, research, and development work for Injera baking have been conducted so far and is critical. The use of energy sources is dominantly biomass is used for Injera baking followed by electricity yet (Mulugeta, 2020). Based on the type of energy used to bake Injera, different types of baking Mitads were developed for baking Injera. The heat supplied to the baking Mitad comes from either burning firewood, cattle dung, or agricultural residue in biomass, solar energy, and electrical power.

2.3.1 Baking Using Open Fire System

Baking Injera Using an Open Fire System in most of the households of the country, traditional baking is carried out using an open fire (three stone, “Gulecha”) baking system and the fuel is biomass. The heat supplied to the mitad in this system is lost through a variety of paths such as: through the sides, through the exhaust gases from the fuel, through convective and radiative heat losses from the pan surface. The fraction of energy that flows into the Injera batter is very limited and therefore this technique is inefficient and wasteful; and also, is unhealthy because of carbon inhalation to the lungs and irritation of the eyes (Mekonnen, 2011).



Figure 2.3 Open fires (gulecha method) injera baking system (Berhanu *et al.*, 2022)

Drawbacks of three stone Injera baking includes but not limited to:

- It uses biomass (wood or animal dung) it has a contribution to deforestation and limits the advantage of dung as plant fertilizer.
- It also produces smoke and results in pollution and it causes health disorders because of carbon inhalation to the lungs and irritation of the eyes.
- Being inefficient and wasteful.

Lucas *et al.* (2012) studied the analysis of wood-fired bakery ovens' baking process and its wood consumption. Thus, the specific firewood consumption of both indirect and semi direct bakery ovens was found to be 0.55 and 0.90 kg of wood per kg of wheat flour baked, respectively.

2.3.2 Miret Mitad Injera Baking System

Patel (2020) reported that manufactured miret stoves from cement and local aggregates such as sand panels or the oven can be made by pressing clay around the mold. This stove is suitable for mass production by casting light concrete. Each Miret saves approximately 10 kg of wood per Injera baking session for an average household. Most household bakes Injera twice a week. Thus, the Miret saves at an average per household nearly 1040 kg of wood per year. This is a significant saving for the average Ethiopian urban household. However, the Miret saves commercial Injera bakers over 3.5 tons of fuelwood per year. Even though the Miret stove is better and efficient compared to the open fire baking system; it has the following drawbacks:

- Since it uses biomass (wood or animal dung) it has a contribution to deforestation and limits the advantage of dung as plant fertilizer.
- It may also produce smoke and may result in producing pollution if baking is in the door.



Figure 2.4 Miret injera baking mitad (Yosef, 2007).

2.3.3 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 gas and solid phases. The gas phase is a combustible gas and is used for power generation or biofuel production. The combustible gas produced, when using air as a gasifying agent, consists mainly of CO, H₂, CH₄, CO₂, and N₂. The solid phase includes char and the inert material present in the biomass (Bhattacharya *et al.*, 2005). 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 were reduced. Still, there is the opportunity for improvement for further reducing the heat losses from the Mitad, initial heat-up time baking system (Kamil *et al.*, 2019).

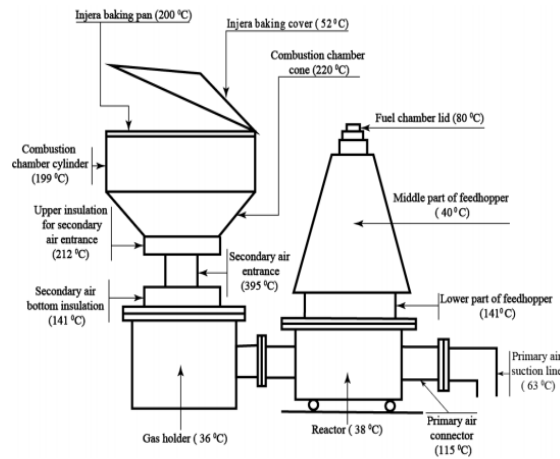


Figure 2.5 Measured surface temperature of injera baking gasifier stove at steady state working condition (Kamil *et al.*, 2019).

2.3.4 Solar Injera Baking System

Mekonnen (2011) presented a solar-powered Injera baking oven, so as to avoid the problems that are caused due to burning of fossil fuels and to assure environmental sustainability. The system uses an electrical heater to heat the heat transfer oil to the required temperature, and then the heated oil is pumped to the baking pan assembly to heat the pan surface and re-circulates in the system using an electrically driven pump. To protect heat loss; an ash insulation system for the heat transfer oil gallery, the oil storage and heating tank, and fiberglass insulation for the piping lines are used. The baking pan surface temperature in the experiment was measured and a temperature of about 215°C on the pan surface was registered; so that it was possible to bake Injera. But the baking cycle needs five minutes.

Asfaw *et al.* (2014) introduced new technology that enables Injera baking using an indirect solar stove. A parabolic dish with an aperture area of 2.54 m², a well-insulated stainless-steel pipe of 10 mm, a coiled stainless-steel heat exchanger, a pressure relief valve, and three gate valves were equipped in the system and K-type thermocouples were used to record the temperature. In the experiment, heat transport without significant loss from the receiver for baking at some distance is demonstrated. In conclusion, unlike previous efforts, the experiment demonstrated that high-temperature indirect baking of Injera is possible.

Hassen *et al.* (2011) proposed, the performance of a solar-powered Injera baking oven, where heat energy is transported to the kitchen by means of a heat transfer fluid as indicated in figure 2.5. The ash insulation used for most of the components is found to be a very effective insulator. The experimental result, showed that it took approximately 1 hour for heating oil to 300° C and 40 minutes to reach the optimum baking surface temperature. Injera is removed

from the baking pan every two minutes and it takes an idle time of three minutes between each Injera to recover to optimum baking temperature. Based on the average family size, 20 Injera can be baked per day in approximately three hours and 28 minutes.

The drawbacks of solar Injera baking system includes: -

- Longer startup heating time.
- Time-consuming and many component-integrated systems.
- The system works only during the sunshine hours and has intermittent nature.
- Requires a high initial investment.

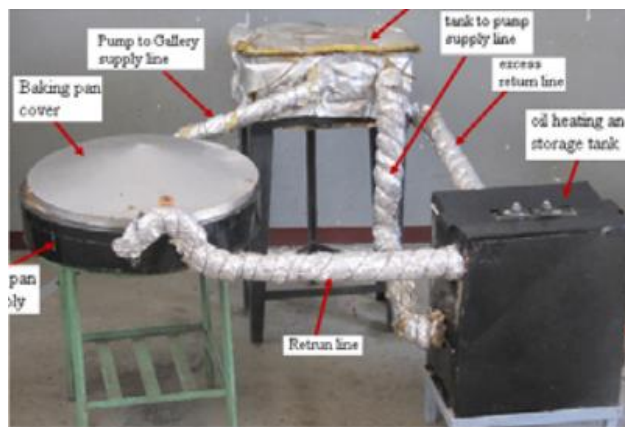


Figure 2.6 Main components of the solar injera baking laboratory model (Hassen *et al.*, 2011).

2.3.5 Electric Injera Baking System

Getnet (2011) experimentally investigated the results of electric Injera baking mitad with a clay pan (thickness 20 mm) and ceramic pan (thickness 8 mm). The comparative result showed that thermal efficiency of clay baking mitad and ceramic plate baking mitad was found to be 53% and 66% respectively. Experimental test on the mass balance of batter and Injera shows that Injera baked with 0.02 conventional clay baking pan has more loss of weight than Injera baked with 0.008 ceramic baking pan. The result showed that the utilized energy by the ceramic baking pan is smaller than the conventional clay baking pan.

Berhanu *et al.*, (2022) proposed, the improvement of an electric Injera baking Mitad using copper powder as an additive material. The initial heating time required to reach the baking surface temperature, 200°C was about 11 and 21 minutes for the improved and conventional baking Mitads, respectively. Using composite materials instead of clay reduces the initial heating time, i.e., it reduces the energy consumptions and increases efficiency. The heating

rate of the baking Mitad was found to be 15.6°C/min and 8.2°C/min for the improved and conventional baking Mitads, respectively.

Garedewu (2011) investigated the parameters which affect the efficient and reliable operation of the bakeware and identified that the heat capacity, thermal conductivity and the density are more significant in determining the heat flow characteristics; the efficiency and the cooking quality of the product. The energy consumption for 10 cycles of Injera baking was calculated from measured current flow and voltage values, the result indicated 1.996 MJ/kg of total energy intensity, which is comparably close to the value of the conventional clay mitad. The possibility of baking at a reduced surface temperature of 147 to 150 °C makes the ceramic bakeware preferable and the larger heat up time required becomes insignificant for larger cycles of baking; so, the result concluded that ceramic bakeware can be a suitable alternative to the conventional clay bakeware for Injera baking applications.

Yesehak (2019) on the other hand proposed a baking machine which integrate the dough preparation and the baking operations to work simultaneously for continuous Injera production as shown in figure 2.6. The dough was prepared in a mixer container which is connected to a baking conveyor unto which the precise quantity of dough is squeezed onto the baking chamber through the conveyor. The baking conveyor is controlled to operate in steps with controlled speed and appropriate delay for Injera to bake, which is achieved by using a stepper motor with a control unit. The component design and the assembly have been done by CATIA and the real-time simulation has been performed by ANSYS. The machine is highly recommended to save energy, minimize individual energy bills per month and minimize operation costs of hotels and restaurants.

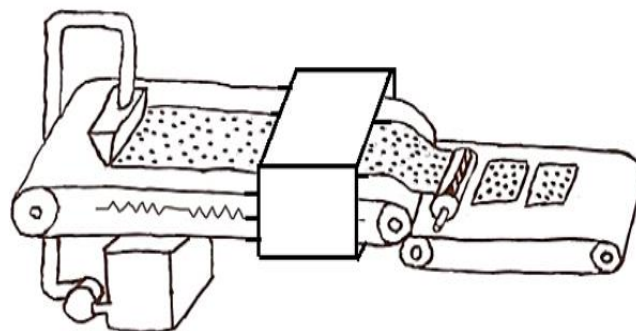


Figure 2.7 Baking design concept (Yesehak,2019).

Double sided electric injera mitad was design by Mesele *et al.* (2017). In the design, two mitad plates one over the top of the other is allowed to rotated 180° as shown in figure 2.7

and the batter will be poured on either of the mitad. The result showed that the system reduced baking energy consumption and time by 50%.



Figure 2.8 Double sided electric injera mitad (Yesehak, 2019).

2.4 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 (Kreith *et al.*, 1999).

2.4.1 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 stovetop cooking, where heat is conducted from the heat source, gas flame or electric coils directly to the bottom side of the pan. Conduction continues as heat passes through the pan to the food from the baking pan. Even after the pan is removed from the heat, conduction continues until the pan and the food reach the same temperature.

$$Q_c = \frac{kA(T_{pb} - T_{pt})}{x} \quad 2.15$$

2.4.2 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.

$$Q_F = hA_p(T_{bs} - T_{lc}) \quad 2.16$$

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

2.4.3 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 Kelvin, all substances emit electromagnetic radiation. In contrast with conduction and convection, heat transfer by radiation does not require the presence of a material medium. The hot mitad 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.

$$Q_r = (T_{bs}^4 - T_{lc}^4) \quad 2.17$$

2.5 Insulation and Insulating Materials

Insulation is defined as a material or combination of materials, which retard the flow or loss of heat and is used in heating, air conditioning, and refrigeration systems. Use of 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. Most insulation is used to prevent the conduction of heat. In some cases, radiation is a factor. A good insulator is obviously a poor conductor. Less dense materials are better insulators. The denser the material, the closer its atoms are together. That means the transfer of energy of one atom to the next is more effective. Thus, gases insulate better than liquids, which in turn insulate better than solids.

2.5.1 Advantages of Insulation Systems

The following are the basic advantages of insulating systems (GSU, 2005; Molla, 2020):

- **Energy Savings:** Significant quantities of heat energy are wasted because of un-insulated heated surfaces. Properly designed and installed insulation systems will immediately reduce the need for energy and benefits to the industry include enormous cost savings, improved productivity, and environmental quality.
- **Process Control:** By minimizing heat loss or gain, insulation can help maintain process temperature to a pre-determined value or within a predetermined range.
- **Personnel Protection:** Thermal insulation is one of the most effective means of protecting workers from burns resulting from skin contact with surfaces of hot surfaces and equipment working at higher temperatures. Insulation minimizes the surface temperature of piping or equipment to a safer level, consequential in increased worker safety and the avoidance of worker downtime due to injury.
- **Fire Protection:** Used in combination with other materials, insulation helps provide fire protection in fire stop systems designed to provide an effective barrier against the spread of flame, smoke, and gases at penetrations of fire resistance rated assemblies by ducts, pipes, and cables.

Desired properties of insulating materials to be considered during the selection of insulation materials include;

- Non-toxic, non-flammable,
- Non- corrosive and
- Low thermal conductivity

2.6. Factors Affecting Performance of Electric Mitad

- Absence of standard on the sizes of Injera Mitad, electrical heating elements(Resistors) and the method of installation,

Different sizes of electric Injera Mitad are produced. Size ranges from 40 Cm diameter to 60 Cm diameter. There is different level of power requirement for the different sizes of the clay plates. As size increases heat requirement increases. However, similar sizes of heating elements are used for clay plate sizes starting from 56 to 60 cm resulting in high or low heat responses.

- Type of insulating material,

In an electric injera baking mitad, there is always a heat loss from, bottom, side and top of the mitad. Major heat loss occurs at the bottom of the clay plate in a form of convection and radiation. Those heat losses result in reduced efficiency for the mitad. To reduce such losses heat insulation is commonly made using either of Pumice, Sandstone, Gypsum and mixture of soil. The thermal conductivity of pumice and sandstone, Gypsum is relatively high.

- Heat loss during overheating of the Mitad

While baking Injera the electric mitad will overheat if no temperature regulating devices are installed on the system to control overheating. Traditionally those overheating and underheating conditions are managed through manual observation and the effects on the baked Injera. Unless controlled, unnecessary wastage of energy will occur which in turn result in performance reduction in the system.

- Proportion of clay to sand ratio,

Proportion of sand to clay ratio is the main factor for uniform temperature distribution. Thus, if the temprature distribution is un-even the performance of mitad will decrease.

- Absence of uniformity in placing electrical resistor in clay plate,

Resistor is placed in spirally made grooves at the bottom side of the clay plate in the case of the single clay type. After the resistor is placed, the groove is sealed with Gypsum material. There is no uniformity or accepted standard adhered to in fixing the clay plate thickness and the size and depth of the grooves. Deep groove leads to overheating as the resistor will be closer to the baking surface whereas shallow groove makes the clay plate unresponsive to the heat applied. Besides groove spacing used among producers is different. Spiral grooves from 12 to 14 circles are practiced. More number of spiral grove circles lead to heat uniformity across the clay plate.

- Groove depth,

The physical dimension of groove depth on conventional electric mitad done by hand with out standard so the depth of the groove have effect on the performance of electric mitad.

- Insulation thickness,

The insulation thickness of conventional electric mitad is not saintific they use insulator by gussing so it has effect on the performance of electric mitad, the thicker the insulation, the

lower the heat transfer rate. This is expected, since the heat transfer area A is constant, and adding insulation always increases the thermal resistance of the wall without increasing the convection resistance.

2.7 Limitations on Existing Electric Injera Mitad

The Existing Electric Injera Mitad technology is believed to be in the market for over 40 years. The performance efficiency is on the lower side and the product has not been standardized so far. The electric Injera Mitads, the majority of which are rated at 3.7 to 4.0 kW power, are estimated to constitute about 60 % of the power demand of a typical residential household. It is customary to see the dimming of light bulbs, lessening of power level, and the high level of steam and heat generated while Injera is baked. Other electrical devices like stoves and water heaters will not be turned on once Mitads are in operation. Electric Injera Mitads contribute to the bulk of the electric power demand and consumption of a typical residential household and the nation.

The core problem of the existing electric Injera Mitad is that it is energy inefficient. The causes of energy inefficiency are mainly attributed to the high amount of electrical energy needed to heat up to the set temperature of about 200 – 250°C required to bake Injera. This high energy requirement is due to high heat load (parts of the Mitad to be heated up), heat losses, poor heat insulation, and the method of producing the Mitad. And most of the existing electric mitads are single clay electric mitads that are used for households but doing business of exporting and selling Injera by single clay mitad consumes more energy and time. Therefore, to reduce the problems associated with using biomass, solar-powered Injera baking, and Injera baking using existing electric mitad, baking electric mitad design is expected in this study.

2.8 Summary of Literature and Research Gap

Different injera baking methods were studied with different source of energy like wood, biogas, solar and electric energy by previous researches as discussed. The reviewed literature covered the performance investigation on mitads powered by solar energy, biogas and electric. These different pervious works are summarized as follows:

- The system uses an electrical heater to heat the heat transfer oil to the required temperature, and then the heated oil is pumped to the baking pan assembly to heat the pan surface and re-circulates in the system using an electrically driven pump (Mekonnen,2011)

- Introduced new technology that enables Injera baking using an indirect solar stove (Asfafaw *et al.*, (2014))
- The performance of a solar-powered Injera baking oven, where heat energy is transported to the kitchen by means of a heat transfer fluid is investigated (Hassen *et al.*, 2011)
- This experimental investigation results of electric Injera baking mitad with a clay pan (thickness 20mm) and ceramic pan (thickness 8mm) have been compared (Getnet, 2011)
- The improvement of an electric Injera baking Mitad using copper powder as an additive material (Berhanu *et al.*, 2022)
- The parameters which affect the efficient and reliable operation of the bakeware and the stove were investigated and simulated (Garedewu, 2011)
- The proposed machines have been achieved by integrating the dough preparation and the baking operations to work simultaneously for continuous Injera production (Yesehak, 2019)

In literature survey, both conventional single electric mitad and modified electric mitad has been reviewed. Most of the literatures associated with conventional single mitad system showed that those systems are easy to construct, maintain and less expensive. However, such systems have both convective and radiation loses where considerable heat loss is present which makes those system inefficient. Comparatively, literature showed that modern automatic injera baking system have mass production ability but they are relatively more expensive to be afforded by private microscale business owners.

Reviews of literatures indicated that considerable efforts have been invested in research and development of different injera baking mitads powered by electricity. Most of the literatures focuses on the performance investigation of single clay electric mitad. However, limited research works were reported on performance investigation of multi injera baking mitad. Furthermore, those limited works in literature focuses only on energy efficiency of the systems whereas works on heat loss reduction and mass production of injera have given lesser attention. Thus, the present work aims to design multi mitads arranged vertically for mass production of injera and using the bottom loss of the top mitad as an input heat for another mitad underneath it.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

The present study applies theoretical and experimental analysis as the main approach which is used as a methodology. In this section the research design techniques, process model, different data sources and collection methods, material and equipment used, and experimental data presentation and analysis methods which will be employed for experimental investigation and performance evaluation of the present baking electric mitad are presented.

3.2 Materials and Equipment

Materials, measuring devices, and system components required for developing the experimental prototype and measuring the system parameters are obtained by purchasing from the local market in Adama and Addis Ababa cities (Ethiopia). Materials used to construct the experimental setup were selected based on local availability and cost-effectiveness. The main materials and measuring devices used in the experiment are presented.

Materials;

- Aluminum sheet: used for constructing the lid cover.
- Sand and clay: used for constructing baking pan.
- Ash and fiberglass: used as insulating material to prevent bottom and side losses.
- Nichrome resistance wire: used to input power to the baking Mitad.

Measuring Instruments

- Weight Balance: used for measuring the weight of the batter and weight (difference) loss of Injera sample after baking.
- Infrared thermometer: used to measure the baking pan surface temperature.
- Thermocouple: used to measure temperature.
- Multi meter: used to measure power.

3.3 Methodology and Research Design

The procedures of the research are mixed analytical and experimental research design where both qualitative and quantitative research techniques are employed. The baking electric mitad is evaluated based on the existing hypothesis and experiential testing of the hypothesis. The general process layout of the methodology followed in the research is presented in figure 3.1.

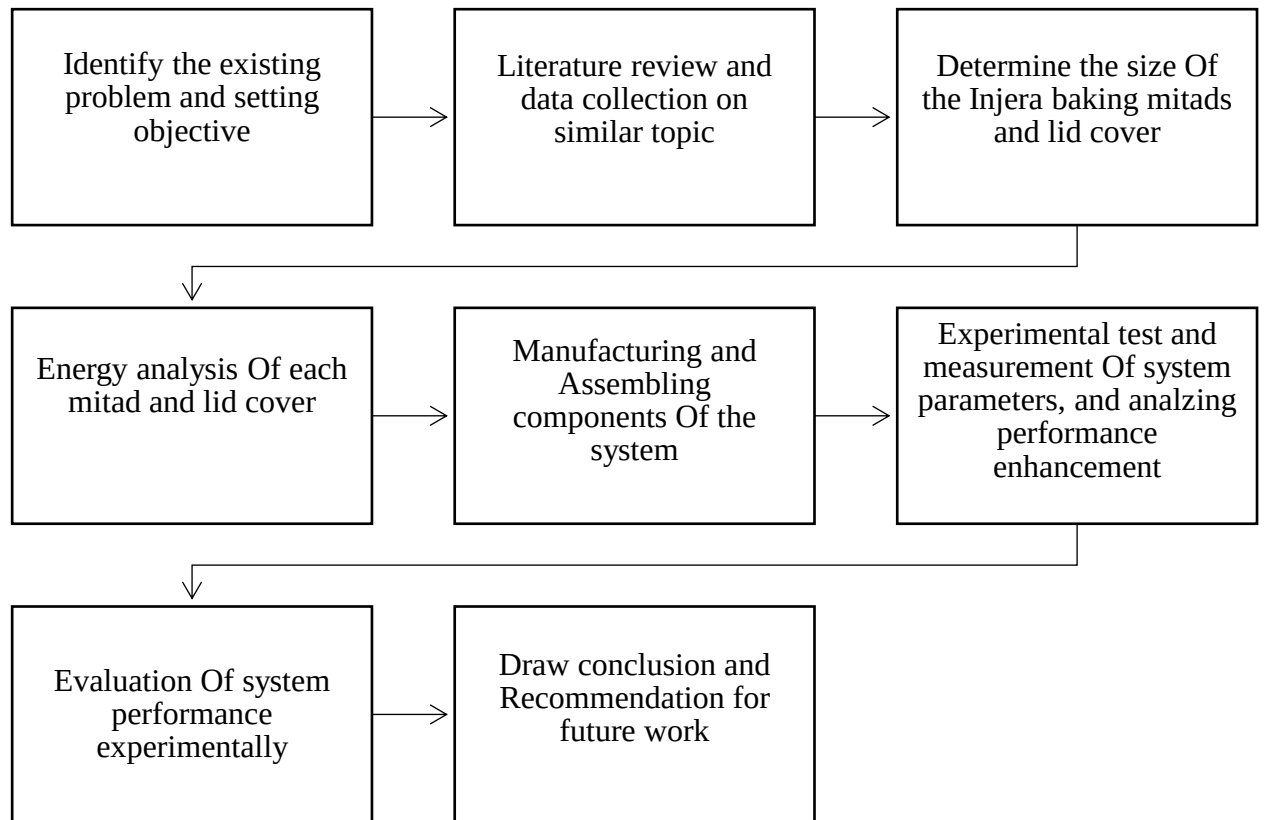


Figure 3.1 Methodology of the study.

3.4 Data Collection Method

The data required for the whole work is obtained from both primary and secondary sources of data. The primary data sources would be taken by direct measure of temperature such as the ambient temperature of the air, temperature of baking mitad and temperature of lid cover. Secondary data are obtained from different sources on the internet such as books, documents from websites, literature from local and international journal articles, and data from the deep literature reviews.

In this thesis Excel (spreadsheet) is the basic software that is used as a data storage, estimation, analysis, and interpretation tool for the temperature variation and timely varying measured parameters during the experimental tests.

CHAPTER FOUR

NUMERICAL HEAT TRANSFER STUDY OF THE BAKING MITADS

4.1 Introduction

In this chapter energy balance equation was determined numerically for all mitads with and without lid cover. Generally, heat can be lost in three directions of the baking mitad. Those are bottom, lateral and top directions of the mitads which energy dissipates to the environment (or surrounding). injera baking mitad use all three fundamental heat transfer modes; free convection, conduction, radiation, and various combinations. The bottom surface of Injera is heated mainly through conduction and only a little part of the heat is transferred to its upper surface by means of convection and radiation mechanism.

4.2 Power Estimation and Distribution in Injera Baking Electric Mitad

Electric power is the source of power for conventional electric baking mitads. The electric power is converted into heat energy using resistors inserted on grooves at the back side of the mitad. The power developed in the resistor can be obtained from equation 4.1, and varies depending on the material type and size (diameter and length) of the resistance wire used. For higher power consumption a resistance wire with larger diameter and longer length is required.

$$P = I^2 \times R \quad 4.1$$

The resistors used in heating applications are almost exclusively metallic. Such materials as platinum, tungsten, and alloy of nickel, iron, and chromium are commonly used. Local electric pan manufacturers use R08, and R09 types of resistors made of nickel-chromium alloys. The existing type of electric baking pan uses 3W power source and has 12 loops of resistors (Tafere, 2010). The power estimated for R-07, R-08, and R-09 resistors for stretched length of 10, 11, and 12 is 1.867, 2.2 and 2.5 W respectively (Tafere, 2010).

4.3 Energy Required for Injera Baking

Baking Injera requires intensive energy and this energy can be defined as the energy necessary to raise the batter to a particular temperature, and evaporate the amount of water that is to be lost during the baking process. To measure the energy utilized in cooking Injera, the initial mass of batter, and the total amount of Injera produced from this batter were measured. Thus, the mass of water vapor can be obtained by reducing the mass of the Injera

produced from the initial mass of batter. It is assumed that the energy utilized in cooking the Injera is the energy required in raising the temperature of the batter from room temperature to the boiling point of water which is called sensible heat, plus the energy required to evaporate water which is called latent heat. It is also assumed that the heat capacity of Injera batter is the same as that of water in order to calculate the energy required to raise the batter temperature to boiling point. The following assumptions are made in order to calculate the amount of utilized energy by a baking mitad (Ezana *et al.*, 1999):

- The average mass of injera and moisture loss for every single injera is constant.
- The heat capacity of the batter is nearly equal to the heat capacity of water.
- The difference in weight between the baked injera and the initial batter is equal to the weight of moisture loss during baking.

Applying the above assumptions, the utilized energy can be obtained from the following equation.

$$E_{utilized} = m_{batter}C_{p\ water}(T_{boil} - T_{room}) + (m_{batter} - m_{injera})h_{vaporization} \quad 4.2$$

4.4 Theoretical Design of the Multi Electric Mitad System Components

This section briefly describes the design and sizing of components of injera baking electric mitad system while SOLIDWORKS is employed as a modeling software.

4.4.1 Lid Cover

To protect heat loss from injera during baking, lid cover is required. The dimension for the lid cover is obtained from the dimension of conventional electric mitad covers available in the market. figure 4.1 shows the selected lid cover dimension for the present work.

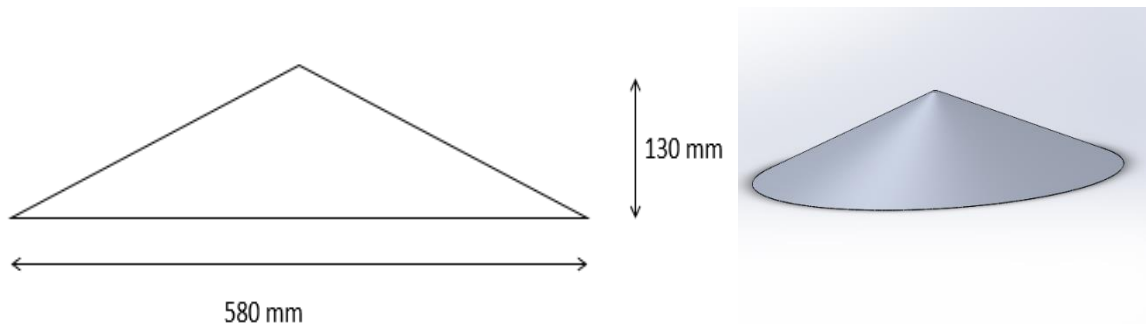


Figure 4.1 a) Dimensions of lid cover b) 3D model of the lid cover

4.4.2 Baking Mitad

A baking pan is a flat circular pan commonly about 50 to 60cm in diameter and traditionally used over large clay hearths to bake injera (Mekonnen, 2010). The selected dimension of baking plate for the present work was 1 cm thick and 58 cm diameter. As figure 4.2 the dimension of the baking mitad was similar with conventional one found in the local market.

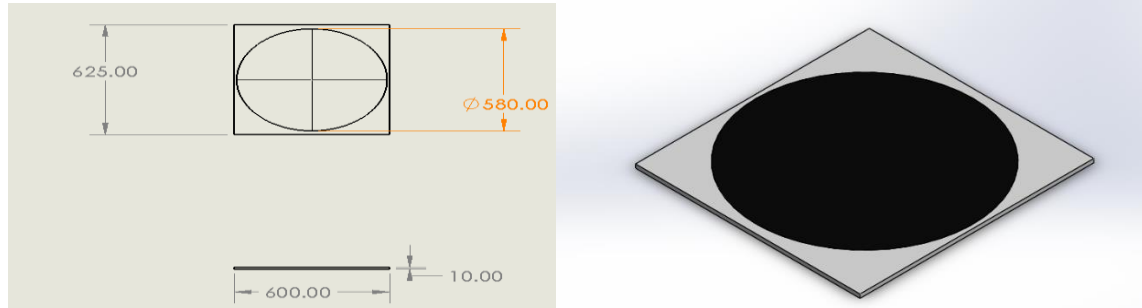


Figure 4.2 a) Dimension and b) 3D model of baking mitad

4.4.3 Cuboidal Housing

The cuboidal housing is used to support and enclose mitads arranged vertically in a single column and used to reduce heat loss from consecutive mitads. This cuboidal housing intended to reduce the waste heat and reuse it as a heat source for the other consecutive mitads. figure 4.3 depicts the dimension of the selected cuboidal housing and it was designed in the dimension as shown.

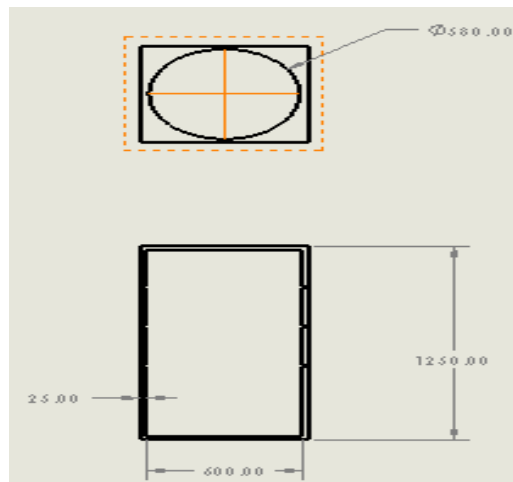


Figure 4.3 Dimension of cuboidal housing

4.4.4 Conceptual Model of Baking Electric Mitad Assembly

Figure 4.4 illustrates the schematic diagram of baking electric mitad drawn using SOLID WORKS 2019. The system consists of four electric mitads arranged vertically with lid cover,

sliding plate, separate switches for each mitad and cuboidal housing made of insulating materials.



Figure 4.4 Conceptual schematic diagram of injera baking electric mitad assembly.

4.5 Energy Balance Equations

4.5.1 Modeling of the Baking Temperature

The assumptions taken to model the baking temperature of the multi mitads

- the mitad materials are clay with thickness $\Delta y = 20$ mm;
- The properties of the clay such as density, specific heat and thermal conductivity are constant;
- The mitad is initially at room temperature ($T_a = 27^\circ C$);
- Heat transfer happens by conduction, natural convection and radiation;
- Heat diffusion by conduction in the mitad is neglected.
- As per the second law of thermodynamics heat always flows from the higher temperature to the lower temperature direction and thus, in the present study the temperature of mitad 4 is assumed to be greater than mitad 3 and so on(*i.e.* $T_4 > T_3 > T_2 > T_1$).
- The heat generation $\dot{q}$; in the clay mitads is assumed to be uniform.
- The electric mitads are assumed to be parallel plates with characteristic gap $L = 20$ cm;
- The 35% bottom heat loss from mitad 1 is assumed as input to the mitad 2 and the 35% heat loss from mitad 2 is assumed as input to mitad 3 and the 35% heat loss from mitad 3 is assumed as input to mitad 4

- Each mitad has same mass, m.

The governing equations of each mitad can be derived from the general form of the conservation of energy equation:

$$\text{Energy stored} = \text{Energy transfered} + \text{energy generated} \quad 4.3$$

$$\Delta E = E_{in} - E_{out} + \dot{q} \quad 4.4$$

The energy stored in the mitad can be found from

$$\Delta E = mc_p \frac{dT}{dt} \quad 4.5$$

The energy balance for each mitad can be written by considering the case of each mitad energy input (E_{in}) and output (E_{out}) using equation 4.4 and using the respective resistance thermal network model.

4.5.2 Energy Balance Equations of Each Mitads with Lid Cover

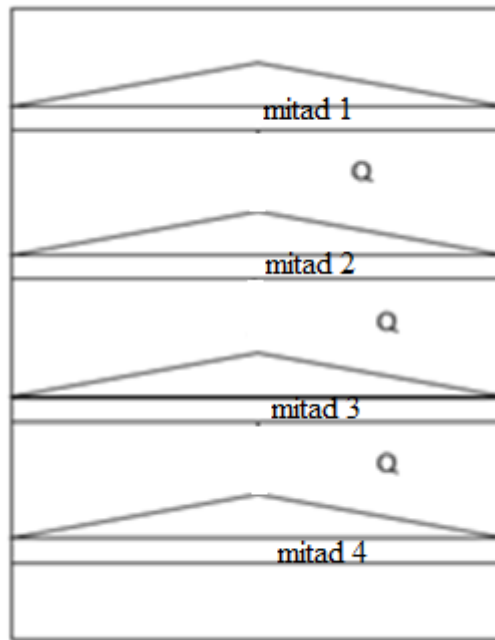


Figure 4.5 Schematic baking electric mitad with lid cover

The bottom surface of Injera is heated mainly through conduction and only a little part of the heat is transferred to its upper surface by means of convection and radiation mechanism. Table 4.1 shows the parameters and temperature assumptions used in calculation.

Table 4.1 Parameters and their value

Parameters	Values
Baking time	120 second
Density of mitad	1900 kg/m ³
Density of lid cover	2700 kg/m ³
Diameter of mitad	0.58 m
Thickness of mitad	0.02m
Emissivity of mitad	0.98
Emissivity of lid cover	0.11
Specific heat of mitad	835 J/kg.k
Specific heat of lid cover	903 J/kg.k

Then, the amount of heat generated can be calculated as;

$$\dot{q}_{gen} = \frac{Q_e}{V_m} = \frac{Q_e}{\frac{\pi D_m^2}{4} \Delta y} \quad 4.6$$

Where; D_m diameter of the mitad (m) and Δy thickness of mitad (m)

1. Energy Balance for lid cover one

Energy balance equation is calculated for lid cover one from the thermal resistance circuit diagram shown in the figure 4.6 by neglecting side loss.

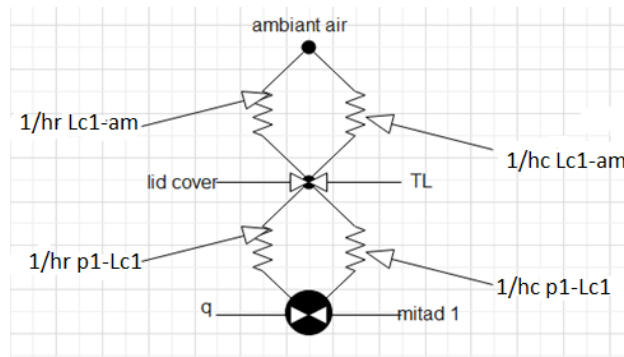


Figure 4.6 Thermal circuit diagram for lid cover one

Lid cover one gains heat by convection and radiation from mitad one and it loses heat to the ambient by convection and radiation.

$$E_{out} = h_2 A (T_{lc1} - T_{am}) + A \varepsilon_{lc} \sigma (T_{lc}^4 - T_{am}^4) \quad 4.7$$

The energy gain of lid cover one by convection and radiation from mitad one can be expressed as;

$$E_{in} = h_1 A (T_{p1} - T_{lc1}) + A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc1}^4) \quad 4.8$$

But there is no heat generation for lid covers then substitute equation 4.5, 4.7 and 4.8 into equation 4.4 results the governing equation for the temperature field for lid cover one as;

$$m c_p \frac{dT_{lc1}}{dt} = h_1 A (T_{p1} - T_{lc1}) + A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc1}^4) - h_2 A (T_{lc1} - T_{am}) - A \varepsilon_{lc} \sigma (T_{lc}^4 - T_{am}^4) \quad 4.9$$

2. Energy Balance for mitad one

Energy balance equation for mitad one is calculated using the thermal resistance circuit diagram shown in figure 4.7 neglecting side loss. Mitad one gains heat from heat generated and it loses heat to the lid cover one and lid covers two by convection and radiation.

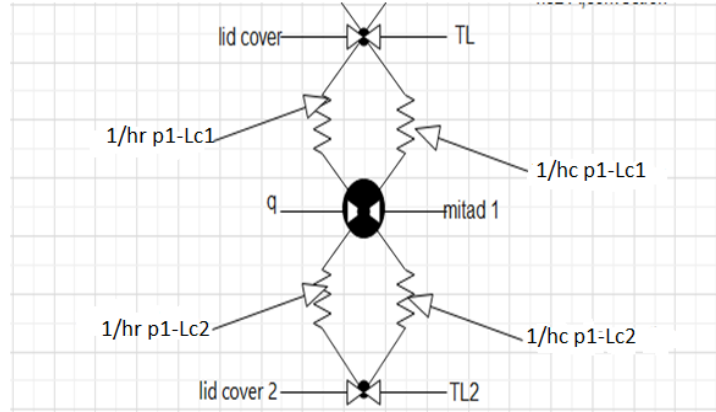


Figure 4.7 Thermal circuit diagram for mitad one

$$E_{out} = h_1 A (T_{p1} - T_{lc2}) + A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc2}^4) + A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc1}^4) + h_2 A (T_{p1} - T_{lc1}) \quad 4.10$$

The energy gain of mitad one from heat generated expressed in equation 4.6. Substituting equation 4.5, 4.6 and 4.10 into equation 4.4 results the governing equation for the temperature field for mitad one as.;

$$m c_p \frac{dT_{p1}}{dt} = q_{gen} \times v_m - h_1 A (T_{p1} - T_{lc2}) - A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc2}^4) - A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc1}^4) - h_2 A (T_{p1} - T_{lc1}) \quad 4.11$$

3. Energy Balance for lid cover two

From the thermal circuit diagram in figure 4.8, energy balance equation is calculated for lid cover two.

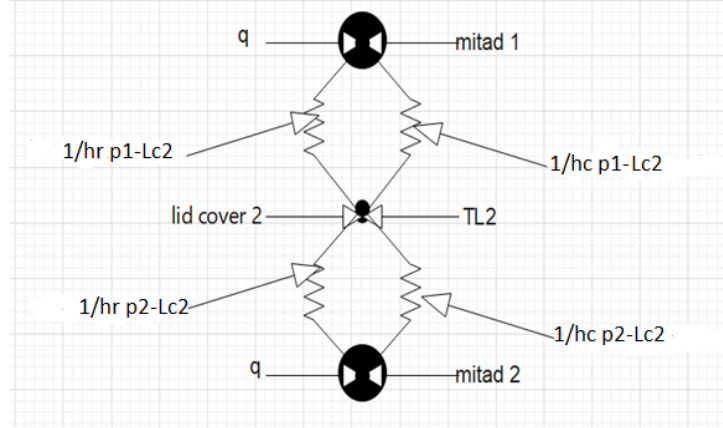


Figure 4.8 Thermal circuit diagram for lid cover two

Lid cover two gains heat by convection and radiation from mitad one and mitad two and it has no losses because temperature of lid cover two is lower than temperature of mitad one and mitad two.

$$E_{out} = 0 \quad 4.12$$

The energy gains of lid cover two by convection and radiation from mitad one and mitad two can be expressed as,

$$E_{in} = h_1 A (T_{p2} - T_{lc2}) + A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc2}^4) + h_2 A (T_{p1} - T_{lc2}) + A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc2}^4) \quad 4.13$$

But there is no heat generation for lid covers upon substituting equation 4.5, 4.12 and 4.13 into equation 4.4 results the governing equation for the temperature field for lid cover two as;

$$m c_p \frac{dT_{lc2}}{dt} = h_1 A (T_{p2} - T_{lc2}) + A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc2}^4) + h_2 A (T_{p1} - T_{lc2}) + A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc2}^4) \quad 4.14$$

4. Energy Balance for mitad two

Energy balance equation for mitad two is calculated from the thermal resistance circuit in figure 4.9.

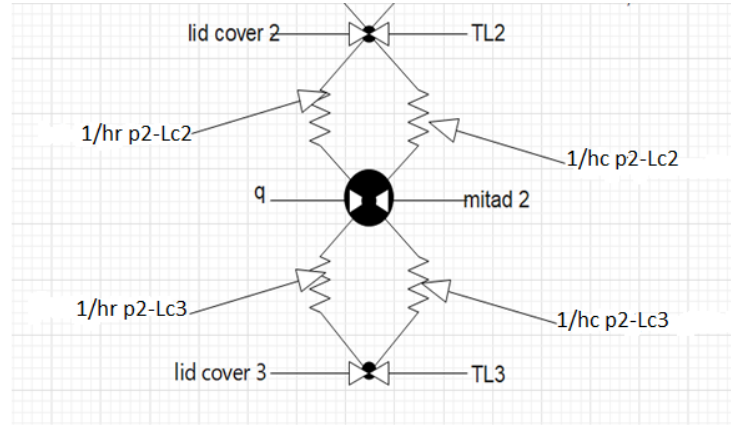


Figure 4.9 Thermal circuit diagram for mitad two

Mitad two gains heat from heat generated and it loses heat to the lid cover two and lid covers three by convection and radiation.

$$E_{out} = h_1 A (T_{p2} - T_{lc3}) + A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc3}^4) + A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc2}^4) + h_2 A (T_{p2} - T_{lc2}) \quad 4.15$$

The energy gain of mitad two from heat generated expressed in equation 4.6. Substituting equation 4.5, 4.6 and 4.15 into equation 4.4 results the governing equation for the temperature field for mitad two as;

$$m c_p \frac{dT_{p2}}{dt} = q_{gen} \times v_m - h_1 A (T_{p2} - T_{lc3}) - A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc3}^4) - A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc2}^4) - h_2 A (T_{p2} - T_{lc2}) \quad 4.16$$

5. Energy Balance for lid cover three

Energy balance equation for lid cover three is calculated from the thermal resistance circuit diagram in figure 4.10.

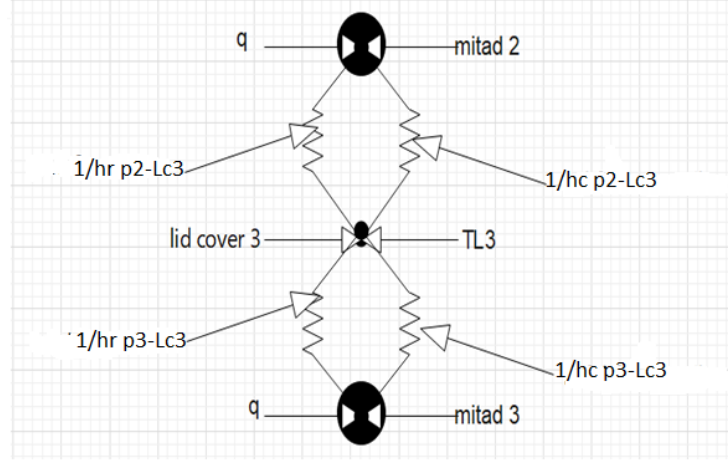


Figure 4.10 Thermal circuit diagrams for lid cover three

Lid cover three gains heat by convection and radiation from mitad two and mitad three and it has no loses because temperature of lid cover three is lower than temperature of mitad two and mitad three.

$$E_{out} = 0 \quad 4.17$$

The energy gains of lid cover three by convection and radiation from mitad two and mitad three can be expressed as,

$$E_{in} = h_1 A (T_{p3} - T_{lc3}) + A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc3}^4) + h_2 A (T_{p2} - T_{lc3}) + A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc3}^4) \quad 4.18$$

But there is no heat generation for lid covers then substitute equation 4.5, 4.17 and 4.18 into equation 4.4 results the governing equation for the temperature field for lid cover three as;

$$m c_p \frac{dT_{lc3}}{dt} = h_1 A (T_{p3} - T_{lc3}) + A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc3}^4) + h_2 A (T_{p2} - T_{lc3}) + A \varepsilon_{eff} \sigma (T_{p2}^4 - T_{lc3}^4) \quad 4.19$$

6. Energy Balance for mitad three

Energy balance equation for mitad three is calculated from the thermal circuit diagram shown in figure 4.11 by neglecting side loss;

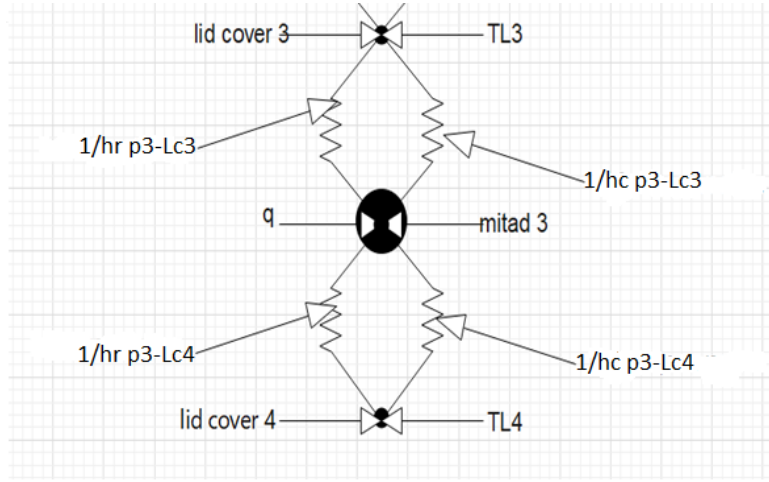


Figure 4.11 Thermal circuit diagram for mitad three

Mitad three gains heat from heat generated and it loses heat to the lid cover three and lid covers four by convection and radiation.

$$E_{out} = h_1 A (T_{p3} - T_{lc4}) + A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc4}^4) + A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc3}^4) + h_2 A (T_{p3} - T_{lc3}) \quad 4.20$$

The energy gain of mitad three from heat generated expressed in equation 4.6. Substituting equation 4.5, 4.6 and 4.20 into equation 4.4 results the governing equation for the temperature field for mitad three as;

$$m c_p \frac{dT_{p3}}{dt} = q_{gen} \times v_m - h_1 A (T_{p3} - T_{lc4}) - A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc4}^4) - A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc3}^4) - h_2 A (T_{p3} - T_{lc3}) \quad 4.21$$

7. Energy Balance for lid cover four

Energy balance equation is calculated for lid cover four from the thermal circuit diagrams shown in figure 4.12 by neglecting side loss.

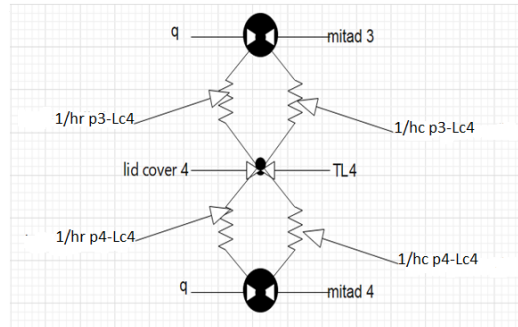


Figure 4.12 Thermal circuit diagram for lid cover four

Lid cover four gains heat by convection and radiation from mitad three and mitad four and it has no losses because temperature of lid cover four is lower than temperature of mitad three and mitad four.

$$E_{out} = 0 \quad 4.22$$

The energy gains of lid cover four by convection and radiation from mitad three and mitad four can be expressed as,

$$E_{in} = h_1 A (T_{p4} - T_{lc4}) + A \varepsilon_{eff} \sigma (T_{p4}^4 - T_{lc4}^4) + h_2 A (T_{p3} - T_{lc4}) + A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc4}^4) \quad 4.23$$

But there is no heat generation for lid covers then substitute equation 4.5, 4.22 and 4.23 into equation 4.4 results the governing equation for the temperature field for lid cover four as

$$m c_p \frac{dT_{lc4}}{dt} = h_1 A (T_{p4} - T_{lc4}) + A \varepsilon_{eff} \sigma (T_{p4}^4 - T_{lc4}^4) + h_2 A (T_{p3} - T_{lc4}) + A \varepsilon_{eff} \sigma (T_{p3}^4 - T_{lc4}^4) \quad 4.24$$

8. Energy Balance for mitad four

Finally, energy balance equation for mitad four is calculated from the thermal circuit diagram shown in figure 4.13 by neglecting side loss.

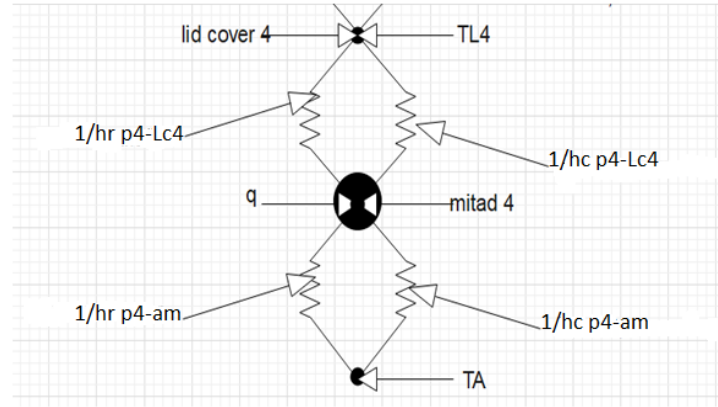


Figure 4.13 Thermal circuit diagram for mitad four

Mitad four gains heat from heat generated and it loses heat to the lid cover four and to the ambient air by convection and radiation.

$$E_{out} = h_1 A (T_{p4} - T_{lc4}) + A \varepsilon_{eff} \sigma (T_{p4}^4 - T_{lc4}^4) + A \varepsilon_p \sigma (T_{p4}^4 - T_{am}^4) + h_2 A (T_{p4} - T_{am}) \quad 4.25$$

The energy gain of mitad four from heat generated expressed in equation 4.6, substituting equation 4.5, 4.6 and 4.25 into equation 4.4 results the governing equation for the temperature field for mitad three as;

$$m c_p \frac{dT_{p4}}{dt} = q_{gen} \times v_m - h_1 A (T_{p4} - T_{lc4}) - A \varepsilon_{eff} \sigma (T_{p4}^4 - T_{lc4}^4) - A \varepsilon_p \sigma (T_{p4}^4 - T_{am}^4) - h_2 A (T_{p4} - T_{am}) \quad 4.26$$

4.5.3 Energy Balance Equations of Each Mitads Without Lid Cover

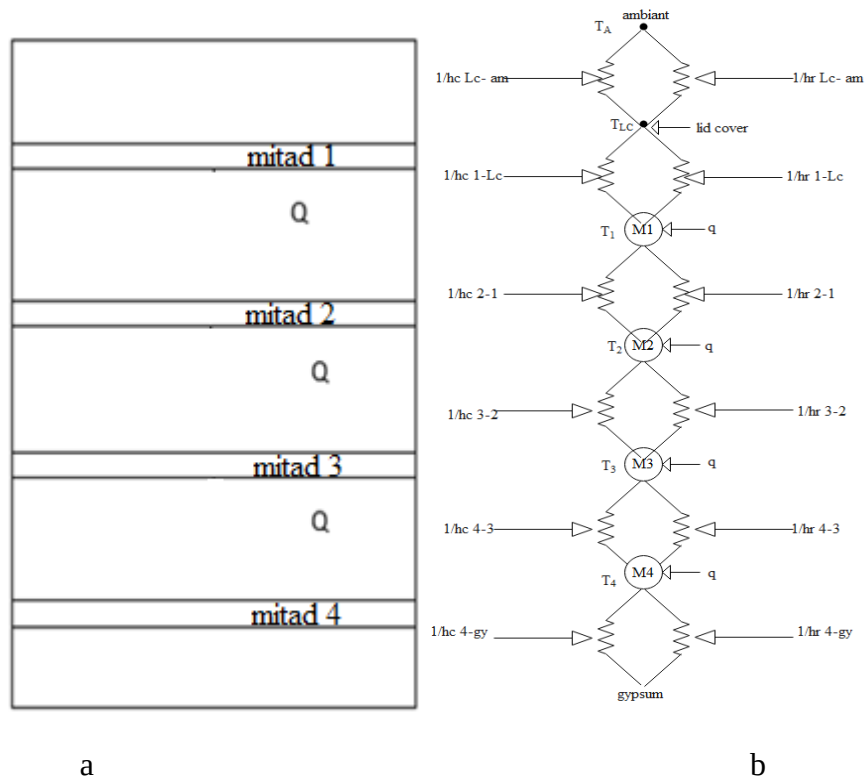


Figure 4. 14 a) Schematic of mitads without lid cover b) Thermal circuit diagram for baking mitad without lid cover

Table 4.2 Parameters and their value

Parameters	Values
Diameter of mitad	0.58 m
Thickness of mitad	0.02m
Emissivity of mitad	0.98
Emissivity of lid cover	0.11
Specific heat of mitad	835 J/kg.K

1. Energy Balance for mitad one

Energy balance equation is calculated for mitad one from the thermal circuit diagram shown in figure 4.15.

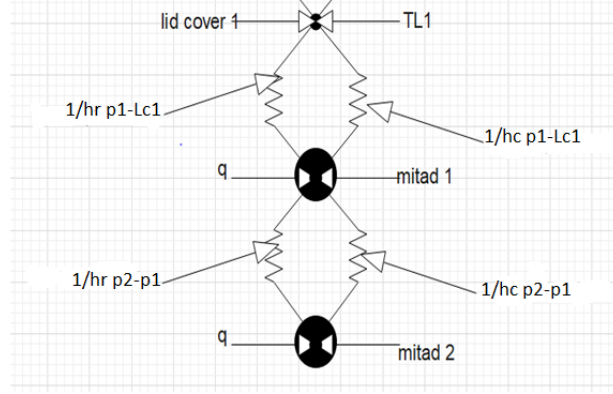


Figure 4.15 Thermal circuit diagram for mitad one

Mitad one gains heat from mitad two by convection and radiation and heat generated and it loses heat to the ambient air by convection and radiation.

$$E_{out} = A\varepsilon_{eff}\sigma(T_{p1}^4 - T_a^4) + h_1A(T_{p1} - T_a) \quad 4.30$$

The energy gain of mitad one from heat generated expressed in equation 4.6. The possible heat input to mitad one based on assumption are radiation and convection from mitad 2 because heat is transferred from high temperature to low temperature and conduction between mitad one and wire, the effect of conduction heat transfer is insignificant so neglect conduction.

$$E_{in} = A\varepsilon\sigma(T_{p2}^4 - T_{p1}^4) + h_1A(T_{p2} - T_{p1}) \quad 4.31$$

Then substituting equation 4.5, 4.6, 4.30 and 4.31 into equation 4.4 results the governing equation for the temperature field for mitad one as;

$$mc_p \frac{dT_{p1}}{dt} = q_{gen} \times v_m + A\varepsilon\sigma(T_{p2}^4 - T_{p1}^4) + h_1A(T_{p2} - T_{p1}) - h_1A(T_{p1} - T_a) - A\varepsilon_{eff}\sigma(T_{p1}^4 - T_a^4) \quad 4.32$$

2. Energy Balance for mitad two

The second mitad have also no lid cover an energy balance equation for mitad two is calculated from the thermal circuit diagram shown in figure 4.16 by neglecting side loss.

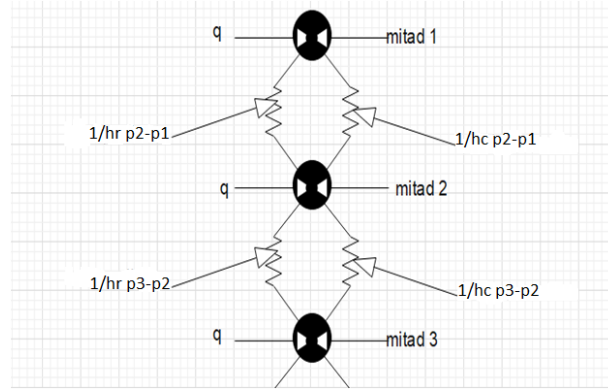


Figure 4.16 Thermal circuit diagram for mitad two

Mitad two gains heat from mitad three by convection and radiation and heat generated and it loses heat to mitad one by convection and radiation.

$$E_{out} = A\varepsilon\sigma(T_{p2}^4 - T_{p1}^4) + h_1A(T_{p2} - T_{p1}) \quad 4.33$$

The energy gain of mitad two from heat generated expressed in equation 4.6. The possible heat input to mitad two based on assumption are radiation and convection from mitad three because heat is transferred from high temperature to low temperature and conduction between mitad two and wire, the effect of conduction heat transfer is insignificant so neglect conduction.

$$E_{in} = A\varepsilon\sigma(T_{p3}^4 - T_{p2}^4) + h_1A(T_{p3} - T_{p2}) \quad 4.34$$

Then substituting equation 4.5, 4.6, 4.33 and 4.34 into equation 4.4 results the governing equation for the temperature field for mitad two as;

$$mc_p \frac{dT_{p2}}{dt} = \dot{q} \times v_m + A\varepsilon\sigma(T_{p3}^4 - T_{p2}^4) + h_2A(T_{p3} - T_{p2}) - h_1A(T_{p2} - T_{p1}) - A\varepsilon\sigma(T_{p2}^4 - T_{p1}^4) \quad 4.35$$

3. Energy Balance for mitad three

The third mitad have no lid cover. Thus, energy balance equation for mitad three is calculated from the thermal circuit diagram shown in figure 4.17 by neglecting side loss,

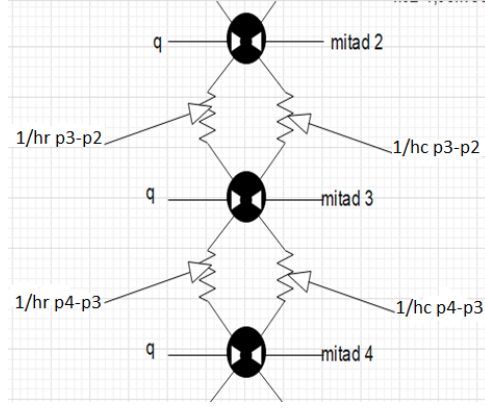


Figure 4.17 Thermal circuit diagram for mitad three

Mitad three gains heat from mitad four by convection and radiation and heat generated and it loses heat to mitad two by convection and radiation;

$$E_{out} = A\varepsilon\sigma(T_{p3}^4 - T_{p2}^4) + h_1A(T_{p3} - T_{p2}) \quad 4.36$$

The energy gain of mitad three from heat generated expressed in equation 4.6. The possible heat input to mitad three based on assumption are radiation and convection from mitad four because heat is transferred from high temperature to low temperature and conduction between mitad three and wire, the effect of conduction heat transfer is insignificant so neglect conduction.

$$E_{in} = A\varepsilon\sigma(T_{p4}^4 - T_{p3}^4) + h_2A(T_{p4} - T_{p3}) \quad 4.37$$

Then substitute equation 4.5, 4.6, 4.36 and 4.37 into equation 4.4 results the governing equation for the temperature field for mitad three as

$$mc_p \frac{dT_{p3}}{dt} = \dot{q} \times v_m + A\varepsilon\sigma(T_{p4}^4 - T_{p3}^4) + h_2A(T_{p4} - T_{p3}) - A\varepsilon\sigma(T_{p3}^4 - T_{p2}^4) - h_1A(T_{p3} - T_{p2}) \quad 4.38$$

4. Energy Balance for mitad four

The fourth mitad have no lid cover. Thus, energy balance equation is calculated for mitad four from the thermal circuit diagram shown in figure 4.18 neglecting side loss,

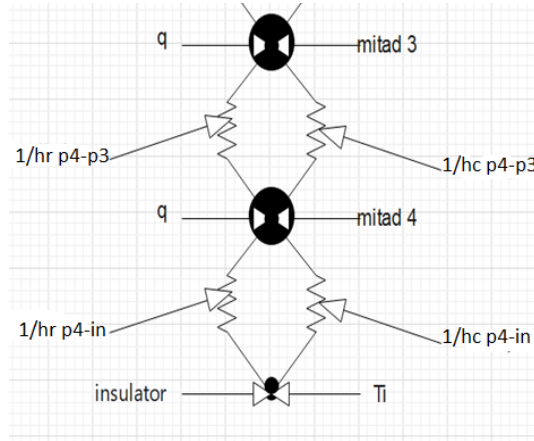


Figure 4.18 Thermal circuit diagram for mitad four

Mitad four gains heat from heat generated and it loses heat to mitad three by convection and radiation.

$$E_{out} = A\varepsilon\sigma(T_{p4}^4 - T_{p3}^4) + h_1A(T_{p4} - T_{p3}) \quad 4.39$$

The energy gain of mitad four from heat generated expressed in equation 4.6. The possible heat input to mitad four conduction between mitad four and wire, the effect of conduction heat transfer is insignificant so neglect conduction.

$$E_{in} = 0 \quad 4.40$$

Then substitute equation 4.5, 4.6, 4.39 and 4.40 into equation 4.4 results the governing equation for the temperature field for mitad four as;

$$mc_p \frac{dT_{p4}}{dt} = \dot{q}_{gen} \times v_m - A\varepsilon\sigma(T_{p4}^4 - T_{p3}^4) - h_1A(T_{p4} - T_{p3}) \quad 4.41$$

Where:- m is mas of clay pan or mitad (kg); c_p is specific heat capacity of mitad (kJ/kgK); T_i is temperature (K); $i=1$ mitad 1, $i=2$ mitad 2 , $i=3$ mitad 3 and $i=l$ lid cover; $\varepsilon_{e,i-j}$ is effective emittance between mitads or mitad 1 and lid cover; $\sigma = 5.67 \times 10^{-8}$ (W/m² · K⁴) is the Stefan–Boltzmann constant; A is the area of mitads or projected area of lid cover (m²); h_{i-j} is the convective heat transfer coefficient (W/m²K) between mitads or mitad 1 and lid cover;

The convective heat transfer coefficient of air between the lid and the ambient air is estimated using the McAdam equation, for free convection case ($V=0$), given by (Duffie and Beckman,2013)

$$h_w = 5.87 + 3.8 V \quad (\text{W/m}^2\text{K}) \quad 4.42$$

The convective heat transfer coefficient of air between the lid and mitad or mitads enclosures can be estimated from correlations (Cengel, 2003):

$$h_{i-j} = \frac{N_{u,i-j} k}{L} \quad 4.43$$

The Nusselt number for the air trapped between the lid cover and mitad 1, mitad 1 and 2 and mitad 2 and 3, can be obtained from the recommend correlation for horizontal enclosures (Cengel, 2003):

$$N_{u,i-j} = 1 + 1.44 \left[1 - \frac{1708}{Ra_L} \right]^+ + \left[\frac{Ra_L^{\frac{1}{3}}}{18} - 1 \right]^+ \quad Ra_L < 10^8 \quad 4.44$$

If the quantity in $[]^+$ is negative, it should be set equal to zero.

The Rayleigh number can be estimated from

$$Ra = Gr \times Pr = \frac{g \Delta T \beta L^3}{\nu^2} Pr \quad 4.45$$

Where: g is gravitational acceleration, (m/s²); ν is kinematics viscosity (m²/s); Pr is Prandtl number; $\Delta T = T_i - T_j$ is change in temperature L =gap between the mitads or mitad and lid cover (m); β is the coefficient of volume expansion (1/K).

The coefficient of volume expansion can be expressed as

$$\beta = \frac{1}{\frac{T_i + T_j}{2}} \quad 4.46$$

The effective emittance between mitads or mitad 1 and lid cover can be estimated from

$$\varepsilon_{e,i-j} = \frac{1}{\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j} - 1} \quad 4.47$$

4.6 Numerical Temperature Solution Procedure for Multi Mitad With and Without Lid Covers

The equations that govern the temperature distribution of the mitads with and without lid covers are coupled nonlinear algebraic and ordinary differential equations. These equations can be solved simultaneously using numerical iterative solution scheme. The input parameters to solve the governing equations were taken from literature; emittance of lid and mitad were taken as 0.11 and 0.98, respectively. The density and specific heat capacity of the clay were taken to be 1900 kg/m³ and 835 kJ/kg.K (Getnet, 2011). The solution procedure starts by assuming the temperatures of the lid covers, and the four mitads. Then the values

of the convection heat transfer coefficients and effective emittance will be calculated as shown **APPENDIX B** for mitads with lid cover and the values of the convection heat transfer coefficients and effective emittance calculated as shown in **APPINDEX C** for mitads without lid cover.

The values of these heat transfer coefficients and effective emittance are replaced into equation and these equations are solved simultaneously to obtain the new temperature values of the mitads and the lid covers. The newly obtained temperature values of the lid cover and mitads are then compared with the previous values. If these values are close to the initial guess, no further calculations are done. Else, the newly calculated values of the mitads and lid covers temperatures are used to calculate the convective heat loss coefficient and emittance and the numerical process is repeated. Solution of the mixture of the nonlinear ODE and algebraic equation for the temperature of the mitads and lid covers were obtained after considerable number of numerical iterations. The result was found to be relatively independent of the initial guess. The solution algorithm used is indicated as in figure 4.19.

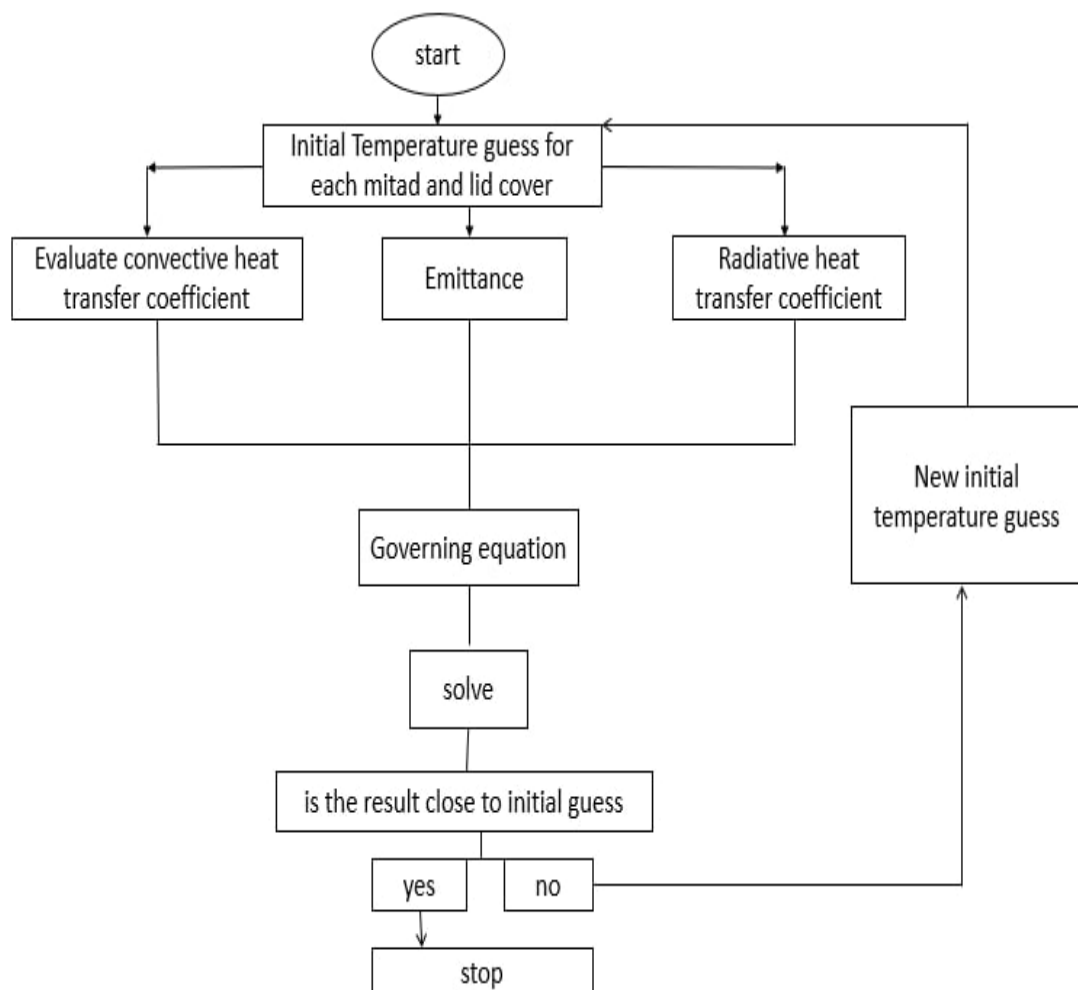


Figure 4.19 Flow chart of numerical procedure

CHAPTER FIVE

EXPERIMENTAL SETUP AND PROCEDURE

5.1 Introduction

This section presents manufacturing process and the whole experimental setup of the present work. The whole manufacturing process used for preparing the components of prototype is also presented in detail with descriptive photos. The experimental setup and the testing procedure for the prototype of single and multi-electric mitad with and without load and at varies gap between mitads is described. In addition, the surface preparation steps and techniques of the electric are also described in detail. Finally, the measuring and testing devices used in the experiment are presented.

5.2 Manufacturing Processes

This section describes the manufacturing process conducted while preparing the components of experimental prototype of the system.

5.2.1 Baking Mitad

The baking mitad was made of conventional mitad size of 580 mm diameter and 20 mm thickness of clay. The process starts with grooving the bottom side of clay made baking plate for embedding the heating element inside the grooves and the upper side was provided a smooth nonstick baking surface as shown in figure 5.1 a and b.



Figure 5.1 a) Smooth top surface and b) Grooved bottom surface of the mitad.

For the purpose of resistance heating, two R09 type 1500 W resistor wires as shown in figure 5.2 (a) were uniformly stretched and embedded in the bottom groove of each mitad as shown

in figure 5.2 (b). To prevent the bottom heat loss from the mitad, the resistance wires were sealed with gypsum and fiber glass insulation as shown in figure 5.2 (c).

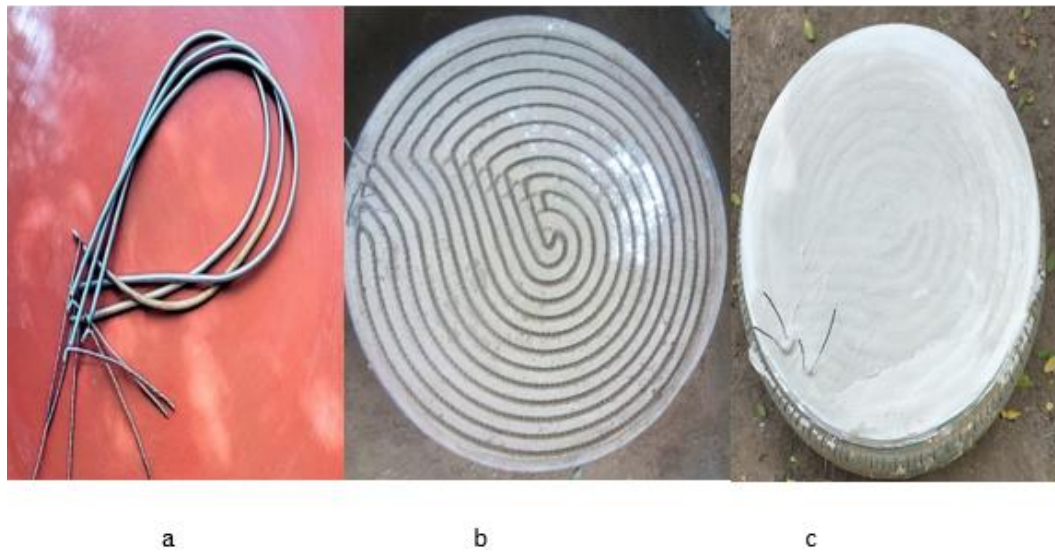


Figure 5. 2 a) Resistance wires b) Wire inserted in groove and c) Gypsum insulation

5.2.2 Lid Cover

Lid cover helps to protect top heat loss from Injera during baking process. In the present work four lid covers were manufactured from aluminum sheet and used to minimize the top heat loss during heating up and baking process as indicated in figure 5.3. Aluminum is selected as a material for lid cover based on availability and its suitability for food preparation utility.



Figure 5.3 Lid cover

5.2.3 Sliding Plate and Mitad Casing

For smooth operation of consecutive mitads while baking, sliding plate having mitad casing at the center was manufactured from a sheet metal and angle iron as shown in figure 5.4.



Figure 5.4 Sliding plate

5.2.4 System Housing and Insulation

In order to have a rigid movable structure, better service life and minimum heat loss, rectangular box housing was constructed from sheet metal and angle iron as shown in figure 5.6 (a). The total dimension of the box was 690 mm X 660 mm X 1300 mm. To reduce side heat loss, all sides of the housing box was insulated with ceramic of thickness of 5 mm and ash of 25 mm thickness using polyester putty bonding material as shown in figure 5.5. To accommodate four mitads with their sliding plate, the housing box was divided vertically into four separate regions as shown in figure 5.6 (c). The arrangement makes the heat loss from one mitad to be used as an input heat source for the other one which is underneath it. To reduce frontal heat loss, separate door was prepared for each of sliding mitad assemblies as shown in figure 5.6 (d) and (e). As figure 5.5 (f) shows, the maximum allowable sliding distance was controlled using hanging chains welded on the front side of housing.

- **Selection of Insulation Materials:**

There are different types of insulation materials among those; fiber glass, cellular glass, foamed plastic and calcium silicate are the most commonly used materials. In the present study, the following insulation materials were selected and used.

a. Ceramic insulation

Ceramic used as insulator for housing. In metals, resistivity increases as temperature increases. In contrast, valence electrons in ceramic materials are usually not in the conduction band, thus most ceramics are considered insulators. Ceramic was used as insulator due to the following criteria.

- High wear, heat, pressure, and chemical attack resistance (gas and liquids)
- High temperature resistance
- Extreme hardness.

- Excellent electrical insulation.



Figure 5.5 Polyester putty bonding material



a) Housing frame

b) Insulation of housing

c) Sliding plate assembly



d) Closing door of housing

e) Final slider plate assembly

f) Hanging chains

Figure 5.6 Manufacturing process of housing

b. Fiberglass insulation

Fiberglass insulation is fibrous glass, made either plain or with a heat-resistant binder in order for the fiberglass to hold its shape. Fiberglass is the most popular insulation, and it

comes in many forms. Fiber glass used as insulation in the bottom of electric mitad and the casing. Fiber glass is recommended for temperatures up to 422°C. A high temperature, flexible blanket can be used with temperatures up to 530 °C (Muluken, 2018). Fiber glass used as insulator at the bottom of each mitads as shown in the figure 5.6 (a).

c. Ash insulation

Ash is a by-product (waste) from the combustion of fuel wood especially in the preparation foods with the largest share in baking Injera. In some cases, ash from fuel wood is used as nutrient for plants because it improves the fertility of soil. In this particular case, the wood ash was used for insulation due to the following reasons: -

- ✓ Ash is completely burned material, so should have very low thermal conductivity,
- ✓ Ash is a waste material, so there is no cost for it and available everywhere locally,
- ✓ There is no fire hazard and is not toxic, so there is no problem of safety.

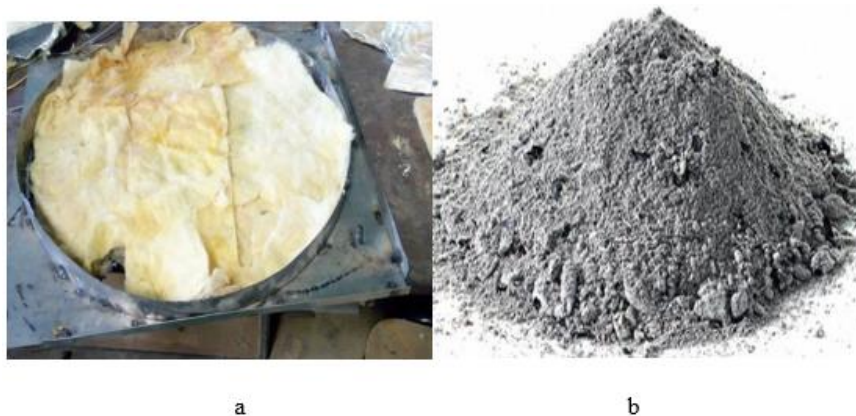


Figure 5.7 a) Fiber glass b) Ash

In selection of the thickness of the insulation material it is advisable to select the correct thickness. As thickness of insulation is increased, the cost of material and installation goes up. On the other hand, the energy cost savings also goes up, but at a slower rate of increase than the cost of materials and installation. At some point, then, the total cost, which is the sum of the lost energy cost and the material cost, reaches a minimum point, that amount of insulation is called the economic thickness.

5.3 Surface Preparation for Baking

Electric mitad surface preparation is essential to generate a non-stick and smooth top surface for injera quality. Like previous researches and traditional techniques, the present study initially uses a layer of vegetable oil on top mitad surface to create a black organic tar. In

doing so, the black organic tar will fill the rough surface of the mitad to make it so smooth. Then after the surface is smoothed and hardened, crushed traditional oil seed (“*gomenzer and gulo*”) and flax is burnt on the heated surface and the burning seeds are rubbed into the surface to create the final smooth no-stick coating and wax of candle also used to increase smoothness of the surface. After such preparation, the mitad was tested for injera baking applications. After applying surface preparation, thicker injera (*mushit*) as shown in figure 6.9 was baked as a cleaning and making the surface ready to bake regular quality injera

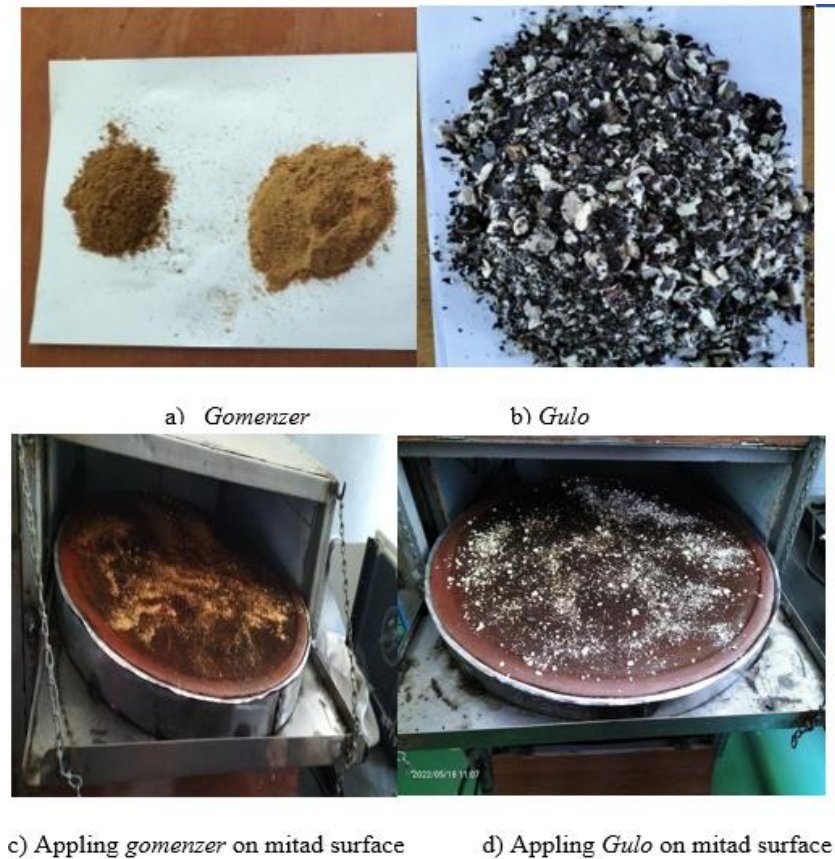


Figure 5.8 Surface preparation of electric mitad



Figure 5.9 Baked thicker injera for surface preparation (*mushit*)

5.4 Experimental Setup

The experimental investigation of the present multi-mitad electric injera baking system was conducted in thermo-fluid laboratory of ASTU. Figure 5.11 depicts the whole setup consists of housing box, baking mitads putted on sliding plates arranged vertically, hanging chain and electrical installation with main power source having separate switches.



Figure 5.10 Assembly of multi mitad injera baking electric system

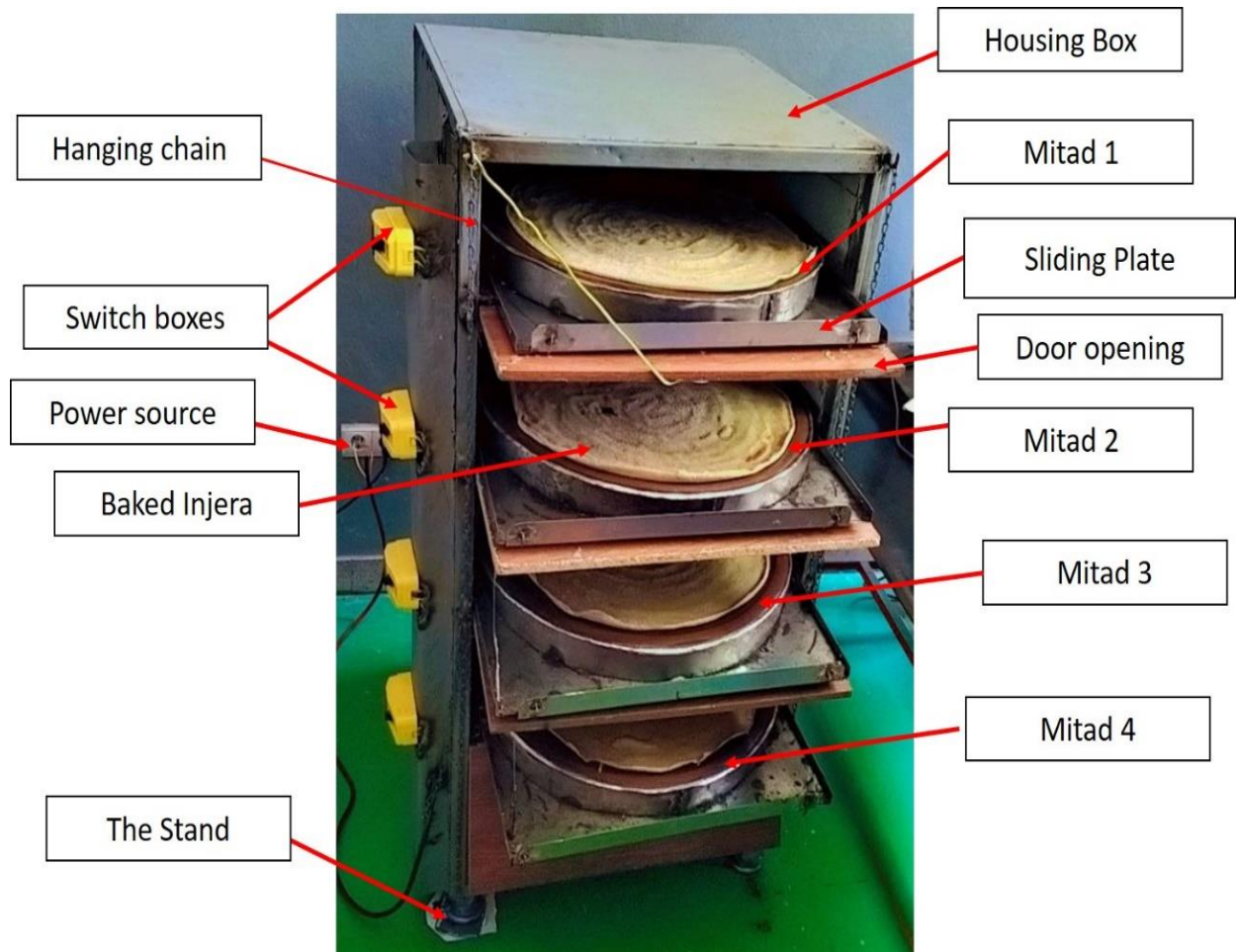


Figure 5. 11 Complete experimental setup

5.5 Experimental Test Equipment's and Procedures

The following equipment were used for experimental testing of the baking electric Mitad, for collecting data's during the initial heating and baking processes.

i. Infrared Thermometer

An infrared thermometer is a non-contact temperature measurement device. It detects the infrared energy emitted by all materials at temperatures above absolute zero, (K) and converts the energy factor into temperature reading. This configuration facilitates temperature measurement of the object from distance without contact with the object to be measured. The infrared thermometer was used to measure the baking pan surface temperature during baking time as shown in figure 5.12.



Figure 5.12 Infrared thermometer

ii. Thermocouples

Temperature sensor and k-type thermocouples were used during the experiment to measure the surface temperature of the mitad. One end of tagged thermocouple wires as shown in figure 5.13 (a) was plugged to the temperature sensors and the other end was fixed to the surface to be measured.

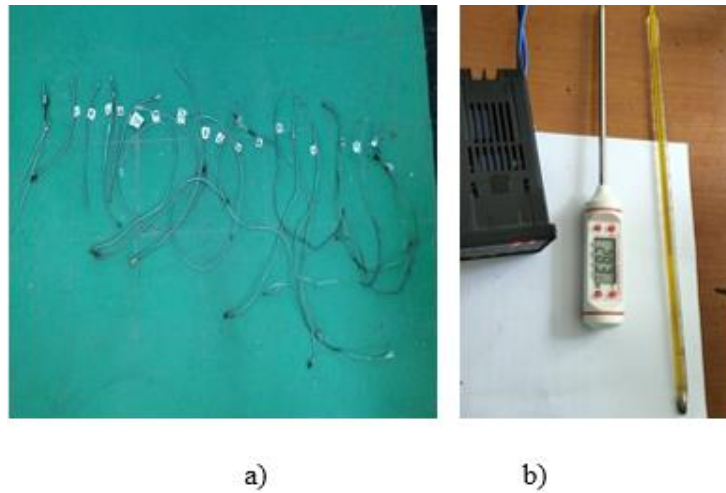


Figure 5.13 Temperature measuring device a) Tagged thermocouple wires b) Temperature sensors

iii. Multi-Meter

Figure 5.14 shows an electronic multi meter which is used to measure the supply voltage, current and resistance during the experiment. Input power was obtained from the measured values of voltage current and resistance.



Figure 5.14 Electronic multi-meter

iv. Digital mass Balance

Digital mass measuring device was used to measure the initial mass of the dough and the final mass of the product (injera). The evaporated mass of the dough is the difference between the mass of dough and mass of injera. Figure 5.15 (a) and (b) indicates the use of digital mass balance for measuring dough and injera respectively.

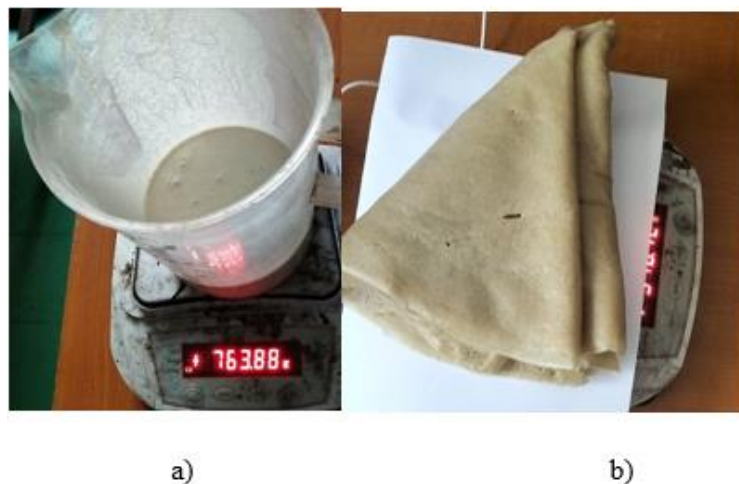


Figure 5.15 Digital mass balance used to measure a) Dough b) Injera

5.5.1 Experimental Procedure

The experimental study of baking electric mitad system was carried out for different condition of the electric mitad namely;

- i. Experimental study of the electric mitads with and without load
- ii. Experimental study of the electric mitads with and without lid cover
- iii. Experimental study of the electric mitads at different gaps between them.

Under those categories, different temperature measurement was taken. In the system where all mitads arranged vertically, the mitads will pulled out horizontally for pouring the dough on the mitad (process of *Masifat*) and pushed back in for baking. During the experiment, temperature distribution on the mitad surface were measured on different positions as shown in figure 5.16.

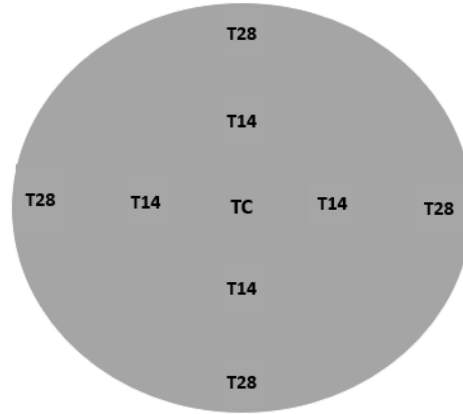


Figure 5. 16 Positions of temperature measurement on mitad surface

The surface positions were used evaluate the initial heating up, heating rate and temperature distribution and energy consumption analysis. To find out the heat loss, additional measurement positions at the center tip of the aluminum lid cover and sides of the baking mitad were also selected.

5.5.2 Experimental Performance Estimation Method

The experimental performance of the multi mitad was determined for no load test and load test.

$$\eta = \frac{M_w C_{pw} \Delta T + M_{wv} h_{fg}}{Q_e} \quad 5.1$$

where M_{wi} is the initial mass of water (kg), C_{pw} is the specific heat capacity of water (4.18 kJ/kg.°C), ΔT is the temperature change of water from ambient temperature up to and boiling point (°C), M_{wv} is the mass of water evaporated (kg), h_{fg} is the latent heat of evaporation of water at boiling point temperature (2,260 kJ/kg). Q_e is electric energy utilized for boiling water (kJ).

5.6 Economic and Energy Saving Advantages of the Multi Mitad Injera Baking Electric System

In the utilization of new technology like multi mitad injera baking electric system, the main thing that arose in customers mind is its economical point of view. Generally, this system is characterized by low first cost and low operating costs because this prototype is manufactured from locally available materials. The total initial investment cost of the present multi mitad includes the cost of the mitads, lid cover, nichrome wires and all other housing and supporting units of the system. **APPENDIX E** summarizes the details of all the costs associated with the present multi mitad injera baking electric system.

CHAPTER SIX

RESULTS AND DISCUSSIONS

6.1 Introduction

This chapter presents the results obtained from the numerical and experimental analysis of the multi injera baking electric mitad. The first section presents the results of numerical simulation made on the multi injera baking electric mitad using numerically iterative

solutions scheme. The next section presents the experimental investigations made on the multi injera baking electric mitad and it was validated with the numerical one. The heat performance results with and without load, with and without lid cover were reported in terms of 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 also presented and discussed.

6.2 Numerical Results of Multi Injera Baking Electric Mitad

The input for the numerical simulation of multi injera baking electric mitad were obtained from the general energy conservation equation whereas convective heat transfer coefficients were evaluated from the initial guessed temperature. The data obtained was imposed to the excel spread sheet to get the following results.

6.2.1 Temperature Distribution of Multi Injera Baking Mitad With Lid Cover

For all mitads having lid covers, heat is transferred between mitads and lid cover. Thus, the temperature distribution on the mitads and its lid cover were numerically determined using the solution procedure 4.18 and result is as shown in the figure 6.1. As the result indicates higher temperature distribution up to 327°C were obtained in mitad three with in the first 16 minutes. The increase in temperature is due to the fact that mitad three gets heat from bottom loss of mitad two and top loss of mitad four. Comparatively the temperature mitad is one lower than other mitads as it is subjected to top loss. It was expected that lid covers have lower temperature than mitads as there is no resistance wire heat generation inside them.

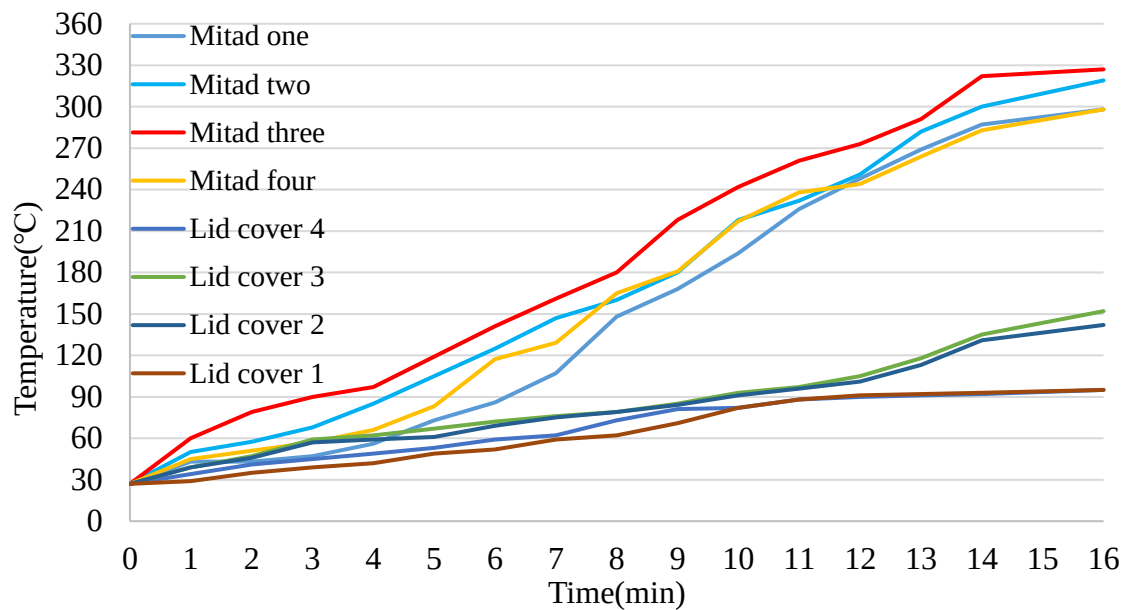


Figure 6. 1 Temperature distribution of mitads with lid cover

6.2.2 Temperature Distribution of Multi Injera Baking Mitad Without Lid Cover

Whenever all mitads have no lid cover, the numerically obtained temperature distribution is indicated on figure 6.2. As the result shows temperature of mitad three is higher than that of mitad two and the latter is also higher than that of mitad four and one, where the lowest temperature increment is observed with mitad one. The positive effect of having lid cover in temperature distribution of mitad three is depicted in figure 6.3. As the graph shows mitad three with lid cover has comparatively higher temperature distribution than mitad one without lid.

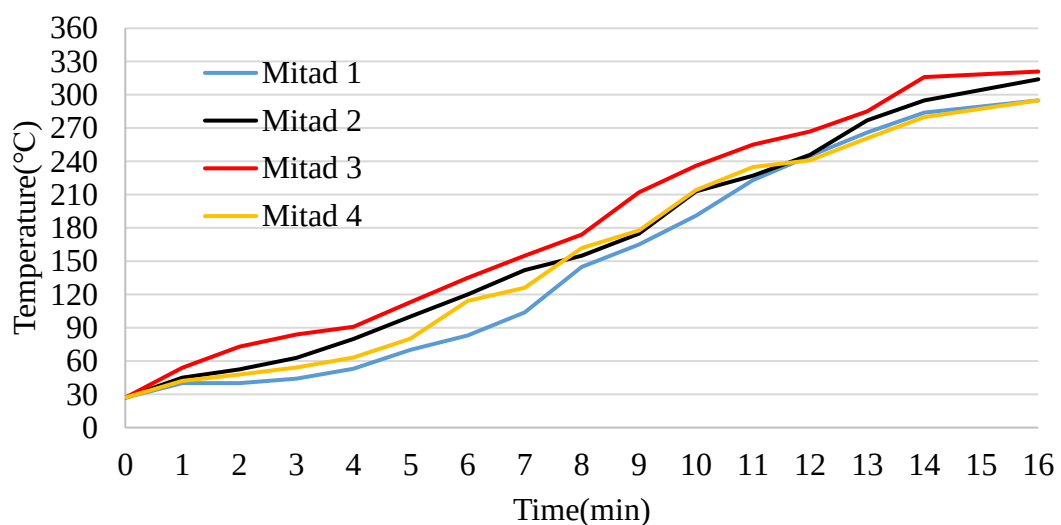


Figure 6. 2 Temperature distribution of mitads without lid cover.

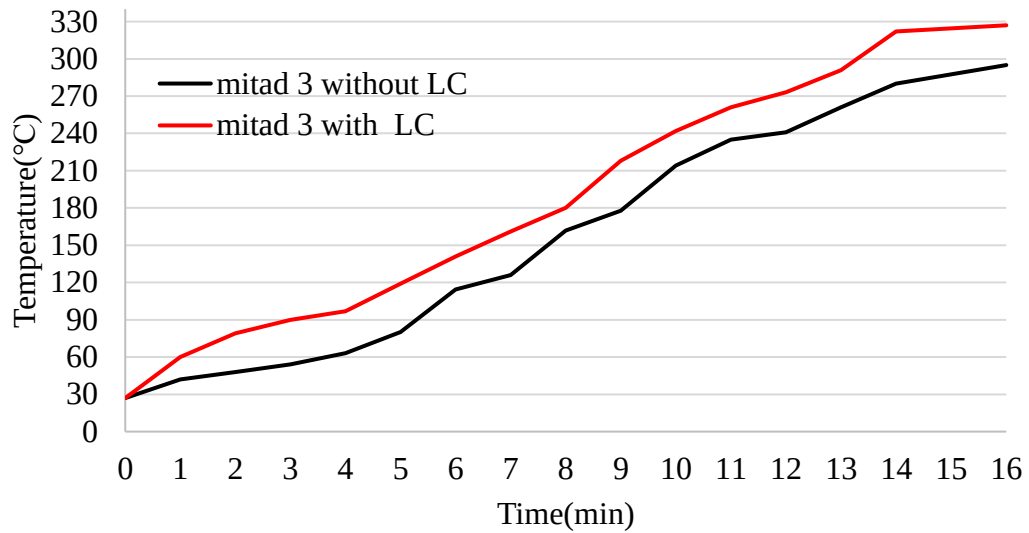


Figure 6. 3 Comparison of temperature distribution with and without lid cover

6.2.3 Initial Heating Up Time for Different Power Sources

Figure 6.4 shows the surface temperature profile of 0.02 m thick electric injera baking mitad as a function of heating up time for different input power. The result indicated that for a given mitad thickness, the heat up time increases as the power source decreases. As the power input decreases the amount of time it takes to reach a baking temperature increases. Thus, 3.5 kW power input is selected for the present study.

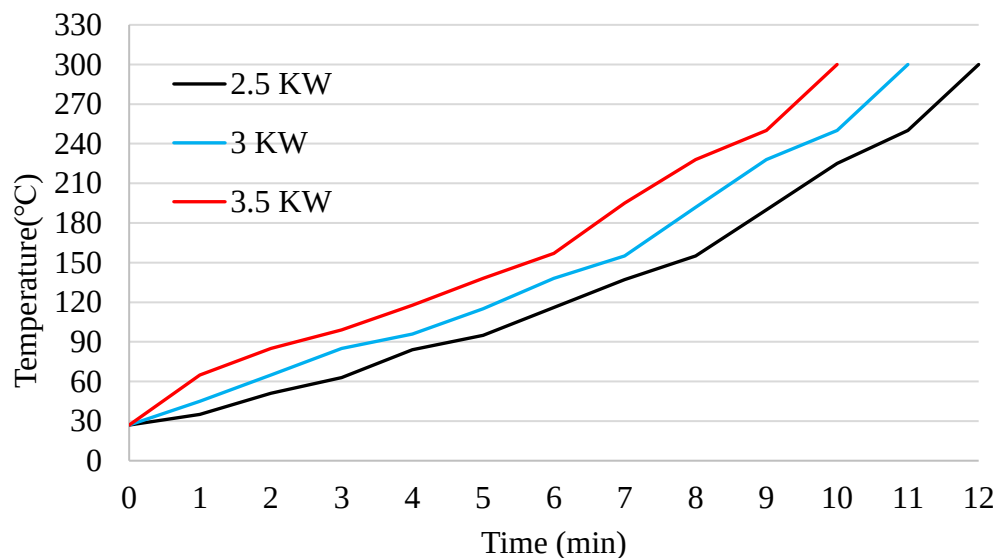


Figure 6.4 Heating up time for different power sources

6.3 Experimental Results of Multi Injera Baking Electric Mitad

This sub section presents the experimental result and findings of the electric injera baking system under actual baking test.

6.3.1 Temperature Distribution for Different Gap Variation

The surface temperature profile of 0.02 m thick electric injera baking mitad as a function of heating up time for different gap between consecutive mitads is presented in figure 6.5. The result indicated that for a given mitad with gap 15 cm between them has higher result and reach 195.2 °C around 7 min but at such a gap it is difficult to use lid cover which can significantly reduce quality of injera. And mitads with gap 25 cm between them have lower temperature which is 156.2°C around 7 min so the initial heating up time for this gap increase. At the gap 20 cm between mitads reach at temperature of 183.9 °C at 7 min and it is good to use lid cover to increase the quality of injera. Finally, as the gap between mitads increase the heating up time also increase and as the gap between mitads decrease the heating up time also decrease but the quality of injera decrease. Thus, for the present study 20 cm gap is selected.

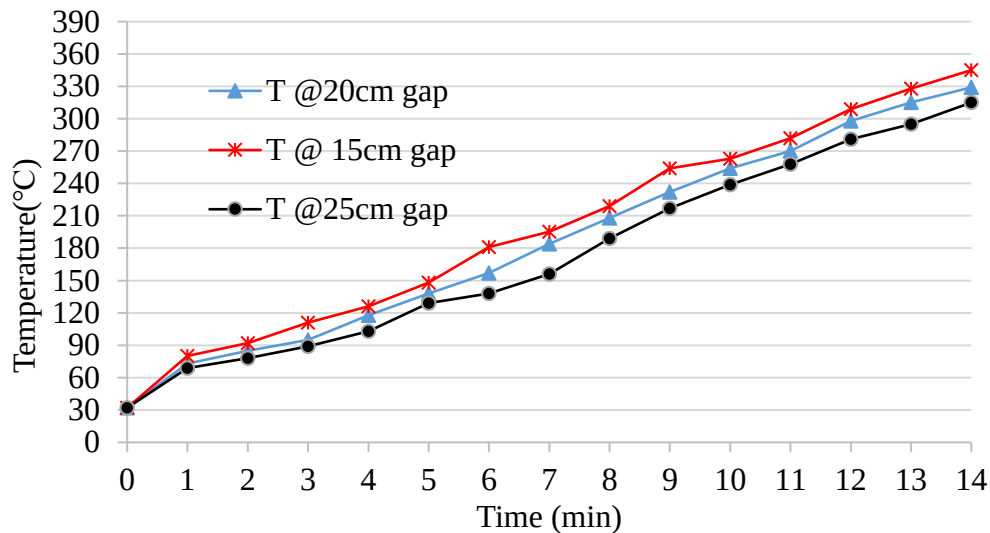


Figure 6.5 Heating up time for different gaps between consecutive mitads

6.3.2 Initial Heating Up Time

Initial heating up time is an indicator for how fast the mitad reaches baking temperature (reportedly varies from 180-220°C) within lower energy consumption rate. It is an important factor to determine initial heating up time, heating rate and energy requirement. Figure 6.6 shows the comparison of average variation of mitad surface temperatures of the present mitad one with that of conventional mitad during the initial heating up process. As the graph indicates the present mitad one has reduced initial heating up time of around 9.5 min (185°C) than of conventional mitad with around 18 min (180°C).

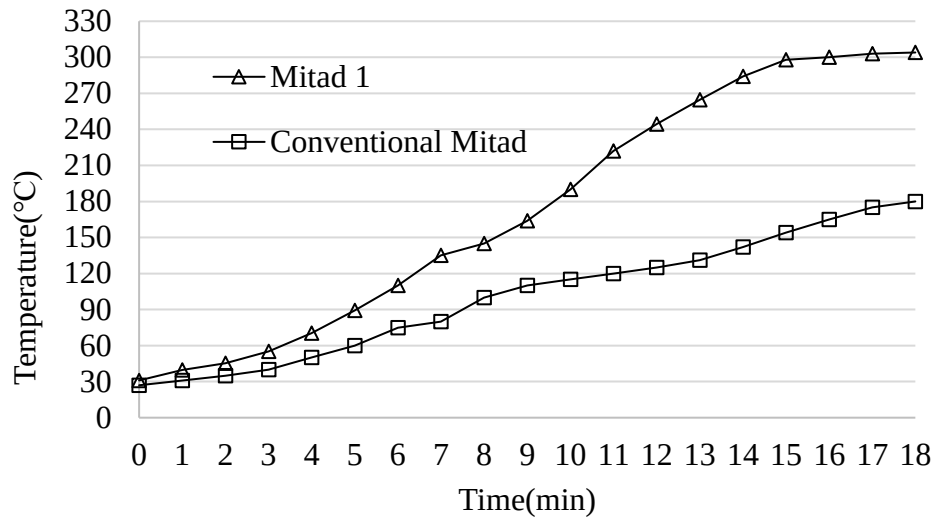


Figure 6.6 Comparison of initial heating up time for mitad one and conventional mitad

6.3.3 Initial Heating Up Time with And Without Lid Cover for Multi Mitad Injera Baking System

The result of initial heating up time for multi mitad with lid cover is shown in figure 6.7. As the graph indicated the initial heating up time of mitad one, two, three, and four was found to be 10 min, 8 min, 7 min and 9 min respectively with mitad three having a reduced heating up time than the other three. The effect of having lid cover on the initial heating up time is presented in figure 6.8. As the graph shows the use of lid cover on mitad three reduce the heating up time with about one minute.

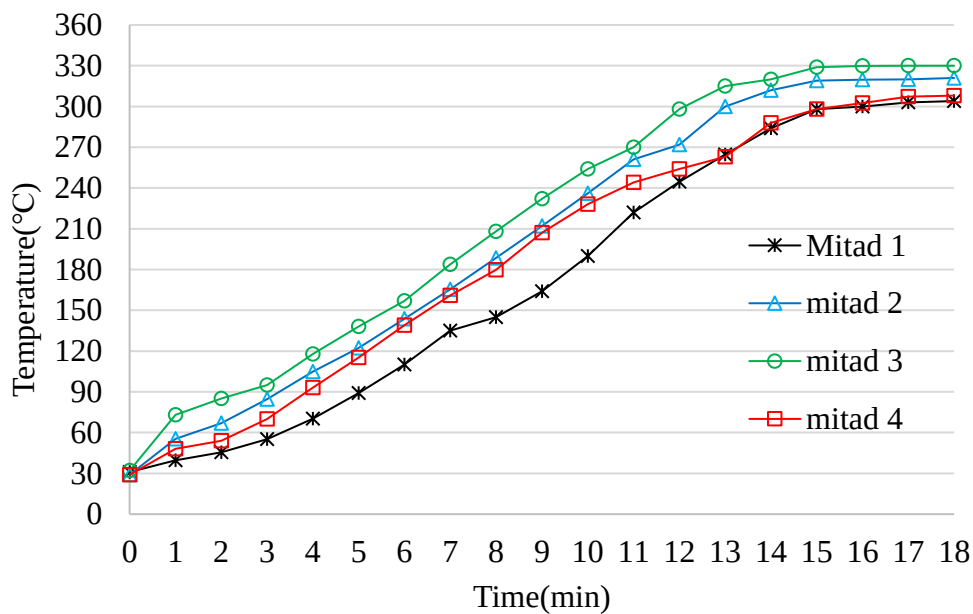


Figure 6.7 Initial heating up time for mitads with lid cover

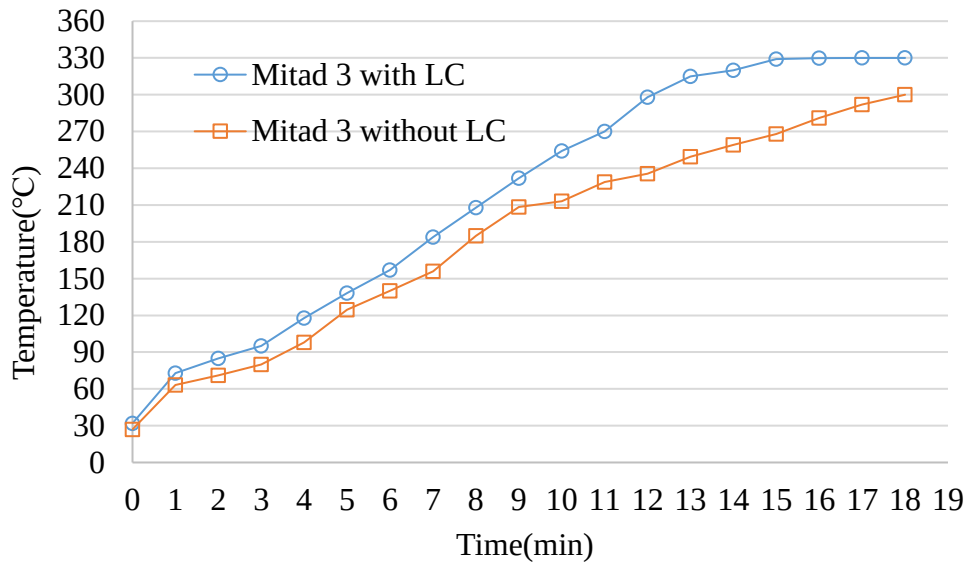


Figure 6. 8 Comparison of initial heating up time of mitad three with and without lid cover

6.3.4 Initial Heating Up Time for Multi Mitad Injera Baking Mitad for Closed System

Figure 6.9 shows the initial heating up time of multi mitads for a closed system. The result reveals initial heating up time for the closed system is reduced due to the reduction of heat loss though the door opening. Comparatively, the initial heating up time for open system of mitad one up to four was found to be 10 min, 8 min ,7 min and 9 min respectively whereas the initial heating up time of mitad one up to four for a closed system was found to be 8 min, 6 min ,6 min and 7 min respectively. Thus, the result indicates that the closed system can significantly reduce the amount of heat loss and initial heating up time.

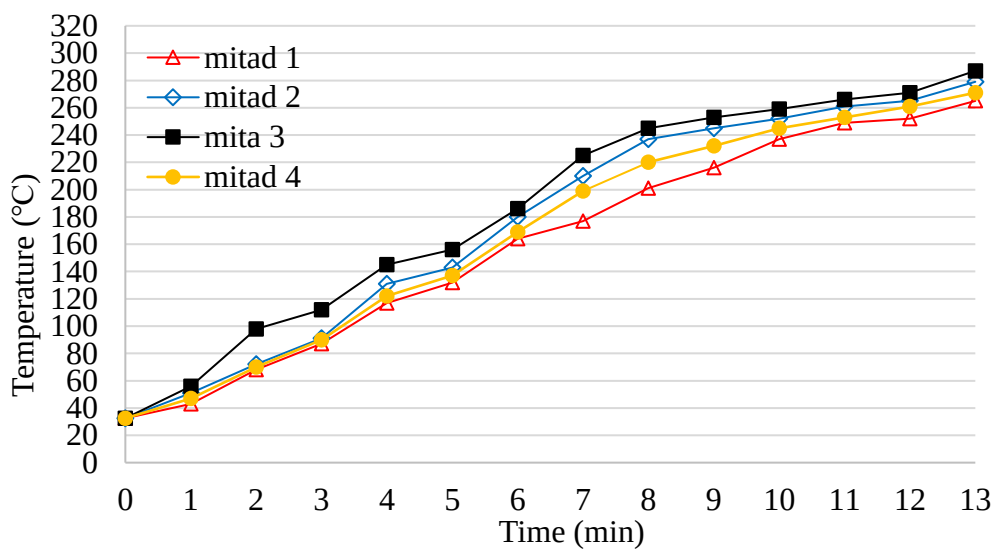


Figure 6. 9 Initial heating up time of mitads for a closed system

6.3.5 Baking Surface Temperature Distribution Profile of Baking Electric Mitad

Figure 6.10 shows the average surface temperature variations of the present electric mitad measured at different upper smooth surface, bottom and side of the mitad. Those temperature measurements were recorded under no load condition at the center, 14 cm and 28 cm away from the center of all direction on the baking surface. As the result indicated the temperature distribution on the baking surface is almost uniform this is due to constant groove depth and uniform separation between resistor wires. The uniform distribution of temperature on the surface of baking mitad is important factor for quality of injera. The temperature distribution on the bottom and side of mitad is comparatively very low which is desirable factor for heat loss reduction.

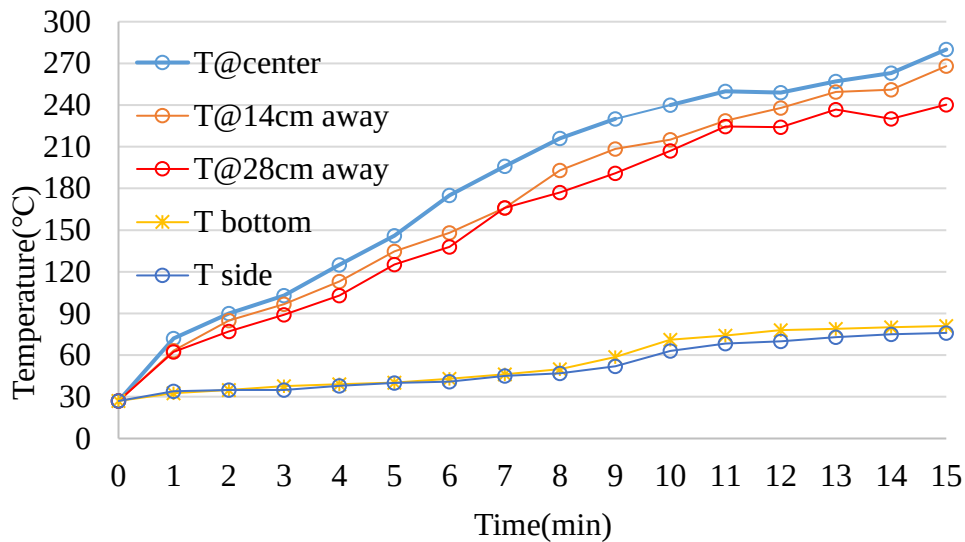


Figure 6.10 Baking surface temperature distribution

6.3.6 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 test temperature measurement was conducted. Figure 6.11 shows the temperature profile of multi electric Injera baking Mitad during the baking process. 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 was found to be about 90 seconds with 40 seconds idle time between successive Injera. The temperature of the batter in conversion to Injera starts from ambient temperature and reaches to 87 °C, whereas the temperature of the baking surface reduces from baking temperature to 87 °C. 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 there is continues supply of electric power. During the cyclic baking process similar values observed with small variations.

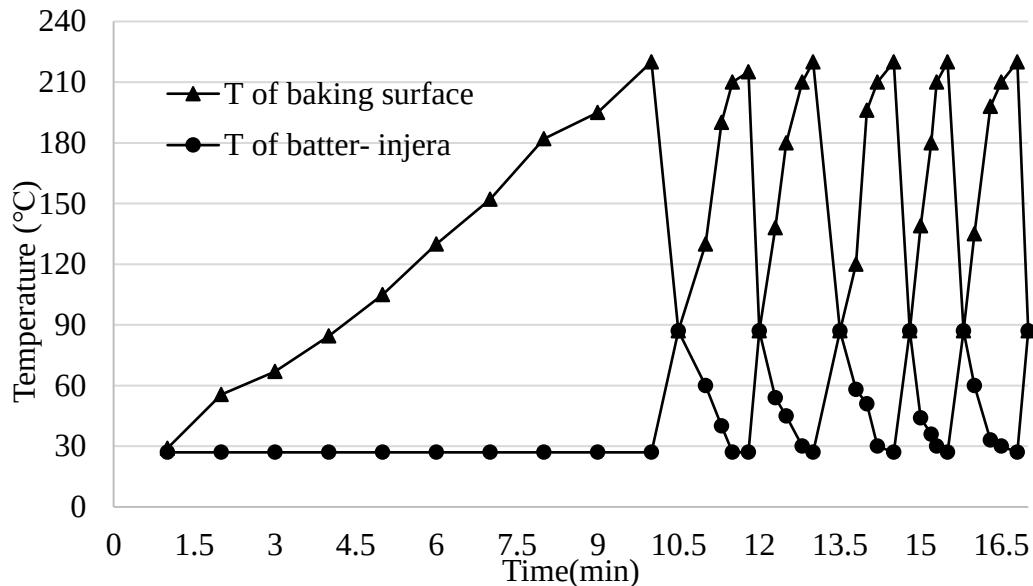


Figure 6.11 Temperature profile of baking mitad and injera during baking process

Figure 6.12 shows a magnified view of the temperature profile of the baking plate surface and Injera surface. The baking surface temperature reduced from 220 °C to 87 °C, whereas the temperature of batter in conversion to Injera increased from ambient temperature to 87 °C. This is the implication of heat transfer from baking plate to Injera through conduction and reaching thermal equilibrium.

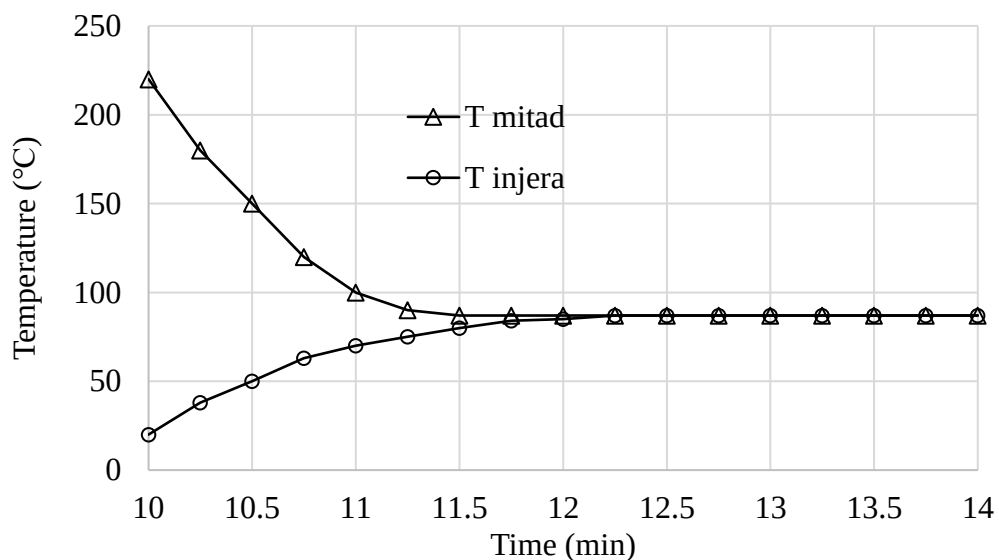


Figure 6. 12 Temperature profile of baking surface and first baked injera surface

6.4 Energy Utilization and Efficiency of Baking Mitads

There are three quantities to be noted with regard to the energy use of baking mitads: the total energy, the utilized energy, and efficiency of baking mitads. These quantities are used in the study of the performance of multi mitad injera baking electric system.

6.4.1 Energy Utilization

The total energy is the amount of energy used to bake a certain amount of injera. It includes both the energy actually utilized in baking injera and the energy lost during baking. The utilized energy is the amount of energy which is actually used in injera baking, excluding the losses from the total energy during the process. The utilized energy during injera baking is the sum of the energy required to raise the temperature of the batter to the boiling point of water and the energy required to vaporize a portion of the water in the batter. 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 is plotted in figure 6.13. The terminal voltage supplied to the heating element average value was 220 V and using the current variation, the power dissipation in the multi mitad calculated.

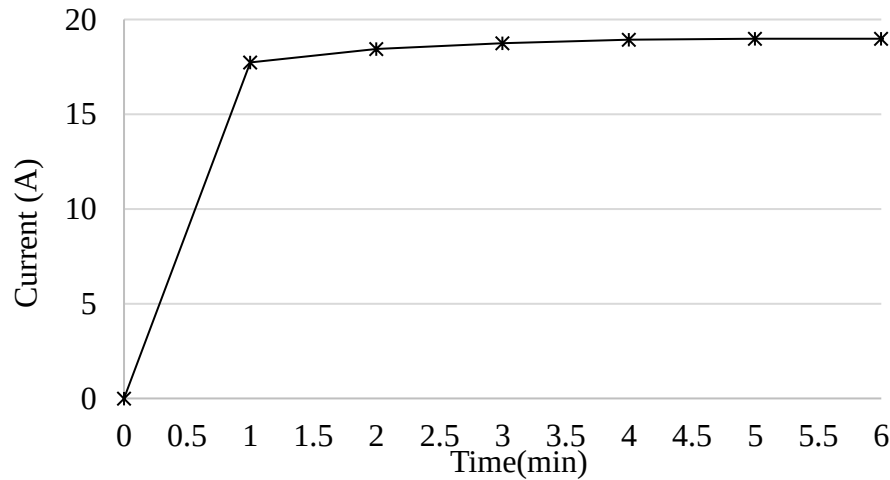


Figure 6.13 Current flow variation of multi mitad injera baking electric system

$$E_{utilized} = m_{batter} C_{p\ water} (T_{boil} - T_{room}) + (m_{batter} - m_{injera}) h_{vaporization} \quad 6.1$$

The average mass of injera and batter during baking using multi mitad injera baking electric system is obtained experimentally using mass balance by taking three different samples as shown in table 6.1.

Table 6.1 Mass balance of injera, batter and evaporated water (or transferred mass) during baking

Sample	Mass of batter (kg)	Mass of injera (kg)	Mass loss (kg)
1	0.50625	0.42082	0.08543
2	0.44025	0.34582	0.09443
3	0.42825	0.32282	0.10543
Average	0.45825	0.36315	0.09509

6.5 Load Test with Different Food Items

Based on the results of no-load test, a final set of experiments has been conducted on the multi mitad injera baking system with different actual baking loads. As figure 6.14 a through 6.14 e shows baking process starting from surface preparation up to final baking. After the mitad shows its ability to bake a quality injera, bread baking ability was tested without the power where the dough has a mass of 321.5 g and it takes around 15 minutes to bake. After the baking process the mass of bread were around 254.6 g this indicates that some water evaporated during baking and baking without power source indicates mitad store energy after the power was off. Figure 6.15 a and b shows bread baking test on the electric mitad.

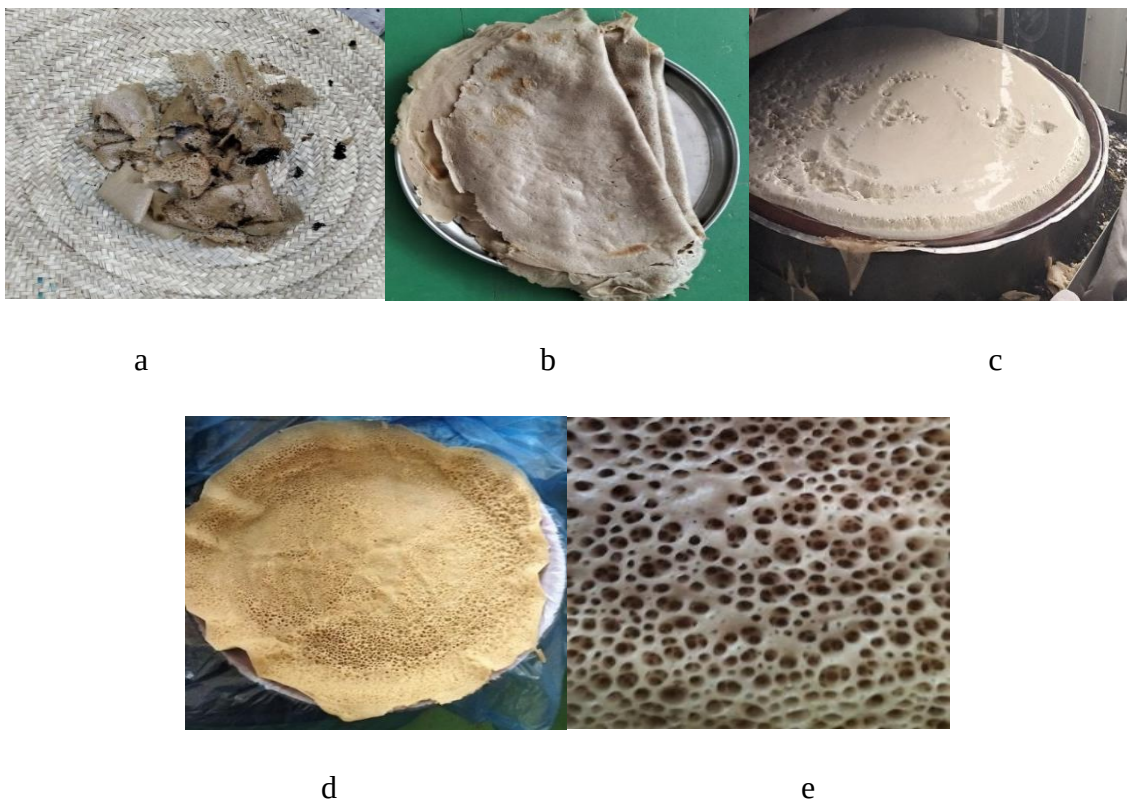


Figure 6.14 Actual injera baking test on the multi mitad baking system (a) Before surface preparation, b) During surface preparation(*mushit*) c) Pouring of batter d) Baked quality injera e) Upper surface quality of injera(eye)



Figure 6. 15 Actual bread baking tests of the electric mitad a) Dough on surface of mitad b) Baked ready bread

6.6 Heat Loss Coefficient Analysis of Multi Mitad Injera Baking Electric System

Heat lost coefficients are the losses that take place by conduction, convection and radiation as shown in the thermal resistance circuit. The heat source of the electric baking mitad is the current flow through Ni–Cr coil (or wire) that inserted in the bottom side of the baking mitad. This is heated due to the resistance and an electric current flow through the wire called ohmic heating.

6.7 Sankey Diagram for Multi Mitad Injera Baking Electric System

Based on the experimental result obtained, the Sankey diagram is drawn for 5 Injera baked per cycle for each mitad and it shows that the thermal efficiency of each Injera baking Mitads as shown in figure 6.16-figure 6.20 the bottom loss of each mitad is higher than other losses and which is considerable that the present study developed multi mitad injera baking electric system in order to use the bottom loss as an input heat for another mitad which is underneath it. The Sankey diagram is drawn for 20 Injera baked per cycle and it shows that the thermal efficiency of the multi mitad injera baking electric system. In the present multi mitad injera baking electric system highest energy loss occurs at the side surface of the system with 6.44% losses as shown in figure 7.22 which is due to the surface area of side of the system is larger than both top and bottom surface area of the system. Generally, the thermal efficiency of multi-mitad injera baking system is higher than the efficiency of each mitad this is due to the use of top and bottom loss of one mitad as input heat for another mitad. During the baking process, the two extra injera was baked in each mitad without electric power supply due to amount of energy stored in the system. **APPENDIX D** presents the

details of all the heat losses associated with the present multi mitad injera baking electric system.

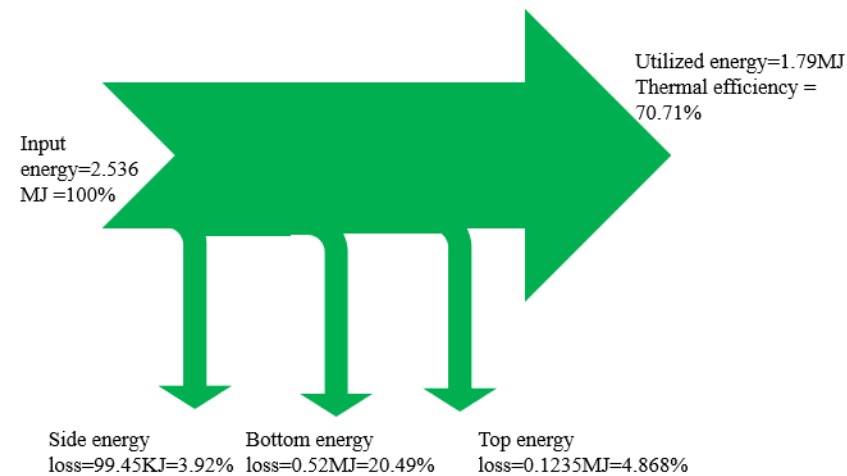


Figure 6.16 Sankey diagram of mitad one

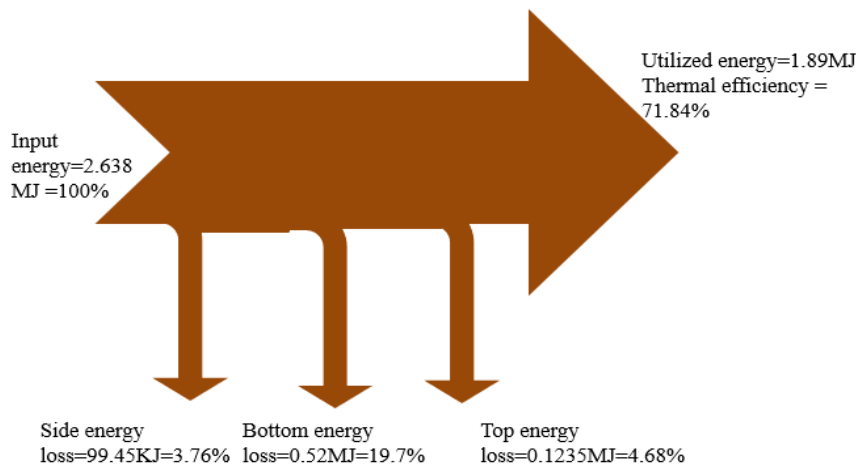


Figure 6.17 Sankey diagram of mitad two

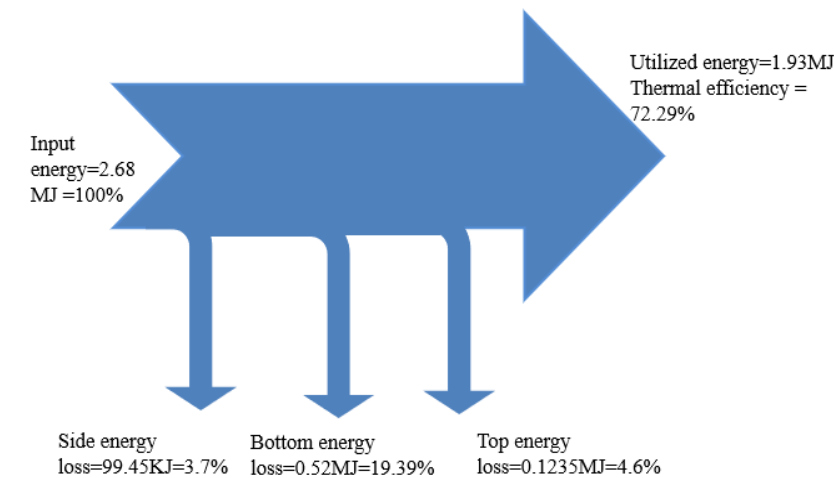


Figure 6.18 Sankey diagram of mitad three

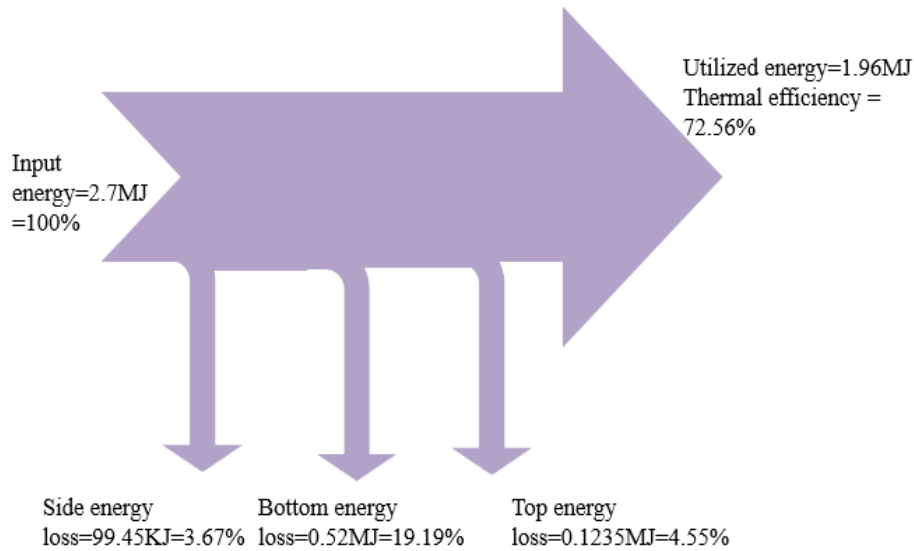


Figure 6.19 Sankey diagram of mitad four

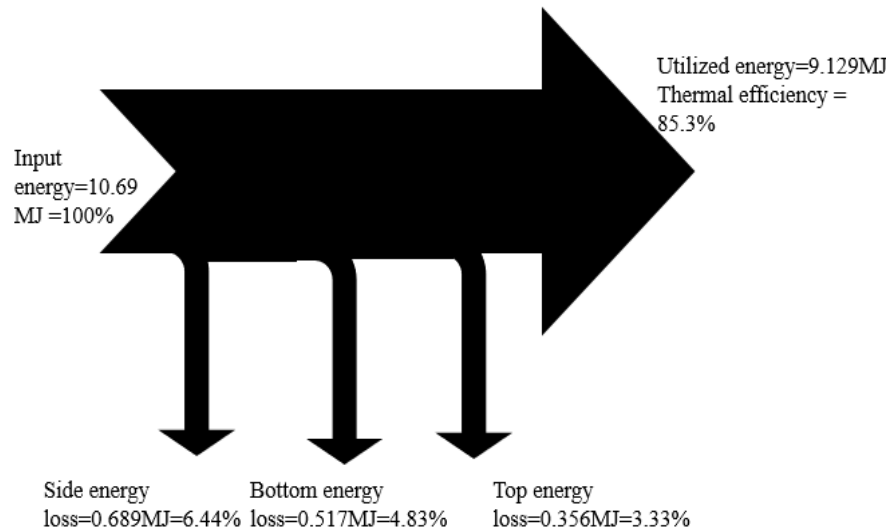


Figure 6.20 Sankey diagram of multi mitad injera baking system

6.7.1 Efficiency of Multi Mitad Injera Baking System

The efficiency of a baking mitad is simply the ratio of utilized energy to the total energy input. From the consecutive injera baking process the average overall efficiency of multi mitad was found to be 85.3%.

6.8 Comparison of Present Work with Previous Works

The present work, performance investigation of single electric mitad injera baking system is compared with previous research works. The parameters used for comparisons are initial heating time, baking time for each Injera and idle time between successive as shown in table 6.2. 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 6. 2 Electric mitads performance indicators comparison

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 (Multi Electric mitad)	480	90	40	0.1625
Conventional (Electric Mitad)	1260	120	60	0.385
Berhanu <i>et al.</i> , (2022) (Electric mitad)	660	100	50	0.272
Getnet (2011) (Electric mitad)	845	120	100	-
Garedew (2015) (Electric mitad)	1200	120	120	0.554

6.9 Cost and Energy Saving of Multi Mitad Injera Baking System

Using the multi mitad injera baking electric system for baking Injera, it is possible to save energy, energy bill cost and time consumption for mass production of injera. It saves about 1.15 kWh of energy per each Injera. For the current charging fee of electric energy in average consumption range about 2.4 Birr per kWh which saves about Birr 2.76 per Injera i.e. (1.15 kWh $\times$ 2.4 Birr/kWh). The system can also save time consumption for injera baking for instance the time taken for baking 20 injeras using the present system takes 20 minutes whereas the conventional system takes about 78 minutes. The energy efficiency of conventional single mitad with thickness 20 mm was reported to be dependent on the baking cycle (Getnet, 2011). For example, for input power of 1.867, 2.2, 2.5 and 3 kW, the energy efficiency of single mitad this mitad efficiency were reported to be 52.3, 58.1, 56.8 and 53.1 %, respectively in baking injera for 10 baking cycle whereas for 20 baking cycle the energy efficiency was reported to be 59.8, 67.5, 65.5 and 60.2 %, respectively (Getnet, 2011). The efficiency of this mitad was also reported to be 53.9% by Hialu and Hassen (2018) and 47% by Mesel *et al.* (2017). The highest efficiency was reported by Berhanu *et al.*, (2022) as 87.5 which was attained as a result of improvement of the mitad material made of copper powder mixed with clay. The energy efficiency of the individual mitad in this thesis work was found

to be in the order of 70% which differs from the prevails studied mainly by arrangement of the mitads compared to the conventional electric mitad. This result indicates that the mitad arrangement design studied in this research has a good scope in saving energy and also reducing heat up time of the mitad and also in energy saving.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this study experimental investigation and performance evaluation of multi mitad injera baking electric system has been carried out. The components of the multi mitad injera baking electric system were designed, sized and fabricated based on predetermined capacity of the system. Multi mitad injera baking system in one stand, arranged vertically on top of each other, was developed using SOLIDWORKS that utilizes the bottom loss from the upper mitad as useful heat input to the lower mitad. This baking system is more useful for mass production of injera and it reduces heat up time consumption and electric power input to bake injera. A numerical baking temperature predicting scheme for the multi mitads was derived using the conservation of energy equation which resulted in coupled nonlinear differential and algebraic equations. These equations were solved simultaneous using numerical iterative technique with the help of heat transfer correlations and using mitad components thermo-physical properties. Different experimental investigation and tests were conducted to evaluate performance of multi mitad injera baking system such as initial heating up time, baking mitad temperature and efficiency by operating the system with and without lid cover. In addition, no-load condition experiment was conducted to check uniformity of temperature distribution on the baking surface of the Mitad. Good agreement was obtained between the numerical and experimental results. The comparative study of thermal energy efficiencies was investigated from the experimental results of multi mitad injera baking electric system with and without load. Moreover, actual load, mass balance and performance tests were conducted with the developed prototype of the multi mitad injera baking electric system. The main results obtained from the numerical and experimental investigation of multi mitad injera baking electric system is presented in the following section.

From the numerical results obtained, the following points concluded:

- Higher temperature distribution up to 327 °C were obtained in mitad three with in the first 16 minutes, the increase in temperature is due to the fact that mitad three gets heat from bottom loss of mitad two and top loss of mitad four.
- Comparatively the temperature mitad one is lower than other mitads as it is subjected to top convection and radiation losses.

- Mitads having lid cover has high temperature than mitads without lid cover this indicates the positive effect of having lid cover in temperature distribution.
- Different power sources have different initial heating up time for example 3.5 kW power supplied mitad has lower heating up time compared to 3- and 2.5-kW power sources.

From the experimental results obtained, the following points concluded:

- The effect of three different gaps between mitads were studied experimentally. These gaps were 15, 20 and 25 cm and resulted 195.2, 183.9 and 156.2 °C as baking temperature over a period of 7 minute, respectively. As the gap between mitads increase the heating up time also increase and as the gap between mitads decrease the heating up time also decrease but the texture of injera also decrease. A gap of 20 cm is found to be the best or recommended operating gap.
- Mitad, one has reduced initial heating up time of around 9.5 min (185 °C) than that of conventional mitad which reaches 180°C in about 18 minutes.
- Initial heating up time of mitad one, two, three, and four was found to be 10, 8, 7 and 9 minutes, respectively during operating the multi mitad in open operation or without closing their doors.
- Initial heating up time of mitad one, two, three, and four was found to be 8 ,6 ,6 and 7 minutes, respectively for closed door system this indicates that initial heating up time and energy loss of a closed system is reduced compared with open system.
- The temperature distribution on the baking surface is almost uniform this might be due to constant groove depth, uniform back insulator and uniform separation between resistor wires.
- The batter which starts from ambient temperature converted to Injera starts when the temperature reaches to 87 °C, whereas the temperature of the baking surface reduces from baking temperature to 87 °C.
- The average time taken by the mitad to bake each Injera was found to be about 90 seconds with 40 seconds idle time between successive Injera.
- The bottom loss of each mitad was considerable in individual operation whereas the thermal efficiency of multi mitad (the four mitads together) is 85.3% due to the use of losses as an input heat.

- In the multi mitad injera baking electric system highest energy loss occurs at the side surface of the system with 6.44% losses this is due to the surface area of side of the system is larger than both top and bottom surface area of the system.
- The system saves about 0.827 kWh of energy per each Injera. Base on the 2.4 Birr per kWh rate of the current charging fee of electric energy consumption, this multi mitad system saves about Birr 1.98 per Injera.
- The system can also save time consumption for injera baking for instance the time taken for baking 20 injeras using the present system takes 20 minutes whereas the conventional system takes about 78 minutes.

7.2 Recommendations

Multi mitad injera baking electric system provides a solution to reduce energy loss during injera baking by using bottom loss one mitad as input energy for another mitad which is underneath it, and time and energy consumption. This Multi mitad injera baking electric system minimize energy loss, time and energy consumption for mass production of injera. The system is recommended for use by extended families with large members, both macro and micro business owners that do injera selling, hotels/restaurants owners and community cafeterias/canteen that gives service for students, soldier etc. which need large quantity of injera per day. The present study addressed the experimental investigation and performance evaluation of Multi mitad injera baking electric system. Some of future scopes and suggestions for further study are

- Experimental performance studies on same or different multi mitad injera baking electric system using different mitad thickness can be conducted.
- The structural design of the multi mitad injera baking system can be modified by redesigning the mitad arrangement to be retracted say two mitads in the front direction and the other two in the any of the sides/backside relative to the present design. This arrangement gives better comfort and opportunity for one or more than one person to bake injera.
- Fully automatic multi mitad injera baking electric system having temperature sensor can be developed and tested for its performance with further improvement in design

REFERENCE

- Adem, K. D., and Ambie, D. A. (2017). A review of injera baking technologies in Ethiopia: Challenges and gaps. *Energy for Sustainable Development*, 41, 69-80.
- Ali, A. (2018). Design and development of semi-automatic injera making machine for family households in Ethiopia. *International Research Journal of Engineering and Technology (IRJET)*, 5(10), 1465.
- Ashebir D. Hailu , Abdulkadir A. Hassen (2018). Experimental Investigation and Loss Quantification in Injera Baking Process, *Energy Management Research Journal* Vol. 1, No. 1.
- Assefa Abate, (2010). Transient heat transfer analysis of injera baking pan (“mittad”) by finite element method, Unpublished thesis, Addis Ababa University.
- Berhanu, H., Bekele, A., Venkatachalam, C., and Sivalingam, S. (2022). Performance improvement of an electric injera baking pan (Mitad) using copper powder as additive material. *Energy for Sustainable Development*, 68, 242-257.
- Bhattacharya, S. C., and Leon, M. A. (2005, April). Prospects for biomass gasifiers for cooking applications in Asia. In *World Renewable Energy Regional Conference, Jakarta, Indonesia, 18-21 April 2005*.
- Charm, SE. (1978). *The fundamental of food engineering* 3rd ed. Westport, CT: AVI Publishing.
- Choi, Y. and Okos, M.R. (1986). Effects of Temperature and Composition on the Thermal Properties of Foods. *Journal of Food Process and Applications*. 1(1): 93 –101.
- DANAS Electrical Engineering May 2015.
- Ezana Negusse, Robert Van Buskirk, and Haile Teclai, (1999). The Effect of Clay and Iron Cooking Plates on Mogogo Efficiency and Energy use: Experimental Results”, *Energy Research and Training Center*, P.O. Box 5285, Asmara, ERITREA.
- Farinu, A. (2006). *Heat and mass transfer analogy under turbulent conditions of frying* (Doctoral dissertation, University of Saskatchewan).
- Frankel, M., (1988). Thermal Insulation for Plumbing Systems, parts 1 and 2, *Plumbing Engineer*.

- Garedew, A. (2015). Performance analysis and reliability testing of a ceramic bakeware for an electric Injera baking Mitad, Addis Ababa University, Addis Ababa.
- Getenet, G. (2011). Heat transfer analysis during the process of Injera baking by finite element method. *Unpublished thesis, Addis Ababa.*
- GIZ, (2011). The Energy Development Intervention in Ethiopia Report," GIZ Energy Coordination office.
- Gupta, T. R. (2001). Individual heat transfer modes during contact baking of Indian unleavened flat bread (chapati) in a continuous oven. *Journal of Food Engineering*, 47(4), 313-319.
- Hassen, A. A., Amibe, D. A., and Nydal, O. J. (2011). Performance investigation of solar powered Injera Baking oven for indoor cooking. In *ISES solar world congress proceedings, Kassel, Germany* (pp. 186-196).
- Kaletunç, G. (2007). Prediction of specific heat of cereal flours: A quantitative empirical correlation. *Journal of food engineering*, 82(4), 589-594.
- Incropera F. and DeWitt P., (2002). Fundamentals of Heat and Mass Transfer, 5th ed., Wiley, New York.
- John A. Duffie, William A. Beckman, (2013). Solar Engineering of Thermal Processes, 2nd edition, John Wiley and Sons.
- Kamil Dino et al. (2019). First Injera baking biomass gasifier Mitad to reduce indoor air pollution, and fuel use, Addis Ababa University, Addis Ababa,
- Kreith et al., (1999). Heat and Mass Transfer Mechanical Engineering Handbook, LLC: CRC Press.
- Leninger, HA, Beverloo, WA. (1975). Food processing Engineering” Dordrecht: Reidel.
- Lucas, C., Manhica, F. and Richards, T. (2012). Computational Fluid Dynamic Simulation of the flow field in wood-fired bakery ovens. *International Journal of Applied Science and Technology*, 7(2), pp.1 -11.
- Mekonnen, M. T. (2011). Design and manufacture of laboratory model for solar powered injera baking oven.

- Mesele Hayelom et al. (2017). Energy Consumption Performance Analysis of Electrical Mitad, Momona Ethiopian Journal of Science (MEJS), vol. 9, no. 1, pp. 43-65.
- Mulugeta, T. (2020). The developmental patterns of injera baking Stoves: review on the efficiency, and energy consumption in Ethiopia. *International Journal of Mechanical Engineering*, 7(1), 7-16.
- Muluken, B. (2018). Design and experimental investigation of solar cooker with thermal energy storage. Addis Ababa University, Addis Ababa.
- Nalani D. Sabapathy, (2005). Heat and Mass Transfer during Cooking of Chickpea Measurements and Computational Simulation, Unpublished thesis, University of Saskatchewan,
- Patel, R., and Patel, V. (2020). Scheffler reflector for cooking application: a review. *International Journal of Ambient Energy*, 1 -13.
- Purlis, E., and Salvadori, V. O. (2009). Bread baking as a moving boundary problem. Part 1: Mathematical modelling. *Journal of food engineering*, 91(3), 428-433.
- Rahman S., (2005). Food Properties Handbook, Fourth Edition, Washington D.C.: CRC Press.
- Satheshi, N., and Fanta, S. W. (2020). Injera (An ethnic, traditional staple food of Ethiopia): A review on traditional practice to scientific developments. *Journal of Ethnic Foods*, 7(1), 1-15.
- Shahin Rafiee, Alireza Keyhani and Ali Mohammadi, (2008). Soybean Seeds Mass Transfer Simulation during Drying Using Finite Element Method, *World Applied Sciences Journal* 4 (2): 284-288,
- Tafere, A. T. (2011). Experimental investigation on performance characteristics and efficiency of electric injera baking pans ('Mitad'). *Energy Technology*.
- Tong C.H., and Lund, D.B., (1993). Microwave Heating of Baked Dough Products with Simultaneous Heat and Moisture Transfer, *Journal of Food Engineering*, 19,319-339,
- Tsegay, M., (2011). Design and manufacture of a laboratory model for solar-powered Injera Baking Oven (Doctoral dissertation, MSc thesis, Addis Ababa Institute of Technology).

Vincenzini P., (1991). Fundamentals of Ceramics Engineering, New York: Elsevier Science Publisher, Ltd.

World bank, (2016). world development indicators. The World Bank.

Yesihak Tefera, (2019). design of injera processing machine, Addis Ababa University, Addis Ababa,

Yosef Assefa, (2007). Assessing environmental benefits of mirt stove with particular reference to indoor air pollution and energy conservation, Addis Ababa University, Addis Ababa,

Yunus A. Cengel, (2003), Heat transfer; a practical approach, 2nd edition, McGraw-Hill, London.

APPENDIX 1. National Conference Publication

6th Annual Research Conference on “Science, Technology and Innovation for Industry”
(STII 2022)

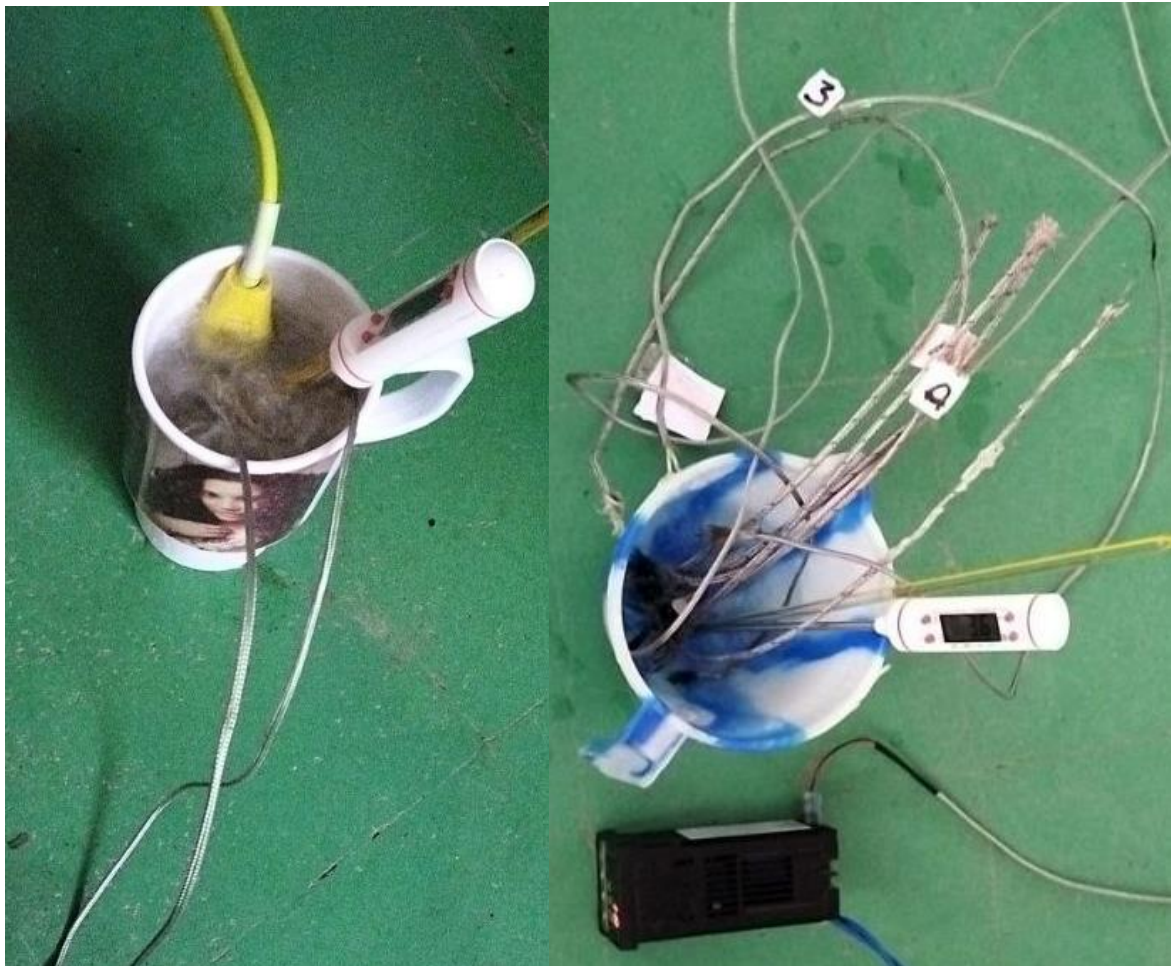


Figure A.1. 1 National conference certificate

APPENDIX A. Calibration of Measuring Instrument

Calibration of the Thermocouple Thermo-Meter

Thermocouples are sensors used to measure temperature by forming a junction between two wires of separate metals. One end of the junction is called the measurement “hot” junction and the other end is called the reference “cold” junction. When there is a temperature variation in the joint, voltage is created and this voltage can be converted into temperature with a thermocouple reference table or data logger. Before taking any measurement in the process of testing the experiments, calibration of measuring device is compulsory. In the present work the thermocouple was calibrated using boiled water (100°C) and ice (0°C). Thermocouples were tagged with number from 1-11 including letters for identification and facilitate measurement.



a)

b)

Figure A.1 Calibration process a) Water boiling and b) Ice water calibration methods

Table A.1 Data from thermocouples during calibration

Thermocouple	Boiled water (100°C)	Uncertainty (%) $\frac{(100 - \text{measured})}{100} * 100$
Digital thermometer	99.7	0.3
Wet-bulb thermometer	99.1	0.9
S1	99.3	0.7
S2	99.6	0.4
S3	99.3	0.7
1	99.2	0.8
2	99.9	0.1
3	99.8	0.2
4	99.7	0.3
5	99.5	0.5
6	99.4	0.6
7	99.1	0.9
8	99.2	0.8
9	99	1
10	99.2	0.8
A	99.7	0.3
B	99.9	0.1
C	99.1	0.9
D	99.3	0.7
Average uncertainty		0.578

APPENDIX B. Energy Balance Equations of Each Mitads with Lid Cover

Table B.1 Initial temperature assumptions

Temprature	Value
Ta	20°C
Tlc1	60 °C
Tp1	180 °C
Tlc2	80 °C
Tp2	200 °C
Tlc3	80 °C
Tp3	220 °C
Tlc4	100 °C
Tp4	240°C

LID COVER ONE

$$\Delta E = E_{in} - E_{out} \quad \text{B.1}$$

$$\Delta E = qc_{p1lc1} + qr_{p1lc1} - qc_{lc1am} - qr_{lc1am} \quad \text{B.2}$$

Where: qc_{p1lc1} = convection heat transfer from plate one to lid cover one

qc_{lc1am} = convection heat transfer from lid cover one to ambient

qr_{p1lc1} = radiation heat transfer from plate one to lid cover one

qr_{lc1am} = radiation heat transfer from lid cover one to ambient

Then, find heat transfer coefficients h_1 and h_2

h_1 is convective heat transfer coefficient between plate one and lid cover one, the air properties will be considered at mean temperature between them

Using this film temperature, the properties of the heat transfer from the Property Design Data table for lid cover one are:

Gravity; $g=9.81 \text{ m/s}^2$

Kinematics viscosity; $\nu = 2.545 \times 10^{-5} \text{ m}^2/\text{s}$

Prattle number; $PR = 0.686$

Coefficient of thermal expansion, $\beta = 1/T_f$

Thermal conductivity; $k = 0.03338$

Now substituting the values of the properties; the Raleigh number and the Nusselt number becomes:

$$Ra = Gr \times Pr = \frac{g \Delta T \beta L_c^3}{\nu^2} \times Pr \quad B.3$$

$$Nu = 1 + 1.44 \left[1 - \frac{1708(\sin 1.8 \beta)^{1.6}}{Ra \cos \beta} \right] \left[1 - \frac{1708}{Ra \cos \beta} \right]^+ + \left[\left(\frac{Ra \cos \beta}{5830} \right)^{\frac{1}{3}} - 1 \right]^+ \quad B.4$$

Where $\beta = 0$ because mitads arranged parallelly

$$h_1 = \frac{Nu k}{L_c} \quad B.5$$

Using equation B.3, B.4 and B.5 rayelign number, Nusselt number and convective heat transfer coefficient calculated 3.96×10^5 , 5.51 and 3.678 respectively.

h_2 is convective heat transfer coefficient between lid cover one and surrounding (ambient),

$$h_2 = 5.7 + 2.8V, \text{ but } V = 0 \text{ therefore } h_2 = 5.7$$

Then substitute values at equation B.2

$$\begin{aligned} & \frac{T_{lc1} - T_{lc0}}{t} \\ &= \frac{0.97(T_{p1} - T_{lc1}) + 1.5 \times 10^{-9}(T_{p1}^4 - T_{lc1}^4) - 1.5(T_{lc1} - T_{am}) - 1.49 \times 10^{-9}(T_{lc}^4 - T_{am}^4)}{mc_p} \end{aligned}$$

Similarly, the governing equation for each mitads and lid covers were calculated.

MITAD ONE

$$\begin{aligned} & \frac{T_{p1} - T_{p10}}{t} \\ &= \frac{q_{gen} \times v_m - 0.92(T_{p1} - T_{lc2}) - 1.5 \times 10^{-9}(T_{p1}^4 - T_{lc2}^4) - 1.5 \times 10^{-9}(T_{p1}^4 - T_{lc1}^4) - 0.97(T_{p1} - T_{lc1})}{mc_p} \end{aligned}$$

LID COVER TWO

$$\frac{T_{lc2} - T_{lc20}}{t} = \frac{0.96(T_{p2} - T_{lc2}) + 1.5 \times 10^{-9}(T_{p2}^4 - T_{lc2}^4) + 0.92(T_{p1} - T_{lc2}) + 1.5 \times 10^{-9}(T_{p1}^4 - T_{lc2}^4)}{mc_p}$$

MITAD TWO

$$\frac{T_{p2} - T_{p20}}{t} = \frac{q_{gen} \times v_m - 0.96(T_{p2} - T_{lc3}) - 1.5 \times 10^{-9}(T_{p2}^4 - T_{lc3}^4) - 1.5 \times 10^{-9}(T_{p2}^4 - T_{lc2}^4) - 0.96(T_{p2} - T_{lc2})}{mc_p}$$

LID COVER THREE

$$\frac{T_{lc3} - T_{lc30}}{t} = \frac{0.99(T_{p3} - T_{lc3}) + 1.5 \times 10^{-9}(T_{p3}^4 - T_{lc3}^4) + 0.96(T_{p2} - T_{lc3}) + 1.5 \times 10^{-9}(T_{p2}^4 - T_{lc3}^4)}{mc_p}$$

MITAD THREE

$$\frac{T_{p3} - T_{p30}}{t} = \frac{q_{gen} \times v_m - 0.95(T_{p3} - T_{lc4}) - 1.5 \times 10^{-9}(T_{p3}^4 - T_{lc4}^4) - 1.5 \times 10^{-9}(T_{p3}^4 - T_{lc3}^4) - 0.99(T_{p3} - T_{lc3})}{mc_p} .4$$

LID COVER FOUR

$$\frac{T_{lc4} - T_{lc0}}{t} = \frac{0.984(T_{p4} - T_{lc4}) + 1.5 \times 10^{-9}(T_{p4}^4 - T_{lc4}^4) + 0.95(T_{p3} - T_{lc4}) + 1.5 \times 10^{-9}(T_{p3}^4 + T_{lc4}^4)}{mc_p} 4$$

MITAD FOUR

$$\frac{T_{p4} - T_{p40}}{t} = \frac{q_{gen} \times v_m - 0.98(T_{p4} - T_{lc4}) - 1.5 \times 10^{-9}(T_{p4}^4 - T_{lc4}^4) - 1.42 \times 10^{-8}(T_{p4}^4 - T_{am}^4) - 3(T_{p4} - T_{am})}{mc_p}$$

APPENDIX C. Energy Balance Equations of Each Mitads Without Lid Cover

Table C.1 Temperature assumptions

Temperature	Value
T _{lc1}	100 °C
T _{p1}	180 °C
T _{p2}	200 °C
T _{p3}	220 °C
T _{p4}	240°C

MITAD ONE

Heat generation to mitad one

Heat input to mitad one (E_{in})

The possible heat input to mitad one based on assumption are radiation and convection from mitad 2 because heat is transferred from high temperature to low temperature and conduction between mitad one and wire

$$E_{in} = qc_{21} + qr_{21} - k\nabla^2 T \quad C.1$$

Where: qc_{21} = convection heat transfer from plate two to plate one

qr_{21} = radiation heat transfer from plate two to plate one

The effect of conduction heat transfer is insignificant so neglect conduction and equation C.1 became

$$E_{in} = A\varepsilon\sigma(T_{p2}^4 - T_{p1}^4) + h_1A(T_{p2} - T_{p1}) \quad C.2$$

Heat loss from mitad one (E_{out})

The possible heat loss from mitad one based on assumption is top loss by convection and radiation from mitad one to lid cover.

$$E_{out} = qr_{1lc} + qc_{1lc} \quad C.3$$

$$E_{out} = A\varepsilon_{eff}\sigma(T_{p1}^4 - T_{lc}^4) + h_1A(T_{p1} - T_{lc}) \quad C.4$$

h_1 is convective heat transfer coefficient between plate one and lid cover one, the air properties will be considered at mean temperature between them;

Using this film temperature, the properties of the heat transfer from the Property design data table are:

Gravity=9.81 m/s²

Kinematics viscosity; $\nu=2.78 \times 10^{-5}$ m²/s

Pradtle number; PR=0.684

Coefficient of thermal expansion, $\beta=1/T_f$

Thermal conductivity; $k=0.03489$

Now substituting the values of the properties; the Raleigh number and the Nusselt number becomes:

$$Ra = Gr \times Pr = \frac{g \Delta T \beta L_c^3}{\nu^2} \times Pr \quad C.5$$

$$Nu = 1 + 1.44 \left[1 - \frac{1708(\sin 1.8 \beta)^{1.6}}{Ra \cos \beta} \right] \left[1 - \frac{1708}{Ra \cos \beta} \right]^+ + \left[\left(\frac{Ra \cos \beta}{5830} \right)^{\frac{1}{3}} - 1 \right]^+ \quad C.6$$

Where $\beta = 0$ because mitads arranged parallely

$$h_1 = \frac{Nu k}{L_c} \quad C.7$$

Using equation C.5, C.6 and C.7 rayelign number, Nusselt number and convection heat transfer coefficient calculated 2.1×10^5 , 4.73 and 3.301 respectively.

$$\Delta E = E_{in} + E_{gen} - E_{out}$$

$$\begin{aligned} & \frac{T_{p1} - T_{p0}}{dt} \\ &= \frac{q_{gen} \times v_m + A \varepsilon \sigma (T_{p2}^4 - T_{p1}^4) + h_1 A (T_{p2} - T_{p1}) - h_1 A (T_{p1} - T_{lc}) - A \varepsilon_{eff} \sigma (T_{p1}^4 - T_{lc}^4)}{m c_p} \\ & \frac{T_{p1} - T_{p0}}{t} \\ &= \frac{q_{gen} \times v_m + 1.4 \times 10^{-8} (T_{p2}^4 - T_{p1}^4) + 0.6359 (T_{p2} - T_{p1}) - 0.87 (T_{p1} - T_{lc}) - 1.5 \times 10^{-9} (T_{p1}^4 - T_{lc}^4)}{m c_p} \end{aligned}$$

Similarly, for mitad 2, mitad 3 and mitad four were calculated.

MITAD TWO

$$\begin{aligned} & \frac{T_{p2} - T_0}{dt} \\ &= \frac{\dot{q} \times v_m + A\varepsilon\sigma(T_{p3}^4 - T_{p2}^4) + h_2 A (T_{p3} - T_{p2}) - h_1 A (T_{p2} - T_{p1}) - A\varepsilon\sigma(T_{p2}^4 - T_{p1}^4)}{mc_p} \end{aligned}$$

$$\begin{aligned} & \frac{T_{p2} - T_0}{t} \\ &= \frac{\dot{q} \times v_m + 1.4 \times 10^{-8}(T_{p3}^4 - T_{p2}^4) + 0.637 (T_{p3} - T_{p2}) - 0.6359 (T_{p2} - T_{p1}) - 1.4 \times 10^{-8}(T_{p2}^4 - T_{p1}^4)}{mc_p} \end{aligned}$$

MITAD THREE

$$\begin{aligned} & \frac{T_{p3} - T_0}{t} \\ &= \frac{\dot{q} \times v_m + 1.4 \times 10^{-8}(T_{p4}^4 - T_{p3}^4) + 0.6314 (T_{p4} - T_{p3}) - 1.4 \times 10^{-8}(T_{p3}^4 - T_{p2}^4) - 0.64(T_{p3} - T_{p2})}{mc_p} \end{aligned}$$

MITAD FOUR

$$\begin{aligned} \frac{T_{p4} - T_0}{dt} &= \frac{\dot{q} \times v_m - A\varepsilon\sigma(T_{p4}^4 - T_{p3}^4) - h_1 A (T_{p4} - T_{p3})}{mc_p} \\ \frac{T_{p4} - T_0}{t} &= \frac{\dot{q} \times v_m - 1.4 \times 10^{-8}(T_{p4}^4 - T_{p3}^4) - 0.631 (T_{p4} - T_{p3})}{mc_p} \end{aligned}$$

APPENDIX D. Heat Loss Coefficient Analysis of Multi Mitad Injera Baking System

i. Top loss Heat Transfer Coefficient

There is top loss at mitad one from mitad one to lid cover and from lid cover to ambient by convection and radiation so top heat transfer of housing calculated as shown below

A, losses from mitad one to lid cover by convection and radiation then heat transfer coefficients of radiation and convection are

$$h_{r1-lc} = \frac{\sigma(T_1^2 + T_{lc}^2)(T_1 + T_{lc})}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

Then find convection heat transfer coefficient between mitad one and lid cover, the air properties will be considered at mean temperature between them

Using this film temperature, the properties of the heat transfer from the Property design data table are:

Gravity; $g=9.81 \text{ m/s}^2$

Kinematics viscosity; $\nu=2.78 \times 10^{-5} \text{ m}^2/\text{s}$

Pradtle number; $Pr=0.684$

Coefficient of thermal expansion, $\beta=1/T_f$

Thermal conductivity; $k= 0.03489$

Now substituting the values of the properties; the Raleigh number and the Nusselt number becomes:

$$Ra = Gr \times Pr = \frac{g \Delta T \beta L_c^3}{\nu^2} \times Pr \quad D.1$$

$$Nu = 1 + 1.44 \left[1 - \frac{1708(\sin 1.8 \beta)^{1.6}}{Ra \cos \beta} \right] \left[1 - \frac{1708}{Ra \cos \beta} \right]^+ + \left[\left(\frac{Ra \cos \beta}{5830} \right)^{\frac{1}{3}} - 1 \right]^+ \quad D.2$$

Where $\beta = 0$ because mitads arranged parallely

$$h_{1-lc} = \frac{Nu k}{L_c} \quad D.3$$

Using equation D.1,D.2 and D.3 rayelign number, Nusselt number and convection heat transfer coefficient calculated 2.089×10^5 , 4.725 and 3.29734 respectively.

The resistance R_1 expressed as

$$R_1 = \frac{1}{h_{r1-lc} + h_{c1-lc}}$$

B, losses from lid cover to ambient by convection and radiation then heat transfer coefficients of radiation and convection based on mcAdams rule

$$h_{rlc-am} + h_{lc-am} = 5.7 + 3.8v$$

$h_{lc-a} = 5.7 + 3.8v$, where $v = \text{wind speed} = 0$ by neglecting wind speed = 5.7

The resistance R_0 expressed as

$$R_0 = \frac{1}{h_{rlc-a} + h_{clc-a}}$$

The overall top loss of mitad one expressed as

$$U_{t1} = \frac{1}{R_0 + R_1}$$

Then the area of top of housing is $A = L \times W = 0.66 \times 0.69 = 0.4554 \text{ m}^2$

And the rate of heat loss from the top can be given as:

$$q_{t \text{ loss}} = u_t A (T_s - T_a)$$

To converting to energy form, multiplying the lost power by number of injera baked in a cycle and the time it takes for baking.

$$E_{top,loss} = 0.356 \text{ MJ} = 3.33\%$$

ii. Side loss Heat Transfer Coefficient

Energy lost from the lateral side of the baking pan casing may be taken to have similar value with the bottom side of the baking pan if the thickness and area of the edge insulation has the same to that of back (or bottom) insulation. But they have different thickness and area. There is side loss by conduction from mitads to the insulator or ash having the insulation thickness of 25mm and convection and radiation heat transfer from housing to the ambient air and side heat transfer of housing calculated as shown below

$$U_s = \left(\frac{t_{ash}}{k_{ash}} + \frac{t_{ceramic}}{k_{ceramic}} + \frac{1}{h_s} \right)^{-1}$$

Then the area of housing side is $A = 2(L \times W) + 2(L \times W) = 3.51 \text{ m}^2$

And the rate of heat loss from the top can be given as:

$$q_{s\ loss} = u_s A (T_s - T_a)$$

To converting to energy form, multiplying the lost power by number of injera baked in a cycle and the time it takes for baking.

$$E_{side,loss} = 0.689MJ = 6.44 \%$$

iii. Bottom loss Heat Transfer Coefficient

Heat is lost from the housing to the ambient, by conduction through the insulation to the plate casing and subsequently by convection and radiation from the bottom housing to the ambient:

$$U_b = \left(\frac{t_{fiberglass}}{k_{fiberglass}} + \frac{1}{h_b} \right)^{-1}$$

Then the area of housing side is $A = L \times W = 0.4554 \text{ m}^2$

And the rate of heat loss from the top can be given as:

$$q_{b\ loss} = u_b A (T_s - T_a)$$

To converting to energy form, multiplying the lost power by number of injera baked in a cycle and the time it takes for baking.

$$E_{bottom,loss} = 0.517MJ = 4.83 \%$$

iv. Overall Heat Transfer Coefficient

Over all energy loss “ Q_L ” is the sum of the top, bottom and edge energy lost. The overall heat loss percentage for 20 number of injera baking per cycles of conventional and multi mitad injera baking electric system to the surrounding was around 48% and 14.61%; and the energy lost was around 6.8 MJ and 1.562 MJ respectively. From the total energy loss, the side loss is higher than top and bottom loss this is due to side surface area is larger than both top and bottom surface.

Over all energy loss (Q_L) = $E_{top,loss} + E_{side,loss} + E_{bottom,loss}$

$$= 3.33\% + 6.44\% + 4.83 \% = 14.6\%$$

$$\text{Overall energy efficiency} = \frac{Q_u}{Q_e} = \frac{9.129MJ}{10.69MJ} \times 100\% = 85.39\%$$

APPENDIX E. Total Cost of multi mitad injera baking electric system

Table E.1 List of components costs

No.	Item	Specification	Qty	Unit price [Birr]	Total price[birr]
1	Mitad	580mm diameter,20mm thickness	4	1000	4000
2	Lid cover	580mm diameter	4	300	1200
3	Insulating material	5mx2m fiber glass 2.5mm thick	1	500	500
4	Housing	660 mm length X 690 mm width X1300 mm height sheet metal	1	2500	2500
5	Sub total				8200
6	Manufacturing, labour and assembly cost	25% material cost			2050
7	Operating(power), maintenance and replacement cost	10% of investment cost			820
	Total cost				11,070