ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Multidisciplinary Center of Renewable Energy

INVESTIGATION OF ELECTRIC INJERA MITAD WITH COPPER WIRE EMBEDDINGS FOR PERFORMANCE IMPROVEMENT

A Thesis Submitted to the School of Graduate studies of Addis Ababa University in Partial Fulfillment of the Requirements for the award of the Degree of Masters of Science in Energy Technology

By: Daniel Asrat

Advisor: Abdulkadir Aman Hassen (PhD)

November 2022

CERTIFICATION

I, the undersigned, certify that I read and hear by recommend for the acceptance by Addis Ababa university, Addis Ababa Institute of Technology, School of Multidisciplinary Center of Renewable Energy, a thesis entitled "Investigation of electric injera mitad with copper wire embeddings for performance improvement". This certificate is used as a partial fulfillment of the requirement for the degree of Master of Science in Energy Technology.

Signature______________________

Date _________________________

DECLARATION

I, Daniel Asrat, hear by declare that the research entitled "Investigation of electric injera mitad with copper wire embeddings for performance improvement" is my independent work, and has not been previously submitted to any other university to obtain a degree.

Candidate name: Daniel Asrat

Signature______________________ Date ______________

Advisor: Dr. Abdulkadir Aman.

Signature ______________ Date ______________

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Multidisciplinary Center of Renewable Energy

Investigation of Electric Injera Mitad with Copper wire Embeddings for Performance Improvement

By

Daniel Asrat

Submitted in accordance with the requirements for the degree

MASTER OF SCIENCE (M.Sc.)

Approved By the Board of Directors

Dr. Abdulkadir Aman, ___________________________ __________________

Advisor: Signature Date

_____________________ _____________________ _____________________

Internal Examiner: Signature Date

_____________________ _____________________ _____________________

External Examiner: Signature Date

_____________________ ____________________ _____________________

Chairman of the School: Signature Date

ACKNOWLEDGMENT

I would first like to thank my thesis advisor, Dr. Abdulkadir Aman, for the support, guidance, and arranging for testing facilities, without which the study could not have been carried out.

I would also like to thank Dr. Solomon T/Mariam for his unreserved support and encouragement during the study. My sincere thanks go to Ato Zewge Worku and Ato Hailu Assefa for their support in lending critical testing equipment determinantal to the study.

Finally, I must express my very profound gratitude to my family for providing continuous encouragement through the process of researching and writing this thesis.

ABSTRACT

Ethiopians make injera, a staple food, on a clay baking pan, mitad, with either biomass or electricity as the energy source. The existing electric mitads in the country are highly inefficient, demand high power, and consume significant energy. The clay plate of the appliance is produced and assembled traditionally and its poor thermal performance created overloading of the electric power distribution network and introduced high energy consumption to the consumer and the nation. Efforts to enhance the thermal properties of the clay plate are yet to address the practicability of casting and producing improved clay plates at the level of local producers. This study examines the effect of copper wire embeddings in the clay plate of electric injera mitad to improve its performance.

The study investigated the development of a CuWE clay plate of electric mitad, determined its effect on performance, and compared this performance with other similar studies. The traditional methods of clay plate production were identified and the Controlled Cooking Tests were conducted. The investigation revealed that, for a triple baking test, 30 injera per baking test, the CuWE clay plate electric mitad's heat-up time, the maximum-to-minimum heat-up temperature difference, and energy consumption were reduced by 3 min, from 64.3 °C to 36.9 °C, and 110 Wh, respectively. Energy efficiency was improved by 10.8% as compared to the base case electric mitad; the cyclic baking time per injera was decreased by 0.6 minutes; the overall baking period, including heat-up time; the specific energy consumption; and the total energy consumption were reduced by 21 minutes, 0.09 kWh/kg of injera, 1.0 kWh, or 15.4%, respectively.

It was revealed in the study that embedding copper wire in the clay plate of electric injera mitad improved baking surface temperature uniformity and injera quality; reduced energy consumption and time to bake. Local manufacturers can produce CuWE electric mitads without the aid of any special equipment or production techniques to reduce the huge impact of electric injera mitads on the power and energy demand of the country.

Key words: Electric mitad, Clay plate, Copper wire embedding, Injera, Baking surface temperature.

NOMENCLATURE

A	Baking surface area (m^2)
A_s	Surface area through which convection heat transfer occurs (m^2),
C_p	Heat capacity, (J/kg.K)
C_b	Specific heat capacity of the batter(J/kg.K)
C_{cp}	Specific heat capacity of the clay plate(J/kg.K)
$E_{generated}$	Thermal energy generated in the Mitad
E_{in}	Energy entering the Mitad
E_{out}	Energy leaving the mitad
E_{stored}	Thermal energy stored in the mitad
h	Convection heat transfer coefficient (W/ m^2.°C).
H_V	Heat of vaporization of water(J/kg)
I	Electric current (A)
k	Thermal conductivity of the clay plate(W/m.K)
L	Thickness of the clay plate from the top of the heating element to the baking surface(m).
$LiBO_2$	Lithium metaborate
m	Mass of the clay plate (kg)
M_b	mass of batter (kg)
M_i	Mass of Injera baked (kg)
Q_{c-BB-a}	Convective heat transfer from Body Bottom to ambient
Q_{c-BS-a}	Convective heat transfer from Body Side to ambient
$\dot{Q}_{cond}$	Conduction heat-transfer rate (W)
$\dot{Q}_{conv}$	Rate of convective heat transfer(W)
$\dot{q}_G$	Rate of heat generation per unit volume (W/m^3)
$Q_{c-R-CP\ top}$	Conductive heat transfer from Resistor to Clay Plate top
$Q_{c-R-CP\ bot}$	Conductive heat transfer from Resistor to Clay Plate bottom
$Q_{c-CP\ Bot-BB}$	Conductive heat transfer from Clay Plate bottom to Body Bottom
$Q_{c-CP\ top-LC}$	Convective heat transfer from the Clay Plate to the ambient

Q_{c-LC-a}	Convective heat transfer from the Lifting Cover to the ambient
$\dot{Q}_{rad}$	Rate of heat transferred by radiation(W)
Q_{r-LC-a}	Radiative heat transfer from the Lifting Cover to the ambient
Q_{r-BB-a}	Radiative heat transfer from Body Bottom to ambient
Q_{r-BS-a}	Radiative heat transfer from Body Side to ambient
$Q_{r-CP\ top-LC}$	Radiative heat transfer from the clay plate top to the Lifting cover
R	Resistance (Ohm)
t	Time (Sec)
T	Temperature, K or ℃
T_{BB}	Mitad body bottom surface temperature(K)
$T_{Boiling}$	Boiling temperature of water(K)
T_{BS}	Mitad body side surface temperature
T_{bs}	Temperature of the baking surface(K)
$T_{CP\ Bot}$	Clay plate bottom surface temperature(K)
$T_{CP\ top}$	Clay plate top baking surface temperature(K)
$T_{Initial}$	Initial temperature of batter(K)
T_{LC}	Lifting cover temperature (K)
T_r	Temperature of the heating element, resistance (K)
T_s	Surface temperature (K)
T_R	Heating element (Resistor) temperature
T_∞, T_a	Temperature of the fluid sufficiently under/over the surface/ambient temperature (K).
Δ T	Change in temperature of the clay plate(K)

GREEK SYMBOLS

α	Thermal diffusivity, (m^2/sec)
ρ	Density of the material, (kg/m^3)
ε	Surface emissivity
σ	Stefan-Boltzmann constant ($W/m^2.K^4$)
η	Thermal efficiency

SUBSCRIPTS

a	Ambient
c	Convective
lc	Lifting cover
mit	Mitad
r	Radiative

ABBREVIATIONS

AAS	Atomic Absorption Spectrometry
℃	Degree centigrade
Cu	Copper
CuWE	Copper Wire Embedded
IR	Infra-red
NTS	Not to scale
QTM	Quick thermal conductivity meter
CCT	Controlled cooking test
NTS	Not to scale
EEA	Ethiopian Energy Authority
Al	Aluminum
Al_2O_3	Aluminum di oxide
CaO	Calcium oxide
CO_2	Carbon di oxide
Cr	Chrome
EC	Ethiopian calendar
EEA	Ethiopian Energy Authority
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
ES	Ethiopian standard
Fe	Iron
Fe_2O_3	Iron oxide
GWh	Giga watt-hour

K_2O	Potassium oxide
KPT	Kitchen performance test
kW	Kilo watt
LLC	Life Cycle Cost
MEPS	Minimum Energy Performance Standard
MgO,	Magnesium oxide
mK	Milli Kelvins
MnO	Manganese oxide
MoWIE	Ministry of Water, Irrigation and Electricity
MV	Mega volt
MW	Mega watt
Na_2O	Sodium oxide
Pcs	Pieces
P_2O_5	Phosphorous pentoxide
PVC	Polyvinyl chloride
$Ti\ O_2$	Titanium di oxide
SiO_2	Silicon di oxide
USD	United states Dollar
2D	Two dimensional
3D	Three dimensional

TABLE OF CONTENTS

CERTIFICATION i
DECLARATION ii
ACKNOWLEDGMENT iv
ABSTRACT v
NOMENCLATURE vi
TABLE OF CONTENTS x
LIST OF TABLES xiii
LIST OF FIGURES xiv
CHAPTER ONE 1
1. Introduction 1
1.1 Background 1
1.2 Problem statement 3
1.3 Objectives 4
1.3.1 General objective: 4
1.3.2 Specific Objective: 4
1.4 Limitations/Delimitation 4
1.5 Scope of the study 4
1.6 Significance of the research 4
1.7 Organization of the research 5
CHAPTER TWO 6
2. Literature review 6
2.1 Cooking technologies in Ethiopia 6
2.2 Injera 6
2.2.1 Injera preparation 7
2.2.2 Tef injera specifications 8
2.3 Injera baking technologies 9
2.3.1 Biomass injera Mitad 9
2.3.2 Biomass gasifier injera baking stove 10
2.3.3 Biogas Injera mitad 10
2.3.4 Solar Injera mitad 11

2.4 Electric Injera Mitad 13

2.4.1 Clay plate of Injera Mitad 13

2.4.2 Production and assembly of the conventional Electric Injera Mitad 14

2.4.3 Power demand of Electric Injera Mitad 15

2.4.4 Electric Injera mitad Standards and regulations in Ethiopia 16

2.4.5 Electrical energy supply and consumption in Ethiopia. 16

2.5 Heat and mass transfer and thermal insulation in electric injera Mitad 17

2.5.1 Heat transfer mechanisms 17

2.5.2 Heat and mass transfer 22

2.5.3 Thermal insulation and properties of insulating materials 22

2.5.4 Energy balance in electric injera mitad and mathematical models 23

2.6 Performance evaluation, parameters, and efficiency testing for electric injera mitad. 25

2.6.1 Types of stove performance tests 25

2.6.2 Parameters 26

2.6.3 Efficiency determinations 26

2.6.4 Quality attributes of injera 27

2.7 Over view of Copper material properties 29

2.8 Performance improvement studies on electric injera mitad 30

2.8.1 General performance improvement studies 30

2.8.2 Clay pate performance improvement studies 32

2.9 Summary of literature reviews 35

2.10 Research Gap 38

CHAPTER THREE 39

3. Materials and Methods 39

3.1 Development of clay plate with Cu wire embeddings 40

3.1.1 Study on the traditional clay plate production 41

3.1.2 Clay plates for the study 44

3.1.3 Preparation of CuWE sample clay plates 45

3.1.4 Development of the base case and CuWE baking clay plate electric mitad 51

3.2 Experimental tests and procedures. 55

3.2.1 Materials and Equipment for experimental test 55

3.2.2 Experimental setup, tests, and procedures 57
3.2.3 Performance Evaluation Methods 60
CHAPTER FOUR 63
4. Results and discussion 63
4.1 Test results during heat up period 63
4.1.1 Heat-up time temperature distribution 63
4.1.2 Time taken for heat up and energy consumption 69
4.2 Test results during the baking period 70
4.2.1 Baked injera 70
4.2.2 Data recorded and results of the CCT. 73
4.2.3 The temperature profile of the baking surface during injera baking 76
4.3 Economic Analysis 79
4.3.1 Life cycle cost of the base case and CuWE electric injera mitads 79
4.3.2 Energy saving of the CuWE mitad per household 81
4.3.3 Avoided costs in implementing the CuWE electric injera mitad 82
CHAPTER FIVE 84
5. Conclusion and recommendation 84
5.1 Conclusion 84
5.2 Recommendation 85
6. References 86
Appendix A. Complete silicate analysis report of raw materials of the clay plate injera Mitad 93
Appendix B. Thermal conductivity test results of the clay plate samples 94

LIST OF TABLES

Table 2-1. Common properties of copper 29
Table 2-2. Summary of clay plate improvement studies by different researchers........ 37
Table 3-1. Number of copper wires in the grooves of clay plate samples........ 48
Table 3-2. Thermal conductivities of the sample clay plates........ 50
Table 3-3. Specification for the CuWE electric mitad........ 55
Table 3-4. The setting used for the Fluke Ti - 125, Thermal imager........ 57
Table 4-1. Data of the electric mitads and average values of the results of CCT experiments. 74
Table 4-2. Cyclic baking periods of injera on the base case and CuWE mitads 76
Table 4-3. Cost of base case electric mitad........ 79
Table 4-4. Annual energy consumption of the base case and CuWE electric injera mitads. 80
Table 4-5. Life cycle cost of the base case and CuWE electric injera mitads 81

LIST OF FIGURES

Figure 2-1. Injera batter preparation 7

Figure 2-2. Injera with wot stew. 8

Figure 2-3. Biomass injera mitads. 9

Figure 2-4. Biogas Injera Mitad. 11

Figure 2-5. Solar injera baking mitads. 12

Figure 2-6. Clay plate grooves, resistance placement, and sealing. 14

Figure 2-7. Electric injera mitad 15

Figure 2-8. Thermal resistance network and heat losses in the conventional injera mitad. 21

Figure 2-9. Model of injera eye formation. 29

Figure 2-10. Columnar structures (tunnels) in a cross-sectional view of injera 29

Figure 2-11. Heat-up time of 0.02m electric clay baking pan with a different power rating of mitads. 34

Figure 2-12. Cyclic baking simulation of electric injera mitad: temperature profile of nodes for baking pan thickness of 0.02m and power of 3kw. 35

Figure 2-13. Summary of experimental and simulation efficiency values by different researchers. 36

Figure 3-1. Overall methodology of the research 40

Figure 3-2. Process flow for the traditional method of clay plate production 42

Figure 3-3. Samples of clay plate raw materials 43

Figure 3-4. Injera mitad clay plate and its schematic diagram 44

Figure 3-5. The clay plate grooved with 14 rounds 45

Figure 3-6. Sample clay plates, 100x50x20 (mm): 45

Figure 3-7. Bottom view of grooved clay plate with heating element placed 46

Figure 3-8. Section A-A view of clay plate of 58 cm diameter with heating element placed and sealed (NTS). 46

Figure 3-9. Section view of the clay plate of 58 cm diameter with heating element placed, conceptual copper wire embedding in grooves and sealed. (NTS). .. 47

Figure 3-10. The layout of sample clay plates with copper wire embeddings 48
Figure 3-11. Clay plate sample for the case of the 2x4 sq. mm Cu wire embedding (NTS). 48
Figure 3-12. Clay plate samples for a thermal conductivity test. 49
Figure 3-13. The QTM- 500 and thermal conductivity measuring experimental setup .. 50
Figure 3-14. Copper wire embedding and clay plate preparation.................................. 53
Figure 3-15. Section C-C view of the clay plate of 58 cm diameter with heating element placed, CuWE, and sealed (NTS). 54
Figure 3-16. The test setup and measuring instruments employed................................. 58
Figure 4-1. Circular marking and IR fusion blending scale.. 64
Figure 4-2. IR image capture details for the base case and CuWE mitad at an initial surface temperature of 23 ℃ and time, t= 0.. 64
Figure 4-3. IR capture temperature distributions of the base case and CuWE mitads at the average baking surface temperature of 200 ℃.................................. 65
Figure 4-4. Temperature histogram within the circular maker of the baking surface 66
Figure 4-5. X profile IR capture temperature distribution.. 67
Figure 4-6. Maximum temperatures of the baking surfaces 68
Figure 4-7. Base case and CuWE mitads heat-up period: time taken, average baking surface temperature, and energy consumption comparison.......................... 69
Figure 4-8. Thermal images of samples of injera baked on the base case and CuWE mitads 71
Figure 4-9. Pictures of baked injera 72
Figure 4-10. Typical thermal image of baked injera with plate temperature captured..... 73
Figure 4-11. Base case mitad baking surface temperature profile for 15 injeras. 77
Figure 4-12. CuWE mitad baking surface temperature profile for 15 injeras. 78

CHAPTER ONE

1. INTRODUCTION

The introduction chapter presents the background on injera and injera baking stoves, the problems the study answers to, objectives, limitations, scope, the primary contributions of the study, and the organization of the research study.

1.1 Background

Ethiopia, having the lowest rates of access to modern energy, has an energy supply share of 87% from waste and biomass, 10.4% from fuel, and 2.6% from hydropower. Households consume 88% of the total national energy consumption [1]. Domestic energy requirements are primarily for baking and cooking purposes [2], [3].

Injera is a traditional pan cake type, flat leavened, bread [4], [5] prepared by the process of fermentation and rigorous baking from different cereals of, teff (Eragrostis tef), millet, sorghum, maize, wheat, rice, etc., or combinations. Injera, the staple food of Ethiopians, is baked using a clay plate called mitad using either biomass or electrical power as a source of energy [6]. The performance of clay plate injera mitad is generally evaluated by its thermal efficiency, specific energy consumption, time to bake, maximum particulate matter, maximum CO emission level depending on the source of energy supply, and the quality of injera.

Most Ethiopians bake injera on open-fire stoves with biomass. Because injera baking biomass burners use a lot of firewood and are inefficient, there is a lot of indoor air pollution, greenhouse gas emissions, and deforestation as a result [7]–[9]. With no significant breakthrough to date, efforts to improve the biomass injera baking stove only slightly increased its efficiency and decreased its pollution emissions [8]. Bio mass gasifier injera mitads have been researched, and performance improvements than the Biomass mitads have been attained by [10] and [11].

Research works and designs that Biogas could be used for injera baking were undertaken by [12] and Dereje, 1996, as reported by [8]. It was noted that further developments will be required to use biogas for injera baking applications as it needs a significant amount of biogas or feedstock for baking injera for a household. Solar Injera "mitads" have also been investigated, designed, and developed by [13], [14], [15], [16], [17], and [18]. However, due to the associated cost and operating procedures, the outcomes of solar injera baking studies and advances, while having promising results, are currently suited for large-scale or community injera baking.

Electric injera mitad is known for its intensive energy and time-consuming cooking [3]. The single clay plate mitad is the most common; its power rating ranges from 3.7 to 4.0 kW and is estimated to constitute about 60% of the electrical power demand of a typical residential household. There are an estimated 1.1 million electric injera baking mitads in Ethiopia in the year 2022/2023 and the estimated total energy consumption including losses are estimated to be 1,111 GWh [6], and mitad consumes 60% to 70% of the total household energy demand [19]. Electrical mitads have designs dating back to the 1960s and are highly inefficient as well and are overloading the electricity grid [20], their energy efficiency has not been improved over the decades. Innovations and development made on the product are limited. However, the clay plate-based unit type electric mitad has thus far been preferred by Ethiopian consumers compared to other types due to the quality of baked injera, affordability of the price, maintainability, and that the appliance is an indigenous product.

Researches and studies indicate that the energy efficiency of the single plate type electric injera mitad is low, 50-55% [21]–[25]. Many kinds of research, experimental investigations, and recommendations have been carried out regarding the performance improvements of electric Injera Mitad, a few being improving the thermal conductivity of the clay plate. [26] [27] [25] conducted investigations and tests on alternatives of ceramic bake ware, sandy clay deposits, and silicate and metallic compositions.

Despite the successful efforts of improving the thermal conductivity of the conventional clay plate at various levels, performance-improved clay plate, and hence electric mitad, has not been practicably developed for use thus far. As the clay plate of injera mitad is produced traditionally, the use of composite materials and additives to enhance the thermal conductivity of the clay plate by local producers and assemblers has not been practicable. Improving the performance of electric injera mitads in a way that local producers can implement will have a significant impact on the power demand and energy consumption in the country and the quality of injera.

Therefore, the current study aims to address the above challenges through a performance investigation of the electric injera mitad using copper (Cu) wire embeddings in the clay plate and conducting the Controlled Cooking Test (CCT).

1.2 Problem statement

The conventional electric injera mitads currently used are not so efficient due to the high heat losses that cause the efficiency to be as low as 50 to 55%. Moreover, the temperature distribution obtained on the clay plate is not uniform during baking injera.

There are about 1.1 million electric injera baking mitads currently in Ethiopia and the demand is growing fast. The poor performance of the appliance affected high power demand, congesting the electric power distribution network, and introducing high energy consumption to the consumer and the nation as the prevalence and the number of new installations of mitads in the country is significant. Efficient use of the meager and costly electric energy resource remains to be necessary for a developing country like Ethiopia, one of the major works to be undertaken in this regard is improving the performance of the existing conventional electric injera mitad without compromising quality.

Studies and experimental investigations to enhance the performance of the conventional electric mitad's clay plate thermal conductivity and temperature uniformity including the use of metallic powder additives have been carried out. However, the practicability of casting and production of improved clay plates at the level of local producers remained to be a challenge. Hence, the difficulty of performance improvement of the clay plate at the producer's level remains to impact the country's electric power and energy demand adversely.

1.3 Objectives

1.3.1 General objective:

To experimentally improve the performance of the conventional electric mitad by embedding copper wire in the clay plate.

1.3.2 Specific Objective:

a) To develop a clay plate of electric mitad with embedded copper wires.
b) To determine the effect of clay plate Cu wire embeddings on energy efficiency, baking time, energy consumption, and baking surface temperature uniformity of electric mitad.
c) To compare the performance of the base case and improved electric injera baking mitads using CCT.
d) To preform economic analysis.

1.4 Limitations/Delimitation

The lack of sufficient related studies conducted on thermal property improvements of the clay plate has been one of the major limitations experienced in the research study. CCT conducted on electric injera mitads are dependent on the ability and experience of the injera baker which imposes a limitation on the evaluation of parameters affecting performance.

1.5 Scope of the study

This study focuses on experimental investigation for performance improvement of single clay plate-based locally manufactured electric injera mitad at Addis Ababa. The tests on the mitads are based on CCT as applicable to teff injera baking using electric mitad. The study of the elemental properties of clay plate mitad raw materials is not covered within the scope of this study. Although several factors affect the performance improvement of electric injera mitad, this study focuses on improving the thermal properties and enhancement of the heat uniformity of the clay plate.

1.6 Significance of the research

The utilization of efficient and performance-improved Electric Injera Mitad is one of the opportunities for the reduction of energy consumption and power demand of the limited resources of the country. Enhancing the functionality of the conventional electric injera mitads will decrease the excessive demand for power and energy consumption, electrical infrastructure congestion, and save the country from significant foreign and local currency costs associated with the construction, operation, and administration of additional electric power generating stations, reduce energy bills to the consumer (user) and improve national economic efficiency. Heat uniformity improvement will increase the quality of injera and consumer satisfaction. The findings of the study are expected to assist local and traditional producers to improve their products without requiring additional machines or manufacturing processes.

1.7 Organization of the research

This research study is organized into six chapters. Chapter one presents the introductory part; the background, the problem statement, the objectives, and the significance of the research study. Chapter two discusses the different theoretical and empirical literature reviews of the research and the research gap. Chapter three presents the materials and methods employed in the study including the development of clay plate with Cu wire embeddings, a study on traditional clay plate production, sample clay preparation, the materials, equipment, methods, procedures, and experimental tests used, and conducted in the study. The results, discussion, and economic analysis are presented in chapter four. The last chapter presents the conclusions and recommendations of the research study.

CHAPTER TWO

2. LITERATURE REVIEW

In this chapter literature of general nature related to injera mitad clay plate performance improvements are discussed. The subsequent sections present reviews on cooking technologies, injera and injera baking, electric injera mitad production and assembly, national energy consumption, heat transfer in electric injera mitad and mathematical models, performance evaluation methods, an overview of copper material properties, and reviews on related empirical literature.

2.1 Cooking technologies in Ethiopia

The fuel and technologies used for cooking in Ethiopia comprise 84% other solid biomass, 8% charcoal, 7% other clean sources, and 1% coal and kerosine. Cooking and baking account for the majority of home energy use [28]. Since the middle of the 1980s, energy efficiency improvement for residential cookstoves has been at the forefront of energy interventions in Ethiopia. Households mostly utilize solid biomass for cooking, and they do so over an open fire or with antiquated, inefficient, and unclean cookstoves [29].

2.2 Injera

Flattened bread/pancakes with or without fermentation having different ingredients and properties are consumed at many locations in the world [30]. Injera leavened round bread, is a processed staple food of Ethiopians and cultural food of some east African countries like Eritrea and to some extent Somalia.

Injera is made from grains such as teff, barley, sorghum, wheat, and maize. Due to the formation and release of carbon dioxide during fermentation and baking, it is distinguished by having "eyes" (honeycomb-like pores) on its top surface [31], [32]. Injera has a shiny, smooth bottom surface. Good injera can be folded up without splitting and is soft and fluffy. The flavor of injera has a faint sourness to it. Because injera is a leavened bread manufactured without the use of gluten, it has a tremendous deal of potential for international commercial manufacturing [32]. Currently, injera is being exported from Ethiopia by various private firms.

2.2.1 Injera preparation

Injera is prepared by the process of fermentation and rigorous baking from different cereals or combinations. It is baked on an indigenous clay plate called mitad which is placed over a three-stone stove or wired with electric resistance to form an electric mitad.

Teff is mainly used for the making of injera [33]. Injera is made by mixing cereal flour with water to make the dough and then triggering the fermentation process by inoculating with “ersho”(yeast), a starter obtained from previous fermentations [34]. The fermentation lasts on average 2-3 days, after which the dough is thinned into a batter, “absit”, fermented batter boiled with water, is added before baking. Injera is similar to Dosa (India), popular fermented breakfast food consumed in the Indian subcontinent, even though its ingredients and processing methods may be different [30]. Figure 2-1, shows the process of injera batter preparations.

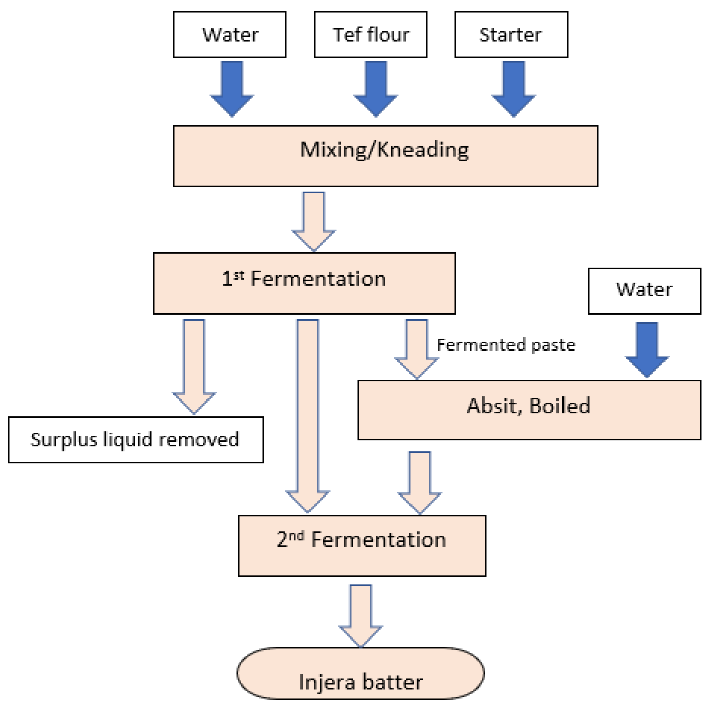


Figure 2-1. Injera batter preparation

To bake injera, the batter of a fermented dough is poured on a hot clay pan to stay until the boiling temperature is reached and bubbles are formed. Many tiny craters (eyes) that give the peculiar injera texture are formed while the boiling water escapes [35], [36]. When the injera is almost half cooked, the lifting cover is closed until it is well cooked. After waiting for a few minutes depending on the injera mitad, the lifting cover is opened and the injera removed. The baking plate will be re-polished using burned ground rape seed for the next baking. Injera is baked on electric injera mitad at a clay plate temperature of 200 to 250 ℃ [6].

Among the traditional foods in Ethiopia, injera and wot (stew) are very common. Except for eating at hotels and markets, these foods are primarily produced and consumed at home [37]. Wot is a common stew found in Ethiopia, whereas injera is a type of circular pancake. Ethiopians consume a lot of injera and wot, which are historically the most significant foods. In Amharic, the word "wot," which means "wet," is synonymous with a stew. Wet is served with injera and is either made from vegetables and animal meat or mixes of the two [30], [38]. Figure 2-2, presents injera and injera with wot.

a) Injera

b) Injera and wot

Figure 2-2. Injera with wot stew.

2.2.2 Tef injera specifications

The Ethiopian standard for Teff injera [39] requires injera shall be free from foreign odors and visible mold growth, have reasonably uniform color according to the type of teff flour used and have a slightly sour taste. The upper side of the teff injera shall have a uniform injera eye (tiny crater), while the back side shall be smooth. It shall have a soft, spongy, and resilient texture, and be from non-porous mass and splits. The minimum size and net mass of teff injera are specified to be 51cm in diameter and 310 gm, respectively.

2.3 Injera baking technologies

2.3.1 Biomass injera Mitad

In most homes of Ethiopian households, the traditional three-stone mounted open fire injera mitad indicated in Figure 2-3 a) is commonly used. The clay plate injera mitad is mounted on three stones of equal sizes usually made of clay sand mix, and maintained in a triangular arrangement and kept at a level. According to [8] the clay plate has got a diameter of 60 cm and a thickness of about 2 cm and its average fuel consumption is 929 gm/kg of injera. Firewood is inserted under the clay plate during the baking process. Due to its configuration and setup, the open fire injera mitad consumes a large amount of firewood and produces high indoor air pollution and CO_2 emission, and has been a cause of high deforestation. The efficiency of biomass mitad is around $8-12\%$ [28].

Various kinds of research have been conducted to improve the efficiency of the open fire injera mitad and reduce its indoor air pollution and CO_2 emission, the most prominent being the developments of the "Mirt" and the "Gonzie" injera baking stoves indicated in Figure 2-3, b) and c), respectively. Both stoves have integrated units for boiling and cooking. Gonzie stove is made of ceramic clay soils, while Mirt stove is made of cement to form a circular enclosure. Gonzie comprises four components that, when put together, form its fundamental circular enclosure. The quadrants' bodies are not solid all in all. Between the inner and exterior walls, there is an enclosed air gap.



a) Three stone Injera Mitad, [40] b) Mirt Injera Mitad, [41] c) Gonzie Injera Mitad [40]

Figure 2-3. Biomass injera mitads.

[8] reported Hatfield et al., 2006, tested an improved Mirt stove which showed reductions in time to boil by 18%, fuel use by 81%, CO by 90%, and PM by 83%. They reviewed that the average specific fuel consumption of the Mirt stove as tested by seven studies is 535

gm/kg of injera. The Gonziye stove test [40] showed that improvements have been achieved compared to the three-stone open fire mitad; specific fuel consumption was reduced from 1038 to 617 gm/kg, a fuel saving of 41%, and baking time saving of 7%.

2.3.2 Biomass gasifier injera baking stove

One method for converting biomass into goods with added value is biomass gasification, which reduces polluting waste disposal methods while simultaneously producing beneficial products such as biofuels, biochar, syngas, power, heat, and fertilizer [42]. [10] in his report on the performance of biomass gasifier injera baking stove; in comparison to the three-stone fire, a thermal efficiency of 16% is attained, specific fuel consumption is decreased by 12.8%, and baking time is decreased by 19%. In comparison to the three-stone fire, there is a 97% and a 99% reduction in carbon mono oxide and particulate matter emissions, respectively. Results indicate that by improving insulation, reducing the heating up time between subsequently baked injeras, and encouraging longer injera baking sessions, such as in community kitchens, it is possible to boost efficiency and decrease fuel use. However, according to [11], the design, production, and scaled-up distribution of household gasifiers in Ethiopia have been hampered by technical and financial constraints, and this goal remains elusive. At the current stage of research findings, the bio-mass gasifier injera mitads would be most appropriate for only large-scale injera baking applications.

2.3.3 Biogas Injera mitad

Research work in biogas use has shown that there exists the potential for use of biogas for injera baking [36], [43]. According to [28] an improved biogas injera mitad of 13mm thick and 540 mm diameter clay plate injera mitad was designed, assembled, and tested. The injera mitad was designed so that the clay plate was made by combining clay with metal powder from workshops, with the top part of the plate being clay, the bottom part clay metal powder mix, and the side body made from two concentric cylindrical casing with insulation of 5 mm thick ash. The findings indicated a thermal efficiency of 57%, with a recorded temperature difference between the maximum and minimum of 55 °C at the baking surface. The integrated biogas injera burner can bake 20 to 25 pieces of injera on average each hour, using 0.0672 m^3 of biogas per injera.

Biogas mitad having a gas consumption rating of 0.93m3/h for community baking has been designed by [12]. [8] reported, Dereje 1996, examined a three-ring biogas burner for injera baking and found that its power output was 11 kW, translating to a gas consumption rate of 41 l/min, a gas consumption per injera of 193 l (3108 kJ/injera), and an average efficiency of 16 percent. Figure 2-4, shows bio gas injera mitad.

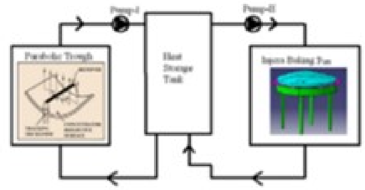
Figure 2-4. Biogas Injera Mitad.
Adopted from [8]

Based on the research findings, a large amount of feedstock will be required to bake injera using biogas considering the number of injera baked per session and the frequency of baking. Hence, further researchers were recommended in the field to develop an efficient injera baking biogas stove.

2.3.4 Solar Injera mitad

Researchers have investigated the use of solar energy for injera baking applications. [13] developed a 42 cm outdoor Injera baking pan using flat, hexagonal panels of Aluminized - Mylor mirrors, Figure 2-5, a). It was concluded that a larger mirror and solar power area are required for baking the traditional large size of Injera. [14] developed and investigated the performance of a laboratory model indirect and indoor injera baking system, suitable for multiple family use, using a ceramic baking pan by transferring solar energy (solar energy is simulated by electrical heating) using a circulating heat transfer fluid which is heated by a parabolic trough, Figure 2-5, b). Furthermore, [15] carried out a 2D transient finite element analysis for a solar-powered injera baking system. [16] designed and developed direct steam-based solar thermal Injera baking mitad, Figure 2-5, c). Further to this effort, [35] developed and tested a phase change material-based heat storage prototype for the steam injera baking mitad making it suitable for use at off-shine hours and indirect/indoor cooking, Figure 2-5, d).

a) Prototype solar frier, (Gallagher, 2011).



b) Solar-powered injera baking oven, (Hassen, Amibe and Nydal, 2011).

c) Direct steam-based solar thermal Injera baking mitad (Tesfay, Kahsay and Nydal, 2014a).

d) Phase change material-based heat storage prototype for the steam injera baking (Tesfay, Kahsay and Nydal, 2014b)

Figure 2-5. Solar injera baking mitads.

[17] demonstrated the possibility of baking Injera on a glass pan, employing a circulating heat transfer fluid heated with solar energy concentrated by a parabolic trough, solar energy being simulated by equivalent electrical energy. [18] developed a direct solar fryer for Injera baking which uses a dish covered with an aluminum reflective sheet, and an aluminum baking plate and is equipped with two-axis manual tracking. The fryer was assessed to provide a baking power of 563W and a system thermal efficiency of 37%, including the collector efficiency.

As there is abundant solar energy available in the country solar injera baking will have a promising future. However, the solar injera baking studies and developments conducted thus far are suitable for large-scale or community injera baking due to the associated cost and operational mechanisms. Although some families might bake using the solar injera baking units, gaining acceptance would be a problem because of the difficulty of cooking/baking a single meal for a single family, as it would have been possible to bake using other means of energy easily.

2.4 Electric Injera Mitad

The framework of the electric injera mitad is built of steel or aluminum sheet metal and features a conical-shaped lifting cover, a short cylindrical enclosure (body), clay plates, electric heating elements encased within the clay plates, heat insulators, and support mechanisms. In the Ethiopian market, there are single and double clay plate electric injera mitad varieties, with the single clay plate type being the most popular [6].

2.4.1 Clay plate of Injera Mitad

A naturally occurring material called clay is excavated from the earth and is a result of millions of years of the earth's crustal rock decomposing. Decomposition happens when water erodes, disintegrates, and deposits the rock. Earthenware clay, mid-fire stoneware clay, and high-fire stoneware clay are the three types of clay that are used most frequently. Earthenware clays are the most prevalent type of clay found and the oldest clays utilized by potters. It can be sticky and is highly plastic. Because of the presence of iron as well as other mineral impurities, the clay reaches its ideal hardness between 950 and 1100 degrees Celsius. Earthenware clays rarely fully vitrify because their melting point is so low. As a result, the fired pottery will keep soaking up liquids [44].

It's crucial to understand that a clay body differs from actual clay. Clay bodies are mixtures of clay and additives or temper that, when worked and fired, give the clay unique qualities. Sand and grog are used as temper in clay plates and pottery [45].

According to [46], traditional ceramics comprise cordierite-based products, earthenware, vitrified tiles, sanitary ware, porcelain (either residential or industrial), and traditional refractories. $SiO_2, Al_2O_3,$ and XO are the main systems at play, with XO standing for a combination of oxides such as, $Na_2O, K_2O, MgO, CaO, Fe_2O_3,$ and $Ti\ O_2$. The amount of SiO_2, is rather high, and silica is typically found in clay both in its mixed form and in its free state (as quartz). The various oxides (XO) are present either because of impurities in the raw materials or because fluxing agents were purposefully added.

The main element of the clay plate, SiO_2, has a thermal conductivity and diffusivity of 1.38 W/m.K and 0.834 x 10^{-6} m2/sec, respectively[47]. SiO_2 has a resistivity of $1x10^{17}$ to $1x10^{21}$ ohm. cm and a dielectric strength or breakdown potential of 25 to 40 MV/m [48].

In the traditional production of clay plates of electric injera mitad in Ethiopia, sand and clay are combined with water in an underground pit by hand and legs. The sensation on the naked leg while combining and kneading the sand and clay mixture indicates if it is sufficient. After the mix is baked and dried, it will be sized, leveled, smoothened, and plastered, and the baking surface treated with red soil (mineral pigment). Injera mitad clay plates come in a variety of sizes. Sizes range from 40 cm to 60 cm in diameter, and they are between 2.3 and 2.5 cm thick [6]. [45] emphasized the significance of burnishing and the use of mineral pigments on pottery vessels since it serves as both decoration and a way to lessen their permeability to liquids. The firing of the locally produced clay plates is accomplished in the open-air using cow dung as a fire source. High-temperature firing reduces the number of pores significantly, increases density, and fuses the components of sand and clay. In the production process, the clay plate is deemed fired when all the cow dung has burned away.

2.4.2 Production and assembly of the conventional Electric Injera Mitad

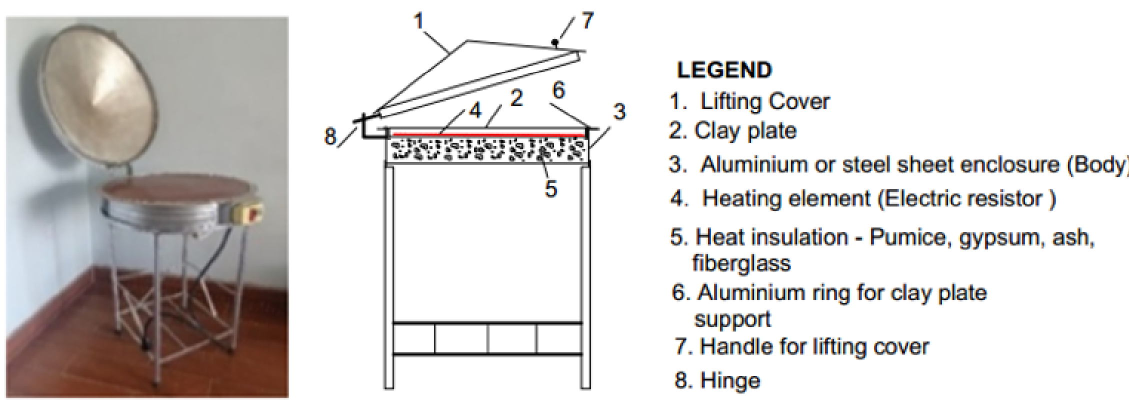
There exist single and double clay plate type electric injera mitads, the positioning of the heating element and the clay plate support mechanism differing. When using a single clay plate (Figure 2-6, a), the electrical heating element (Figure 2-6, b) is kept in the grooves at the bottom side of the clay plate in a helical fashion (Figure 2-6, c) and sealed with gypsum material (Figure 2-6, d). For the double clay plate, the heating element is retained between the upper and lower clay plates. The most popular electric mitad for domestic households has a single clay plate with a diameter of 58 cm, and spiral groves of 12 to 14 rounds are used [6].

a) Grooved clay plate   b) Heating element   c) Heating element placed   d) Sealed clay plate

Figure 2-6. Clay plate grooves, resistance placement, and sealing.

.

The clay plate is fixed into the electric mitad body and enclosure after being sealed with gypsum material and dried. The mitad body is constructed from a framework of steel or aluminum sheet and includes a support stand, a switch, a cable, and a plug for connecting to an outlet, as well as a conical-shaped aluminum lifting cover, a short cylindrical enclosure (body), a clay plate mounting ring inside the enclosure, and a thermal insulator at the bottom. Figure 2-7, a) and b) show assembled electric injera mitad and sectional view of the unit for the case of single clay plate mitad.



a) Assembled single plate electric mitad,

b) Cross section of single clay plate electric mitad [6].

Figure 2-7. Electric injera mitad

2.4.3 Power demand of Electric Injera Mitad

The electric resistance used in the conventional mitads is imported in the form of rolls and wound to the desired length by importers and distributors. According to [49] the resistor employed in the production of electric mitads is classified under Class C, has got an alloy code of Fe70Cr25Al5, and composition of Fe - 70%, Cr - 25%, and Al - 5%.

The majority of electric mitad makers employ two 0.9 mm diameter resistances, which have a 3.7–4.0 kW rating at 220V. About 60% of a typical residential household's power usage is at this level of demand [6]. Electric mitads are placing a huge demand on the country's power supply infrastructure given the prevalence of the appliance and the market for the product. Low energy efficiency is the major issue with electric injera mitads, and this is mostly because it takes a lot of energy to heat up to the predetermined temperature of 180 to 220 ℃ [17] needed to bake injera.

2.4.4 Electric Injera mitad Standards and regulations in Ethiopia

[50] specifies the technical and performance requirements, labeling and packing, testing methods, and procedures for electric injera mitad. The standard among other things specifies that the minimum diameter of the clay plate shall be 53 cm, uniform thickness of 2.0 cm to 2.5 cm, and the placement of the heating element shall be even in slot depth 8mm to 11mm and pitch 2.0 cm to 2.5 cm.

[51] issued a Minimum Energy Performance Standard and Labeling requirement for Clay plate resistor-based electric injera mitad which specifies the minimum allowable value of thermal efficiency for the product and labeling Logo. The requirement specifies that minimum thermal efficiency of not less than 60% and a five-grade thermal efficiency rating with the corresponding efficiency ranges. Manufacturers /suppliers are required to declare the thermal efficiency and label grade of their product as per the specification and test results. Indication of thermal efficiency label grade in the form of a sticker is required to be affixed to the body of the product.

2.4.5 Electrical energy supply and consumption in Ethiopia.

Ethiopia reported a 44 percent energy access rate in the Multi-Tier Framework 1, Energy Access Household Survey performed in 2017 across the nation in both rural and urban areas, with 33 percent of access being provided via grid connections and 11 percent with off-grid options. An estimated 3.1 million customers have official connections [52].

Due to the country's massive electrification projects, lack of firewood and biomass, and rapid population and economic expansion, electrical power, and energy consumption have been steadily rising [53]. About 4,300 MW of installed electricity production capacity in Ethiopia barely produces enough energy to supply about 10% of the country's needs [1]. The domestic tariff category, which consists of households, consumed 36.7 percent of the nation's total electricity consumption in 2018, with the national total energy consumption being around 11,389.07 GWh [54]. In domestic households, cooking, which employs electric injera mitad and stove, is the major energy-consuming activity.

According to the reference, and the universal electrification scenarios, the annual growth rates for electricity demand in Ethiopia from 2012 to 2030 are 9.7 percent and 11 percent, respectively. The government's goal of providing "Light to All" will need an investment in new electricity-producing capacity, which this growth indicates will be necessary [55].
The investment cost of providing electric power in Ethiopia is very high. Electric generating power plant projects currently underway in Ethiopia like Genale Dawa 254MW cost 451Mill USD (1,775.6 USD/kW) and Koisha hydropower plant of 2160MW cost 2.5 Bill Euro (1,157.4 Euro/kW) [56].

2.5 Heat and mass transfer and thermal insulation in electric injera Mitad

2.5.1 Heat transfer mechanisms

As in any other cooking appliance, heat is transferred from and within electric injera mitad in the three modes: conduction, convection, and radiation.

- **Conduction**

Conduction is the process by which energy is transferred by interactions between particles from the more energetic particles of a substance to the nearby less energetic ones. Conduction can occur in gases, liquids, or solids. The rate of heat conduction through a medium is determined by the geometry, material, thickness, and temperature difference across the medium [57].

Heat is generated in the mitad from the resistance wire inserted in the clay plate and transferred to the clay plate top (baking surface) thereby to the injera baked and bottom insulation mainly through conduction. There are also convective and radiative heat transfers depending on the type of bottom insulation.

Assuming the simple case of steady-state one-dimensional heat flow and the temperature gradient and the heat flow does not vary with time, the rate of heat conduction from the heating element to the baking surface is given by [58], in equation 2-1:

$$\dot{Q}_{cond} = -kA\frac{(T_r - T_{bs})}{L} \quad (W), \qquad (2\text{-}1)$$

Where:

- $\dot{Q}_{cond}$ is the conduction heat-transfer rate *(W)*
- T_r is the temperature of the heating element, resistance *(K)*
- T_{bs} is the temperature of the baking surface*(K),*
- A is the baking surface area*(m^2),* and
- k is the thermal conductivity of the clay plate*(W/m.K),*
- L is the thickness of the clay plate from the top of the heating element to the baking surface*(m).*

- **Thermal diffusivity.**

Thermal diffusivity, the ratio of thermal conductivity to heat capacity is an important property in heat transfer studies and is expressed as [57], in equation 2-2:

$$\alpha = \frac{k}{\rho C_p} \quad (2\text{-}2)$$

Where,

- α is the thermal diffusivity, (m^2/sec).
- ρ is the density of the material, (kg/m^3) and
- C_p the heat capacity, (J/kg.K)

Thermal diffusivity gauges a material's thermal energy storage capacity to how well it can conduct thermal energy. With a body's capacity to conduct heat, thermal diffusivity rises. Thus, a vessel's material characteristics, particularly thermal conductivity but also heat capacity and density, determine how heat is transferred within it. For this reason, these material characteristics are crucial for the clay plate of electric mitad exposed to heat [59]. As computed from [47], the thermal diffusivity of sand and clay at 300 K are $2.2x10^{-7}$ m^2/sec and $10.1x10^{-7}$ m^2/sec respectively, whereas that of pure copper material is 1.17×10^{-4} m^2/sec, indicating metallic materials like copper diffuse heat at much higher rates compared to sand and clay.

The general form of the heat diffusion equation in cylindrical coordinates for shapes like clay plates of electric injera mitad where the temperature varies with time and there is internal energy generation is given by [58], equation 2-3 :

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \emptyset^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}_G}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (2\text{-}3)$$

Where,

- $\dot{q}_G$ is the rate of heat generation per unit volume, W/m^3
- T is temperature, K or ℃
- (r, $\emptyset, z$) are cylindrical coordinates

- **Convection**

It is a method of transferring energy from a solid surface to a moving liquid or gas nearby. It combines the effects of conduction with fluid motion. Convective heat is transferred from the clay plate, injera, lifting cover, and body of the mitad during heat-up and baking periods. The rate of convection heat transfer is observed to be proportional to the temperature difference, and is conveniently expressed by Newton's law of cooling [57], equation 2-4 :

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \quad (W), \quad (2\text{-}4)$$

Where, $\dot{Q}_{conv}$ = the rate of convective heat transfer(W)

h = the convection heat transfer coefficient (*W/ m^2.°C)*

A_s= the surface area through which convection heat transfer occurs*(m^2),*

T_s = the surface temperature *(K),*

T_∞= the temperature of the fluid sufficiently under/over the surface*(K).*

The equation for convective heat transfer applies to the heat transfer from the side and bottom of the mitad.

- **Radiation**

Radiation is the name for the energy that a substance emits as electromagnetic waves (or photons) as a result of changes in the electronic structures of the atoms or molecules. Radiation does not require the presence of a medium in between to carry energy, in contrast to conduction and convection. Heat is lost from the body and clay plate of the mitad during heat-up and baking periods through radiation. When a mitad baking surface of emissivity ε and surface area A_{mit} at an absolute temperature of T_{bs} enclosed by the lifting cover at a temperature of T_{lc}, the net rate of radiation heat transfer between the clay plate and the lifting cover is given by [57], equation 2-5:

$$\dot{Q}_{rad} = \varepsilon\sigma A_{mit}(T_{bs} - T_{lc}) \quad (W), \tag{2-5}$$

Where,

$\dot{Q}_{rad}$ = Rate of heat transferred by radiation *(W)*
ε = Surface emissivity
σ = Stefan-Boltzmann constant *($W/m^2.K^4$)*
A_{mit} = Surface area of the Mitad *(m^2)*
T_{lc} = Temperature of the lifting cover *(K)* and
T_{bs} = Baking surface temperature of Mitad *(K)*

The equation for the heat transfer through radiation also applies to the heat transfer from the lifting cover surface to the ambient while injera is cooked and from the baking surface to the ambient during the preparation and polishing of the clay plate for the next baking.

Injera baking involves two distinct phases of operations: heat-up and continuous baking. During the heat-up period, the lifting cover of the mitad stays open until the baking temperature is attained. Heat is transferred from the heating element to the clay plate and the body of the mitad through conduction whereas heat is lost from the clay plate and body of the mitad to the surrounding air through convection and radiation.

The baking of injera involves the sequential activities of polishing the clay plate with rape seed flour while the lifting cover is open, pouring the batter on the heated clay plate, waiting until pores are created, closing the lifting cover until injera is cooked, and opening of the lifting cover to take off cooked injera from the clay plate. Baking of injera is carried out while the heating element is turned on and the heat transfer process occurring during the heat-up period applies to the baking period. However, during the closing of the lifting cover, heat is transferred from the baking plate to the lifting cover through convection and radiation which also involves steam generation or simultaneous heat and mass transfer. There will be heat loss from the lifting cover and the body of mitad to the surrounding through convection and radiation. During the injera take-off period and preparation for the next baking, heat is still transferred from the heating element through conduction and heat will still be lost to the surrounding from the clay plate and body of the mitad through convection and radiation.

- **Thermal resistance network and heat losses in Mitads**

Thermal resistance network and heat losses in the conventional injera mitad are presented in Figure 2-8.

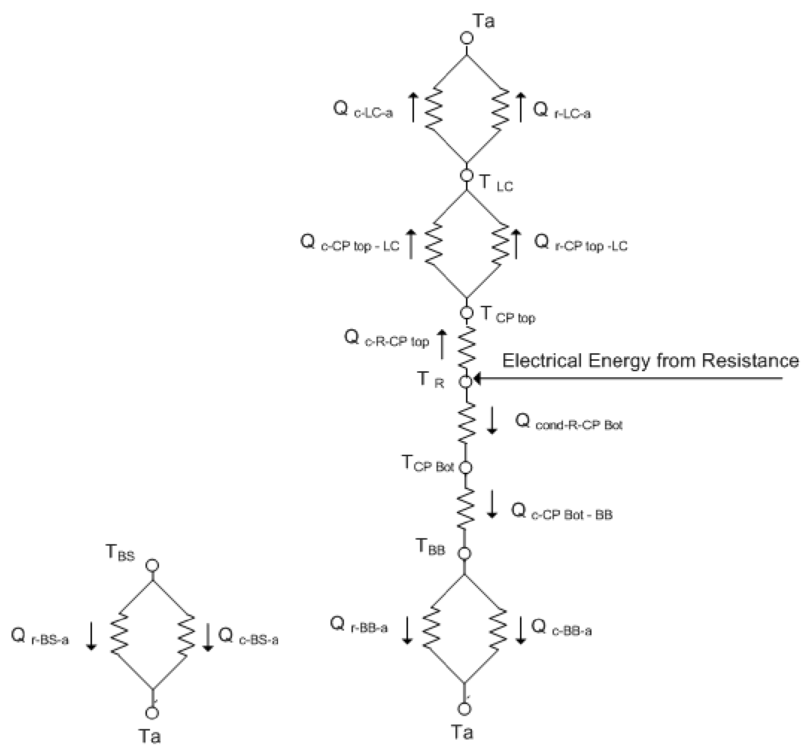


Figure 2-8. Thermal resistance network and heat losses in the conventional injera mitad. Adopted from [3]

Where,

T_a – Ambient temperature
T_{LC} – Lifting cover temperature
$T_{CP\ top}$ – Clay plate top baking surface temperature
T_R – Heating element(Resistor) temperature
$T_{CP\ Bot}$ – Clay plate bottom surface temperature
T_{BB} – Mitad body bottom surface temperature
T_{BS} – Mitad body side surface temperature

Q_{c-LC-a} – Convective heat transfer from Lifting Cover to the ambient
Q_{r-LC-a} – Radiative heat transfer from Lifting Cover to the ambient
$Q_{c-CP\ top-LC}$ – Convective heat transfer from Clay Plate top to Lifting Cover
$Q_{r-CP\ top-LC}$ – Radiative heat transfer from Clay Plate top to Lifting cover
$Q_{c-R-CP\ top}$ – Conductive heat transfer from Resistor to Clay Plate top
$Q_{c-R-CP\ bot}$ – Conductive heat transfer from Resistor to Clay Plate bottom
$Q_{c-CP\ Bot-BB}$ – Conductive heat transfer from Clay Plate bottom to Body Bottom
Q_{c-BB-a} – Convective heat transfer from Body Bottom to ambient
Q_{r-BB-a} – Radiative heat transfer from Body Bottom to ambient
Q_{c-BS-a} – Convective heat transfer from Body Side to ambient
Q_{r-BS-a} – Radiative heat transfer from Body Side to ambient

2.5.2 Heat and mass transfer

Mass transfer is the movement of a chemical species from a location of high concentration toward a zone of lower concentration compared to the other in the medium. It requires the presence of two regions with different chemical compositions. The driving force behind mass transfer is the concentration difference, while the driving force behind heat transfer is the temperature difference. Mass, however, is transferred by conduction (called diffusion) and convection only [57]. A liquid may vaporize in some technical applications, and the vapor may then diffuse into the surrounding gas. Such procedures necessitate the simultaneous transmission of heat and mass to evaporate the liquid, which requires the transfer of the latent heat of vaporization.

2.5.3 Thermal insulation and properties of insulating materials

- **Thermal insulation**

  Thermal insulation is used in electric injera mitads to reduce the flow of heat energy or heat loss from the side and bottom of the product and is commonly provided using either pumice, sandstone, gypsum, wood ash, fiber glass or a mixture of soil. The energy loss at the side and bottom of mitads depends on the thermal properties and thicknesses of the insulation material.

- **Properties of insulating materials**

  Low thermal conductivities are necessary for effective heat insulators to lower the overall coefficient of heat transmission. Density, moisture content, temperature, the direction of heat flow regarding the grain for fibrous materials, the existence of material flaws, and porosity have all been found to affect it differently [60]. The most crucial factor in choosing an insulating material is effective thermal conductivity. Other crucial considerations are density, the maximum temperature, structural rigidity, deterioration, chemical stability, and cost. [58].

2.5.4 Energy balance in electric injera mitad and mathematical models

As [23] described, the ability to control heat distribution to the injera through heat storage and thermal resistance led to the development of the current design of the injera cooking plate.

The increase in the amount of energy stored in an electrical mitad must equal the amount of energy that enters the mitad, minus the amount of energy that leaves the mitad. The equation for the conservation of energy at the clay plate could be given by [47], equation 2-6:

$$E_{in} + E_{generated} - E_{out} = E_{stored}, \qquad (2\text{-}6)$$

where:

E_{in} = Energy entering the mitad

$E_{generated}$ = Thermal energy generated in the mitad

E_{out} = Energy leaving the mitad

E_{stored} = Thermal energy stored over time

In the case of electric mitad,

$E_{in} = 0$; as there is no energy entering the mitad

$$E_{generated} = I^2Rt, \qquad (2\text{-}7)$$

where:

$E_{generated}$ = Energy generated due to the heating effect(Joules)

I = an electric current (A)

R = a resistance in Ohm

$t =$ time(sec),

$$E_{out} = E_{useful,\ injera\ baking} + q_{Loss} \tag{2-8}$$

$$E_{Useful\ ,\ Injera\ baking} = M_b . C_b (T_b - T_i) + H_V (M_b - M_i) \tag{2-9}$$

where:

$E_{\text{Useful, Injera baking}}$ = Energy used for injera baking (Joules)

M_b = Mass of batter (kg)

C_b = Specific heat capacity of the batter(J/kg.K)

T_b = Boiling temperature of water(K)

T_i = Initial temperature of batter(K)

H_V = Heat of vaporization of water(J/kg)

M_b = Mass of batter (kg)

M_i = Mass of Injera baked (kg)

$$q_{Loss} = [h_c A_s (T_s - T_\infty) + \varepsilon A_s \sigma (T_s^4 - T_{surr}^4)]t, \tag{2-10}$$

q_{Loss} represents the heat loss from the surfaces of the baking clay plate, the lifting cover, and the bottom and sides of the mitad body. For the baking surface, the temperature T_s is taken considering the mitad surface and injera as lumped mass.

where:

h_c = the convection heat transfer coefficient W/m^2.°C.

A_s = the surface area through which convection or radiation heat transfer occurs(m^2),

T_s = the surface temperature (K),

T_∞ = the temperature of the fluid sufficiently under/over the surface (K),

T_{surr} = the temperature of the surrounding (K)

t = time (sec)

$$E_{stored} = mC_{cp}\Delta T \tag{2-11}$$

where:

E_{stored} = Energy stored (Joules)

m = mass of the clay plate (kg)

C_{cp} = Specific heat capacity of the clay plate(J/kg.K)

ΔT = Change in temperature of the clay plate(K)

2.6 Performance evaluation, parameters, and efficiency testing for electric injera mitad.

2.6.1 Types of stove performance tests

Cookstove development must consider the monitoring and assessment of its performance. There have been many attempts to develop improved stoves over the years and these stoves have made cooking easier, cleaner, and more convenient to be accepted by communities. Furthermore, stove producers are required to ensure reduced harmful emissions and save fuel at the same time. Any emission should be removed. Many stoves have fulfilled the requirements of removing emissions from the kitchen, either with a chimney and/or good ventilation in the kitchen, but some of them have failed. Stove testing is necessary as stoves differ greatly in technical performance, and to compare different stove models and identify clean stoves. Current developments in stoves focus on quality and performance control. Standards for improved cookstoves have been developed regarding quality and performance. Evaluation of whether these standards are being met is done through stove testing [61]. Furthermore, as stoves differ greatly in technical performance, stove testing is necessary to identify clean stoves and to compare different stove models. The technical performance of stoves is tested according to internationally agreed test procedures related to energy efficiency, emission control, and safe use [62].

[63] indicated several groups working on cookstoves reviewed and accepted the draft protocol, as a provisional international standard procedure in 1985, and the most popular testing methods used by the researchers are the water boiling test (WBT), kitchen performance test (KPT), and controlled cooking test (CCT) protocols.

The Controlled Cooking Test compares the performance of a stove to conventional cooking techniques while a cook makes a dish from the area. The CCT is intended to evaluate stove performance in a controlled environment using a common task selected to reflect local customs. It reveals what a household could accomplish in a perfect world but may not always reflect what a household accomplishes in a daily situation. It should be carried out by someone knowledgeable about the meal being prepared, conventional cooking techniques, and how the stove under test works [64].

CCT is intended to evaluate how well the enhanced stove performs in comparison to the standard or traditional stoves that it is intended to replace. Stoves are compared as they perform a standard cooking task that is closer to the actual cooking. However, the tests are designed in a way that minimizes the influence of other factors related to kitchen management and the environment and allows for the test conditions to be reproduced [62], [65]. The CCT is made to evaluate stove performance in a controlled setting using local fuels, pots, and practice. It reveals what is possible in households under controlled conditions but not necessarily what is achieved by households during daily use [66].

2.6.2 Parameters

The performance of biomass mitad is evaluated by the parameters of thermal efficiency, maximum particulate matter, maximum CO emission level, and minimum specific fuel consumption whereas that of electric injera Mitad is evaluated with its thermal efficiency, specific energy consumption, and time to bake. These parameters are calculated for each baking test as well as the average of three baking tests on each mitad. Qualitative observations are also made during the CCT test.

[40] tested Gonzie injera mitads with the primary goals of determining the quantity of fuel utilized, the specific fuel consumption, and the duration of the average meal preparation process carried out on the mitads and determining whether there are any notable differences between the baseline and the recently enhanced stove. For each of the stoves, at least three tests were made and 25–30 injera were baked for each injera baking test.

[50] requires the thermal performance of electric injera mitad shall be tested by the CCT.

2.6.3 Efficiency determinations

According to [67], where a significant fraction of the energy transferred in a cook stove results in water boiling, the efficiency calculation shall include boiling energy utilized. Thus, the efficiency calculation for one complete cooking cycle, where the energy supply of charcoal is replaced by electricity and the different food items considered replaced by injera batter will be given by equation 2-12:

$$\eta = \frac{M_b \times C_b(T_b - T_i) + H_v(M_b - M_i)}{Energy\ input} \times 100\% \qquad (2\text{-}12)$$

where:

η = Efficiency (%)

M_b = Mass of batter (kg)

M_i = Mass of injera (kg)

C_b = Average specific heat capacity of batter (kJ/kg. °C)

T_b = Boiling temperature of water (°C)

T_i = Initial temperature of batter (°C)

H_v = Heat of vaporization of water at the boiling temperature (kJ/kg)

Energy input = Total energy recorded at the end of the baking session (kwh)

The Ethiopian standard [50] employs the same efficiency calculation equation but uses the water-to-flour proportion of 70% to 30%, and separates specific heat capacities for the flour and water.

[68] conducted the controlled cooking test to assess the performance of the traditional open-fire stove and the Mirt stove using a triplicate test. The amount of fuel utilized and the amount of time needed to complete is the CCT's two primary quantitative outputs.

2.6.4 Quality attributes of injera

The formation and quality of injera baked indicate the performance of electric mitad. The elasticity and eye formation of injera are also significantly affected by fermentation time, viscosity, and carbon dioxide of the batter. It was observed that injera baked from tef batters with low or high apparent viscosities had fewer eyes on their surfaces. The higher the amount of CO_2 or gas bubbles in the fermented batter, the higher the number of eyes formed on the injera [69]. Injera with large, irregularly spaced eyes or those with small eyes is both regarded as being of low quality, according to [70]. A smaller number of eyes manifest also poor injera quality.

In their simulation study, [23] looked at the power delivery to the injera right after the batter is poured and concluded the following. Cooking socially acceptable injeras requires this power delivery function, more notably the large initial surge in power provided to the batter. Injera of high quality must contain a lot of "eyes" or bubbles, which give the injera its light, spongy texture. The injera won't adequately absorb the sauces that are typically placed on top of injera and eaten with it if there are no such bubbles. However, a particular rate of initial power delivery is necessary for the creation of proper injera. Insufficient power delivery prevents the water in the batter from properly boiling to produce bubbles, while excessive power results in uneven boiling and a thin cooked layer that hinders the conduction heat transfer to the remaining batter.

[70], [71] used consumer sensory methods to evaluate sorghum injera-making qualities, whereas [32] employed descriptive sensory and texture analysis for the same evaluation.

There is no specification as to how many eyes should be on the surface of the injera. Injera eyes should be somewhat deep, interlocked with thin cross-walls between them, and distributed equally, according to [72] who conducted an injera baking investigation with a teff proportion of 25 to 35%, on an electric mitad. He employed a 3 × 3 cm frame to count the injera eyes at four randomly chosen spots and determined that between 11 to 15 eyes per cm^2 were an appropriate number, and indicated higher or lower number of eyes is not an indication of better quality.

The front side of a high-quality sorghum injera, according to [70], has evenly spaced "eyes" which resemble honeycombs and range around 4-5 mm in depth and measure 4 mm in diameter. According to their findings, a typical injera is thin - about 6 mm thick - and has roughly 4 injera eyes per square centimeter of injera surface. Injera of lower quality may have large, oddly spaced eyes or small eyes. They pointed out that insufficient fermentation is indicated by large eyes, whereas excessive absit in the dough is indicated by small eyes and typically the rear of the injera is smooth and eyeless.

However, from a practical standpoint, 11 to 15 injera eyes per cm^2 are excessive, and 6 mm thick injera with 4 injera eyes per cm^2 area of injera surface do not agree and require precise evaluation and measurement. Even so, practically, the number and size of injera eyes depend on the temperature of the baking plate, which is also affected by the thickness of the batter at a spot and the uniformity of pouring the batter on the mitad on the last baking.

The model of injera eye formation and columnar structures (tunnels) of injera [69] is presented in Figure 2-9 and Figure 2-10, respectively. Injera's cross-sectional view revealed, according to [69], that during baking, bubbles create tunnels in the batter; and these tunnels seemed more evident in thicker batters.

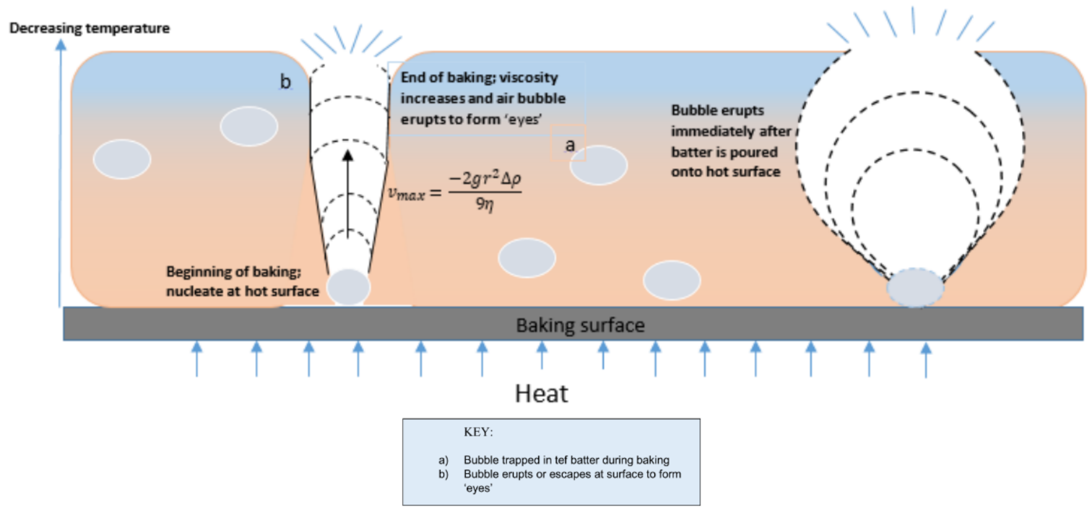


Figure 2-9. Model of injera eye formation
[69]

Figure 2-10. Columnar structures (tunnels) in a cross-sectional view of injera
[69].

2.7 Over view of Copper material properties

Copper is a very high thermal and electrical conductivity, soft, malleable, and ductile metal. Pure copper has a reddish-orange tint when it is first exposed to the air.

The most common properties of copper according to [47] are indicated in Table 2-1.

Table 2-1. Common properties of copper

No	Property at 300 K	Value	Unit
1	Thermal conductivity	401	W/m.K
2	Specific Heat capacity	385	J/kg.K
3	Density	8933	Kg/m^3
4	Melting point	1358	K
5	Thermal diffusivity	1.17×10^{-4}	m^2/sec

After silver, pure copper has the second-highest electrical conductivity. Silver has a conductivity of 6.2x107 Siemens/m, compared to copper's 5.9x107 Siemens/m. When compared to other metals, copper's superior conductivity greatly improves electric motors' efficiency, which is why copper coils are usually employed, especially for small motors. Copper comes in close to the third position behind diamond and silver in terms of the measured thermal conductivity of naturally occurring materials. Because of its high melting point, copper is the ideal material for high-temperature applications, making it ideal for heat exchangers in boilers, heat sinks in electrical equipment, and bases for cooking utensils like saucepans. Copper is easily molded into the shape of a wire due to its malleability and ductility and it is the material of choice for producing wires and cables. Due to its exceptional innate ability to resist corrosion, copper has proven to be a beneficial metal for outdoor, seafaring, and sailing structures [73].

2.8 Performance improvement studies on electric injera mitad

Many factors affect the performance of electric injera mitad. Thermal efficiency is affected by heat losses: bottom, side, and top heat losses; clay plate production quality, makeup, and thickness of clay plate; assembly of the mitad, the number of injera baked per session; and water content of the batter. Heat uniformity at the baking surface is affected by: groove spacing and depth; heating element power rating, stretch uniformity, and method of placing; thickness and density of clay plate; type, thickness, and uniformity of bottom insulation, and experience of the injera baker.

2.8.1 General performance improvement studies

[21] conducted an experimental investigation and numerical calculation of the energy loss of electric injera mitads during baking and concluded that these mitads account for 46.15 percent of heat loss, which is in the range of the predictions made in earlier research (40–50 percent). Their finding indicated that out of the total heat loss recorded in the electric mitads, the bottom insulation accounted for 70.1 percent of heat energy loss, with the remaining 16.2 percent, 6.7 percent, and 7.0 percent coming from the bare plate, cover, and side enclosure, respectively. It was recommended that additional research and development will be needed to improve the properties of bottom insulations to lessen the significant heat loss accounted for by electric injera baking mitads. It can be seen from the study that the

heat loss at the bottom emanates from the clay plate and is an indication of the lower thermal resistance of the bottom insulation.

[74] reported that using an electric injera baking pan in conjunction with a waste heat recovery system increased baking efficiency by 11.53 percent when compared to traditional electric injera mitads. The study indicates there is significant heat loss at the mitad.

According to [20], conventional electrical systems have a design that dates back to the 1960s, are incredibly inefficient, and are overtaxing the electrical grid. It was claimed that the newly created Magic Mitad has a much higher energy efficiency than the electrical clay mitads (up to 45 percent higher). Considering the research-based energy efficiency of 50 to 55% of conventional electric mitads, this finding needs further verification.

[3], experimentally studied the energy consumption and performance of existing electrical mitad in Mekelle city and determined that the electrical mitads have a power consumption of 3.5kW to 3.9kW and are the most energy-consuming device in every household. The energy consumption of the different mitad was measured through a baking process of 8 to 13 pcs injera. The thermal efficiency comparisons conducted by considering baking 6 kg of injera on each of the double clay, single clay, and rotating type mitad revealed the efficiency is 38%, 47%, and 62% for double clay, single clay, and rotating types, respectively. It was recommended, among others, that reduction of the thickness of the baking clay and its thermal conductivity improvement works are the possible options for the energy efficiency improvement of the electric mitad.

[75] used the finite element method to model the heat transfer process during the electric injera baking process and concluded that most of the heat losses from the clay plate surface occur between two injera baking times and during the initial clay plate heat-up. The study revealed that reduced clay pan thickness can be used for injera baking at a lower heating power source and longer total baking time than the conventional clay pans and recommended electric mitad having a 2.5 kW rating and clay plate thickness of 10 mm. Such thicknesses of clay plates are applicable for ceramic baking and no groove baking pans but may not be realizable for grooved electric clay plate baking mitads due to the

requirements of grooves 8 to 11 mm [50] for the heating element and the strength of the clay plate.

According to a study [76], the current Mitad design has several flaws, including high resistance, improperly sized electric wiring, an incorrectly adjusted combustion element, the use of substandard building materials, inadequate insulation, and energy loss of between 40 and 50 percent during baking sessions. The study indicated despite the significant flaws, no worthwhile attempts have been undertaken so far to enhance the mitad design and its energy efficiency and it advised to use energy conservation programs, demand reduction strategies, and energy efficiency measures as a great instrument for adding power supply at a cheap cost.

[77] provided the findings of a finite element heat balance model for an electric injera mitad and contrasted the model's predictions with controlled cooking trials. According to their simulation model, the three main parameters affecting efficiency are the length of the cooking session, the cooking plate's thermal resistance, and the insulation of the cooker. In the comparison between model predictions and experiment-based calculations of cooker efficiency, it was determined that the experimental efficiency and modeled efficiency ranges were 42.2 to 54.1% and 46.9 to 55.3%, respectively. It was claimed by adding more insulation, efficiency gains are only marginally improved and a normal run loses 16 percent of its heat via the bottom and sides, but adding insulation raises interior plate temperatures and losses because the plate retains more heat. The study concluded that the Eritrean highlands' traditional energy-saving technique of utilizing injera batter with little water and cooking it in a way that results in moist, thick to medium-thick injera, yields the biggest energy savings. However, electric mitads are mostly used in households and the cooking session may not be extended to bake more injeras due to the limited family size and injera shelf life of 3 to 4 days [78].

2.8.2 Clay pate performance improvement studies

[26] carried out an experimental investigation to determine the feasibility and dependability of an electric stove based on ceramic bakeware for the application of injera baking and created a mathematical model of the coupled heat and mass transfer of the baking process. Ceramic bakeware with a body thickness of 26mm, a diameter of 585mm, and a

composition of silica (10%), kaolin (55%), feldspar (10%), and alumina (25%) were developed with a resistor wire embedded at the bottom surface. 10 injera baked at a lower temperature between 147 and 150 ℃ demonstrated the bakeware's compatibility for the intended use. Even though the experiment led to bakeware cracking, the simulation demonstrated that 82% efficiency may be achieved by lowering the thickness to 8mm for 20 cycles of injera baking. It was concluded that ceramic bakeware can be an excellent replacement for traditional clay bakeware, both in terms of energy efficiency and superior product formation.

To ascertain whether certain clay and sandy clay deposits utilized for mitad manufacture in the Tigray region were suitable for use as energy-efficient bakeware, [27] examined their qualities and production techniques. The addition of more clay to sandy clay has shown weaker thermal conductivity and greater specific heat capacity; this has made the local mitad high energy consuming and less durable. Thermal conductivity was found to be 0.417 W/m K, thermal diffusivity to be 2.71x10^{-}7 m2/s, and compressive strength to be 12.89 MPa for the sample with 0.7 cm thickness, 45 m crushed sandy clay grain size and 10% clay to sandy clay ratio. It was determined that the local mitad's thermal conductivity increased by 30.72 percent, thermal diffusivity by 10.7 percent, and compressive strength by 46.96 percent. Clay samples in the study on average are mainly composed of: SiO_2 – 53%, $Al_2O_3 -$ 14.5%, and $Fe_2O_3 -$ 3.0%, and sandy clay is composed of: SiO_2 – 52%, $Al_2O_3 -$ 13.5%, and $Fe_2O_3 -$ 10.5%.

The thickness and thermal properties of the ceramic baking pan are two factors that affect how quickly the oven heats up, according to finite element modeling of a solar-powered injera baking oven [15]. The simulation findings indicate that at a particular supply oil temperature, the heat-up time can be shortened by decreasing the baking pan thickness.

Finite Difference modeling and experimental research were done on traditional clay electric mitads and upgraded plates constructed of aluminum silicate and aluminum oxide, with a thickness of 0.71 to 1.0 cm [25]. The results showed that the traditional and enhanced baking pans lose the most energy at the bottom of the ovens, by 35.08 percent and 23 percent, respectively, despite having thermal efficiencies of roughly 52 percent and 75 percent.

[24] studied the modeling and simulation of heat transfer during the process of injera baking and developed mathematical models and finite element formulations for baking pan and injera during baking. A relatively better efficiency was obtained for 10 mm thick clay (83.81% for 30 baking cycles) and 8mm thick ceramic baking pans (77.26% for 30 baking cycles) with a power source of 2.5KW. For 3.0 KW power and clay plate thickness of 20 mm, and 10 baking cycles, efficiency is determined to be 53.11%. The simulation results showed heat up and idle time of a baking pan decreases as thermal conductivity increases, so a major improvement in efficiency will be obtained if the clay plate baking pan's thermal conductivity is improved. The simulation indicated for same clay plate thickness of 20mm, the heat up time increases for decreasing power rating of the electric mitads (Figure 2-11).

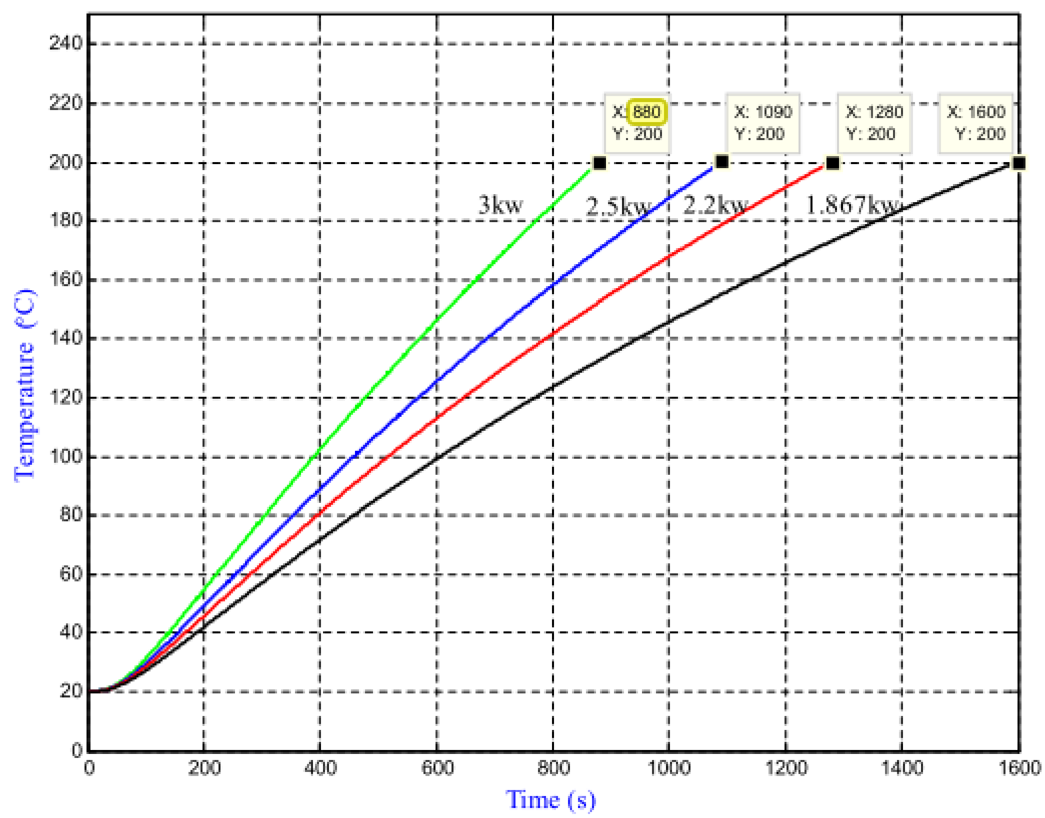


Figure 2-11. Heat-up time of 0.02m electric clay baking pan with a different power rating of mitads.
[24]

In his simulation study on clay baking pan thickness of 0.02m and power of 3kw [24], also determined the cyclic baking (Figure 2-12) for the surface temperature of the baking pan

(Node 118) during heat up, baking, and idle periods, and for the surface temperature of six injeras (Node 149). A baking period of 150 seconds and an idle period of 100 seconds were considered in the simulation.

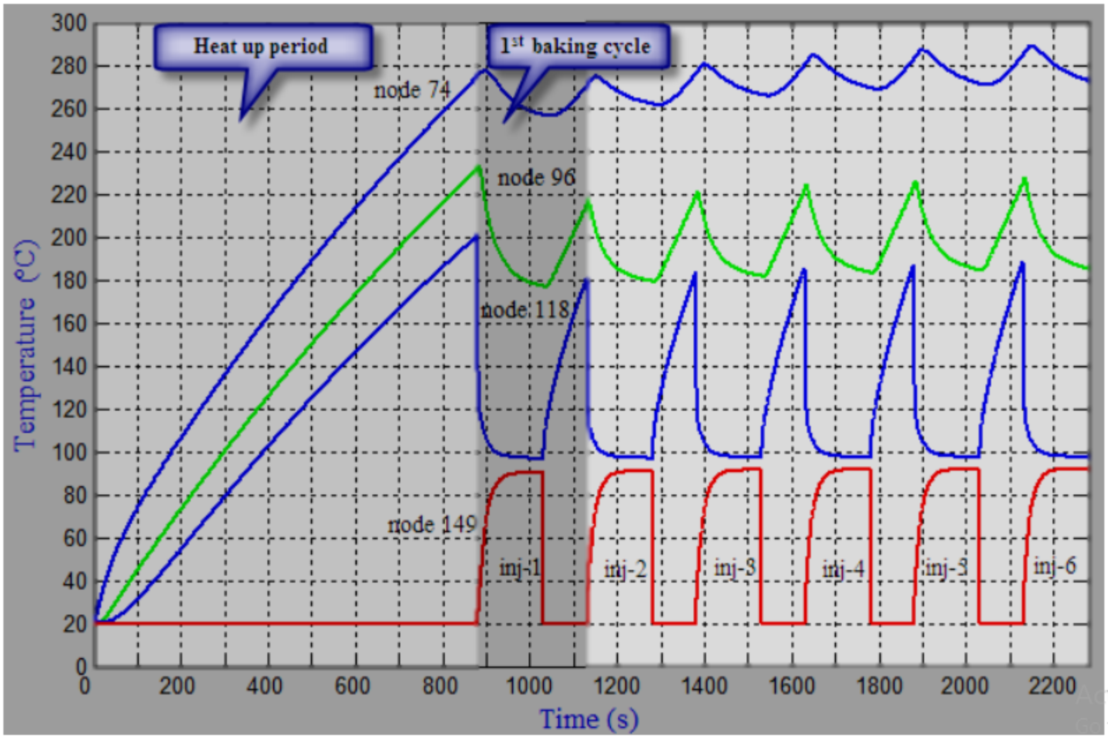


Figure 2-12. Cyclic baking simulation of electric injera mitad: temperature profile of nodes for baking pan thickness of 0.02m and power of 3kw.
[24]

[77] experimentally investigated, and with finite element heat balance model studied, the effect of clay and iron cooking plates on Mogogo (Electric mitad) efficiency and energy use and concluded that the Mogogo design parameter which most effects the efficiency and energy intensity is the thermal resistance of the cooking plate and earlier theoretical work predicted that the energy saving in Mogogo up to 10-20% could be obtained by increasing the thermal conductivity of the cooking plate. It was observed that, in theory, reducing the thermal resistance of the plate by either raising bulk conductivity by adding magnesium salt or decreasing plate thickness significantly improves the mitad's efficiency.

2.9 Summary of literature reviews

In the different research and studies conducted, it is indicated that the conventional mitad is a highly energy-consuming appliance and its energy efficiency is low and ranges from

38% to 54.1%. Figure 2-13, indicates the summary of efficiency values of experimental and simulation studies on conventional and ceramic bakeware electric injera mitads by different researchers, and Table 2-2, shows the summary of studies made on clay plate improvements.

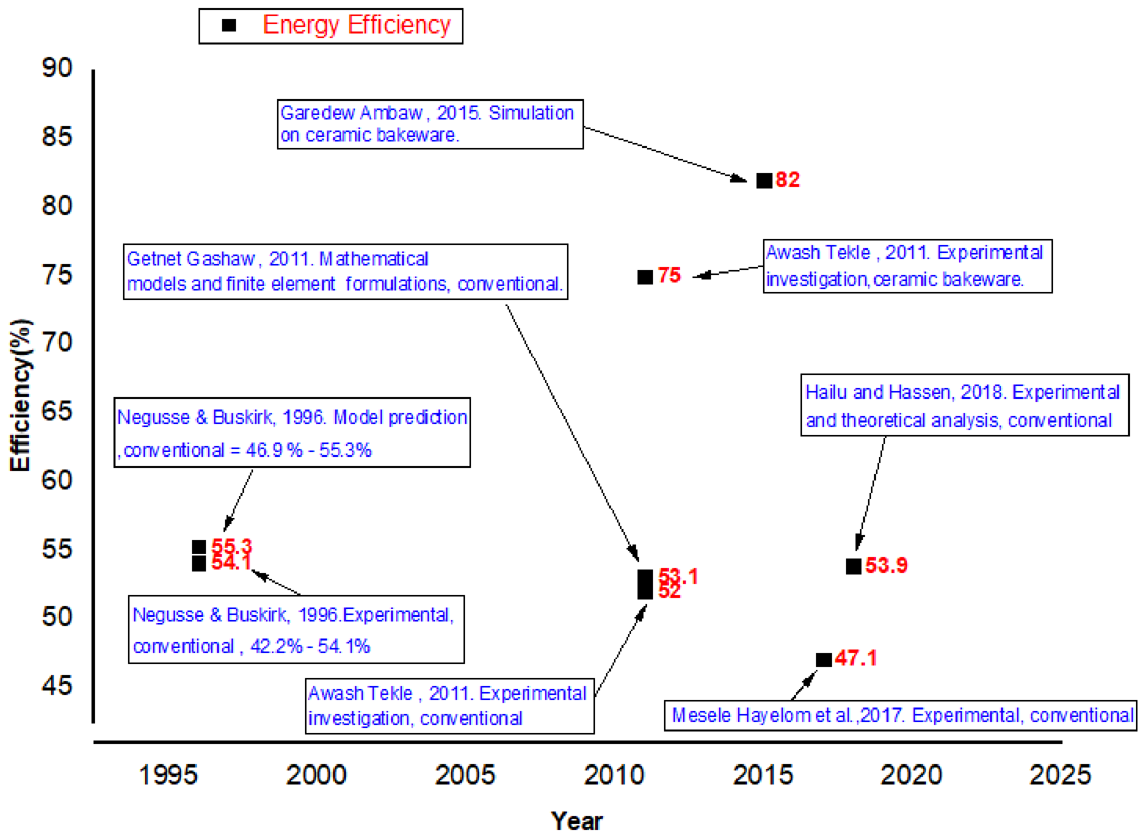


Figure 2-13. Summary of experimental and simulation efficiency values by different researchers.

Table 2-2. Summary of clay plate improvement studies by different researchers

No	Researcher	Experimental investigation	Results
1	[26]	Ceramic bakeware 26mm thick, a diameter of 585mm, composition of silica (10%), kaolin (55%), feldspar (10%), and alumina (25%)	• Bakeware cracking, simulation demonstrated 82% efficiency may be achieved for 8mm thickness.
2	[27]	• Addition of more clay to sandy clay	• Weaker thermal conductivity and greater specific heat capacity
		• Sample 0.7 cm thickness, 45 μm crushed sandy clay grain size and 10% clay to sandy clay ratio.	• thermal conductivity increased by 30.7%, thermal diffusivity by 10.7 %, and compressive strength by 46.9%.
3	[25]	• Plates constructed of aluminum silicate and aluminum oxide, with a thickness of 0.71 to 1.0 cm	• Bottom heat loss was reduced from 35.08% to 23% and thermal efficiency increased from 52% to 75%.
4	[15]	• 2D transient finite element analysis for a new type of solar-powered injera baking system. Baking pan made from ceramic with 8mm thickness.	• The baking pan gives reasonable heat up and baking time for an 8mm thick ceramic pan with a heated oil temperature of 275 ℃. The heat-up time can be shortened by decreasing the baking pan thickness.
5	[24]	• Modeling and simulation • 10 mm thick clay and 8mm thick ceramic baking with a power source of 2.5KW are more efficient.	• Better efficiency attained 83.81% and 77.26% respectively for 30 baking cycles with a power source of 2.5kW. • Clay plate 3Kw, 20mm, efficiency 63.11%
6	[75]	• The finite element method is used to model the heat transfer process	• Major improvements in energy efficiency are predicted if the thermal conductivity and thickness of the plate are improved. • The recommended electric baking pan is a pan made with 2.5 kW and a clay plate thickness of 0.01m.
7	[77]	• Experimentally, and with a finite element heat balance model	• Energy savings in Mogogo up to 10-20% could be obtained by increasing the thermal conductivity of the cooking plate. • Adding magnesium salt or decreasing plate thickness significantly improves the mitad's efficiency.

2.10 Research Gap

Most studies pointed out that the energy efficiency of the conventional electric injera mitad is low and ranges from 38% to 54.1%, the main cause being the poor thermal conductivity of the clay plate. An experimental study revealed that an energy efficiency improvement of 25 % could be achieved with the use of clay plate composite materials of Aluminum silicate and Aluminum oxide metallic powders, whereas another investigation employing 0.7 cm thick clay plate made of crushed sandy clay soil and 10% clay to sandy ratio, the improved thermal conductivity of the clay plate by 30.7%. Modeling and simulation studies have shown that efficiency improvement of up to 83% could be achieved with the use of ceramic bakeware mitads of 8 to 10 mm thicknesses.

Despite successful studies and efforts to increase the thermal conductivity of the conventional mitad clay plates at various levels, performance-improved clay plates and thus electric mitad which can be produced at the level of local traditional producers have not been realized, as the production of the clay plates based on the studies requires manufacturing plants. Even so, performance improvement, temperature distribution uniformity, corrosion, and the electrical short-circuiting of the clay plate with the metallic resistive heating wire remain to be a challenge.

The current study's goal is to improve the performance of the electric injera mitad for production at the level of local producers by using copper wire embeddings in the clay plate, without affecting the quality of injera.

CHAPTER THREE

3. MATERIALS AND METHODS

The various materials and methodological approaches that were applied in the experimental study of the CuWE clay plate electric mitad are discussed in this chapter. The first section presents the methods for the development of clay plates with Cu wire embeddings including the identification, make-up, composition, and methods of traditional clay plate production; preparations of samples of CuWE clay plates for thermal conductivity tests and preparation of CuWE baking clay plates. The second section deals with the experimental tests carried out on the base case and CuWE baking clay plate electric mitads. The materials and equipment employed for the experimental test, the experimental setup, the test procedures, and the performance evaluation methods are presented in this section.

The overall methodological approach followed in the research is presented in Figure 3-1.

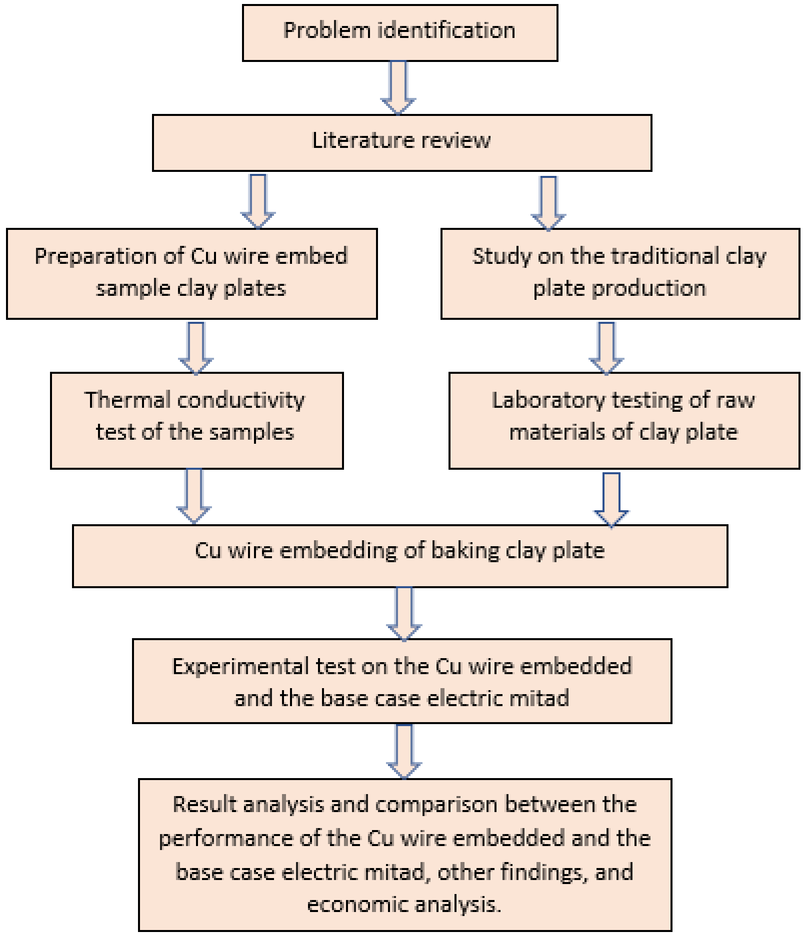


Figure 3-1. Overall methodology of the research

3.1 Development of clay plate with Cu wire embeddings

To develop the CuWE electric mitad, the traditional method of clay plate production has been studied and samples of the clay plate raw materials are tested for elemental composition. Samples of CuWE clay plates were prepared and tested for thermal conductivity. CuWE baking clay plate was produced based on the characteristics of the selected sample embedded with bare Cu wire of 2x4 sq. mm.

3.1.1 Study on the traditional clay plate production

The traditional clay plate production has been studied at the major clay plate production site located in Oromia regional state, Legetafo, Gewassa town. The raw materials for clay plate production were identified and the production process was observed at the renowned clay plate production site of W/ro Jorgo Tulu, who had been in the business for over forty years.

a) Traditional clay plate production methods

The clay plate of electric injera mitad was composed of sand, clay, and red soil pigment materials and was produced traditionally in rural areas. Figure 3-2, shows the process flow to produce clay plates at the production site. The production process starts by mixing clay, sand, and water in an underground pit. The mixture was cast on a bigger clay plate made for casting purposes. The cast clay–sand mixture was allowed to dry in the sun. The dried greenware was trimmed for the desired size of mitad, leveled, the edge formed, and plastered. The greenware mitad was warmed up and then red soil pigment was applied twice and burnished with edible oil. The firing process was done by placing the greenware on a three-stone cow dung fire; the baking side facing the fire underneath.

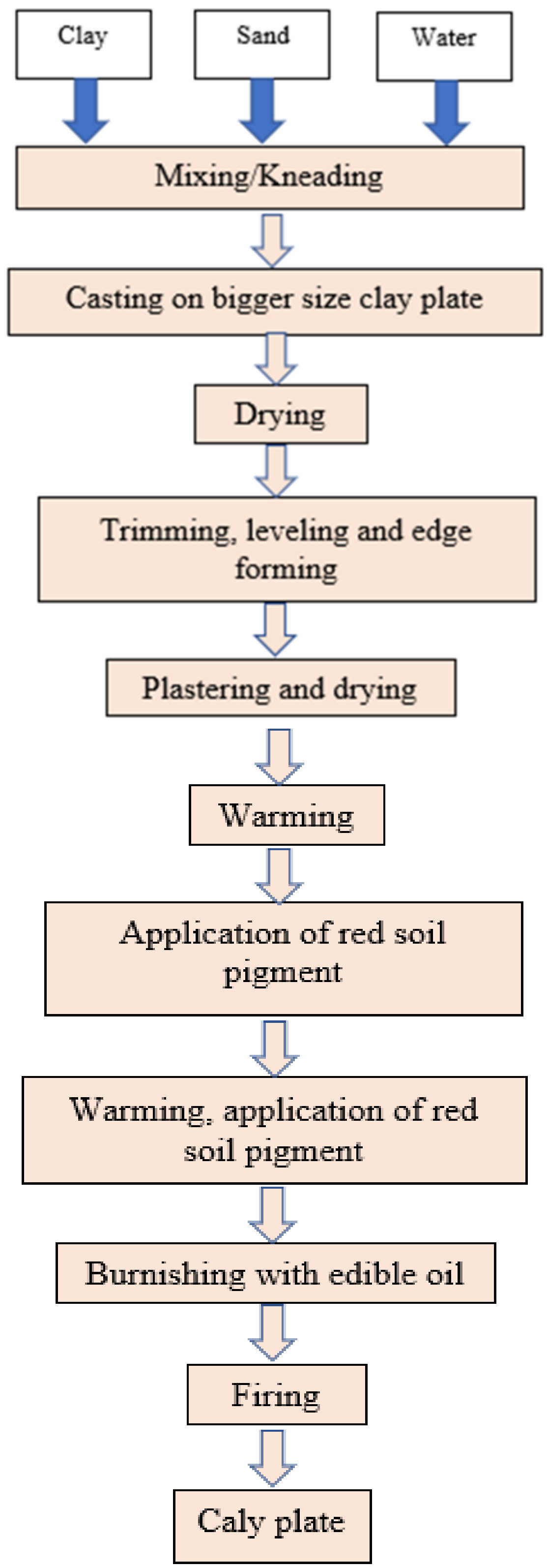


Figure 3-2. Process flow for the traditional method of clay plate production

It has been noted that neither the weight nor the volume of the proportions of the sand, clay, and water in the traditional fabrication of clay plates is clearly defined or exact. Leg-powered mixing and kneading could lead to insufficient mixing, which would limit the intended bonding between the sand and clay. Manually drying and leveling the clay plate introduces thickness differences throughout the plate. Due to the non-uniformity of the cow dung and the dominant wind, the fire intensity and duration vary during the open firing process. Instances of under firing or overfiring are also possible. The clay plate's mechanical strength and heat conductivity are impacted by this. As a result, there would be differences across producers in the mass (weight), thickness, strength, and thermal conductivities of the clay plates.

b) Composition and proportions of the raw materials of the clay plate

Samples of clay, sand, and red soil/pigment raw material indicated in Figure 3-3, were collected from the warehouse of W/ro Jorgo Tulu, at Lege tafo, Gewassa town, for laboratory investigation at the Geological Survey of Ethiopia, Addis Ababa. 200 gms of each material was submitted to the testing laboratory. As per the complete silicate analysis test using Analytical Methods of $LiBO_2$ fusion, HF attack, gravimetric, colorimetric, and AAS, the compositions of the main raw materials of the sand, clay, and red soil/pigment were determined. Detailed report is attached in Appendix A.

a) Clay b) Sand c) Red soil/Pigment

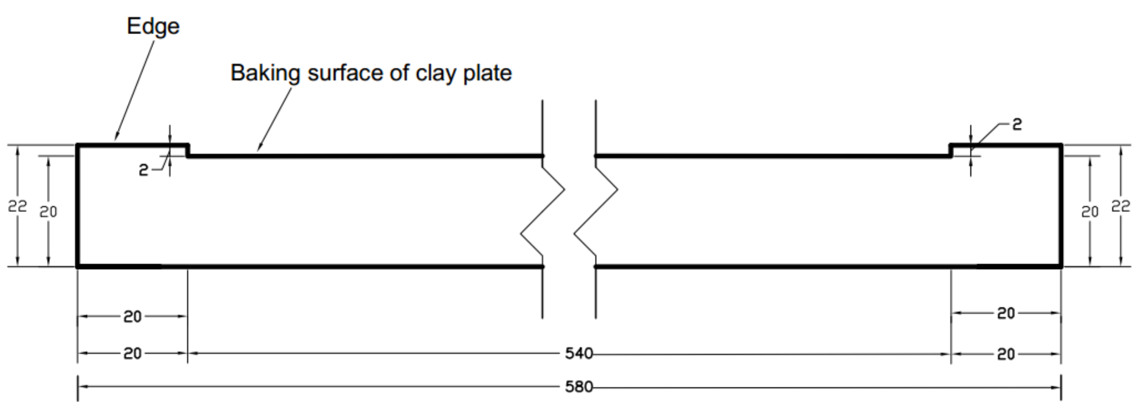
Figure 3-3. Samples of clay plate raw materials

In the traditional method of clay plate production, sand is delivered to the mixing pit by fertilizer sacks and clay is added using a bowl made of straw called "Enkib". The sand and clay components have been weighed using the Dahongyng, 40 kg capacity digital weighs scale, for three sample mixes on the dates of 14, 21, and 28 December 2020. The average weight proportions are determined to be clay - 47% and sand - 53%. Thus, the final dry mix based on these weight proportions was determined to be composed of $SiO_2 - 69\%$, $Al_2O_3 - 13\%$, $Fe_2O_3 - 4\%$, $H_2O - 4\%$, $K_2O - 3\%$, and others -7% (LOI (Loss on ignition) - 5%, $MgO - 1\%$, $Na_2O - 1\%$) indicating SiO_2, is the prime constituent of the clay plate of injera mitad determining its properties, Al_2O_3 being the second one.

3.1.2 Clay plates for the study

Three clay plates of the most common type and size of 58 cm diameter, the thickness of 22 mm, and without grooves were obtained from Oromia regional state, Legetafo, Gewassa town, the warehouse of W/ro Jorgo Tulu. Figure 3-4, a) and b) show the clay plate of injera mitad and the schematic diagram for the 58 cm diameter and 22mm thick size, respectively. The thickness of the baking surface was 20mm, less than the thickness of the edge by 2mm. The thickness of the edge was made bigger to avoid the spillage of the batter and to guide the formation of circular-shaped injera while pouring the batter during injera baking.

a) Injera mitad clay plate.



b) Schematic diagram of 58 cm diameter and 22 mm thick clay plate.

Figure 3-4. Injera mitad clay plate and its schematic diagram

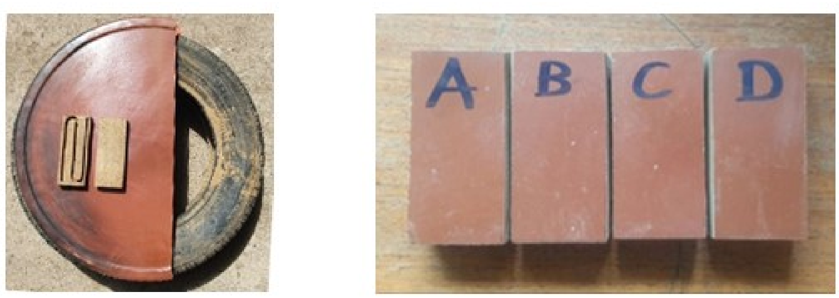
The three clay plates were cast by a single producer on the same date. The clay plates have got the same composition of sand and clay and had undergone the same production process. The first clay plate was used for the cut-out of the samples required. The second clay plate was used for the preparation of the base case electric mitad, and the third clay plate was used for the CuWE electric mitad. The second and third clay plates were grooved with 14 rounds (Figure 3-5) at Merkato Chid Tera, where clay plate grooving in the city takes place.

Figure 3-5. The clay plate grooved with 14 rounds

3.1.3 Preparation of CuWE sample clay plates

a) Sample clay plates

Four sample clay plates of 100x50x20 (mm), to fit with the thermal conductivity testing machine, QTM 500, have been cut out (Figure 3-6, a), using a simple hand-held ceramic cutter from the un-grooved clay plate. Sample "A" represented the base case clay plate without Cu wire, whereas samples "B", "C" and "D" are prepared for an increasing number of embedded Cu wires (Figure 3-6, b).



a) Clay plate cut b) Four sample cut-outs

Figure 3-6. Sample clay plates, 100x50x20 (mm):

The bottom side of a typical clay plate, with 14 round grooves and two parallel circuits of the heating element placed, is shown in Figure 3-7. The typical clay plates produced at Merkato Chid Tera market have an average groove depth of 9 mm, a width of 7mm, and a pitch or width between grooves of 13 mm as indicated in Figure 3-8. The heating element diameter of 0.8 mm has got a coiled diameter of 5 mm.

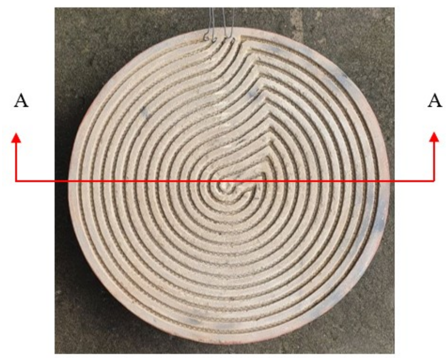


Figure 3-7. Bottom view of grooved clay plate with heating element placed

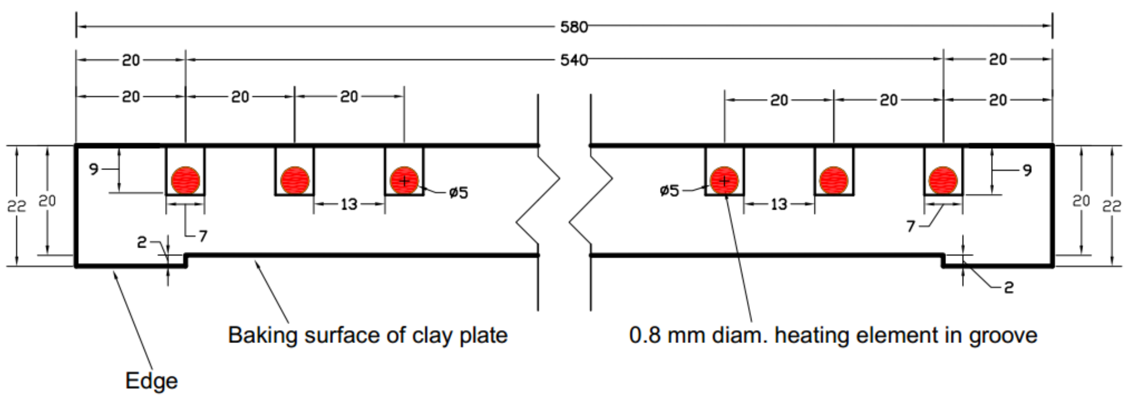


Figure 3-8. Section A-A view of clay plate of 58 cm diameter with heating element placed and sealed (NTS).

Conceptually, the bare copper wires are intended to be inserted in the grooves to be made at the centers of the islands between the concentric grooves of the heating element and run throughout the bottom of the clay plate in the helical fashion similar to the way the heating element has been placed in its grooves. Figure 3-9, shows a sectional view of the heating element and the conceptual copper wire embedding arrangement for the 14-round grooved clay plate. A spacing of 20mm was used between the centers of the copper wires. As indicated earlier, the computed thermal diffusivity of sand and clay at 300 K are 2.2×10^{-7}

m^2/sec and 10.1x10^{-7} m^2/sec respectively, whereas that of pure copper material is 1.17x10^{-4} m^2/sec [47], indicating embedding of copper wire in clay plate of injera mitad could diffuse heat at much higher rates compared to sand and clay composition. SiO_2 has a resistivity of 1x10^{17} to 1x10^{21} ohm.cm and a dielectric strength or break down potential of 25 to 40 MV/m [48]. Hence, the copper wire embedding could be accommodated alongside the heating element with little separation without a problem of electrically short-circuiting.

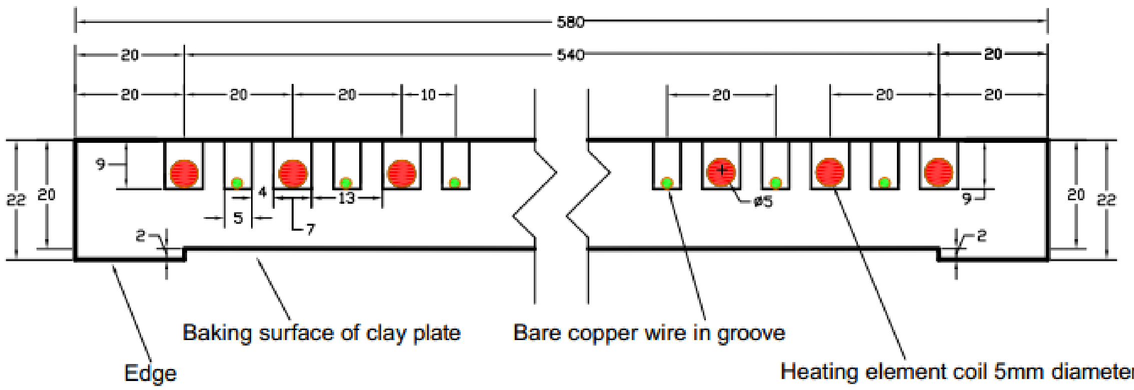


Figure 3-9. Section view of the clay plate of 58 cm diameter with heating element placed, conceptual copper wire embedding in grooves and sealed. (NTS).

Hence, the clay plate samples for the thermal conductivity test were prepared in such a way that the copper wire embeddings were disposed at the same spacing as they would have been for the 58 cm diameter clay plate selected for the experimental investigation shown in Figure 3-9. The sample characteristics were made to be identical to that of the actual CuWE clay plate developed.

Single core rigid Cu wire of 4 sq mm cross-sectional area has been selected for CuWE clay plate sample preparation from the standard wire sizes of 1.5, 2.5, 4, and 6 sq mm available in the market. The bare 4-mm-square wire, which is the largest size that could be accommodated into the grooves of the clay plate singly or bundled and has a manageable bending radius to fit into the grooves, has been selected for the test. The PVC insulation was peeled off using an insulation remover. Figure 3-10, shows the layout of bare copper wires in the clay plate samples.

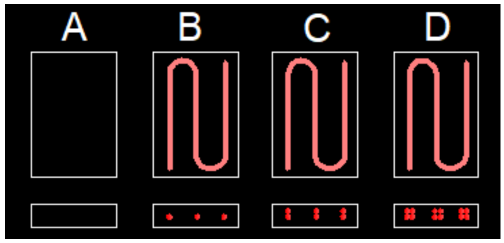
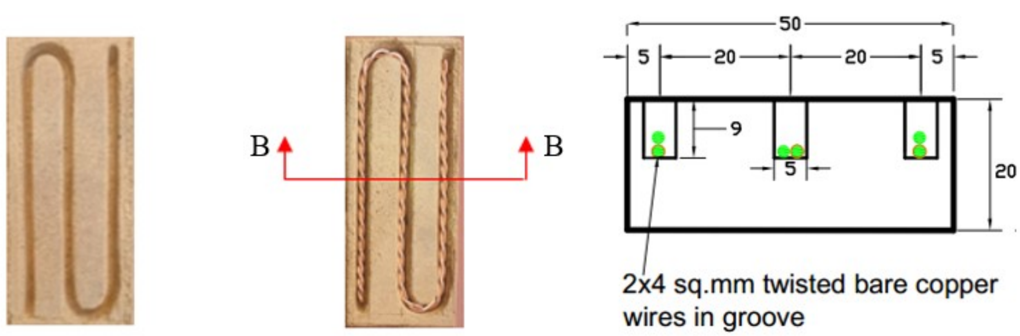


Figure 3-10. The layout of sample clay plates with copper wire embeddings

Single wire, double, and quadrupled wires of 4 sq. mm were used in the clay plate samples "B", "C" and "D", respectively. To increase the number of wires in the limited space and ease of placing wires, the 2x4 sq. mm wire was twisted using a hand drill at random of 15 twists per 10 cm. Table 3-1, presents the number and size of copper wires in the respective samples, and Figure 3-11, shows details of the clay plate sample for the case of the 2x4 sq. mm copper wire.

Table 3-1. Number of copper wires in the grooves of clay plate samples

Sample	CuWE	No of wires in the groove
A(Base case)	None	None
B	1x4 sq.mm	One
C	2x4 sq.mm	Two
D	4x4 sq.mm	Four



a) Grooves for the sample.

b) Twisted 2x4 sq. mm copper wire in the groove.

c) Section B-B of the sealed sample

Figure 3-11. Clay plate sample for the case of the 2x4 sq. mm Cu wire embedding (NTS).

After embedding the copper wires, the samples were sealed with clay and sand mixed and dried in the sun, and thereafter using an electric stove. The samples ready for the thermal conductivity test are indicated in Figure 3-12. Letters "A" to "D" was written on the baking side of the clay plate after removing the thin layer of the red soil/pigment to obtain perfect body contact with the sensor probe of the thermal conductivity testing equipment.

Figure 3-12. Clay plate samples for a thermal conductivity test.

a) Equipment to determine thermal conductivities of sample clay plates.

The thermal conductivities of the samples were measured using the Quick thermal conductivity meter, QTM-500 (Figure 3-13), which measures the thermal conductivity of heat insulation materials and ceramics, among others [60], [79]. The measurements were made at the laboratory of the Materials engineering department of Adama Science and Technology University, Adama.

The thermal conductivity measurement of the equipment is based on the hot wire method in the principle that a heater wire extended through the center of an infinite cylindrical sample with constant power (heat) will warm up at an exponential rate over time. The temperature vs time curve becomes linear when the time axis is transformed to a log scale. The angle of the temperature line on the time log graph can be used to determine the sample's thermal conductivity.

The equation to determine thermal conductivity is given as:

$$\lambda = \frac{q}{4\pi \, . \, \Delta T} \; . \, ln\left(\frac{t_2}{t_1}\right) \qquad 3\text{-}1$$

$where,$

$\lambda \quad = Conductivity\ of\ sample\ \ [W/m.K]$

$q \quad = Thermal\ energy\ of\ heater\ per\ time\ and\ length\ [W/m]$

$t_1,\ t_2 = Time\ [s]$

$T_1, T_2 = Temperature\ at\ t_1,\ t_2\ [K]$

Figure 3-13. The QTM- 500 and thermal conductivity measuring experimental setup

b) Thermal conductivities of sample clay plates

The average thermal conductivity of the three tests on the base case sample was determined to be 0.2611 W/m.K, whereas that of CuWE samples ranged from 0.4477 to 0.6252 W/m.K. Table 3-2, shows the thermal conductivity test result of the sample clay plates. Detailed results of the thermal conductivity test are presented in

Table 3-2. Thermal conductivities of the sample clay plates

Sample	CuWE (sq. mm)	Average Thermal conductivity (W/m. K)	Standard deviation	Thermal conductivity improvement compared to the base case
A (Base case)	None	0.2611	0.0052	Reference
B	1x4	0.4477	0.0176	71.5%
C	2x4	0.5763	0.0209	120.7%
D	4x4	0.6252	0.0136	139.4%

The thermal conductivities of the CuWE samples range from 0.4477 to 0.6252 W/m.K, corresponding to a thermal conductivity increase from 71.5% to 139.4% relative to the base case sample, respectively. The embedding of Cu wire in the samples has improved its thermal conductivity as Cu has a higher thermal conductivity of 401 W/m.K at 20 degrees Celsius. Thus, if Cu wires are interposed with the heating element in the clay plate of electric mitad it would enhance its thermal conductivity, heat uniformity, and diffusion of heat from the heating element. The QTM 500 test results indicated that the thermal conductivity of the clay plate could be improved with copper wire embeddings.

Due to the shallow depth of the groove of the electric mitad clay plate, the rigidity of copper wire and the requirement of sealing the clay plate after insertion of the copper wires, the most suitable wire size which could be accommodated was determined to be the 2x 4 sq. mm. Hence the experimental study was based on the embedding of 2x4 sq. mm bare copper wire (sample C) in the 58 cm diameter clay plate.

3.1.4 Development of the base case and CuWE baking clay plate electric mitad

The base case and CuWE electric mitads were produced using the same type of clay plate (size and weight), heating element type and power rating, and mitad body.

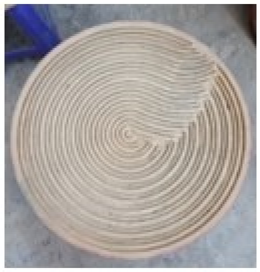
a) Preparation of the base case baking clay plate

The base case electric mitad was prepared using the second 58 cm diameter and 14 round groove clay plate. Groove width of 7mm, depth of 9mm, and width between grooves of 13mm, respectively have been used as per the groove sizes used for the conventional mitad at the Merkato Chid Tera clay plate market (Figure 3-7). Two heating elements of 0.8mm diameter, 15 ohms, with power ratings of 1613.3 W each, totaling 3226.7W at 220V were selected. The thermal conductivity of the base case clay plate was determined to be 0.2611 W/m.K (Sample A) as indicated in Table 3.2, above.

b) Methods to prepare CuWE baking clay plate

On the third 58 cm diameter clay plate, 14 rounds of grooves for the heating element and additional parallel running grooves, alongside the grooves of the heating element, were made for copper wire embeddings. Two heating elements of 0.8mm diameter, 15 Ohms, with power ratings of 1613.3 W each, totaling 3226.7W at 220V were used as in the case for the base case baking clay plate. The Cu wire grooves are made to have a 5mm width and depth of 9mm, to accommodate a maximum of 2x4 sq mm twisted wires. Figure 3-14, a) to e), show the placing and sealing of the heating element and Cu wires in the grooves made both for the heating element and the bare Cu wires embedded side by side. The Cu wires are interposed between grooves of electric resistance wires. The 2x4 wire is twisted using hand held drill at a random 15 twists per 10 cm to save space and for the ease of placing in the grooves. A total stretched the length of 10 meters of 2x4 sq. mm twisted bare Cu wire having an overall weight of 1.0 kg was employed.

As the placing and sealing of the heating element Cu wires were embedded one after the other, sealing was made using clay-sand mix material from which the clay plate has been produced. The clay-sand mix was obtained from Gewassa clay plate producers. Figures 3-14, f), g) and h) show the sealing material, the back side of the sealed clay plate, and the elevation of the finished clay plate respectively. Figure 3-15, indicates the sectional view of the CuWE clay plate.

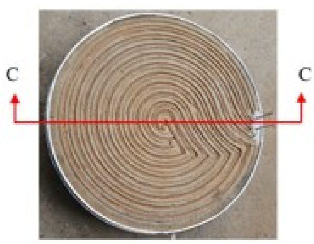


a)Grooves for the heating element and copper wire

b)One heating element circuit placed in grooves

c) Double heating element circuit placed and sealed

d) Placing of one copper wire circuit in grooves



e) Two circuits of copper wires placed in grooves

f) Sealing material

g) Sealed clay plate back side

h) Assembled electric mitad for the test

Figure 3-14. Copper wire embedding and clay plate preparation.

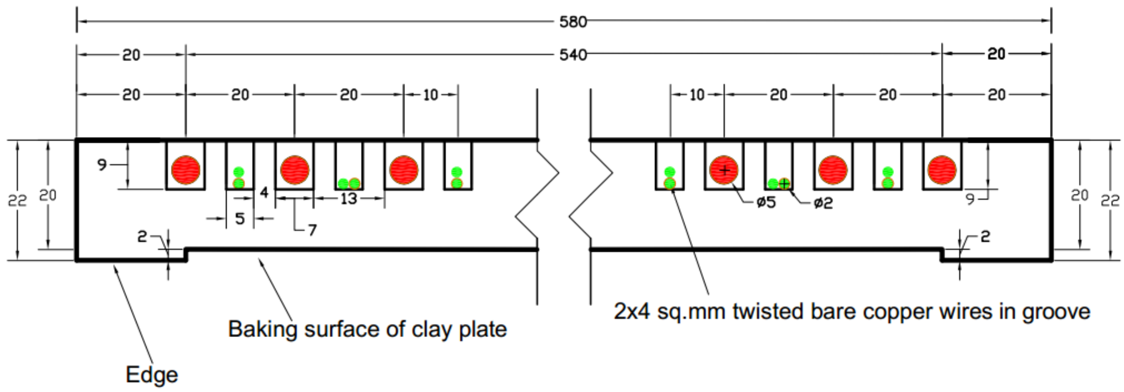


Figure 3-15. Section C-C view of the clay plate of 58 cm diameter with heating element placed, CuWE, and sealed (NTS).

a) Specification of assembled CuWE and base case clay plate electric mitads

i) Specifications for the CuWE mitad

After drying the sealing material and preparing of enclosure and supporting body of the mitad, the CuWE clay plate was assembled to form the electric mitad. The following materials have been used to produce the CuWE clay plate electric injera mitad: CuWE baking clay plate, enclosure/body, the lifting cover, and four-legged supporting stand. Except for the clay plate, other materials have been obtained from Addis Ababa, Merkato Chid Tera electric mitad producers. The specification of the assembled electric mitad is indicated in Table 3-3.

Table 3-3. Specification for the CuWE electric mitad

Item No	Description	Value	Unit
1	Clay plate diameter	58	cm
2	Clay plate thickness	22	mm
3	Clay plate thermal conductivity (Sample C)	0.57630± 0.0209	(W/m. K^o)
4	Clay plate baking surface emissivity	0.9*	
5	Clay plate weight	6.0	kg
6	1x4 sq. mm bare copper wire diameter	2.0	mm
7	Twisted bare CuWE	2x4	Sq. mm
8	Length of 2x4 sq. mm twisted bare CuWE in the two circuits	10	m
9	Weight of CuWE in the two circuits	1.0	kg
10	Heating element (Resistance) diameter	0.8	mm
11	Heating element resistance	15	Ohms
12	Heating element coiled diameter	5	mm
13	Heating element (Resistance) power at 220V	3,226.7	Watt
14	Lifting cover: Aluminum sheet thickness	7	mm
15	Emissivity of Aluminum lifting cover	0.3*	
16	Side body: Sheet metal thickness	0.6	mm
17	Emissivity of Side body (painted mat black)	0.9*	
18	Emissivity of the Bottom body (painted mat black)	0.9*	
19	Bottom insulation: wood ash, thickness	25	mm
20	Bottom insulation: wood ash, thermal conductivity	0.14**	W/m. K

* Emissivity data obtained from [80]
** Thermal conductivity data obtained from [81]

ii) Specifications for the Base case mitad

The base case electric mitad was assembled with the same specification as that of the CuWE mitad indicated in Table 3-3, except for the clay plate and the bare Cu wires. For the base case mitad, the clay plate of thermal conductivity of 0.2611 ± 0.0052 W/m. K^o (Sample A) was employed and the Cu wire was omitted.

3.2 Experimental tests and procedures.

3.2.1 Materials and Equipment for experimental test

Pure teff flour of 50 kg was obtained from a local milling house for the three controlled cooking baking tests to be conducted on each of the base case and the newly developed

CuWE electric mitad. For mitad clay plate baking surface polishing, a ground rape seed of 2 kg was prepared.

The following measuring equipment was used in the experimental test.

a) Electronic Digital Caliper to measure thickness, groove depth, and width of the clay plates and clay plate samples.
b) Fluke 87 Digital multi-meter to measure the resistance of the heating elements.
c) Dahongyng 40 kg capacity digital weigh scale to weigh clay plate, batter, baked injera, and leftover batter under the Controlled Cooking Test.
d) Fluke Ti-125 Thermal imager: The handheld thermal imager captures and creates an image of an object fully radiometric (IR) and visual images by using infrared radiation emitted from the object in a process that is called thermal imaging. The thermal imager has got thermal sensitivity of $\leq$ 100mK (0.1℃ at 30℃ target temperature, [82]), and the created image represents the temperature of the object. The image data was transferred to a Laptop computer using an SD memory card. The analysis was made with the Smart View classic software Ver 4.4 and the Fluke Connect Ver, 1.1.546.0, thermal image editor software to transfer thermographic images to a computer to efficiently manage them, optimize and analyze infrared and visible light control images and create and print detailed reports containing important image data. The thermal imager was used to capture the temperature of the baking surface of the mitad and the body starting from turning on power up to the heat up period every minute until the average baking temperature of 200 ℃ is reached, and during the baking period at intervals. The thermal imager was kept at a height of 165cm above the baking surface to capture the full image of the baking surface.

   As per the [82], the thermal imager was set to the .is2 IR file format to save data of the pictures to make it possible to combine the Infrared photo notes, visible image, radiometric temperature data, and infrared image into one place. The settings in Table 3-4 were used on the Ti -125 thermal imager and Smart View classic software for the analysis of the infrared images of the mitad parts.

Table 3-4. The setting used for the Fluke Ti - 125, Thermal imager

No	Description	Value
1	File format	.is2
2	Time at turn-on of Mitad	0.00
3	Palette color	Blue red
4	Saturation	Standard
5	Color alarm	Disabled
6	Display markers	Circle to fit mitad clay plate showing Min, Avg, and Max temperatures
7	Emissivity as per the emissivity table of [80]	
7.1	Clay plate	0.9
7.2	Black-painted steel bottom body	0.9
7.3	Black-painted steel side body	0.9
7.4	Aluminum lifting cover	0.3

e) The Testo 835 - H1 compact infrared thermometer along with K type thermocouple for contact/non-contact temperature measurement of the batter, bottom, and sides of the mitad enclosure and lifting cover.

f) Yokogawa WT 310E Digital power meter for measurement of the power, energy, time, voltage, and current during the test.

g) H560 DewPoint Pro to measure the ambient temperature.

3.2.2 Experimental setup, tests, and procedures

The performance of the electric injera mitads was investigated using the CCT protocol, which compares mitads as they perform a standard cooking task that is closer to the actual cooking that local people do every day. Measurements and observations were made for the three repetitions of the CCT on each of the base case and CuWE electric injera mitads. CCT procedures, measurements, and recordings were conducted during the pre-test, pre-baking, and baking of injera. The baking surface temperature was captured with the thermal imager, whereas, input power, energy, current, voltage, and time were measured using the power meter. Analysis and calculation were made to determine temperature uniformity, heat-up time and energy consumption, specific energy consumption, thermal efficiency, and total baking time for each test as well as the average of three tests. In addition, qualitative observations made during each test were noted. The experimental setup is shown in Figure 3-16.

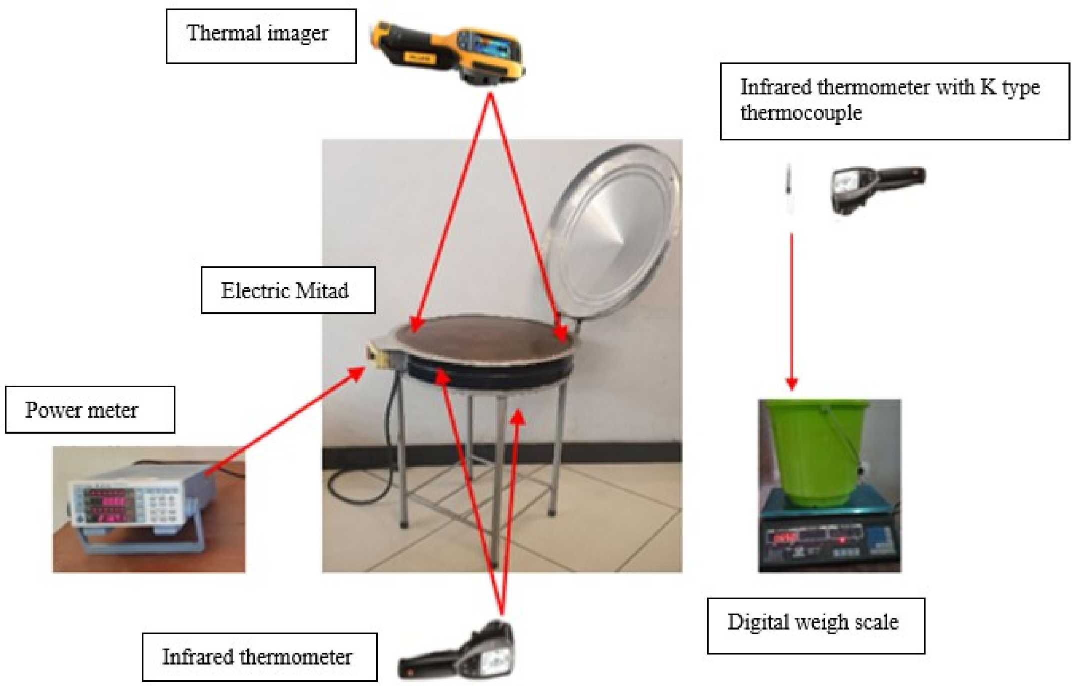


Figure 3-16. The test setup and measuring instruments employed.

a) Preparation of baking mitad before the test

Before the actual test is conducted the following tasks were performed.

i. An experienced baker who is familiar with Injera and the operation of the electric injera mitad to be tested was identified and assigned.

ii. The side and bottom of the body of the mitad were painted matt black oil paint for the maximum emissivity of the body.

iii. The electric mitads were prepared for baking by polishing with partially burned and ground rape seed on the baking surface, three times.

iv. The baking mitad were tested for baking with five injeras, to check for proper removal and baking of injera.

b) Injera batter preparation

Three to four days before the actual baking takes place injera batter was prepared. Measurements were made to determine the ratio of flour to water in the batter as follows.

i. Three days before the test date, 5.5 kg of teff flour, estimated to bake 30 Injeras, and water were mixed in a bucket.

ii. Yeast, a leftover from the previous batter, is added to the flour-water mix.

iii. Excess water was skimmed off each day until the date of baking.

iv. Just a few hours before baking a starter known as “absit” was made using a small mixed batter added to boiling water.

v. The batter waited until the formation of a bubble at the top at which time it was ready for baking.

vi. Water was added to make the batter lean as necessary.

vii. The final batter weight was measured and the batter water ratio was determined. The amount of water added and skimmed was weighed to get a consistent proportion of flour and water in the batter for all the tests.

c) Before and during baking.

The following measurements and tests were made and readings were recorded before and during injera baking.

i. Measured mitad baking surface temperature if it was at ambient temperature.

ii. Measured the batter's initial temperature.

iii. Switched on power and recorded initial readings of voltage, current, and power. The digital power meter was reset to start from zero for time and energy measurement.

iv. The lifting cover (lid) was kept open until the clay plate surface temperature reached the optimum baking average temperature of 200 ^{O}C; the surface was polished with ground rapeseed.

v. Recorded initial time, heat-up time, and baking duration.

vi. Captured the baking surface temperature distribution starting from turning on power up to the baking at an interval of one minute and during baking using the thermal imager.

vii. The same weight of batter is poured for all the injera baked using a marked jug. After pouring the batter and waiting for the formation of injera eyes, the cover was closed and the injera was cooked before taking it out from the baking pan. The procedure was repeated to bake about 30 pieces of injera which is the usual amount baked per session for a single household in Ethiopia.

i) Recorded reading of time, power, and energy during the heat-up and baking process.

j) Recorded any relevant observations while the baker performs the baking task.

k) At the end of the test weighed, counted, and recorded the following:
- The plastic bucket with any remaining batter was weighed, and bucket weight was accounted for.
- The stack of fresh injera on a pre-weighed 'Mesob' weighed, and
- The number of injera counted,

l) Interviewed the baker at the end of all the tests for any comments and opinions.

3.2.3 Performance Evaluation Methods

The performance evaluation of both the base case and CuWE mitad was made based on the heat-up and baking duration temperature distribution, time taken, and energy consumption.

a) Heat-up period temperature distribution, time, and energy consumption evaluations

i. Heat-up temperature distribution: Temperature variation across the baking surface at start-up and the average baking temperature.
ii. Heat-up time: Time taken to reach the average baking temperature
iii. Heat-up energy consumption: Energy consumed to reach the average baking temperature.

b) Baking period evaluations using CCT

i. Time to bake: Time taken to bake 30 injeras per baking session. The average time to bake one injera was determined as the total baking time including heat up period divided by the total injera baked (min/injera)
ii. Specific energy consumption: Energy consumed per injera or unit weight of injera, determined as the total energy consumed including heat-up period energy consumption divided by total injera baked or mass of injera baked (kwh/injera or kwh/kg).

iii. Energy efficiency

The energy utilized to bake injera was defined as the energy necessary to raise the batter to a particular temperature, and evaporate the amount of water that was observed to be lost during the cooking process [3], [83].

The energy used was determined by equation 3-2, assuming the average mass of injera and moisture loss for each injera are constant, and the mass difference between the baked injera and the original batter is equal to the mass of moisture loss during baking.

$$E_{utilized} = M_b \times C_b(T_b - T_i) + H_v(M_b - M_i) \quad (3\text{-}2)$$

Where,

$E_{utilized}$ = Energy utilized to bake injera(Joules)
M_b = Mass of batter (kg)
C_b = Average specific heat capacity of batter (3.4 kJ/kg. °C)
T_b = Boiling temperature of water at Addis Ababa(92.0 °C)
T_i = Initial temperature of the batter(°C)
H_v = Heat of vaporization of water at the boiling temperature at Addis Ababa (2,277.4 kJ/kg)
M_i = Mass of injera baked (kg)

The weight of the teff flour and the amount of water added were defined before the actual test is conducted to establish the flour and water proportions of the batter. The energy efficiency was calculated as in equation 3-3:

$$\eta = \frac{E_{utilized}}{Energy\ input} \times 100\% \qquad (3\text{-}3)$$

Where,

η = Efficiency (%)

Energy input = Total energy consumed during the entire baking session (Jouels)

CHAPTER FOUR

4. RESULTS AND DISCUSSION

This chapter presents the results, analysis, and interpretation of the experimental investigation to show the effect of Cu wire embeddings in the performance improvement of clay plate electric injera mitad. The first section presents results and discussion during the heat-up period and the second section addresses the baking session of the CCT, both sections covering the surface temperature distribution profile, baking time, and energy consumption.

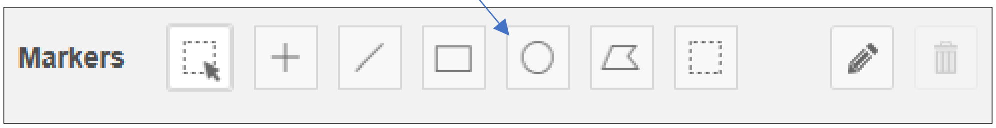
4.1 Test results during heat up period

The heat-up test results indicate the comparison between the base case and CuWE mitads in terms of the baking surface temperature uniformity and the time and energy the mitads require to reach the baking temperature. It helps to understand the major behavior as to how the mitads respond to the energy generation within and energy storage for the subsequent baking session.

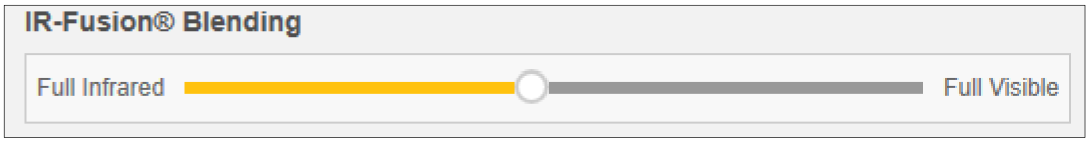
4.1.1 Heat-up time temperature distribution

The temperature distribution and time for the baking surface of the mitads plugged into an average power source of 204V (average of 203V to 205V), were read from the IR thermal image files captured and analyzed using both the Smart view classic 4.4 and the Fluke connect thermal image editor software. In analyzing the IR images using the Fluke Connect software, the “Ellipse Marker” was adjusted to a circular marker (Figure 4-1, a) to delineate the circular baking surface of the mitads by adjusting the “IR fusion Blending” slide (Figure 4-1, b), to show the visible image. The Circular Marker was then overlayed on the visual image of the mitad to fit on to the baking surface, then the same circular marker was overlayed on the IR image.

Ellipse marker for circular marking



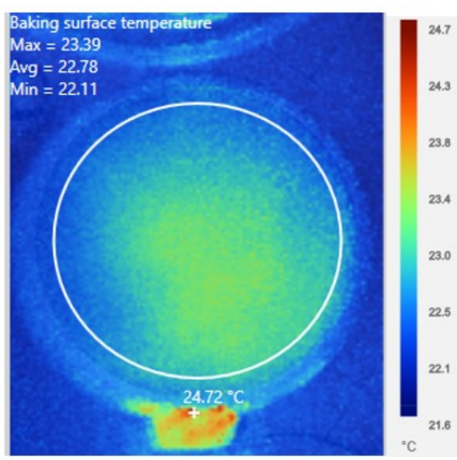
a) Ellipse marker for circular marking of the baking surface



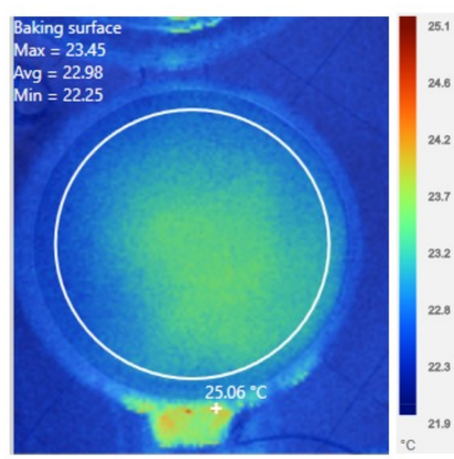
b) IR-fusion blending scale

Figure 4-1. Circular marking and IR fusion blending scale

The result in Figure 4-2, a) and b), indicate both baking mitad surfaces initially or before turning on power have got a temperature variation of about 1 ℃ between the maximum and minimum within the circular marker (baking surface), which could have resulted due to the one side of the mitad bodies facing colder air in the testing room or vice versa. Both mitads' baking surfaces were initially at the same average temperature of 23 ℃ so that the effect of added heat during the heat-up test could be evaluated starting from the same temperature. The mitad body part where the electrical switch is located shows a temperature of 2℃ higher than the average of the baking surface on both mitads due to retained heat of the switch from previous tests.



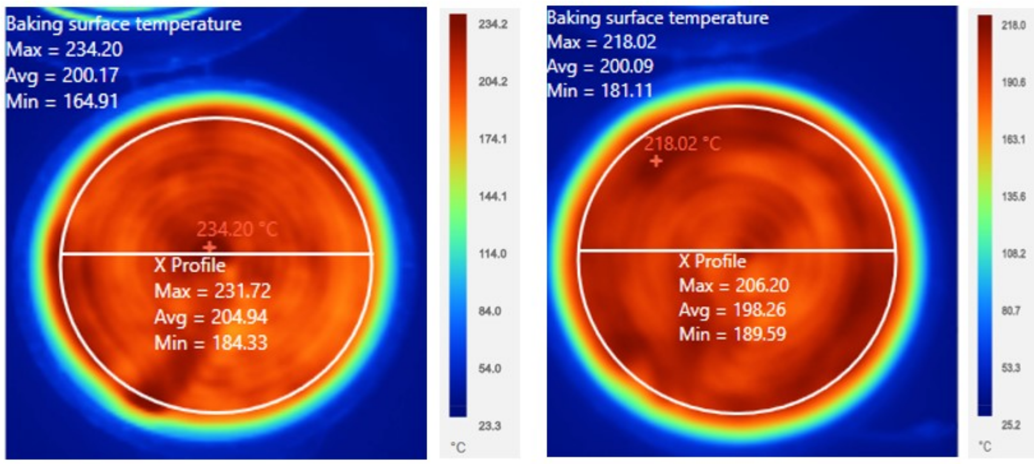
a) Base case mitad IR capture



b) CuWE mitad IR capture

Figure 4-2. IR image capture details for the base case and CuWE mitad at an initial surface temperature of 23 ℃ and time, t= 0.

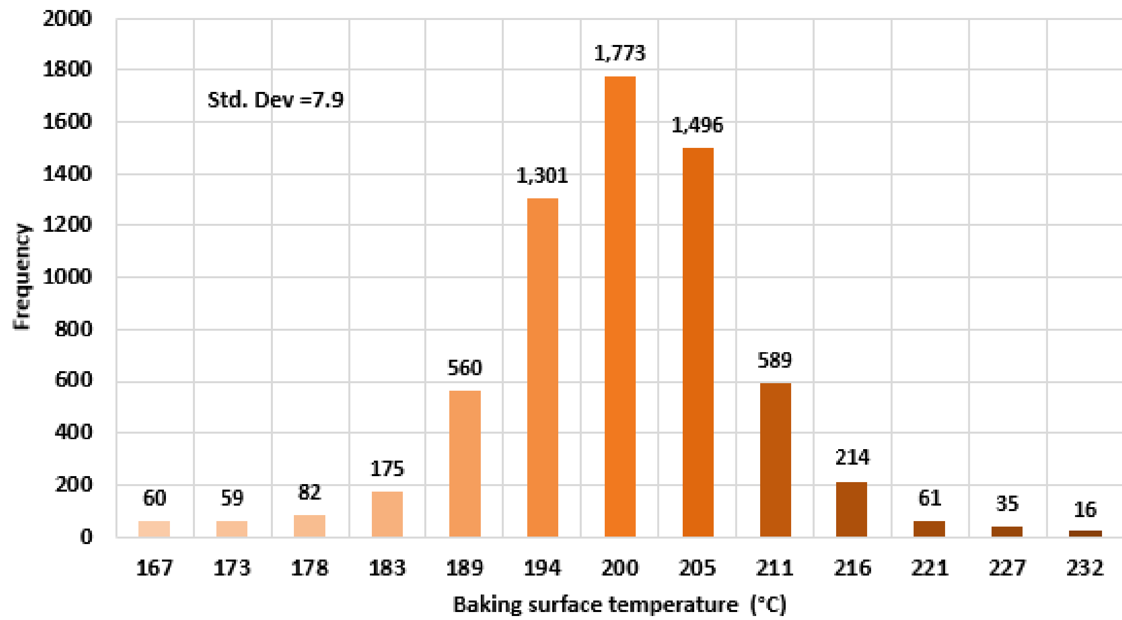
The difference between the maximum and minimum temperatures at the average heat-up temperature of 200 °C resulted to be 64.3°C and 36.9 °C for the base case and CuWE mitad, respectively (Figures 4.3, a, and b).



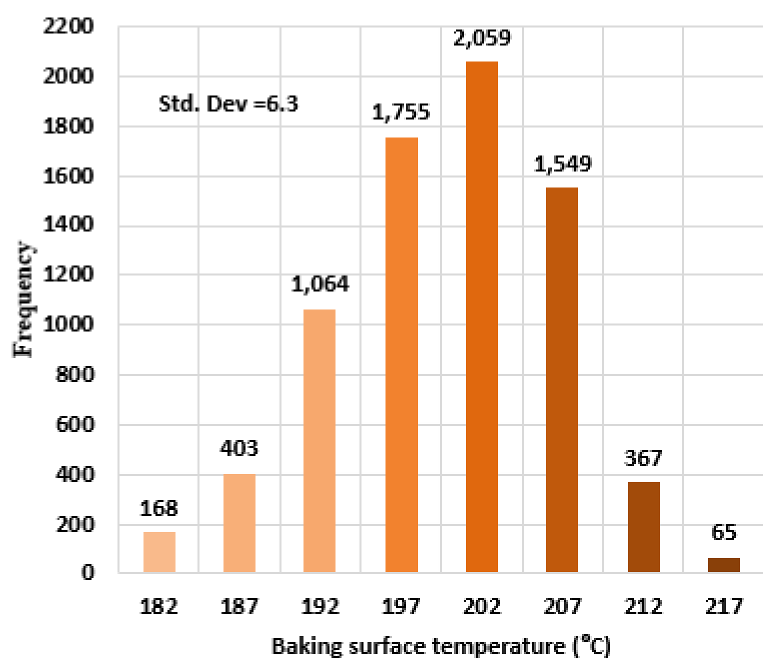
a) Base case mitad IR capture b) CuWE mitad IR capture

Figure 4-3. IR capture temperature distributions of the base case and CuWE mitads at the average baking surface temperature of 200 °C.

The temperature - frequency (occurrence) data within the baking surface (circular markers) in Figures 4.3 a) and b) for the base case and CuWE mitads, as recorded from the thermal image analysis software, were plotted in a histogram in Figures 4.4 a) and b), respectively. Even though the two histograms look similar in shape, the frequency of temperatures close to the average temperature of 200 °C was higher for the CuWE mitad. The range of temperature within the baking surfaces was 218 °C to 182°C for the CuWE mitad, while it was 232 °C to 167°C, for the base case mitad. The result shows standard deviations from the mean of 7.9 and 6.3 for the base case and CuWE mitads, respectively, indicating lower uniform heat distribution for the base case mitad at the baking temperature of 200 °C.



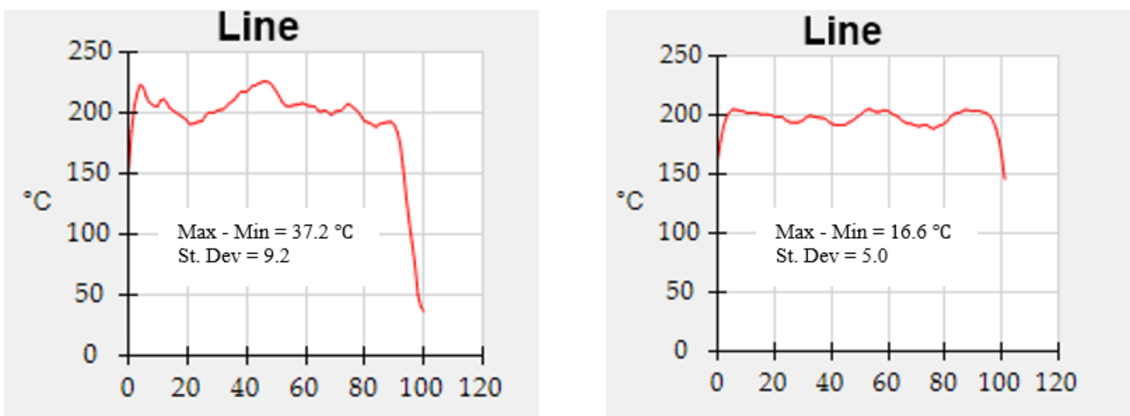
a) Base case mitad



b) CuWE mitad

Figure 4-4. Temperature histogram within the circular maker of the baking surface

The "Line marker" (X profile IR capture temperature distribution) in Figure 4-3, a) and b) for the base case and CuWE electric mitads were plotted in Figure 4-5 a) and b), respectively. The result for the base case (Figure 4-5, a) indicates multiple high and low readings above the average baking temperature, and the temperature falls off at the right side sharply indicating that the right-hand side area of the baking surface exhibits lower temperature as distinguished from the color of the images. The X profile for the CuWE mitad (Figure 4.5, b) has got almost leveled and balanced temperature values at the right- and left-hand sides. The difference between the maximum and minimum temperature at the X profile is doubled for the case of the base case (37.2 °C) mitad as compared to that of the CuWE one (16.6 °C).



a) Base case mitad b) CuWE mitad

Figure 4-5. X profile IR capture temperature distribution

The results in Figures 4-3 to 4-5 above indicate that even though both the base case and CuWE electric mitads are produced with the same specification except for the Cu wire embeddings, the CuWE mitad has shown better heat uniformity at the baking temperature of 200°C, with lesser variation from the mean. This indicates the Cu wire embeddings have improved the heat diffusion in the clay plate and brought the baking surface temperature to be more uniform as compared to that of the base case mitad.

The differences between the maximum and minimum temperature of the baking surface result of 55 °C in the study of improved biogas bakery stoves by [28] fall within the range of the current test results for the base case and CuWE mitads of 64.3°C and 36.9°C, respectively. The CuWE mitad's maximum to minimum difference was less than what could be achieved by the biogas mitad, which gets better uniform baking surface temperature distribution due to the underside heating of the clay plate.

The average of three tests of maximum temperatures on the baking surface captured with the thermal imager every minute during the heat-up period was plotted for the base case and CuWE mitad in Figure 4-6. During the analysis of the thermal images of the baking surface with circular markers, the maximum temperature (Figure 4-3) was the actual data read from the thermal images at a specific point, while the minimum was read by superimposing the circular marker onto the circular baking area manually. At the average baking surface temperature of 200 °C, the maximum temperature for the CuWE mitad was 21.8.02 ℃ while it was 234.02 ℃ for the base case mitad. This shows the base case mitad was to be heated up further to reach the average baking temperature compared to the CuWE mitad, which relatively distorts the heat uniformity and needs additional energy consumption. The actual maximum temperature curve for both mitads fits the trend line of the polynomial equation in the form of $-ax^2 + bx - c$ with more than 0.99 value of R^2, showing a strong correlation. This indicates that the rise in temperature at a specific point on both the base case and CuWE mitad baking surfaces follow a similar pattern during the heat-up time regardless of the thermal conductivity of the clay plate.

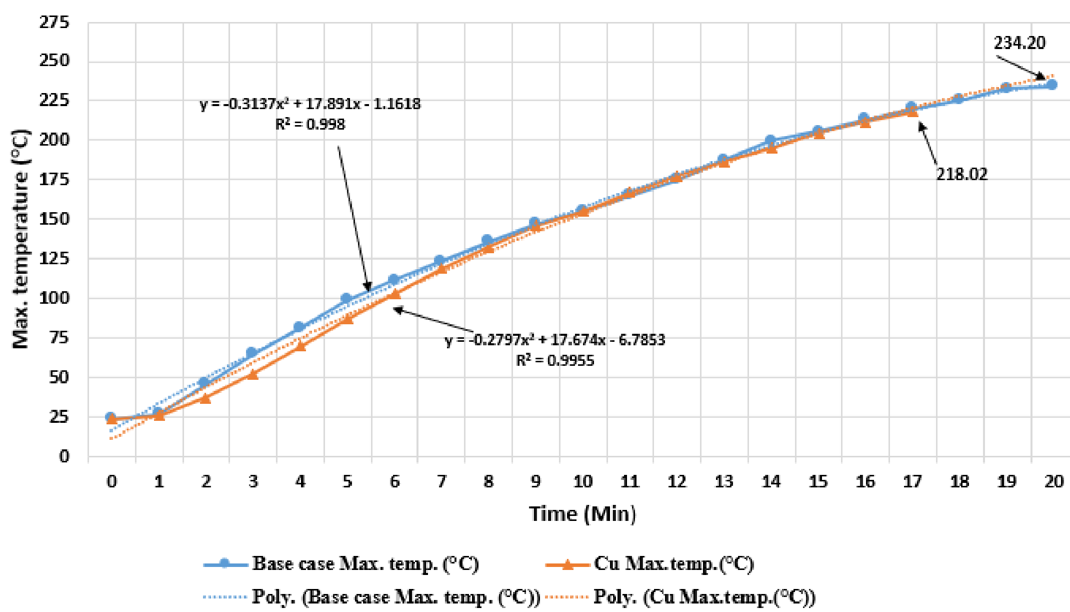


Figure 4-6. Maximum temperatures of the baking surfaces

4.1.2 Time taken for heat up and energy consumption

a) Time taken for heat-up

The results of average time taken for heat-up and energy consumption for the base case and CuWE mitads, for three tests during the heat-up period are shown in Figure 4-7. The comparison shows the CuWE mitad reaches the average baking temperature of 200°C three minutes earlier, indicating a shorter time to heat-up. The heating rates after the 6^{th} minute were 11.1°C/min and 9.7 °C/min for the CuWE and base case mitads, respectively. The CuWE mitad heated up at a faster rate. The study by [25] for 3.5kW conventional electric mitad revealed a heating rate of 15.1°C/min which is higher than that obtained for the base case and the CuWE mitads; these mitads are rated for 2.8 kW and have got lower heating rates.

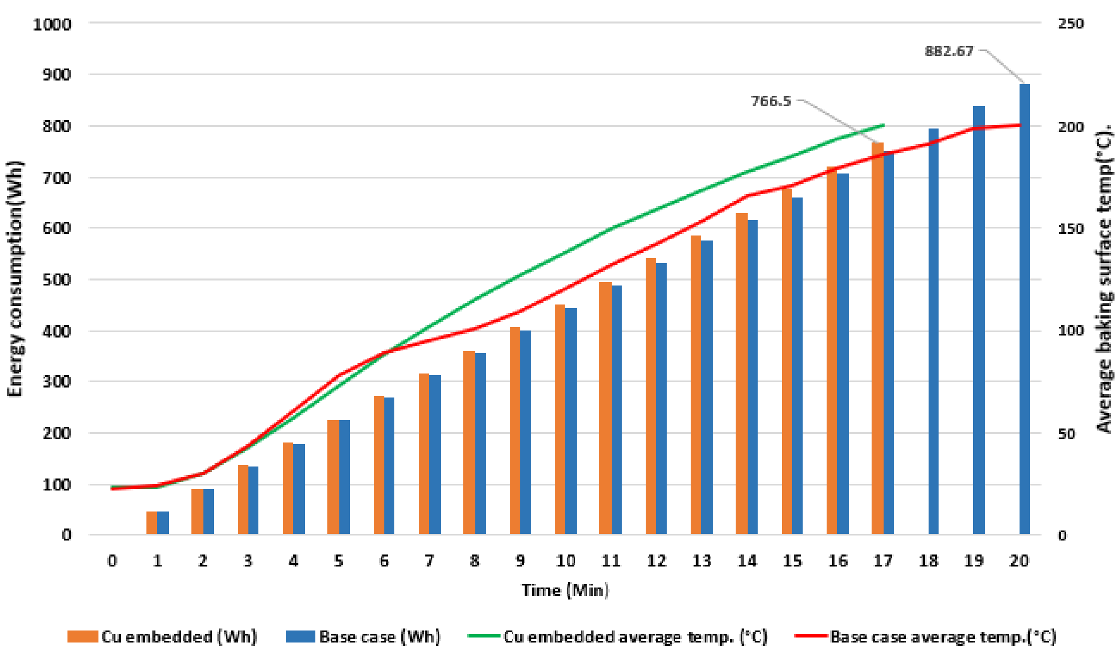


Figure 4-7. Base case and CuWE mitads heat-up period: time taken, average baking surface temperature, and energy consumption comparison.

From the results in figure 4-7, the heat-up time for the 20 mm thick clay plate, 2.8 kW, base case mitad (0.2611W/m.k), and CuWE mitad (0.5763 W/m.k), was 20 minutes (1200 sec) and 17 minutes (1020 sec), respectively. This outcome is consistent with the simulation findings of [24] that a baking pan's heat-up and idle time, which varies based on the thickness, and power input of the baking pan, decreases as thermal conductivity increases. His study indicated also that the heat-up phase for the 20 mm thickness clay plate of conventional electric mitad of 3 kW took 880 seconds (15 min) to reach 200 ℃ from the initial temperature of 20 ℃ deg.

b) Energy consumption

The difference in the energy consumption between the CuWE and the base case mitad to reach the average baking temperature of 200 ℃ was determined to be 116.2 Wh as in Figure 4-7. Even though both electric mitads have the same specifications, the difference in energy consumption resulted due to the difference in the thermal conductivity difference of the CuWE clay plate (0.5763 W/m.k) and the base case clay plate (0.2611W/m.k), and also due to the higher thermal diffusivity of the CuWE as compared to the clay /sand material of the clay plate.

Energy consumption at 200 ℃ was 767 Wh and 883 Wh for the CuWE and base case mitads, respectively. Both mitads have the same power rating of 2.8 kW at an input voltage of 204 Volts. The current study's result is lower than the energy consumption of 1.1kWh determined by [3] for 3.52 kW at an input of 207 V and 17A mitad in 20 minutes. Linear interpolation for the 2.8 kW, 766 Wh consumption to that of the 3.52 kW power mitad gives 970Wh heat up energy consumption.

4.2 Test results during the baking period

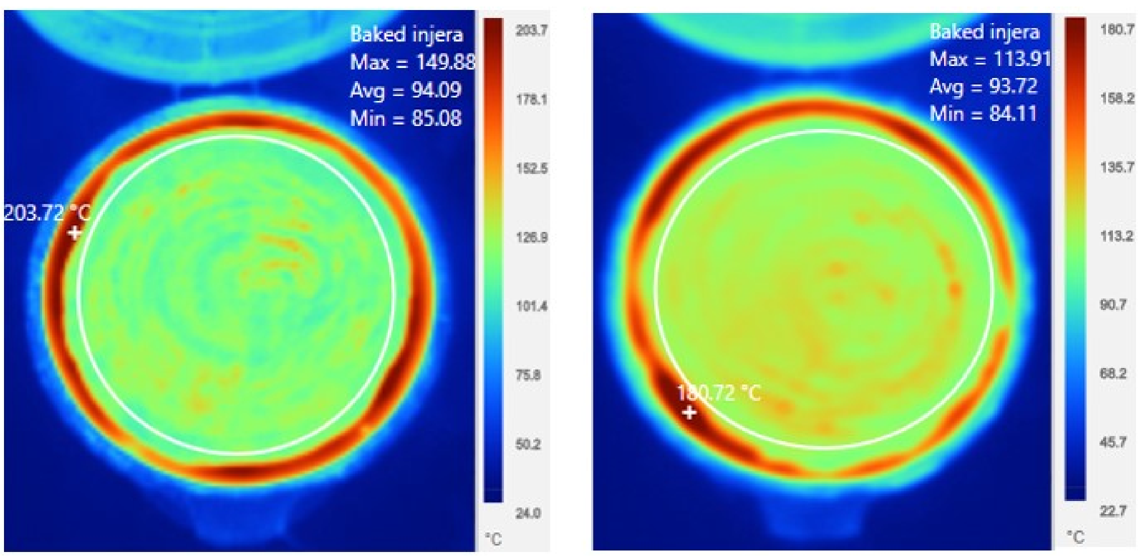
The baking period test results indicate the temperature variations of the baking surface and injera baked, energy consumption, and the performance of the electric mitad during the baking of the 30 injeras and show how both mitads perform under practical baking activities.

4.2.1 Baked injera

a) Thermal images of baked injera.

The average temperatures of injera from the thermal images of baked injera (Figure 4-8) taken immediately at the taking-off injera from the baking surface indicate injera cooking takes place at 93-94 ℃, the temperature at which thermal equilibrium between the baking surface temperature and the baked injera takes place. This concurs with the study of [15] in Addis Ababa that during baking the injera temperature at the interface with the baking pan reaches the local boiling temperature of 92℃ .

The thermal image of baked injera reveals temperature variation of 65 ℃ (Figure 4-8, a) and 30 ℃ (Figure 4-8, b) for the base case and CuWE mitads, respectively. This shows the temperature uniformity of the clay plate affects the temperature of the injeras during baking even though the average baking temperature is almost the same for the two backings. It was observed that a difference above 40 ℃ between maximum and minimum baking surface temperatures resulted in poor injera quality. The color difference on the injeras (Figure 4-8, a, and b) was a result of the different scales of the color palette or color scale on the right-hand side of each figure. In the figures, the edges of the baking clay maintained a higher temperature as it was not cooled down during baking; application of the batter at 25℃ excluded these surfaces.



a) Injera baked on the base case mitad b) Injera injera baked on CuWE mitad

Figure 4-8. Thermal images of samples of injera baked on the base case and CuWE mitads

Referring to the Tef injera specification [39] requirement of uniform injera eye on the upper side, back side smooth, and the injera shall have a soft, spongy texture, and be free from splits, the injeras baked on the base case (Figures 4-9, a, and c) and the CuWE mitad (Figures 4-9, b, and d), both have acceptable qualities. However, the upper side of the injera baked on the CuWE mitad (Figure 4-9 b) resulted in more uniform injera eyes compared to the one baked on the base case mitad (Figure 4-9, a). The improved uniformity of the injera eye for the CuWE mitad resulted from the improved heat uniformity of its clay plate which has got a maximum to a minimum temperature difference of 36.9 ℃ , as discussed under section 4.1.1 above.

.

a) Upper side of baked injera on base case mitad

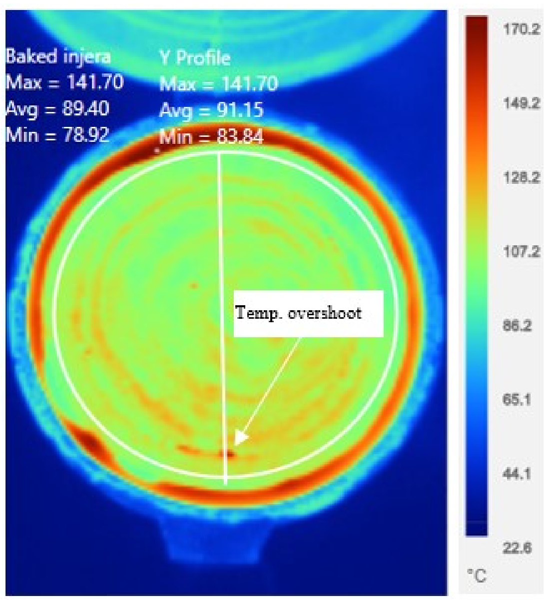
b) Upper side of baked injera on CuWE mitad

c) Back side of baked injera on the base case mitad

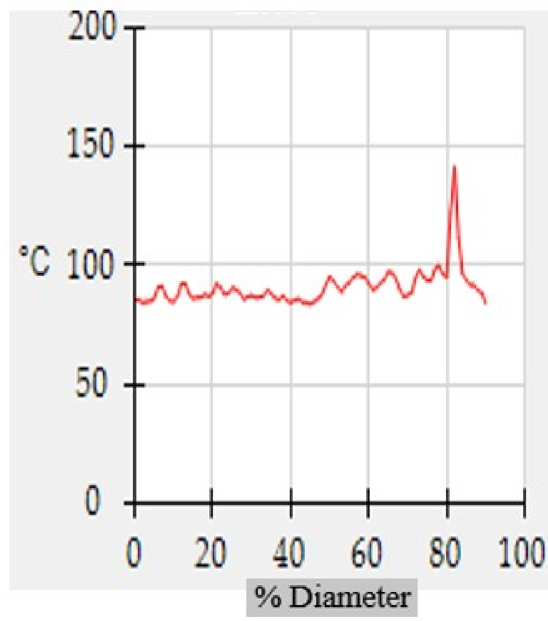
d) Back side of baked injera on the CuWE mitad

Figure 4-9. Pictures of baked injera

During the injera baking process it was noted that as the pouring of the batter is made manually over the baking surface, there was nonuniformity in the placement of the batter. At locations where the batter is not poured and or thinner, the injera temperature was higher or the clay plate temperature is read directly by the thermal imager. At these locations, the clay plate will have higher temperature readings for the next baking as the clay plate was not cooled sufficiently with the batter in the previous baking. Hence, to get an accurate temperature reading on baked injera, a uniform application of batter on the baking surface is required. The typical thermal image and Y- temperature profile (Figure 4-10, a) and b) of injera baked on the base case mitad indicates a temperature overshoot of 51 ℃ above the average, at a point where the temperature of the bare plate is captured. It was also noted that the baking surface temperature uniformity of the mitad is best determined at the end of heat-up time before baking begins.



a) Thermal image of injera baked



b) Y profile temperature distribution

Figure 4-10. Typical thermal image of baked injera with plate temperature captured.

4.2.2 Data recorded and results of the CCT.

The base case and CuWE electric mitads were made from the same specification of clay plate, power rating, tested on equal input power with flour to water proportions of 31.5%

to 68.5%, the same amount of 15.9 kg batter, and 30 injera baking. The data of the electric injera mitads and the averages of three test results of the CCT are summarized in Table 4-1.

Table 4-1. Data of the electric mitads and average values of the results of CCT experiments.

Description	**Electric Mitad**	
	CuWE	**Base case**
Water and flour proportion of batter	68.5%, 31.5%	68.5%, 31.5%
Ambient temperature (℃)	23.5	23.0
Batter initial temperature (℃)	25	25
Baking plate average initial temperature(℃)	23.0	23.0
Average Voltage (V)	204.0	204.0
Average initial current (A)	13.6	13.6
Average power(kW)	2.8	2.8
Clay plate thermal conductivities(W/m.k)	0.2611	0.5763
Mass of flour (kg)	5.5	5.5
Net mass of batter baked (kg)	15.9	15.9
Number of injera baked (Pcs)	30	30
Net mass of injera baked (kg)	11.0	11.0
Heat up time (min)	17	20
Energy consumption for heat- up (Wh)	766.5	882.7
Baking cycle per injera (min/Injera)	3.4	4.0
Total time to bake 15.9 kg batter including heat up time (Min)	119	140
Total Energy consumption for baking including heat-up energy (kWh)	5.5	6.5
Specific energy consumption including heat-up energy (kwh/kg injera)	0.5	0.59
Total useful energy utilized(kWh)	4.03	4.07
Sensible energy in Injera (kWh)	0.99	0.99
Latent energy for vaporization of water in batter (kWh)	3.04	3.08
Energy efficiency (%)	73.3	62.5

The CCT result revealed that, compared to the base case mitad, for the same type and size of batter and number of injera baked, the performance of the CuWE electric mitad was improved:

- Heat-up time reduced by 3 min,
- Heat-up energy consumption was reduced by 116.2 Wh,
- Time to bake one injera was reduced by 0.6 min,

- Total baking time for 30 injeras reduced by 21 minutes
- Total energy consumed was reduced by 1.0 kwh, a 15.4% reduction.
- Specific energy consumption reduced by 0.09 kWh/kg of injera
- Energy efficiency improved by 10.8%.

Furthermore, 75.4% of the useful energy was attributed to latent energy to vaporize the water in the baked batter.

The average specific energy consumption for the base case mitad and the CuWE mitad was 0.50 kWh/kg and 0.59 kWh/kg, respectively, for 30 pieces of injera baking. This result is less than the average specific energy consumption, including heat up energy, of 0.73 kWh/kg for the 3.52kW mitad and 12 injera baking of the single clay plate mitad as determined by [3].

The energy efficiency of the base case mitad of 62.5% was in agreement with the previous cooking simulation study by [77] which revealed, by increasing cooking sessions to bake 30 medium-sized injeras, an efficiency of 62% was attained. The result also concurs with the result of heat transfer analysis by [24] where efficiency for 20cm thick clay plate, 3 kW, and baking of 30 injeras was determined to be 63.11%, and the finite element modeling by [15], [75], which determined, by baking more injera every baking session, one can increase energy efficiency.

The energy efficiency for the CuWE mitad in the current study was improved from 62.5% (Base case) to 73.3% (CuWE), a 10.8 % increase, for thermal conductivity improvement of the clay plate from 0.2611 W/m.K(Base case) to 0.5763 W/m.K (CuWE), 120.7% increase. This is in line with the study by [77] also, in which they determined increasing the thermal conductivity of the clay plate from 0.45 W/m.K to 1.2 W/m.K (an increase of 166%) improved the thermal efficiency of the electric mitad from 53% to 68%, by 15%.

The result in Table 4-1 indicates that latent heat shares 75% or the major portion of the useful energy implying that the energy efficiency is strongly affected by the water content of the batter - the thinner the injera, the higher will be the efficiency. This agrees with the finding of [77] in which they determined efficiency increases when thinner injeras with high water proportion batter are cooked, though the minimum net mass of injera of 310 gm per [39] shall be maintained.

4.2.3 The temperature profile of the baking surface during injera baking

The cyclic baking of injera involved five basic steps. Polishing of the mitad surface took place at the heat up temperature, followed by pouring of batter, waiting for eye formation while the lifting cover was open and lifting cover closed/injera cooked, lifting cover opened and injera taken off, and rape seed burning and gap until next heat-up temperature raeched. The average cyclic baking periods of three baking tests for the base case and CuWE mitads were determined to be as indicated in Table 4-2. The average baking period and the average idle period for the base case mitad were determined to be 153 sec and 87 sec, respectively, whereas for the CuWE mitad it resulted to be 131 sec and 73 sec, respectively.

Table 4-2. Cyclic baking periods of injera on the base case and CuWE mitads

Baking Step	Period	Base case (Sec.)	CuWE mitad (Sec)
Polishing of clay plate at the average baking temperature of 200 ℃	Idle	15	15
Pouring of batter	Baking	15	15
Waiting time for eye formation and lifting cover closing/cooking	Baking	117	95
Lifting cover opened/injera take-off	Baking	21	21
Gap until heat-up to the average baking temperature of 200℃ reached and rape seed burning	Idle	72	58
Total (sec)		240	204
Total(min)		4.0	3.4

The results in Table 4-2, for the base case mitad (baking period of 153 sec and idle period of 87 sec) are comparable with the simulation study basis of [24] discussed under section 2.8, of this study, in which for 20mm thick and 3kw mitad the baking period and idle periods were considered to be 150 sec and 100 sec, respectively. The time for waiting for eye formation and lifting cover closing/cooking and idle period of gap until next heat-up (Table 4-2) varies with the thermal conductivity of the clay plates. These values were 117 and sec 72 sec for the base case mitad respectively, and 95 sec and 58 sec for the CuWE mitad, respectively. The values mentioned are lower for the CuWE mitad due to the thermal conductivity improvement of the clay plate as a result of the Cu wire embeddings.

Figure 4.11 shows the average of three backings of temperature profile for the base case mitad during the heat up period and the baking of the first fifteen injeras, respectively, out of total baking of thirty injeras. After the baking surface reached the heat up temperature of 200 °C, its temperature was dropped due to pouring of the batter having the temperature of 25 °C. The injera was cooked at the water boiling temperature of 92-94°C in Addis Ababa, where thermal equilibrium is reached between the batter and the baking surface. The baking surface temperature risen due to the continued heating of the clay plate by the electrical energy supply and injera was taken-off at an average baking surface temperature of 140 °C. The clay plate was continued to be heated up to the baking temperature of 200 °C. The average cyclic baking for the base case mitad indicated in Table 4-2, was repeated for the fifteen injera with slight variations of the baking surface temperatures. The temperature data for the overall thirty injera baking has got a similar profile.

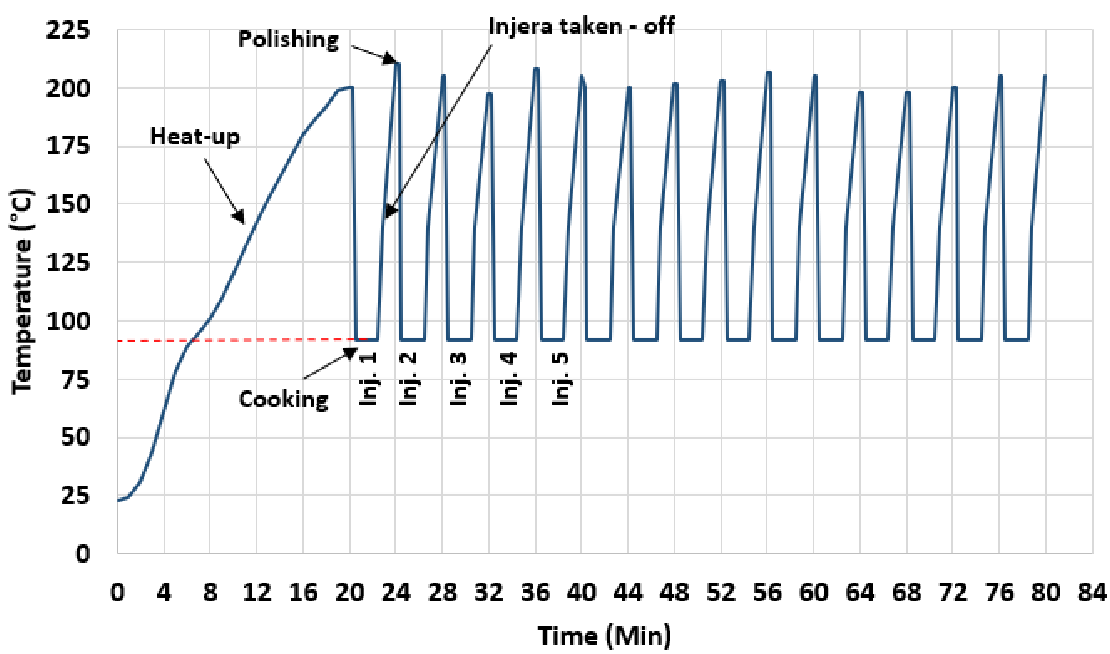


Figure 4-11. Base case mitad baking surface temperature profile for 15 injeras.

The temperature profile for the CuWE mitad was similar to that of the base case except for the heat up time duration, the idle period and the period for the waiting time for eye formation and lifting cover closing/cooking (Table 4-2), which was lower than that for the base case mitad. Figure 4.12, shows the average IR image captures temperature profile for three backings of the CuWE mitad. The difference in the heat up period and cyclic baking of the two types of mitads are reflected in the respective temperature profiles of Figure 4-11 and Figure 4-12 for the base case and CuWE mitads, respectively. It took a total baking time of 80 min and 68 min for the base case mitads and the CuWE mitad to bake the 15 injeras, respectively.

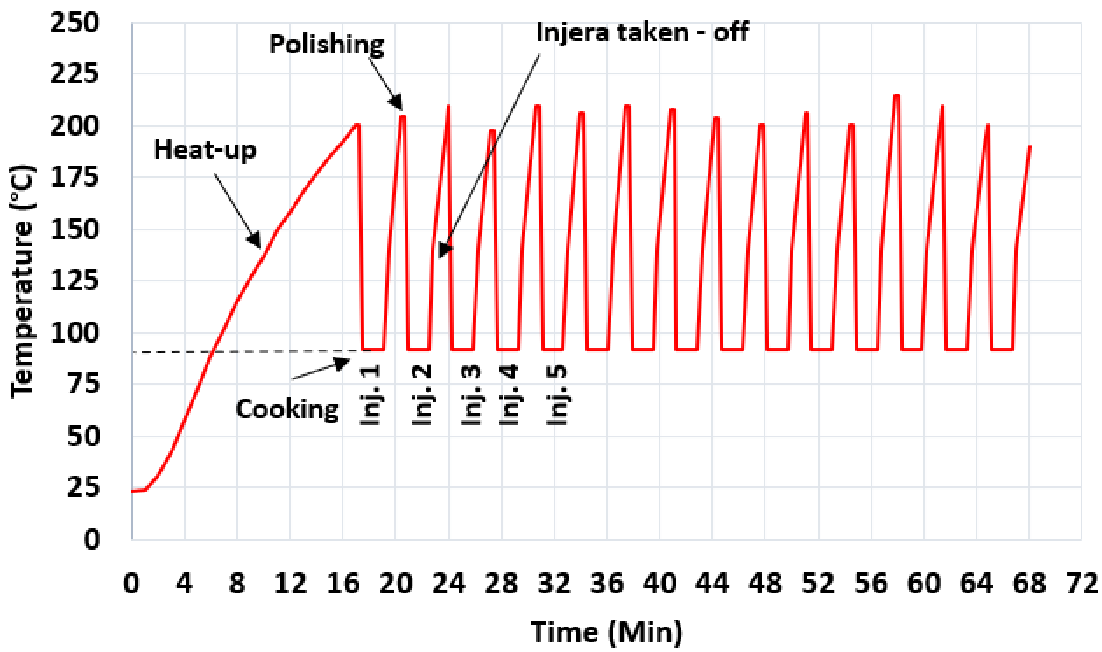


Figure 4-12. CuWE mitad baking surface temperature profile for 15 injeras.

The temperature profiles in Figure 4.11 and Figure 4.12 are similar to Figure 2-12, of the simulation findings of [24], except for the polishing activity which was considered as an idle time activity under this study.

4.3 Economic Analysis

4.3.1 Life cycle cost of the base case and CuWE electric injera mitads

Life Cycle Cost (LLC) analysis is regarded as appropriate among the economic tools frequently used as analytical tools for the evaluation of an investment in energy conservation because it necessitates the addition of the energy costs of the equipment along with the purchase cost, operation, maintenance, and replacement. Based on their LLC, the base case and CuWE electric mitads were assessed. Table 4-3, displays the initial expenditure made to produce the base case electric mitad.

Table 4-3. Cost of base case electric mitad

No	Item	Unit	Quantity	Unit Price (Birr)	Amount (Birr)
1	Mitad body for 58 mm clay plate made of 0.6 mm sheet metal, aluminum lifting cover of 0.6 mm, aluminum ring for clay plate support, and four-legged support stand.	Pc	1	2700.00	2,700.00
2	Clay plate of 58 cm diameter, 2 cm thick, fourteen round grooves	Pc	1	450.00	450.00
3	Resistor, 0.8mm diameter, 30 ohm	Pc	2	85.00	170.00
4	Connecting lead	Lm	0.5	40.00	20.00
5	Single ceramic connector, 16 A rating	Pc	2	30.00	60.00
6	Double pole on-off switch of 16 Amper rating, made of a ceramic base, with fusible link and indicator light.	Pc	1	270.00	270.00
7	PVC insulated PVC sheathed 3x2.5 sq cable	Lm	1.5	110.00	165.00
8	Plug of 16 A rating with earthing contact	Pc	1	100.00	100.00
9	Bottom insulation material of wood ash	LS	LS	50.00	50.00
10	Paint	LS	LS	200.00	200.00
	Subtotal material cost				4,185.00
	Labor, profit, and overhead cost @ 30%				1,255.50
	Total cost				5,440.50

The cost of producing the CuWE electric mitad includes the cost of additional grooves for Cu wires as well as the cost of 20 meters of 1x4 sq. mm wire at 300 Birr on top of the total cost of the base case mitad, totaling 5,837 Birr.

Table 4-4, shows the annual cost of energy consumption for both the base case and CuWE electric injera mitads, assuming 30 injeras baked 10 times per month for a typical family of five and an electricity rate of 2.24 birr per kWh (EEU tariff for less than 400 kWh consumption per month).

Table 4-4. Annual energy consumption of the base case and CuWE electric injera mitads.

Description	Base case mitad	CuWE mitad
Voltage (V)	204.0	204.0
Resistance (Ohm)	15.0	15.00
Power(kW)	2.8	2.8
Duration of a single baking session (hr)	2.33	1.98
Energy consumption per baking session(kWh)	6.5	5.5
Annual baking session (10 times a month x12 months a year)	120	120
Annual energy consumption(kWh)	782.00	665.0
Cost of energy (Birr/kWh)	2.24	2.24
Annual cost of energy consumption (Birr)	1,752.58	1,489.15

From the experience of electric injera mitad producers, the life of an electric injera mitad ranges from 5 to 10 years, depending on the application: whether it is for business purposes or households; the type of bottom insulation, including whether it corrodes the metallic body or not; the location of the mitad's installation: wet areas, which reduce appliance life due to corrosion; and water ingress from the lifting cover to the insulation. Clay plate life depends on the thickness, methods of grooving, application, and handling of the baker. A lifetime time of 10 years for the body, considering the use of wood ash bottom insulation, and 5 years for the clay plate were taken, respectively.

The LLC of the base case and CuWE electric injera mitads was computed assuming a lifetime of 10 years, a replacement cost of the clay plate at the end of the 5th year, a maintenance cost of 2% annually, and a residual value of 5% at the end of the useful life of the appliances. Table 4-5 shows the LCC for both the electric mitads. The present value of the costs was computed with a discount rate of 10.5%, [84] and using the present value formulas:

The present value for the operating cost and maintenance cost was given by equation 4-1,

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad ,(4\text{-}1)$$

The present value for the replacement cost and residual cost was given by equation 4-2,

$$P = F\frac{1}{(1+i)^n} \ , \quad (4\text{-}2)$$

Where,

P = Present value
A = Series of payments over the 10 years lifetime
F = Single future amount
n = Discount rate

Table 4-5. Life cycle cost of the base case and CuWE electric injera mitads

Cost item	Base case mitad (Birr)	CuWE mitad (Birr)
Initial cost (Birr)	5,440.50	5,837.00
Operating cost	10,812.84	9,187.57
Maintenance cost	671.32	720.25
Replacement cost	890.18	890.18
Residual value at 5% of the initial cost	(95.80)	(102.79)
Total LLC	17,719.04	16,532.21

Considering the cost comparison of the two electric mitads, the CuWE mitad has a lower LLC.

4.3.2 Energy saving of the CuWE mitad per household

Compared to the base case mitad the CuWE mitad would have an energy saving of 117 kwh/yr (Table 4-4), a 15 % saving. The energy saving amounts to a cost saving of 117 kwh/yr x 2.24 Birr/kwh = Birr 262.00/yr, at the current rate of electricity. The cost of energy saved was low compared to the purchase cost of the CuWE mitad of Birr 5,837.00 (Section 4.3.1) as the current rate of electricity is low.

According to the study conducted by [3], the conventional electric injera mitad rated at 3.52 kW at 207 V power source, 55 to 58 cm average diameter has heat-up time energy consumption of 1.42 kWh and its specific energy consumption, without heat-up energy, for baking 6 kg of injera was determined to be 0.49 kwh/kg of injera. Interpolating this result for 11.0 kg of injera baking would give a total energy consumption of 1.42 kwh + (0.49 kwh/kg x 11kg) = 6.81kwh. Assuming the flour-to-water proportion of the batter, the electric mitad manufacturing, and the experience of the injera baker are similar to that under the current study, the energy consumption of the conventional mitad was compared with that of the CuWE mitad. Thus, if the CuWE mitad, which consumed 5.5 kwh for baking 11.0 kg of injera (Table 4-1), replaces the above mentioned conventional mitad, there will be an energy saving of 19.2%.

For typical baking of 30 injeras (11.0 kg) per session, baked 10 times per month for a family of five per household, the energy saving of the CuWE mitad per year compared to the conventional electric mitad, would be: (6.81-5.5) kwh/baking session x 10 baking /month x12 months = 157.2 kWh/yr, which would be equivalent to a saving of Birr 352.00/yr, at the current electricity tariff of 2.24 birr per kWh.

4.3.3 Avoided costs in implementing the CuWE electric injera mitad

[85] states that when assessing energy efficiency improvement programs, there are two basic categories of avoided costs: capacity-related avoided costs and energy-related avoided costs. Costs associated with energy include losses and market pricing for energy. Infrastructure investments, including power plants, transmission lines, and distribution lines, are included in capacity-related avoided costs. Hence, for the case of electric injera mitads in this study, the avoided cost considered the cost of energy and power demand was avoided as a result of implementing the CuWE electric mitad in the country.

a. Avoided energy cost by the CuWE electric mitad regarding the base case electric mitad.

Considering the number of electric injera mitads in the country in 2021/22 of 1.1 million [6], the annual cost of energy savings for the CuWE electric mitad with reference to that of the base case was calculated from Table 4-4, to be :

(782.00 – 665.0) kWh/year x 2.24 Birr/kWh x 1.1 million mitads = 288.3 million Birr/year, or if the energy is exported = (782.00 – 665.0) kWh/year x USD 0.07/kWh [52] x 1.1 million mitads = 9.01 million USD /year.

b. Avoided energy cost by the CuWE electric mitad replacing the conventional electric mitad.

The avoided cost of replacing the conventional mitad by the CuWE mitad was calculated to be : Birr 352.00/yr (Section 4.32) x 1.1 million mitads = 387.2 million Birr/year, or if exported = 157.2 kWh/year x USD 0.07/kWh [52] x 1.1 million mitads = 12.1 million USD /year.

c. Avoided power demand by the CuWE electric mitad replacing the conventional electric mitad.

At a nominal voltage of 220 V and resistance of 12 ohms, the typical electric injera mitad is rated for 4.0 kW [6]; at the test voltage level of 204.0 V, the power rating would be 3.7 kW. Considering the power loss data of 22.6% of the Ethiopian Power System Expansion Master Plan Study [86] for the year 2022, and assuming the CuWE electric injera mitad replaces the conventional electric injera mitad, the avoided power demand based on the power rating of 2.8 kW of the CuWE mitad (Table 4.4) would be:

Power demand: ((3.7-2.8) kW x 1.1 million mitads) / (1- 0.226) = 1.28 MW.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study aimed to experimentally investigate electric injera mitad using copper wire embeddings in the clay plate for performance improvement. In the experimental investigations and analysis made, the CuWE electric injera mitad was developed, the effect of Cu wire embedding on the performance of electric mitad was determined, and its performance was compared with the base case electric injera mitad in terms of thermal efficiency, time to bake, energy consumption, and baking surface temperature uniformity. The CuWE electric mitad was successfully developed and proved to have better performance compared to the base case electric mitad. The LLC for the CuWE mitad was lower than that of the base case mitad. The copper wire embeddings can be carried out at the level of local producers without requiring additional machines or manufacturing processes.

The study proceeded by preparing clay plate a sample without copper wire (Base case) and samples with an increasing number of CuWE, for thermal conductivity tests. The base case and CuWE electric mitads' were produced from clay plates having the same characteristics as the respective sample clay plates. The CCT was conducted on both the electric mitads during the heat-up and baking periods to evaluate their performance. A thermal imager was used to accurately determine the baking surface temperatures. The heat-up tests better showed the performance of the mitads in that it was done without the intervention of the injera baking activities, which depends at large on the experience of the baker.

The energy efficiency improvement and savings resulting from copper wire embedding in the clay plate of electric injera mitad would have a significant reduction on the country's energy demand considering the existing huge number of the conventional electric injera mitads and the continuous demand for the appliance, injera being the main staple food in Ethiopia. The consumer will have better economic welfare due to reduced energy bills and baking time. The baking surface heat uniformity improvement enhances the satisfaction of consumers and the quality of injera baked. Application of the research findings in the production mitad would have more benefits as the conventional mitads are rated at higher power compared to the base case mitad in this study.

5.2 Recommendation

To develop performance enhanced electric injera mitad with Cu or other metallic wire materials, future research works may consider the following:

a) Simulation study on the effect of Cu wire or galvanized iron wire embeddings on the thermal conductivity and diffusivity of the clay plates of electric injera mitads.
b) The use of thinner coil diameter of electric heating element and accommodation of more copper or metallic wires in the clay plate to achieve higher thermal conductivity.
c) The use of automatic batter dispenser to get uniform batter distribution during CCT test and,
d) Employing fixed thermal imager over the surface of the mitads to better capture the thermal images of injera and baking surface temperatures.

6. REFERENCES

[1] EEA, Energy Efficiency Strategy for Industries, Buildings and Appliances. Ethiopian Energy Authority , Addis Ababa., no. January. 2019.

[2] K. W. Liyew, N. G. Habtu, Y. Louvet, D. D. Guta, and U. Jordan, "Technical design, costs, and greenhouse gas emissions of solar Injera baking stoves," Renew. Sustain. Energy Rev., vol. 149, no. February, p. 111392, 2021, doi: 10.1016/j.rser.2021.111392.

[3] M. H. Hailu, M. B. Kahsay, A. H. Tesfay, and O. I. Dawud, "Energy consumption performance analysis of electrical mitad at Mekelle City," Momona Ethiop. J. Sci., vol. 9, no. 1, p. 43, 2017, doi: 10.4314/mejs.v9i1.4.

[4] A. T. Tiruneh, G. Bultosa, T. A. Zewdie, and A. A. Abera, "Effect of mango and carrot fortification on proximate composition, β-carotene and sensory properties of teff injera," Cogent Food Agric., vol. 6, no. 1, 2020, doi: 10.1080/23311932.2020.1844513.

[5] T. Girma, G. Bultosa, and N. Bussa, "Effect of grain tef [Eragrostis tef (Zucc .) Trotter] flour substitution with flaxseed on quality and functionality of injera," Int. J. Food Sci. Technol., vol. 48, pp. 350–356, 2013, doi: 10.1111/j.1365-2621.2012.03194.x.

[6] Danas, "Project document on Electric Injera Mitad Energy Efficiency Standards and Labeling. Prepared for :Ethiopian Energy Authority, Addis Ababa.," 2015.

[7] F. Mamuye Bayu, "Cost reduction and forest preservation potential of advanced stoves and challenges of their adoption in higher education: the case of werabe university, Ethiopia," Heliyon, vol. 6, no. 8, p. e04693, 2020, doi: 10.1016/j.heliyon.2020.e04693.

[8] K. D. Adem and D. A. Ambie, "A review of injera baking technologies in Ethiopia: Challenges and gaps," Energy Sustain. Dev., vol. 41, pp. 69–80, 2017, doi: 10.1016/j.esd.2017.08.003.

[9] Z. Gebreegziabher, A. D. Beyene, R. Bluffstone, P. Martinsson, A. Mekonnen, and M. A. Toman, "Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia," Resour. Energy Econ., vol. 52, pp. 173–185, 2018, doi: 10.1016/j.reseneeco.2018.01.006.

[10] K. D. Adem, D. A. Ambie, M. P. Arnavat, U. B. Henriksen, J. Ahrenfeldt, and T. P. Thomsen, "First injera baking biomass gasifier stove to reduce indoor air pollution, and fuel use," AIMS Energy, vol. 7, no. 2, pp. 227–245, 2019, doi: 10.3934/ENERGY.2019.2.227.

[11] D. T. Bantelay, "Design, Manufacturing and Performance Evaluation of House

Hold Gasifier Stove: A Case Study of Ethiopia," Am. J. Energy Eng., vol. 2, no. 4, pp. 96–102, 2014, doi: 10.11648/j.ajee.20140204.12.

[12] D. Kebede and A. Kiflu, "Design of Biogas Stove for Injera Baking Application," Int. J. Nov. Res. Eng. Sci., vol. 1, no. 1, pp. 6–21, 2014.

[13] A. Gallagher, "A solar fryer," Sol. Energy, vol. 85, no. 3, pp. 496–505, 2011, doi: 10.1016/j.solener.2010.12.018.

[14] A. A. Hassen, D. A. Amibe, and O. J. Nydal, "Performance investigation of solar powered injera baking oven for indoor cooking," 30th ISES Bienn. Sol. World Congr. 2011, SWC 2011, vol. 6, pp. 1–11, 2011, doi: 10.18086/swc.2011.30.08.

[15] A. A. Hassen and D. A. Amibe, "Finite element modeling of solar powered injera baking oven for indoor cooking," World Renew. Energy Forum, WREF 2012, Incl. World Renew. Energy Congr. XII Color. Renew. Energy Soc. Annu. Conf., vol. 1, pp. 349–356, 2012.

[16] A. H. Tesfay, M. B. Kahsay, and O. J. Nydal, "Design and development of solar thermal Injera baking: Steam based direct baking," in Energy Procedia, 2014, vol. 57, doi: 10.1016/j.egypro.2014.10.330.

[17] A. A. Hassen, S. B. Kebede, and N. M. Wihib, "Design and Manufacturing of Thermal Energy Based Injera Baking Glass Pan," Energy Procedia, vol. 93, 2016, doi: 10.1016/j.egypro.2016.07.164.

[18] M. H. Hailu, O. J. Nydal, M. B. Kahsay, and A. H. Tesfay, "A direct solar fryer for injera baking application," ISES Sol. World Congr. 2017 - IEA SHC Int. Conf. Sol. Heat. Cool. Build. Ind. 2017, Proc., pp. 1475–1485, 2017, doi: 10.18086/swc.2017.24.02.

[19] F. Fanta, "Improving Performance of Electromagnetic Induction Injera Mitad," Int. Res. J. Eng. Technol., vol. 07, no. 04, pp. 1–5, 2020.

[20] R. Jones, J. C. Diehl, L. Simons, and M. Verwaal, "The Development of an Energy Efficient Electric Mitad for Baking Injeras in Ethiopia," in Proceedings of the 25th Domestic Use of Energy Conference, 2017, pp. 1–9, doi: 10.23919/DUE.2017.7931827.

[21] Hailu and Hassen, "Abdul and Hailu Experimental investigation and loss quantification in Injera baking process," Energy Manag. Res. J., vol. Vol. 1, no. 1, pp. 1–7, 2018.

[22] M. H. Kebede, S. D. Gont, and M. Hailu Kebede, "Home Appliances Efficiency Improvements for Energy Conservation in Debre Berhan City; Ethiopia," Am. J. Energy Eng., vol. 6, no. 1, p. 14, 2018, doi: 10.11648/j.ajee.20180602.11.

[23] R. Van Buskirk, H. Teclai, and E. Negusse, "The Effect of Clay and Iron Cooking

Plates on Mogogo Efficiency and Energy Use: Experimental Results.," Eritrean Stud. Rev., vol. 3, no. 1, pp. 105–126, 1999.

[24] G. Getenet, "Heat Transfer analysis during the process of Injera baking by finite element method, MSc Thesis, Addis Ababa University, Addis Ababa," 2011.

[25] Awash Tekle, "Experimental investigation on performance characteristics and efficiency of electric mitad, (MSc Thesis), Addis Ababa University, Addis Ababa.," 2011.

[26] G. Ambaw, "Performance analysis and reliability testing of a ceramic bake ware for Injera baking 2015(Msc Thesis), Addis Ababa University, Addis Ababa.," 2015.

[27] A. K. Alula Gebresas, Asmamaw Tegegne, Hadush Berhe, "Improving energy consumption and durability of the clay bakware (Mitad)," Int. J. Softw. Hardw. Res. Eng., vol. 1, no. 3, pp. 7–14, 2013.

[28] D. T. Nega, B. Mulugeta, and S. W. Demissie, "Improved biogas 'Injera' bakery stove design, assemble and its baking pan floor temperature distribution test," Energy Sustain. Dev., vol. 61, 2021, doi: 10.1016/j.esd.2020.12.009.

[29] SNV, "Review of Policies and Strategies Related to the Clean Cooking Sector in Ethiopia Final Report Strengthening the Enabling Environment for Clean Cooking Project," no. May, 2018.

[30] S. Neela and S. W. Fanta, "Injera (An Ethnic , Traditional Staple Food of Ethiopia): A review on Traditional Practice to Scientific Developments," J. Ethn. Foods, vol. 7, p. 32, 2020.

[31] S. Yetneberk, L. W. Rooney, and J. R. N. Taylor, "Improving the quality of sorghum injera by decortication and compositing with tef," J. Sci. Food Agric., vol. 85, no. 8, pp. 1252–1258, 2005, doi: 10.1002/jsfa.2103.

[32] S. Yetneberk, H. L. De Kock, L. W. Rooney, and J. R. N. Taylor, "Effects of Sorghum Cultivar on Injera Quality," Cereal Chem., vol. 81, no. 3, pp. 314–321, 2004, doi: 10.1094/CCHEM.2004.81.3.314.

[33] K. Baye, "Teff : nutrient composition and health benefits,Ethiopia Strategy suport Program, Addis Ababa.," 2014.

[34] K. Baye, C. Mouquet-Rivier, C. Icard-Vernière, I. Rochette, and J. P. Guyot, "Influence of flour blend composition on fermentation kinetics and phytate hydrolysis of sourdough used to make injera," Food Chem., vol. 138, no. 1, pp. 430–436, 2013, doi: 10.1016/j.foodchem.2012.10.075.

[35] A. H. Tesfay, M. B. Kahsay, and O. J. Nydal, "Solar powered heat storage for Injera baking in Ethiopia," Elsevier B.V., 2014. doi: 10.1016/j.egypro.2014.10.152.

[36] A. T. Bicks, "Investigation of Biogas Energy Yield from Local Food Waste and Integration of Biogas Digester and Baking Stove for Injera Preparation : A Case Study in the University of Gondar Student Cafeteria," Hindawi J. Energy, vol. 2020, 2020, doi: 10.1155/2020/8892279 R.

[37] B. Kebede, "Food People Eat : the Energy Economics of Injera and Wot," Ethiop. Econ. Struct. Probl. Policy Issues, pp. 211–219, 1992.

[38] A. Zegeye, "Acceptability of injera with stewed chicken," Food Qual. Prefer., vol. 8, no. 4, 1997, doi: 10.1016/S0950-3293(96)00055-9.

[39] ES 3788, "Ethiopian Standard ES3788 : 2013, Teff injera Specification, Ethiopian Standards Agency.," 2013.

[40] A. Gulilat, "Stove Testing Result, A Report on Controlled Cooking Test of Gonzie Stove, GIZ Energy Coordination Office (GIZ ECO), Addis Ababa, Ethiopia," 2014.

[41] A. Gulilat, W. Girma, T. Wedajo, and Y. Tessema, "Stove testing results, A Report on Controlled Cooking Test Results Performed on 'Mirt with integrated chimney' and 'Institutional Mirt' Stoves, Addis Ababa .," 2011.

[42] A. AlNouss, G. McKay, and T. Al-Ansari, "Superstructure Optimization for the Production of Fuels, Fertilizers and Power using Biomass Gasification," in Computer Aided Chemical Engineering, 2019, vol. 46, pp. 301–306, doi: 10.1016/B978-0-12-818634-3.50051-5.

[43] Gebreegziabher Zenebe., Household fuel consumption and resource use in rural-urban Ethiopia. 2007.

[44] A. Balasubramanian, "Materials Science-Ceramics (Report) , University of Mysore, India," 2017.

[45] M. S. Tite, "Ceramic production, provenance and use - A review," Archaeometry, vol. 50, no. 2, pp. 216–231, 2008, doi: 10.1111/j.1475-4754.2008.00391.x.

[46] M. R. Anseau, F. Cambier, and A. Leriche, "Vitrification," Concise Encyclopedia of Advanced Ceramic Materials. pp. 506–509, 1991, doi: 10.1016/B978-0-08-034720-2.50140-4.

[47] D. P. D. Theodore L. Bergman, Adrienne S. Lavinne, Frank P. Incorpera, Fundamentals of Heat and Mass Transfer(7th ed.,), no. 1. 2011.

[48] AZO materials, "Silicon di oxide," 2020. https://www.azom.com/properties.aspx?ArticleID=1114 (accessed Aug. 20, 2020).

[49] ES 3978:2017, Ethiopian Standard ES 3978:2017: Electrical Materials and Conductors- Specification for Metallic resistance materials for electrical purpose,

Ethiopian Standards Agency. 2017, p. 22.

[50] ES 6084:2017, Ethiopian standard ES 6084:2017 : Technical and Performance Requirements For House Hold Single Plate Resistor Based Electric Injera Mitad / Stove, Ethiopian Standards Agency. 2017.

[51] EEA, Minimum Energy Performance Standard (MEPS) and Labeling for Clay plate resistor based electric Injera Mitad. Ethiopian Energy Authority , Addis Ababa. 2020, p. 6.

[52] MoWIE, National Electrification Program 2.0, Integrated planning for Universal Access, Lighting to all, Ministry of Watter Irrigation and Electricity,Ethiopia, no. October. 2019, p. 49.

[53] Fantu Guta;Abebe Damte;Tadele Ferede, "The Residential Demand for Electricity in Ethiopia, Environment for Development Centers, Discussion paper," 2015.

[54] Danas, "Induction Motor Energy Efficiency Assessment and MEPS Proposition for Ethiopian Market. Prepared for :Ethiopian Energy Authority, Addis Ababa," 2021.

[55] M. A. H. Mondal, E. Bryan, C. Ringler, D. Mekonnen, and M. Rosegrant, "Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions," Energy, vol. 149, pp. 161–172, Apr. 2018, doi: 10.1016/j.energy.2018.02.067.

[56] EEP, "Construction of the Koysha hydroelectric dam, Genale Dawa III Hydro power project. Ethiopian Electric Power. Retrieved from www.eep.com.et, on 17 Oct 2020," 2020. .

[57] Y. A. Cengel, Heat transfer a practical approach(2nd ed.,) McGraw-Hill, London, 2003. 2003.

[58] R. M. M. Frank Kreith and M. S. Bohn, Principles of Heat Transfer, 7th edn, vol. 55, no. 5. 2011.

[59] N. S. Müller, A. Hein, V. Kilikoglou, and P. M. Day, "Bronze Age cooking pots: Thermal properties and cooking methods," Préhistoires méditerranéennes, no. 4. 2013, doi: 10.4000/pm.737.

[60] Ayugi Gertrude, "Thermal properties of selected materials for thermal insulation available in Uganda, (MSc thesis), Makerere univesity, Uganda.," 2011.

[61] I. Woodfuel, "Testing of Woodfuel Stoves," 2021. https://energypedia.info/wiki/GIZ_HERA_Cooking_Energy_Compendium (accessed Jan. 25, 2020).

[62] R. Bailis, "Controlled Cooking Test (CCT) Version 2(Report)," Househ. Energy Heal. Program. Shell Found., no. August, pp. 1–2, 2004.

[63] R. R. Pande, S. K. Sharma, and V. R. Kalamkar, "Experimental and numerical analyses for designing two-pot biomass cookstove," J. Brazilian Soc. Mech. Sci. Eng., vol. 41, no. 8, 2019, doi: 10.1007/s40430-019-1839-z.

[64] K. Weinbaum, "Standard Stove Performance Testing, Darfur stoves project, Environmental Science, Policy & Management, UC Berkeley," 2015.

[65] Hassan Rajabu and Arfaxad Ndilanha, "Improved Cook Stoves Assessment and Testing, University of Dar es Salaam,Tanzania," 2013.

[66] C. C. Alliance, "Controlled Cooking Test (https://www.cleancookingalliance.org/search.html?q=CCT, accessed 10 Jan 2021)," 2021. .

[67] H. S. Geller, "Fuel efficiency and performance of traditional and innovative cookstoves," Proc. Indian Acad. Sci. Sect. C Eng. Sci., vol. 5, no. 4, pp. 373–393, 1982, doi: 10.1007/BF02904587.

[68] T. Yayeh, A. Guadie, and S. Gatew, "Adoption and fuel use efficiency of mirt stove in Dilla district, southern Ethiopia," Clean. Eng. Technol., vol. 4, p. 100207, 2021, doi: 10.1016/j.clet.2021.100207.

[69] D. A. Wendy, "Influence of processing parameters on eye size and elasticity of tef based injera, MSc thesis," Pennsylvania State Univ. ,USA, 2014.

[70] B. Gebrehiwot and Gebrekidan, "International Symposium on Sorghum Grain Quality," in Sorgum Injera preparations and quality parameters, Icrisat, 1981, pp. 55–66.

[71] A. Zegeye, "Acceptability of injera with stewed chicken," Food Qual. Prefer., vol. 8, no. 4, pp. 293–295, 1997, doi: 10.1016/S0950-3293(96)00055-9.

[72] H. Cherinet, "Composite flour development for injera Haregewoin Cherinet," Ethiop. J. Heal. Dev., vol. 7, no. 2, pp. 71–77, 1993.

[73] "Properties of Copper," 2022. https://matmatch.com/learn/material/copper-properties (accessed Aug. 04, 2022).

[74] A. Dingeto, "Design numerical investigation of waste heat recovery system coupled to Electric Injera baking pans(Msc Thesis)," 2018.

[75] A. Ayalew, "Heat transfer analysis of Injera baking pan by Finite element method, National Conference in Mechanical Engineering Research and Postgraduate Students (1st NCMER 2010) 26-27 MAY 2010, FKM Conference Hall, UMP, Kuantan, Pahang, Malaysia; pp. 125-134," 2010.

[76] D. Sood, "Injera Electric Baking : Energy Use Impacts in Addis Ababa (World bank funded study), Addis Ababa, Ethiopia.," 2010.

[77] E. Negusse and R. Van Buskirk, “Electric enjera cooker (mogogo) efficiency,” 1996.

[78] Z. Ashagre and D. Abate, “Improvement of injera shelf life through the use of chemical preservatives.,” African J. Food, Agric. Nutr. Dev., vol. 12, no. 5, 2012, doi: 10.18697/ajfand.53.10910.

[79] QTM 500, “Thermal conductivity meter_Operation_Manual,” 2021. https://cdn2.hubspot.net/hubfs/105273/Manuals/QTM-500_Operation_Manual_Ver08.pdf. (accessed Jan. 10, 2021).

[80] Fluke Corporation, “, Fluke SmartView 3.10,” 2015. www.fluke.com, (Accessed 22 Jan 22).

[81] A. L. Robinson, S. G. Buckley, and L. L. Baxter, “Experimental measurements of the thermal conductivity of ash deposits: Part 1. Measurement technique,” Energy and Fuels, vol. 15, no. 1, pp. 66–74, 2001, doi: 10.1021/ef000036c.

[82] Fluke Corporation, “Fluke Ti 125 thermal imager Users Manual,” 2012. http://www.myflukestore.ca/pdfs/cache/www.myflukestore.ca/fluke/thermal_imager/ti125_30hz/manual/fluke_ti125_30hz_thermal_imager_manual.pdf, (Accesed 22 Jan. 22).

[83] A. D. Hailu and A. A. Hassen, “Experimental Investigation and Loss Quantification in Injera Baking Process,” Energy Manag. Res. J., vol. 1, no. 1, pp. 1–7, 2018.

[84] NBE, “National Bank of Ethiopia Annual Report,” 2021.

[85] Energy and Environmental Economics Inc., National action plan for Enegy efficieicny. Understanding Cost-Effectiveness of Energy Efficiency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy- Makers., no. November. 2008.

[86] Parsons Brinckerhoff, “Ethiopian Power System Expansion Master Plan Study Interim Report Volume 2, Distributed Load Forecast Report,” 2013.

APPENDIX A. COMPLETE SILICATE ANALYSIS REPORT OF RAW MATERIALS OF THE CLAY PLATE INJERA MITAD

GEOLOGICAL SURVEY OF ETHIOPIA	Doc.Number: GLD/F5.10.2	Version No: 1
GEOCHEMICAL LABORATORY DIRECTORATE		Page 1 of 1
Document Title: Complete Silicate Analysis Report	Effective date:	May, 2017

Issue Date: -18/02/2021

Customer Name:-

Request No:- GLD/RQ/517/20

Report No:- GLD/RN/155/21

Sample type :- Rock

Sample Preparation: - 200 Mesh

Date Submitted :-25/12/2020

Number of Sample:- Three(03)

Analytical Result: In percent (%) Element to be determined Major Oxides & Minor Oxides

Analytical Method: $LiBO_2$ FUSION, HF attack, GRAVIMETERIC, COLORIMETRIC and AAS

Collector's code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
Clay	61.61	14.23	6.28	0.74	0.82	0.10	0.86	0.22	0.08	0.46	7.04	6.39
Sand	75.92	11.27	2.62	<0.01	<0.01	2.50	3.92	0.06	0.06	0.05	0.72	3.79
Red Soil	43.76	15.60	20.00	<0.01	0.24	<0.01	<0.01	0.16	0.47	1.06	10.84	7.92

Note: - This result represent only for the sample submitted to the laboratory.

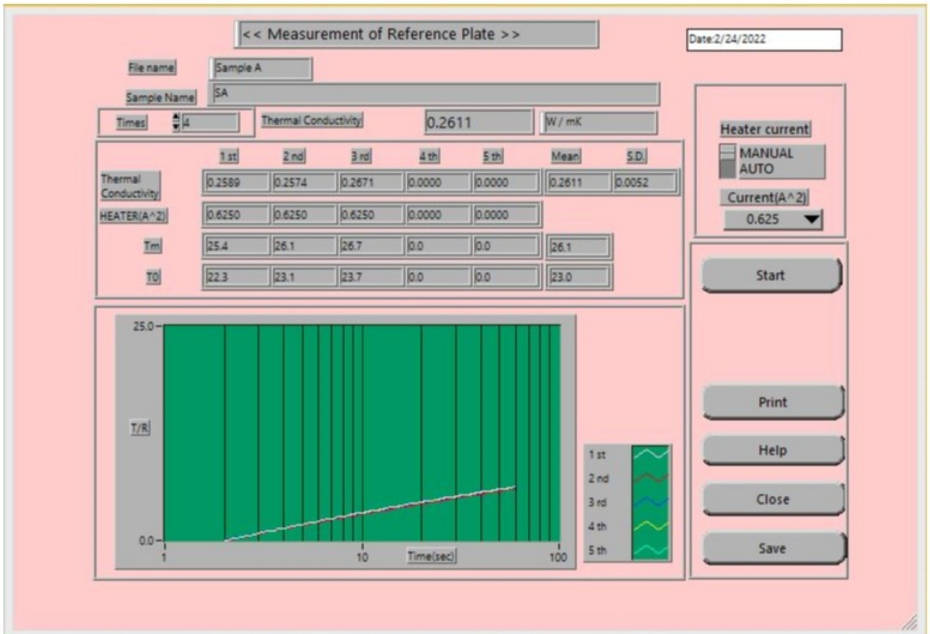
Analysts: Lidet Endeshaw, Nigist Fikadu, Habtamu Alehegn

Checked By: Tizita Zemene

Approved By: Yohannes Getachew

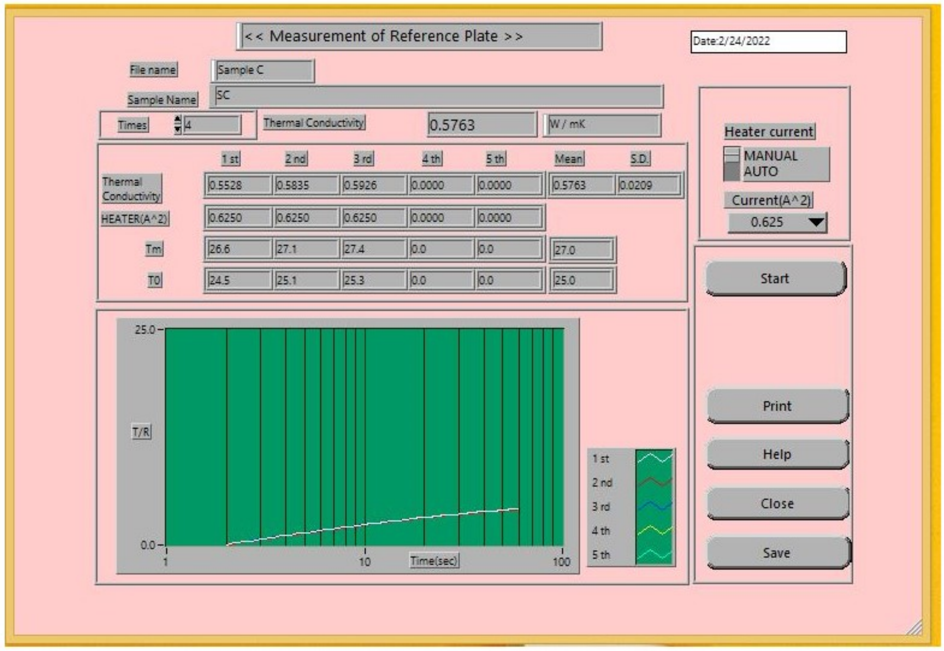
Quality Control: Gosa Haile

APPENDIX B. THERMAL CONDUCTIVITY TEST RESULTS OF THE CLAY PLATE SAMPLES

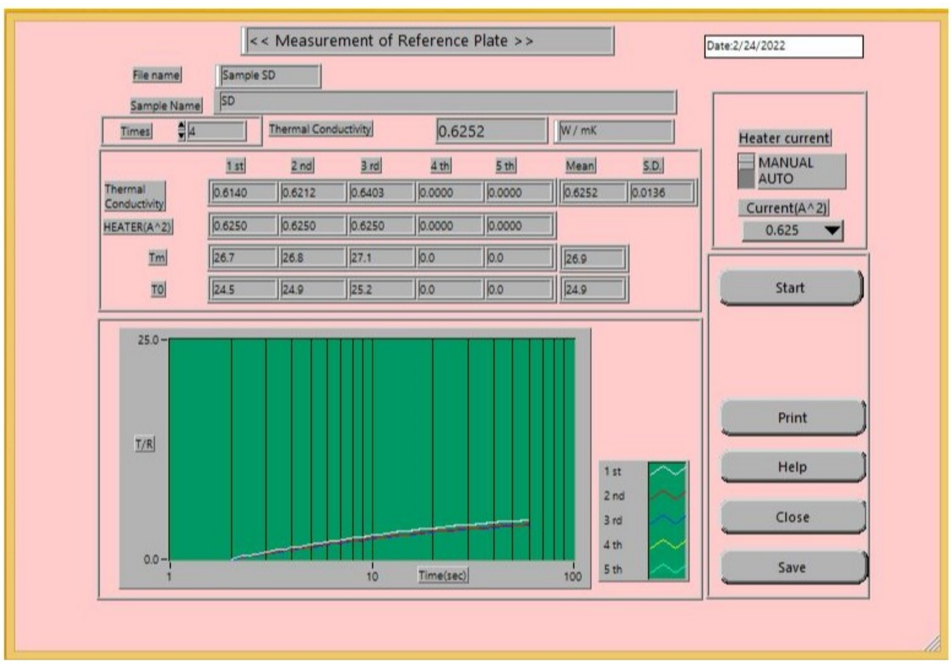


a) Thermal conductivity test result of sample A (Base case)

b) Thermal conductivity test result of sample B.



c) Thermal conductivity test result of sample C.



d) Thermal conductivity test result of sample D.