ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

EXPERIMENTAL INVESTIGATION ON PERFORMANCE CHARACTERISTICS AND EFFICIENCY OF ELECTRIC INJERA BAKING PANS (‘MITAD’)

BY:

AWASH TEKLE TAFERE

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN ENERGY TECHNOLOGY

November, 2011

Addis Ababa, Ethiopia

Addis Ababa University

School of Graduate Studies

Institute of Technology

Energy Technology Department

Experimental Investigation on Performance Characteristics and Efficiency of Electric Injera Baking Pans '(Mitad)'

By

Awash Tekle Tafere

<u>Approved by Board of Examiners</u>:

Dr.-Ing. Abebayehu Assefa : ________________ ______________

Chairman, Department Signature Date

Graduate Committee:

Dr.-Ing. :________________ ______________

Signature Date

Advisor:

Dr.-Ing. Demiss Alemu : ________________ ______________

Signature Date

Co-Advisor:

Ato Abdulkadir Aman : ________________ ______________

Signature Date

Internal Examiner:

Dr.-Ing. Abebayehu Assefa : ________________ ______________

Signature Date

External Examiner:

Dr. Tesfaye Dama : ________________ ______________

Signature Date

Dedication

I dedicate this thesis to my beloved family, Adisey Ayalneh and Birchiko Gerechaal.

ABSTRACT

Enjera baking is the most energy intensive activity in Ethiopia; and preparation of enjera is rather a long process relative to other Ethiopian food. The aim of this thesis work is to investigate the performance characteristics and efficiency of the electric baking pan ('mitad') experimentally and to prove the efficiency of improved 'mitad' is best. Experimentation and processing of data were performed to study the energy consumption cost and ways to increase the performance of the baking pan. Thermo-physical properties were determined quasi experimentally before, during, and after baking processes of the product ('Enjera').

Initial heating up and cyclic enjera baking time with its power consumption and heat loss analysis of the system were presented for performance comparison of the baking pans. Experiments were conducted to measure temperature profile during initial heating up and cyclic baking of the pans. Maximum energy losses are occurred at the bottom of conventional and improved baking pans with the efficiency of 52% and 75% respectively. Even though the efficiency of improved electric 'mitad' was higher than the conventional one, still there was high energy loss due to poor insulation material. Performance improvement options of each baking pans can be made by increasing the number of cycles and density of the batter. This alternative can be increase the efficiency by 5-10% of the baking pans. Economic result illustrates that improved baking pan has higher initial capital investment than the conventional one; but they have lower operating costs. Then overall present worth of improved baking pan has lower cost than conventional baking pan.

Finally, based on the points outlined above, improved electric 'mitad' have an advantage over conventional electric 'mitad' and our recommendation is to install improved baking pans in the kitchens of the Ethiopian house hold.

Key words: Experimental investigation, Thermophysical Property, Heat Transfer Analysis.

ACKNOWLEDGEMENT

I would like to express my deep appreciation and gratitude to the following people for helping me to complete this thesis.

I would like to express my deepest gratitude to the thesis advisor Dr.–Ing. Demiss Alemu for his skillful guidance, encouragement, enormous patience, and willing attitude throughout this thesis work. I would also like to thank my co- advisor Ato Abdulkadir Aman for his support in giving me important software and other materials in sharing of his significant ideas and experimental works friendly.

Special thanks on to Energy Technology Engineering, without the financial support, it would have been difficult to accomplish the research. I would like to thank AAiT–Mechanical Engineering staff.

Last, but not least, I would like to thank all my parents, especially my brother Ato Mebrahitu Tekle, Arafine Ayalineh and my special thanks for my friends Kassahun Derbew and Hailemariam Seyum for their unending confidence, constant support and encouragement during my stay in the postgraduate study.

TABLE OF CONTENTS

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

CHAPTER SIX

CHAPTER SEVEN

APPENDIXES

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	contact area (m^2)
c_p	Specific heat (J/ kg.K)
D	Diffusion coefficient (m^2/ s)
h_b	Boiling coefficient (W /m^2K)
h_c	Convection coefficient (W /m^2K)
h_r	Radiative coefficient (W /m^2K)
h_{fg}	Latent heat (J/ kg)
k	Thermal conductivity (W /m.K)
L_w	Latent heat of vaporization (J/ kg)
m	Mass (kg)
n	Normal to the surface outside
Q	heat lost or gained (J),
q	Rate of heat input (W)
q_l	Heat generation per unit area (W/ m2)
T	Temperature (K)
ΔT	Temperature change (°C)
t	Time (s)
x_i	Mass fraction of ith component
ETB	Ethiopian currency
FDM	Finite Difference Method

Greek letters

ε_i	Volumetric fraction of ith component
ε_r	Ratio of vapor diffusion coefficient to the coefficient of total moisture diffusion
δ_t	Thermo-gradient coefficient (J /kg)
Γ	Boundary (periphery) of the element
ρ	Density (kg /m^3)
ε	Emissivity
δ	Stefan–Boltzmann constant

Geez words

Enjera	an Ethiopian traditional bread
Injera	an Ethiopian traditional bread
Mitad	Ethiopian cooking appliance
Teff	Ethiopian grain

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem:

Ethiopia has experienced a rural energy crisis where demand for household energy has outstripped supply. Biomass, including wood, dung and crop residues, the source for 90% of Ethiopia's total energy use, is used primarily in the household. The combination of high demand aggravated by low use efficiency has contributed to deforestation, rural poverty and energy shortage in Ethiopia. The energy use survey indicated that about half of biomass is used for cooking the traditional bread, injera, in the traditional injera stove, called 'mitad' [15]. One response to reducing the pressure of urban centers on their rural hinterlands could be switching from one fuel source to another, known as energy transition. Switching from fuel wood to electricity, for instance, leads to reduced pressure on the forest resources and lower indoor air pollution. Then the aim of this paper is to investigate the performance characteristics and efficiency of the electric enjera baking pan /'mitad'/, and to identify possible ways to decrease the energy consumption cost and increase the performance of the baking pan to bake traditional bread /'injera'/ using electric source.

Injera is the staple bread in Ethiopia, Eritrea and parts of Sudan. It is perhaps consumed by over 50 million people on a daily basis, and a major element of the diet and household energy use in this region [29]. Injera is also consumed in some parts of Somalia [35]. In Ethiopia one of the most popular foods is injera, which is a large flat pancake eaten by the majority of Ethiopians at least once a day. Injera baking is the most energy intensive activity in Ethiopia and the countries which apply this baking pan [30, 35].

For electric mitad, the batter was poured on to a conventional and improved baking pan surface at a thickness of 1.8–2.5 liters/m². An average power consumption of the conventional electric mitad was around 12 - 14 kW/m² of pan surface area for 52% efficient cooker [9]. Typical baking pans were 58 cm in diameter but the effective diameter of the baking pan was 55cm. The aim of this paper is to replace a conventional baking pan by other efficient and improved enjera baking pan, by minimizing the energy wastage and consumption of the baking pans, for the same quantity and quality of the product; because this electric mitad is very energy intensive types of Ethiopian house hold equipment.

1.2 Objectives of the Study

General Objective

The general objective of the thesis work is to investigate the performance characteristics and efficiency of the electric 'mitad' (improved and conventional baking pans) experimentally and to prove the efficiency of improved 'mitad' is best.

Specific Objective

- To study the geometry , composition and thermo physical properties
- To study the time required for initial heat up and the temperature variation on the surface of the baking pans
- To determine optimum baking temperature and measure moisture loss of the injera batter
- Log the temperature distribution on the baking pan surface during a single and cyclic injera baking
- To compare the performance of the conventional and improved baking pan
- To study the factors affecting baking pan efficiency and suggest options to improve the electric 'mitad' efficiency
- To perform economic analysis comparison for both improved and conventional electric 'mitad'

1.3 Review of Enjera Production

Injera is a specific type of bread that is part and parcel to the Ethiopian culture. Injera is prepared by majority of all Ethiopians and utilized in almost all-traditional cuisine. The bread is unique in appearance and texture. It is one of the most delicate food items to automate due to its characteristics that includes; "bubbly eye", circular flat geometry, very elastic, smooth back surface and a fluffy texture [35]. Preparation of enjera is rather a long process relative to Ethiopian food preparation; it usually takes two to four days from mixing to cooking. Enjera can be produced from almost any staple grain, such as sorghum, millet and teff being the most common in Eritrea, Ethiopia and part of Somalia & Sudan.

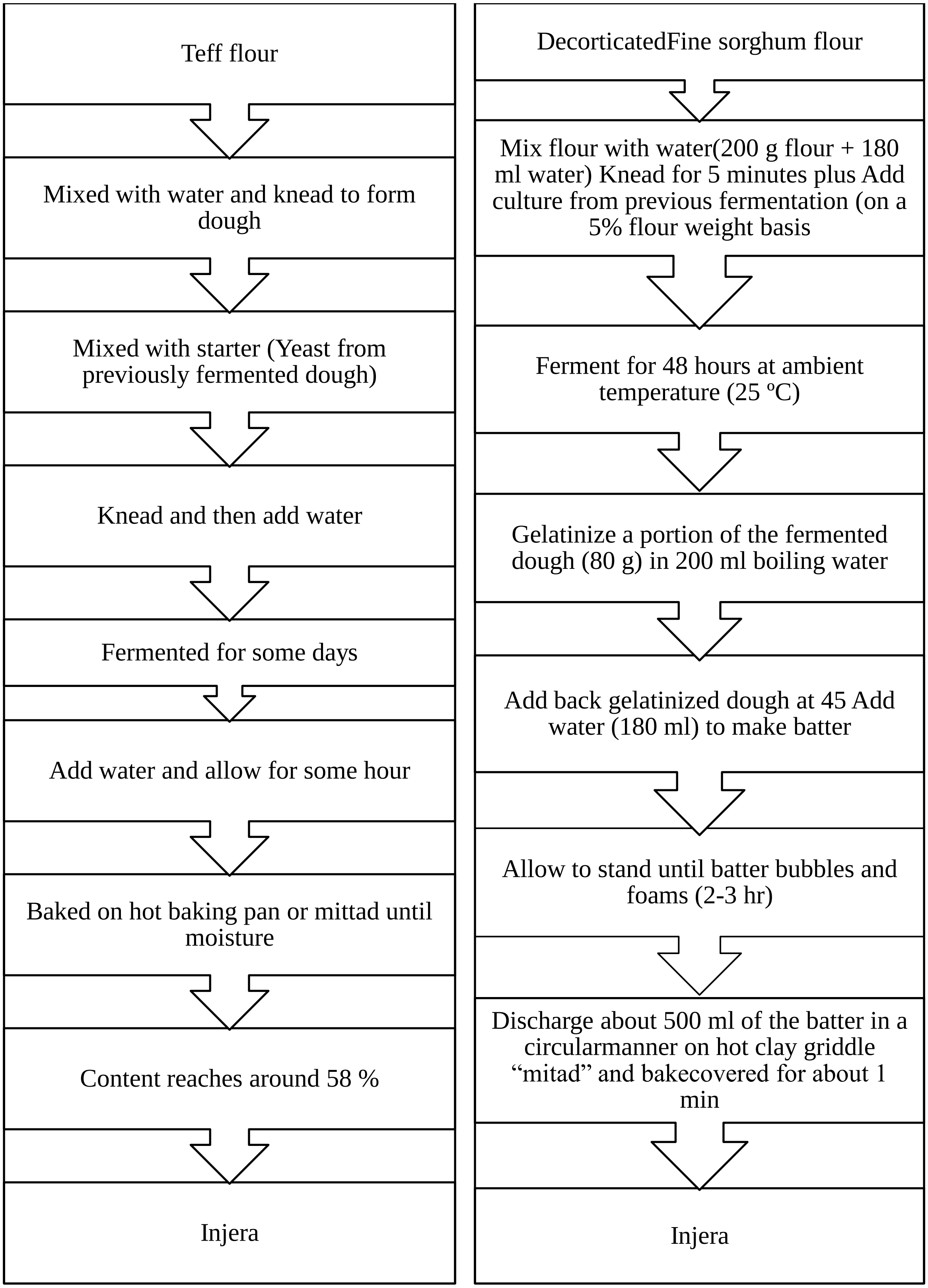


Figure 1.1: Flow chart for injera making processes of teff and sorghum [27, 29].

1.4 Methodology

The methodology followed in the present research process is based on the objectives formulated in section 1.2. Literature review, experimentation and processing of data are methodologies of this work to arrive at conclusion. The logical sequence of activities in the methodology used in this work is given in Figure (1.2).

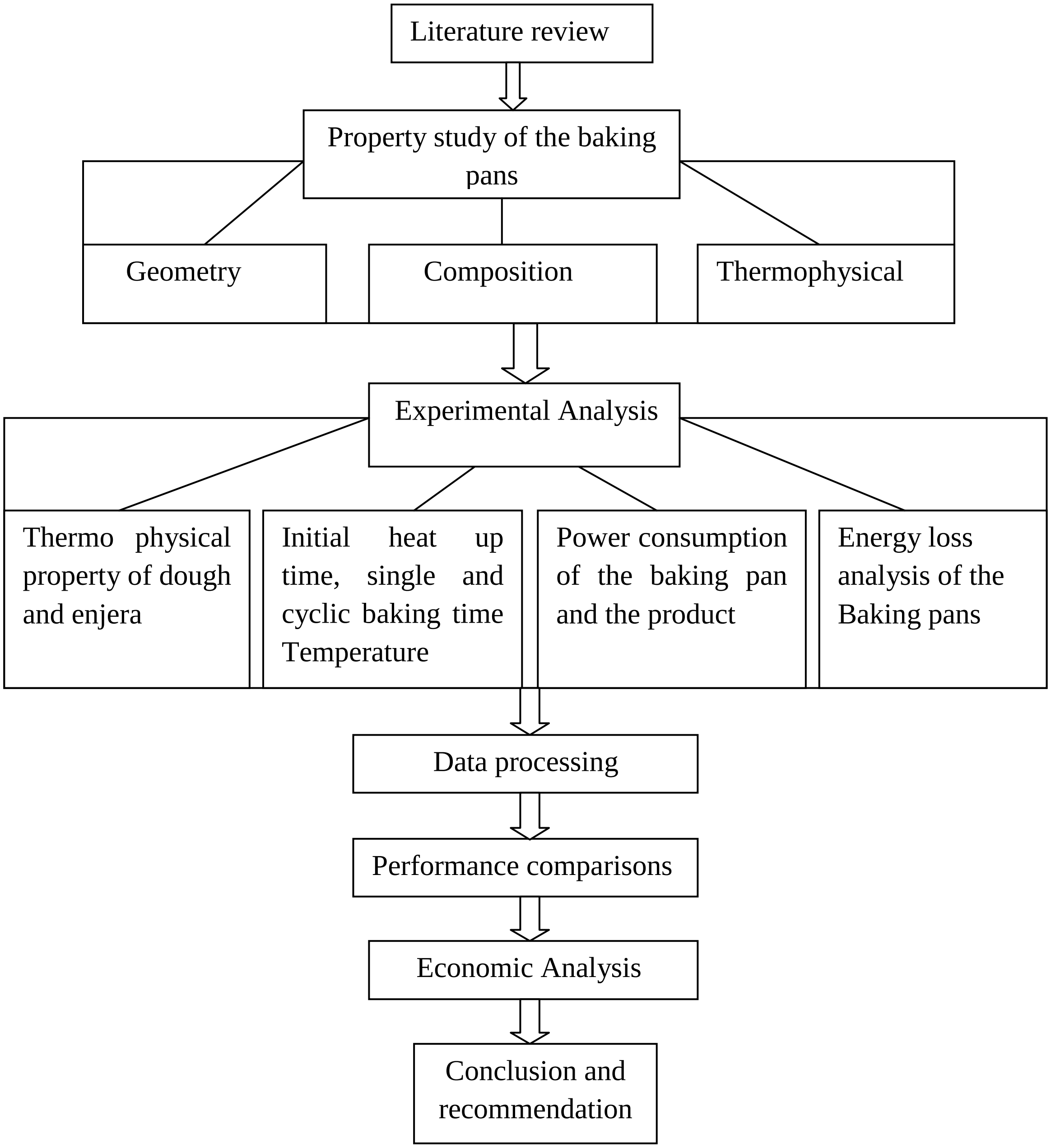


Figure 1.2: Flow chart for methodological approach

CHAPTER TWO

LITERATURE REVIEW

The literature survey is basically works along the areas of this study found in background and theory of the thesis. It is basically a review on injera baking pan, thermo-physical property measurement and analytical values of injera as well as baking pan, injera baking process, and modeling of each composition. It also discusses about the type of energy source and heat transfer of the electric injera baking pan /‘mitad’/.

2.1 Injera Baking Pan

In Ethiopia and Eritrea, the baking of traditional yeast-leavened flat bread ‘(enjera)’ is responsible for a majority of national domestic energy consumption. Yet no or rare literature exists in international journals, reviewing or analyzing the efficiency or energy intensity of enjera production. The aim of enjera making process is quite simple to convert teff flour and other grain into a light, aerated and palatable food. Injera is probably the oldest “processed” food.

Injera bakker (‘mitad’) come in several forms: electric, liquefied petroleum gas (LPG) and traditional wood baking pans and also almost two types of electric baking pans those are Electric-Iron Plate and Electric-Clay plate even though these are not effective[29]; and in this paper also a third type (Electric-ceramic pan) is considered.

2.1.1 Source of Energy for Baking

The electric line is bought from the Ethiopian electric power corporation (EEPCO) and consumers are charged monthly consumption fee. The price for consumption depends on the number of kWh used per month.

2.1.1.1 Resistance Heating System of the Baking Pan

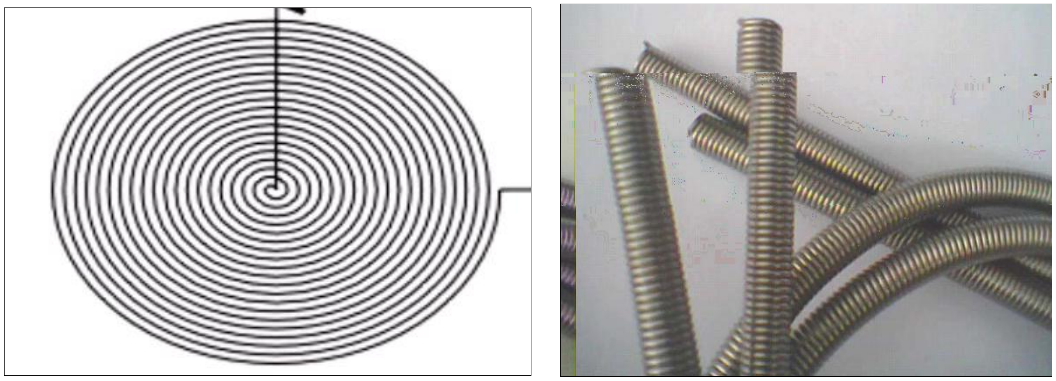
Indirect resistance heating involves passing line frequency current through high resistance heating elements. The resistance to the current flow generates heat in the Ni-Cr coil; and the heat is transferred to the process material or baking pan via conduction.

The power source of the conventional and improved baking pan /‘mitad’/ is an electrical power. This electrical power is converted to heat energy using an electric flow resistance wire inserted on the backside of the grooved baking pan. In general, mathematical power dissipated in an electric resistance wire can be expressed as ohmic heating; occurs when a resistor is heated as current flows through it.

$$P = I^2 R = \frac{V^2}{R} \tag{2.1}$$

Where; P = Power (in Watts), R= Resisrance (in Ohms) and

I = Current (in amps)



(A) (B)

Figure 2-1: Electrical coil images when (A) Helical and (B) UN stretched of Ni-Cr wire

The amount of resistance of a resistor depends on its length, cross-sectional area, and resistivity.

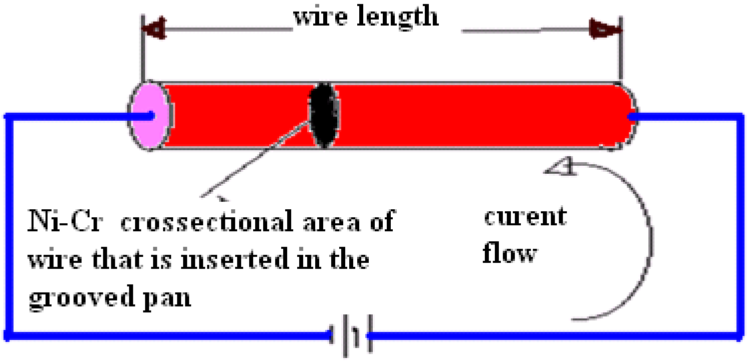


Figure 2-2: Electrical resistance of a wire area, length and current flow

$$R = \frac{\rho}{A} L \tag{2.2}$$

Where; L= Length of the electrical wire,

A= cross-sectional area, and

ρ= resistivity

The electrical resistance of a wire expected to be greater for a longer wire, less for a wire of larger cross sectional area, and depends upon the material out of which the wire is made. The specific resistivity of conductor's changes with temperature in a limited temperature range; it is approximately linear:

$$\rho(T) = \rho(T_0)\,(1 + \alpha\,(T - T_0)) \tag{2.3}$$

Where, α − the coefficient of temperature,

T_0− ambient temperature,

ρ (T_0) − the electrical resistivity at ambient temperature

ρ (T) − the resistivity at a given temperature

The construction of such a transfer helical line through the grooved baking pan /'mitad'/ is described using (80/20%) nickel-chromium heating wire wrapped in a helical coil and powered by AC 220 V. Ni-Cr alloy has earned a reputation as the most suitable element for domestic appliances where consistent high quality is essential. The resistance of the electrical wire varies with temperature.

$$R_T = R_{@20^0c}\, C_t \tag{2.4}$$

Where, R_T = resistance at a given temperature,

$R_{@20^oC}$ = resistance at ambient temperature (20°C), and

Ct = temperature factor.

2.1.2 Construction Procedure of Improved Electric Baking Pan /‘Mitad’/:

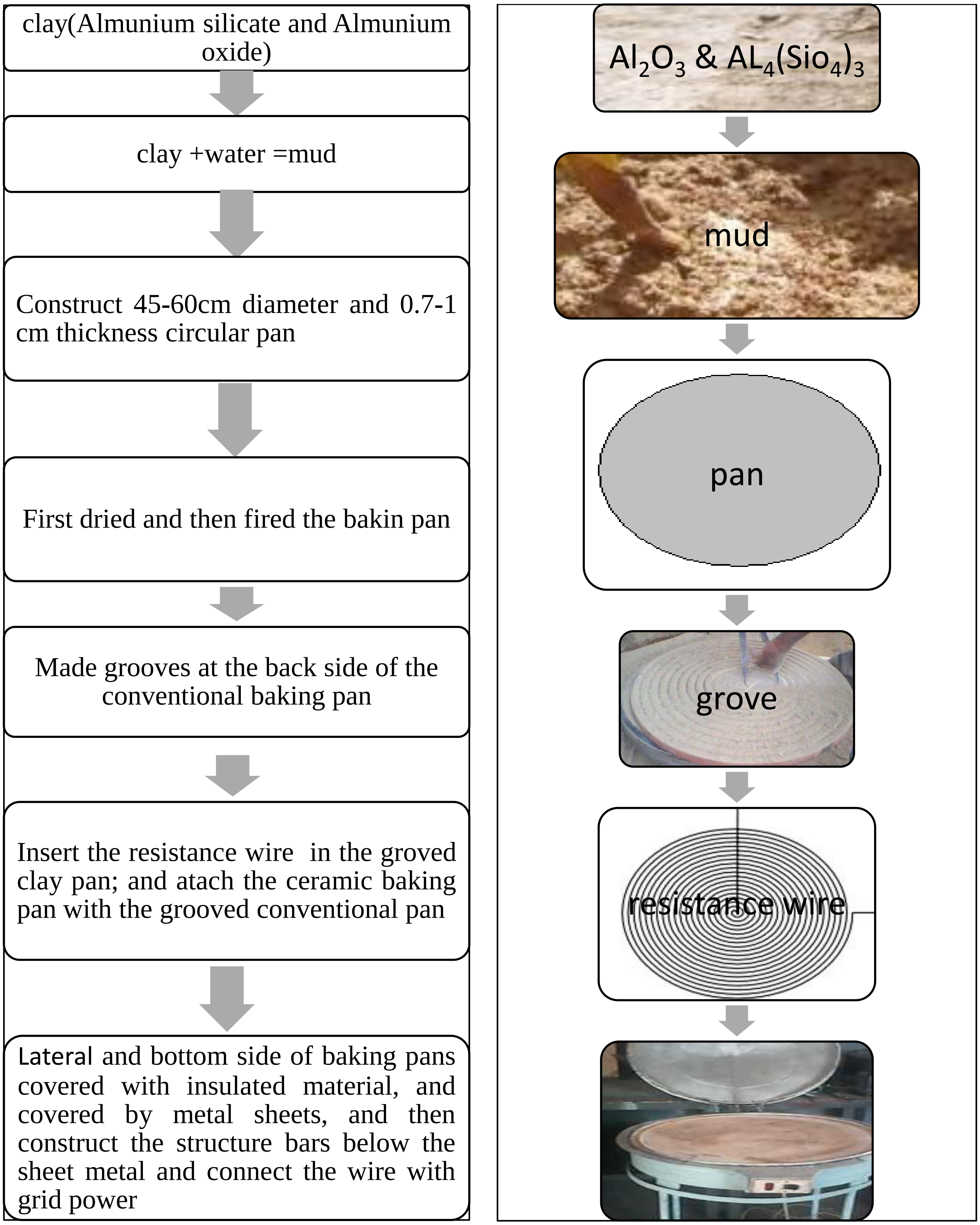


Figure 2.3: Manfucturing processes of Ethiopian electric ‘mitad’

2.2 Conventional and Improved Baking Pan Properties

2.2.2 Clay (Conventional baking) Pan

Clay is a very fine grained, unconsolidated rock matter, which is plastic when wet, but becomes hard and stony when burned [19]. The thermal conductivity of clay, which is the property of a material that indicates its ability to conduct heat, is mostly controlled by water content. For clay, an average thermal conductivity is 0.25 W/m K for no moisture, about 1.0 W/m K for 10% clay moisture content (% by volume), about 1.25 W/m K at 14%, 1.67 W/m K at 30% and about 2.0 W/m K at 50 % [11].

2.2.2 Ceramics (Improved Baking Pan) and its Surface Preparation

Almunium silicate and allmunium oxide are dried and are fired over 1000^oC to turn them in to ceramic. Like most materials, ceramics conduct heat poorly relative to metals; but they retain heat well once they are hot, making them useful for slow cooking. For high thermal conductivity of plates, the temperature of the plate surface varies from 140 to 110 degrees as thermal conductivity of the plate varies from 2 W/mK to 50 W/m.K [9]. On this thesis, improved baking pans are made in three basic steps; those are:

Step 1 - Shaping

Almunium silicate and allmunium oxide are mixed together and soaked in water. The excess water is squeezed out to make clay with a moisture content of about 20%, and the mixture is shaped appropriately.

Step 2 – Drying and smoothing

The items are dried slowly in an oven, during which stage they lose all of the water except that which is bound up in crystal lattices. The volume reduction is about 3 - 7% and smooths it.

Step 3 – Firing

The item is heated to temperatures up to 1170^oC, firing serves three primary functions: to substantially reduce the number of pores in the ceramic, to increase the density of the ceramic, and to bond together the individual material grains into a strong, hard mass (high bond).

Surface preparation of ceramic pan to make it no-stick surface, initially a layer of vegetable oil is putt on the ceramic pan surface and the pan was heated until the vegetable oil is burned and creating a black organic tar which filled in the rough surface of the baking pan. Then after this surface smoothed and hardened, crushed a traditional oil seed (‘gui'lo’) and flax seed is burnt on the heated surface and the burning seeds are rubbed into the surface to create the final smooth no-stick coating. After such preparation, the pans cooked good quality of enjera [29].

2.3 Thermophysical Properties of Food

Properties of food and its ingredient are critical parameters in the design of a process used in the manufacturing of food products. Thermo physical properties are unique and influence the design of any thermal process; a food manufacturing processes involving change in temperature and moisture content of the product. Knowledge of the thermal properties of foods are required to perform the various heat transfer calculations that are involved in the design of food storage and refrigeration equipment, and estimating process times for refrigerating, freezing, drying of foods. Thermal properties of foods are strongly dependent upon chemical composition and temperature [3, 4, 7, 14 and 21].

Thermo physical constituents commonly found in food items include water, protein, fat, carbohydrate, fiber, and ash; listed by Choi and Okos (1986). Thermo physical properties normally include specific heat, density, and thermal conductivity. From the combination of the three properties, thermal diffusivity is a key property in the analysis of unsteady state of heat transfer. The over all objective of the information to be presented is to discuss models for the prediction of thermo physical properties of food and its ingredients based on composition. The following are more specific objectives of thermophysical property of foods, which are used [13]:

- To present and discuss models for the prediction of foods based on composition of foods and its ingredient with emphasis on the application of models to processes design.
- To present and discuss models for the prediction of density of foods based on composition of foods and its ingredients, with emphasis on the physical structure of the product.

- To present and discuss models for the prediction of the thermal conductivity of foods as a function of composition and temperature, with emphasis on the use of models that incorporate the influence of physical structure of the product.

2.3.1 Specific Heat(c_p)

Specific heat is the amount of heat needed to raise the temperature of unit mass by unit degree at a given temperature. It also defined as the ratio of the heat capacity of a given mass of substance to the heat capacity of the same mass of water amount and the SI units for c_p is kJ per kg.K. Specific heat of solids and liquids depends upon the temperature but is generally not sensitive to pressure. Only with gasses it is necessary to distinguish between c_p and c_v, the specific heat at a constant pressure and volume. Assuming there is no phase change, the amount of heat 'Q' that must be added to a unit mass m (kg of mass or specific weight kg/m^3) to raise the temperature from T_2 to T_1can be calculated using the following equation:

$$Q = mc_p (T_2 - T_1) \tag{2.5}$$

Heat capacities are usually measured directly in an instrument known as a calorimeter. In calorimeter measurement, a known amount of heat is supplied to a known mass of substance at constant pressure and the temperature change is measured. Then the average heat capacity over the temperature range is then given by solving the above equation (2.5).

$$c_p = \frac{Q}{m\,(T_2 - T_1)} \tag{2.6}$$

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

$$c_p = (0.5m_f + 0.3m_s + m_w)\ x\ 4.18 \tag{2.7}$$

Where; m_f =mass fraction of fat, m_s= mass fraction of non fat solids and m_w = mass fraction of water and references the specific heat of water 4.18kJ/kg at 20^0C; and a very similar relation ship was suggested by Charm:

$$c_p = 1.094m_f + 1.256m_s + 4.187m_w \tag{2.8}$$

The charm equation uses the specific heat of water at 75^0C and the coefficient for the fat and non fat solids are the same as with the above equation 2.7, when the temperature is adjusted.

Batter and its products /‘injera’/ are a multiphase and multi component system, mainly composed of proteins, lipids, carbohydrates, water and ash. The specific heat of the food can be predicted in most cases accurately from the chemical composition of the major food components weighted by the mass fractions (Choi and Okos).

$$c_p = \sum_{i=1}^{n} x_i p_i \tag{2.9}$$

Where, x= the food composition

i= represent for ash, protein, carbohydrate, fat and moisture content of the food

p= is the percentage of each composition

Table 2.1: Specific heat (c_p) of composition of foods **(**-40°C to 150°C)

Component	**Choi and Okis model**	**M.A. Akintunde, model**
Carbohydrate	$1.5488 + 1.9625\times 10^{-3}\,T - 5.9399 \times 10^{-6}T^2$	1.544exp(0.00013T)
Protein	$2.0082 + 1.2089\times 10^{-3}\,T - 1.3129 \times 10^{-6}T^2$	2.0071exp(0.0006T)
Fat	$1.9842 + 1.4733\times 10^{-3}\,T - 4.8008 \times 10^{-6}T^2$	1.98065exp(0.0007T)
Fiber	$1.8459 + 1.8306\times 10^{-3}\,T - 4.6509 \times 10^{-6}T^2$	1.8422exp(-0.001T)
Ash	$1.0926 + 1.8896\times 10^{-3}\,T - 3.6817 \times 10^{-6}T^2$	1.089exp(0.0017T)
water	$4.1762 - 9.0864\times 10^{-3}\,T + 5.4731 \times 10^{-6}T^2$	

2.3.2 Thermal Conductivity (k)

Thermal conductivity is a basic thermo physical property of any material. It represents the quantity of heat ‘Q’ that flows per unit time through a unit thickness and unit area having unit temperature difference between faces; and its SI unit is [W / m.K]. The rate of heat flow through a material by conduction can be predicted by Fourier’s law of heat conduction. A simplified approximation as follows:

$$\frac{dQ}{dt} = \frac{kA(T_1 - T_2)}{x} \tag{2.10}$$

Where; A= Surface area of the food, x − is thickness of the food,

T_1= Temperature at the outer surface where heat is absorbed

T_2= Temperature at the inner surface, and

K= Thermal conductivity of the product

The models for the prediction of the thermal conductivity of foods have been empirical and based on experimental data; one of the earliest models was proposed by Riedel:

$$k = (326.58 + 1.0412T + 0.00337T^2)\ (0.46 + 0.54m_w)\ x1.73x10^{-3} \tag{2.11}$$

Where; T = Temperature of the product, and

m_w = Mass of the moisture content.

This empirical expression is based on experimental data for fruit juices, sugar solutions and milk over a temperature range from 0^oc to 180^oc. A similar analysis was completed by sweat to create the following model:

$$k = 0.25m_c + 0.161m_f + 0.155m_p + 0.135m_a + 0.58m_w \tag{2.12}$$

Where; c, f, p, a, and w –represents for carbohydrate, fat, protein, ash, and moisture content of the product, listed in Table (2.2).

The prediction accounts for the temperature used during the collection of the experimental thermal conductivity more general model was proposed by Choi and Okos:

$$\mathbf{k} = \sum_{i=1}^{n} \mathbf{k}_i \mathbf{E}_i \tag{2.13}$$

Where; the volume fraction (E_i) is estimated for each compositional component by:

$$\mathbf{E}_i = \frac{\frac{\mathbf{m}_i}{\rho_i}}{\sum_{i=1}^{n} \frac{\mathbf{m}_i}{\rho_i}} \tag{2.14}$$

Where; i = Represents for ash, carbohydrate, protein, fat and moisture content of enjera

m = Mass of each composition

ρ = Density of the composition

The general prediction model is adequate for the prediction of the thermal conductivity of food as a function of temperature and product composition, by Choi and Okos 1986 and M.A. Akintunde, be combined with individual compositions to obtain the over all thermal conductivity (k) of food materials (Table 2.2).

Table 2.2: Thermal conductivity (W/mK) of individual component (-40°C to 150°C),

Component	**Choi and Okos model**	**M.A. Akintunde model**
Water	$0.57109 + 1.762 \times 10^{-3}\,T - 6.7036 \times 10^{-6}\,T^2$	
Proteins	$0.17881 + 1.1958 \times 10^{-3}\,T - 2.7178 \times 10^{-6}\,T^2$	0.1742exp(0.0069T)
Fats	$0.18071 - 2.7604 \times 10^{-3}\,T - 1.7749 \times 10^{-7}\,T^2$	0.1647exp(-0.0171T)
Carbohydrates	$0.20141 + 1.3874 \times 10^{-3}\,T - 4.3312 \times 10^{-6}\,T^2$	0.1951exp(0.0072T)
Fibers	$0.18331 + 1.2497 \times 10^{-3}\,T - 3.1683 \times 10^{-6}\,T^2$	0.1782exp(0.0041T)
Ash	$0.32961 + 1.4011 \times 10^{-3}\,T - 2.9069 \times 10^{-6}\,T^2$	0.04T+0.3277

Both theoretical and empirical models have been developed by the researchers to predict thermal conductivities of composite materials. Empirical relationships of ‘k’ as a function of temperature and composition were given above for many products (Table 2.2). Theoretical models are more general in nature but they need to assume a description of the topology of the matter, that is, the spatial distribution of different constituents. Also some models derived from theoretical considerations are actually semi empirical as they have parameters which are to be fitted for particular products from measured values. The most elementary models are those assuming that different components are arranged in layers either parallel or normal to the heat flow, resulting in the following expressions based on the electric analogy of heat transmission, where the effective property is noted simply as ‘k’:

Series Model:

In this model, layers of components placed normal to the heat flow, in a serial arrangement of resistances and the effective thermal conductivity ’k’ of the products can be calculated as follows:

$$k = \frac{1}{\sum_{i=1}^{n} \frac{\Phi_i}{k_i}} \tag{2.15}$$

Where, k_i –is individual thermal conductivity of each constituent (also known as the intrinsic thermal conductivity), and Φ_i–is a volume fraction of each constituent. Series model, as recommended by Andrieu et al. (1987), is the best prediction for quasi homogeneous foodstuffs, such as proteins, gels, meat, and in both the frozen and unfrozen state. Where the volume fraction of constituent Φ_i − is given by:

$$\Phi_i = \frac{\frac{w_i}{\rho_i}}{\sum_{i=1}^{n} \frac{w_i}{\rho_i}} \tag{2.16}$$

Parallel model:

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

$$k = \sum_{i=1}^{n} \Phi_i \, k_i \tag{2.17}$$

2.3.3 Density (ρ)

There are only a limited number of models for predicting the density of a food product based on composition. These are suggested by Heldman. These models are similar to the general model for density prediction as proposed by Choi and Okos:

$$\rho = \frac{1}{\sum \frac{m_i}{\rho_i}} \tag{2.18}$$

Where, m_i = Represent for protein, fat, carbohydrate, ash, and water components, and

ρ_i = Represent for the density(moisture free) each component

The density data to be used as inputs to the proposed model were published by Choi and Okos, and Akintunde as shown in the Table (2.3).

Table 2.3: Density (ρ) of food product components with in two models

Component	**Choi and okis model**	**M.A. Akintunde, model**
Protein	$1.3299 \times 10^{3} - 5.1840 \times 10^{-1} T$	1329.8exp(-0.0004T)
Fat	$9.2559 \times 10^{2} - 4.1757 \times 10^{-1} T$	9.25.53exp(-0.0005T)
Carbohydrate	$1.5991 \times 10^{3} - 3.1046 \times 10^{-1} T$	1.599.1exp(-0.0002T)
fiber	$1.3115 \times 10^{3} - 3.6589 \times 10^{-1} T$	1311.5exp(-0.0003T)
Ash	$2.4238 \times 10^{3} - 2.8063 \times 10^{-1} T$	2423.8exp(-0.0001T)
water	$9.9718 \times 10^{2} + 3.1439 \times 10^{-3} T - 3.7574 \times 10^{-3} T^{2}$	

2.3.4 Thermal Diffusivity (α)

Thermal diffusivity determines the speed of heat of three-dimensional propagation or diffusion through the material. It is represented by the rate at which temperature changes in a certain volume of food material, while transient heat is conducted through it in a certain direction in or out of the material (depending if the operation involves heating or cooling). Thermal diffusivity defines the rate at which heat diffuses by conduction through a food composite, and is related to k and c_p through density ρ [kg/ m^3] as follows:

$$\alpha = \frac{k\,(T)}{\rho\, c_p\,(T)} \qquad (2.19)$$

Where, k (T) = Thermal conductivity of the product at temperature 'T'

c_p (T) = Specific heat of the product at temperature 'T'

ρ = Density of the product

The thermal diffusivity data to be used as inputs to the proposed model were published by Choi and Okos, and Akintunde as shown in the Table (2.4).

Table 2.4: Thermal Diffusivity of Food Components in two models,

Component	**Choi and Okos model**	**M.A. Akintunde, model**
Protein	$6.8714 \times 10^{-8} + 4.7578 \times 10^{-10}T - 1.4646 \times 10^{-12}T^2$	$7x10^{-8}exp(0.0073T)$
Fat	$9.8777 \times 10^{-8} - 1.2569 \times 10^{-10}T - 3.8286 \times 10^{-14}T^2$	$10^{-7}exp(-0.0013T)$
Carbohydrate	$8.0842 \times 10^{-8} + 5.3052 \times 10^{-10}T - 2.3218 \times 10^{-12}T^2$	$8x10^{-8}exp(0.0069T)$
Fiber	$7.3976 \times 10^{-8} + 5.1902 \times 10^{-10}T - 2.2202 \times 10^{-12}T^2$	$7x10^{-8}exp(0.0074T)$
Ash	$1.2461 \times 10^{-7} + 3.7321 \times 10^{-10}T - 1.2244 \times 10^{-12}T^2$	$1x10^{-7}exp(0.003T)$
water	$1.3168 \times 10^{-7} + 6.2477 \times 10^{-10}T - 2.4022 \times 10^{-12}T^2$	

2.3.5 Moisture Diffusivity(m^2/se)

Moisture diffusivity is a measure of a product’s tendency to produce entropy when it is disturbed from equilibrium by imposition of a concentration gradient. For any drying and baking application the internal moisture migrates towards the external surface of the product by means of a number of mechanisms such as diffusion, capillarity and sequences of evaporation condensation. Moisture diffusivity ‘DWI’ is one of the moisture transport properties of building materials frequently used in hygrothermal analysis. Hygroscopic materials are which adsorb or desorbs moisture depending on their ambient environment. It appears in the moisture transport equation as follows:

$$\frac{\partial m}{\partial t} = D(\frac{\partial^2 m}{\partial r} + \frac{\partial m}{r\partial r} + \frac{\partial^2 m}{\partial z^2}) \qquad (2.20)$$

Fick’s second law of diffusion is widely used to gather all of the mass transfer mechanisms into one equivalent moisture transport coefficient, given as follows:

$$\frac{\partial m}{\partial t} = D(\frac{\partial^2 m}{\partial z^2}) \qquad (2.21)$$

Where, m = Moisture concentration [kg/kg (dry basis)],

D = Moisture diffusivity (m^2/h), r–radial coordinate (m),

z = Axial coordinate (m), and t –time variable (h)

2.4. Heat and Mass Transfer of the Baking Pans /‘Mitad’/

Generally, heat flows from the cooking plate to the different baking pan /‘mitad’ /components and product /‘injera’/. The primary paths of heat flows are the following [9]:

- From the heating element conducted to the plate surface, where either heat is lost through convection and radiation, or heat is transferred to the enjera batter.
- From the baking pan to the sides of the baking pans via conduction through the glue/clay connection and the sheet metal. Heat is then lost through radiation and convection from the sides.
- From the baking pan through primitive dried mud insulation to the galvanized iron sheet metal bottom. Heat is then lost through radiation and convention from the bottom.
- A minor heat-flow path is from the baking pan surface to the lid cover and hence to the surrounding through convection and radiation.

2.4.1 Mechanisms of Heat transfer in Ethiopian Enjera Baking Pan

The second law of thermodynamics states that heat always flows over the boundary of the system in the direction of falling temperature. Heat transfer occurs mainly via three fundamental mechanisms: conduction, convection and radiation [12, 18 and 32].

2.4.1.1 Conductive Heat Transfer

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

$$q_c = \frac{K\,A_b\,(T_{pb} - T_{Pt})}{x} \tag{2.22}$$

Where: q_c = Heat transfer due to conduction,

A_b= Area of the pan surface, T_{pb}– the temperature of bottom plate,

T_{pt} = Temperature top pan surface and x – is the average thickness of the pan.

The rate of heat input to the slice/pan (q_i) is not equal to the rate of heat output (q_o). The difference is the accumulated of heat q_a (which can be positive or negative). If there is no heat generation in the slab, heat balance requires that:

$$q_i - q_o = q_a \tag{2.23}$$

2.4.1.2 Convective Heat Transfer

Convection aids heat transfer through liquids and gases, which otherwise conduct heat slowly. It involves the constant movement of cold currents of air or liquid toward warmer currents. Because warmer liquids and gases are less dense and rise up while colder liquids and gases are denser and they sink. Heat and mass transfer in fluids occur, almost always, simultaneously with bulk movement of the medium. This system is called convection heat transfer. In the Ethiopian flat bread /'enjera'/ convection heat transfer is considered as heat loss/gain of the system even if in such cases it uses for heat balance of the product.

$$q_F = h_F\,Ap\,(T_p - T_{lc}) \tag{2.24}$$

Where; q_F = Heat transferred by convection, kJ;

h_F = Convective heat transfer coefficient, W/m^2 K; A_p = Surface area of the product, m^2

T_{lc} = Temperature of the lid cover; and T_p = Temperature of the pan surface in ^{o}C

The movement is caused by heat or mass transfer itself, usually by virtue of density differences is known as natural (free) convention heat transfer. Air in contact with the stove surface is heated, expands, becomes less dense, moves upwards and is replaced by colder, heavier air. Empirical correlations for convection heat and mass transfer for natural (free) convection, which is essentially based on differences in density, hence on thermal expansion of the fluid, the correlations contain the Grashof number (Gr). This dimensionless group contains the term Δρ, the difference in the density of the fluid, which in turn is related to the differences in temperature (ΔT) and the coefficient of thermal expansion, β. The following correlation is often recommended for the calculation of natural convection heat transfer from vertical surfaces:

$$\mathrm{Nu} = 0.59\,\mathrm{Gr}^{0.25}\,\mathrm{Pr}^{0.25} \qquad (2.25)$$

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

$$\mathrm{Nu} = 2 + 0.6\mathrm{Gr}^{0.25}\,\mathrm{Pr}^{0.33} \qquad (2.26)$$

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

$$\mathrm{Nu} = 0.54(\mathrm{Ra})^{(1/4)}, \text{for } 10^{5} < \mathrm{Ra} < 2\mathrm{x}10^{7}, \text{and} \qquad (2.27)$$

$$\mathrm{Nu} = 0.14(\mathrm{Ra})^{(1/3)}, \text{for } 2\mathrm{x}10^{7} < \mathrm{Ra} < 3\mathrm{x}10^{10} \qquad (2.28)$$

Where; Ra=Rayleigh number, and

Pr = Prandl number

2.4.1.3 Radiation Heat Transfer

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

$$q_r = F_{pr}\, A_p\, \sigma\, (T_H{}^4 - T_{pt}{}^4) \qquad (2.29)$$

Where: q_r = Heat transferred by radiation, kJ;

A_p= Surface area of the pan

σ = Stefan-Boltzman constant, $W/m^2\,K^4$;

T_H = Hood (refractory surface) temperature, °K;

T_{pt}= Top lid cover temperature, °K, and

F_{pr} = Overall coefficient for radiation heat transfer is given by:

$$Fpr = \frac{1}{\{1/f_{pr} + (1/\varepsilon_p - 1) + (A_p/A_r).(1/\varepsilon_H - 1)\}} \tag{2.30}$$

Where; f_{pr} = Geometrical factor, ε_p= Emissivity of the lid cover,

ε_H = Emissivity of the pan and A_r= Area of the radiating refractory surface, m^2.

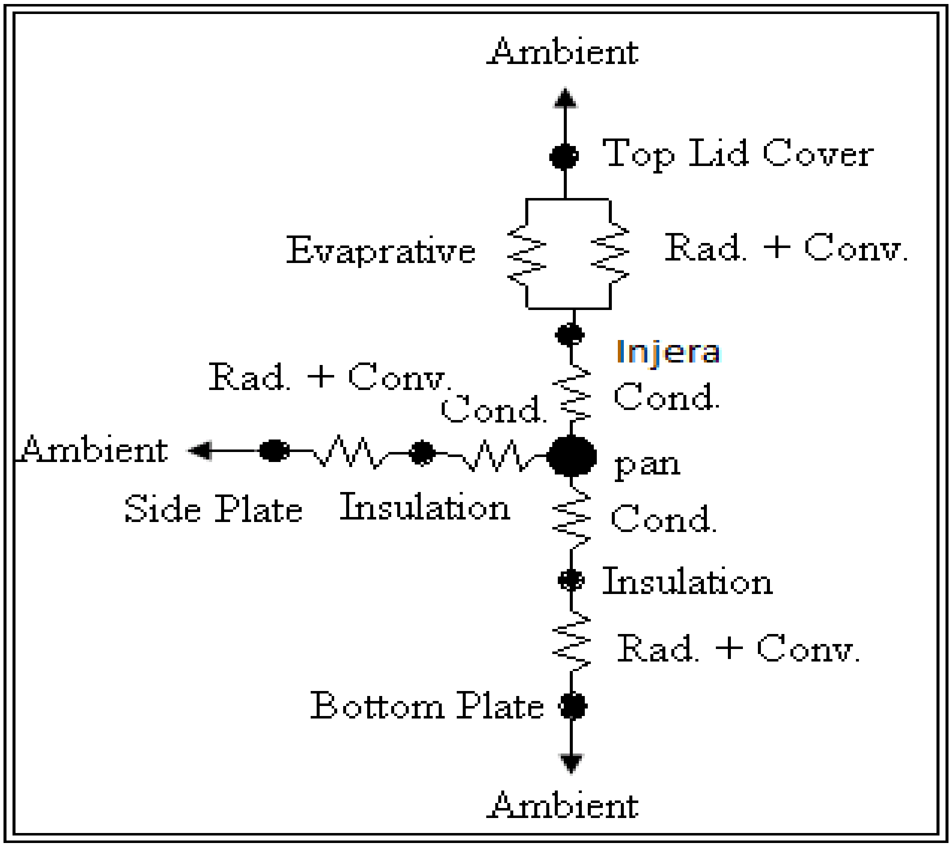


Figure 2.4: Equivalent thermal circuit diagram of an electric source of Ethiopian baking pan /‘mitad’/

2.5. Insulations

The main objective of insulation is to reduce the amount of heat escaping from the oven to atmosphere. In order to work effectively, the insulation material must have a low thermal conductivity. Insulations are used to decrease heat flow and surface temperatures. Usually, the engineering approach to insulation is the addition of a low-conducting material to the surface [24, 28and 33]. The values of conductivity of gypsum plasterboard at very high temperatures and specific heat have been modified to some extent in the calibration of the heat transfer model. Conductivity was increased substantially at higher temperatures to allow for ablation. The 1947 Guide lists a thermal conductivity of 0.20 W/ (m-k) for gypsum board at a density of 1005 kg/m^3, based on tests at the Armour Institute of Technology (a precursor to the Illinois Institute of Technology). Valore (Valore, 1988) provides a correlation for the conductivity of gypsum as a function of density (ρ), where;

$$k = 0.025 \exp(0.08 \rho^{1/2}) \tag{2.31}$$

Where; ρ = Density of the insulation in kg/m3 and

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

Generally, a substance which has lower thermal conductivity than the other can be used as insulation of the system. For instance, fired clay, primitive dried clay and clay brick can be used as good insulation for high thermal conductivity of metals for 50-250kW/m^{2}K.

CHAPTER THREE

DETERMINATION OF THERMO-PHYSICAL PROPERTIES OF ENJERA AND BAKING PAN

In this chapter thermo-physical properties of enjera was determined analytically (from thermo physical properties of the constituents) and experimentally (based on temperature and moisture content of the product) during injera baking processes.

3.1 Thermo Physical Property of Teff Flour

Thermo physical properties normally include some property like specific heat, density, and thermal conductivity. Teff constituents commonly found in food items include water, protein, fat, carbohydrate, fiber, and ash. Choi and Okos (1986) have developed the equation, which shows the relationship among the thermophysical property with its constituents. The application of thermophysical property's of teff flour analysis uses for direct analysis of teff product at any amount of water addition to the flour. Based on direct analysis of each composition, the density of enjera was 1175 kg/m^3 (Figure 3.3) and this value can approximate from the thermophysical property of flour and water as follows:

$$\begin{aligned}\text{Density of enjera} &= x_f \text{ x } \rho_{(\text{teff flour})} + x_w \text{ x } \rho_{\text{water}} \\ &= 0.42 \text{ x } 1455.902 \text{ kg/m}^3 + 0.58 \text{ x } 100 \text{ kg/m}^3 \\ &= 1181.67 \text{ kg/m}^3\end{aligned}$$

Where; x_f = Mass percentage of the composition of teff flour

x_w = Water content percentage at enjera state

ρ = Density of water and teff flour

We can proof the similarity of this approximation by using error percentage determination.

$$\%\text{error} = \frac{(1181.678 - 1175)}{1175} = 0.9\% < 5\%$$

From the above error calculation, it was similar to get thermophysical property of the product (batter and enjera) using direct analysis of each composition and average mass fraction of each teff flour and water content. The chemical composition of teff flour (Table 3.1) was used for its thermo-physical property analysis (Table 3.2).

Table 3.1: Chemical composition property of teff flour [23, 34 and 36]

Chemical Composition of Teff Flour	**Number of Grams Per Total 100 Gram (%)**
Carbohydrate	73.00
Protein	9.60
Fat	2.00
Fiber	3.10
Ash	2.90
moisture	9.60

Table 3.2: Thermo physical property of teff flour and its analytical results

Thermo Physical Property Teff Flour	**Numerical Values**	**SI Unit**
Specific heat(c_p)	1.625	kJ/kg.K
Thermal Conductivity (k)	0.25802	$W/m^2.K$
Density (ρ)	1455.902	kg/m^3
Thermal diffusivity (α),	$1.02x10^{-4}$	m^2/s

3.2 Thermo-physical Property of Teffs' Batter and Enjera

Thermo-physical property was determined from the compositional results of batter and enjera by using appropriate terms. The three parameters like: moisture diffusivity (D), specific heat (c_p), and thermal conductivity (k) are temperature and moisture dependant parameters. One thermocouple was positioned through the hole at the center, and the other two thermocouples were positioned 20 cm far from the center inorder to measure enjera and pan surface temperature. To determine the thermo-physical properties of the product, it was also essential to measure individual weight of the batter, enjera and removed moisture content (Table 3.3).

Table 3.3: Experimental data logging: net weight of batter, enjera and removed moisture content

	Mass of Batter (gram)		**Mass of Enjera (grams)**		**Mass of Moisture Content Loss (grams)**	
Test No.	conventional	improved	conventional	improved	conventional	improved
1	563.1	564.3	381.4	387.83	181.70	176.47
2	560.5	585.5	371.3	398.00	189.20	185.50
3	559.8	560.5	372.7	378.24	187.10	182.26
4	561.1	594.0	373.4	404.50	190.10	189.50
Average	561.1	576.1	374.7	392.14	187.03	183.43

Moisture content of enjera and batter, using moisture balance equipment of AMB 310, was measured as shown in Tables (3.4 and 3.5). It measures moisture content as well as solid content of the batter and enjera. Solid and water (or moisture) content of the batter was 27.32% and 72.68% respectively.

Table 3.4: Measurement of moisture content of batter

Test No.	**Total Mass of Batter(M_t) in Gram**	**Solid Mass of Batter(M_S) in Gram**	**Final Solid Percentage $\frac{m_s}{m_T}$ (%)**	**Solid Percentage of Batter (Final Reading)**
1	43.91	12.21	27.80	27.90
2	19.25	5.19	26.94	26.95
3	20.66	5.63	27.22	27.28
Average	27.94	11.01	27.32	27.38

Moisture and solid percentage measurement of enjera and batter are required to find thermo-physical property of the product. The numerical value of moisture and solid percentage of enjera was 57.67 and 42.33 % respectively (Table 3.5).

Table 3.5: Measurement of moisture content of enjera

Test No.	**Total Mass of Enjera(M_t) in Gram**	**Solid Mass of Enjera(M_s) in Gram**	**Solid Percentage of Enjera $\frac{m_s}{m_T}$ (%)**	**Solid Percentage of Enjera (Final Reading)**
1	15.96	6.78	42.48	42.51
2	12.70	5.85	46.06	46.13
3	17.53	6.74	38.44	38.70
Average	15.40	6.46	42.33	42.45

Based on the experiment, to produce 72.68 % moisture containing batter, it needs a net 265 ml of water added to 100 gram of flour; and to produce 57.67% moisture content of the product at least it needs around 125-135 ml of water removal during baking time of enjera.

Generally, 100 gram flour mixing with water to form net fermented dough (or batter) was as shown below:

100 gram of flour + ≈ 265 ml net addition of water = an average 365 gram of batter formation

And the removal of water from net weight of batter to produce enjera was:

net weight of 365 gram of batter – 125-135 ml removal of water = An average of 236 gram of enjera production

The chemical composition can depend on water content of the product. According to the experiment, percentages of chemical composition of teff at three states are listed in Table 3.6, these are: powder (or flour), batter and enjera.

Table 3.6: Chemical composition of teff's flour, batter and enjera (mass fraction (%))

Percentage of Chemical Composition (or number of grams per total 100 gram)			
Composition	Flour (%)	Batter (%)	Enjera (%)
Carbohydrate	73.00	22.10	34.27
Protein	9.60	2.90	4.50
Fat	2.00	0.60	0.94
Fiber	3.10	0.90	1.45
Ash	2.90	0.88	1.36
moisture	9.60	72.68	57.67
Total Amount	100%	100%	100%

From Table 3.5, moisture content of batter and enjera was 72.68% and 57.67% respectively. The equation and graphical representation of the moisture content (m_c) of enjera during baking and after baking (cooling) time using regression line was given as follows:

$$\%m_c = \begin{cases} 73 - 0.075 \times t; \text{for } t \leq 180 \\ 10^{(1.91 - 0.0261 \times \log(t))}; \ \text{for } 180 < t \leq 280 \end{cases}$$

Where; t = Baking and cool down time taken.

This equation assumed linear relationship among moisture content and time during baking processes of the product. In order to bake injera, it takes around 160-200 seconds. And there was an additional time to cool down after being removed from the hot pan; which was around 90-120 seconds. The product was heated to vaporization temperature and heating with moisture loss at constant temperature.

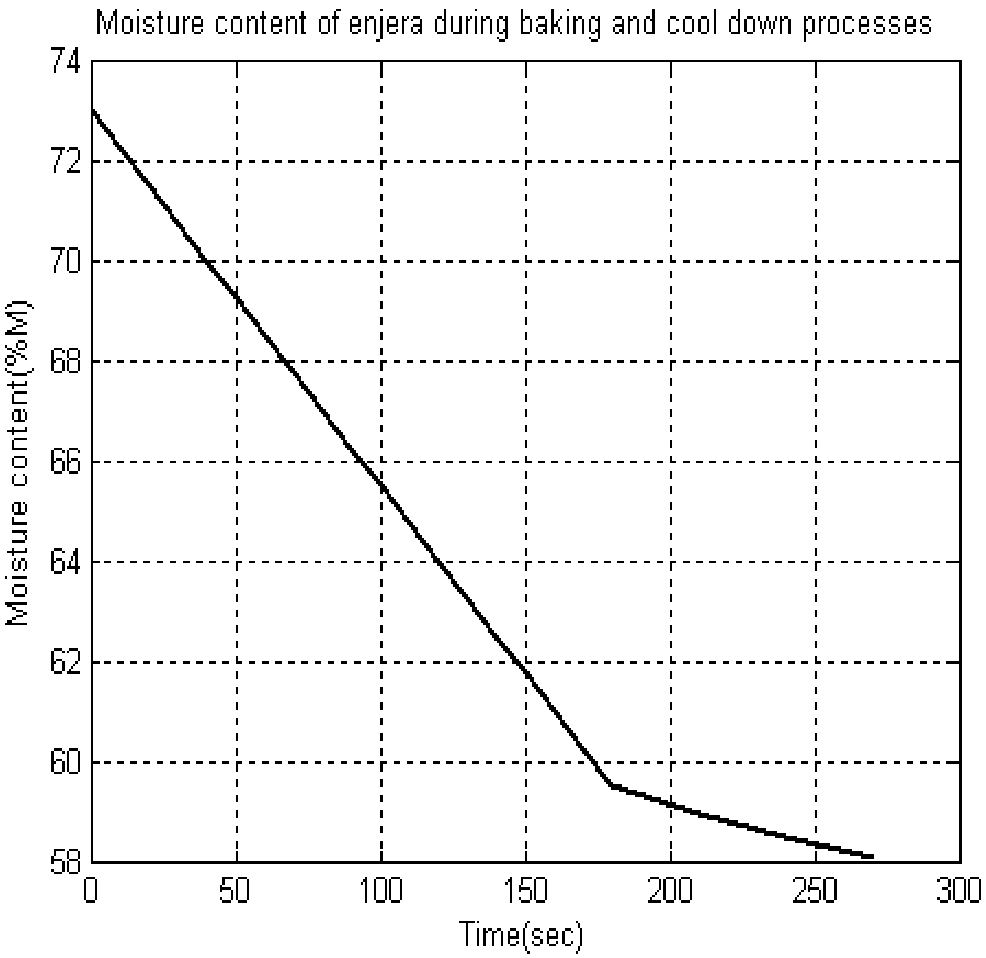


Figure 3.1: Moisture content of the product during and after baking time

3.2.1 Specific Heat (c_p)

Thermo-physical properties of the product like specific heat, thermal conductivity, thermal diffusivity and density were determined and plotted. Simulations of all thermo-physical properties of the product (batter and Enjera) depends on the experimental results (Temperature and moisture content variation) and Choi and Okos model as described in Equations (2.9, 2.13, 2.18, and 2.19) and Tables (2.1, 2.2, 2.3, and 2.4).

The temperature of the batter increased from ambient temperature to boiling temperature during baking time. An average specific heat of the product, at the mean moisture content and boiling temperature, was around 2960J/kg.K. Specific heat of batter, at ambient temperature and 72.68 %

of moisture content, was 3.35kJ/kg.K; and specific heat of enjera, at boiling temperature during baking and 57.68 % moisture content, was 2.63kJ/kg.K (Figure 3.2).

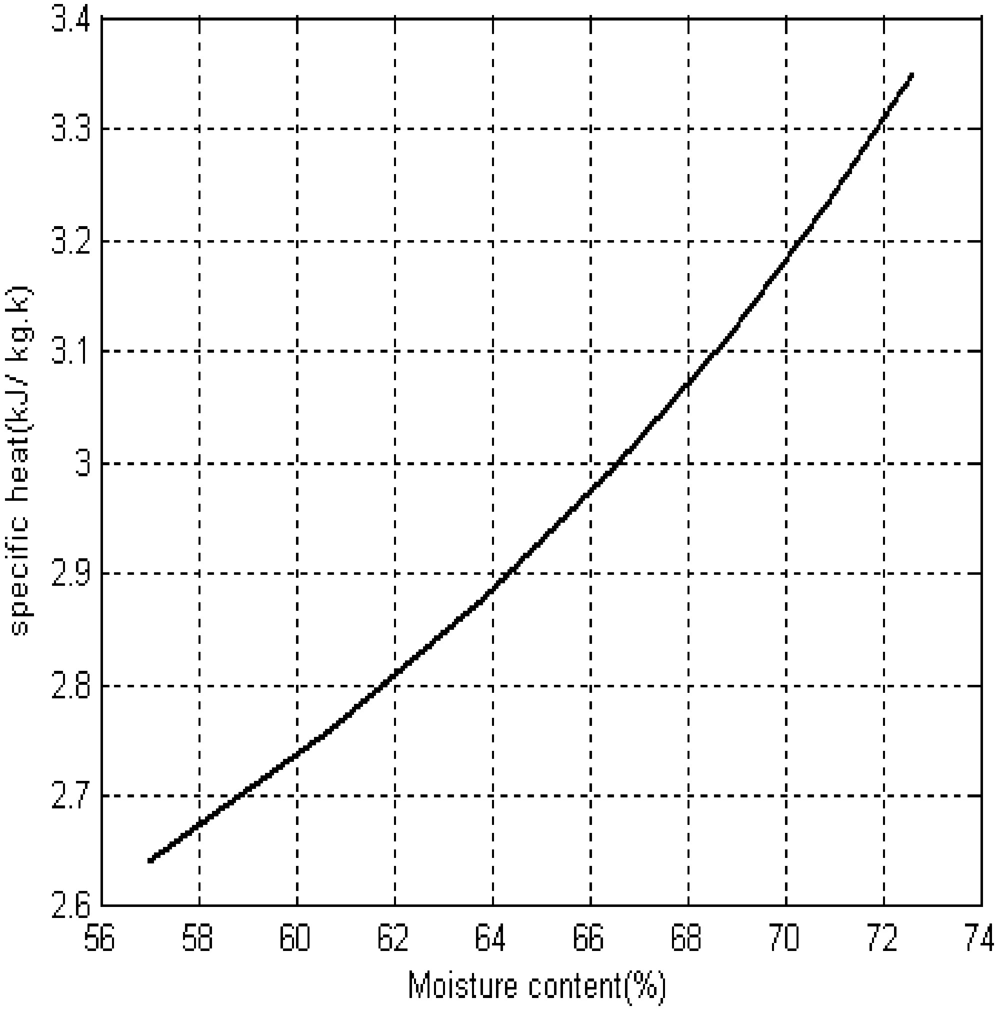


Figure 3.2: Specific heat vs moisture content of the product

3.2.2 Density (ρ)

If the moisture content of the product decreased, the density of the product increased. Density of teff enjera, at ambient temperature with moisture content of 57.67%, was 1175 kg/m^3. Density of teff batter, at ambient temperature with moisture content of 72.68%, was 1103 kg/m^3. It is obvious that the density of solids is greater than liquids, as shown in Figure 3.3.

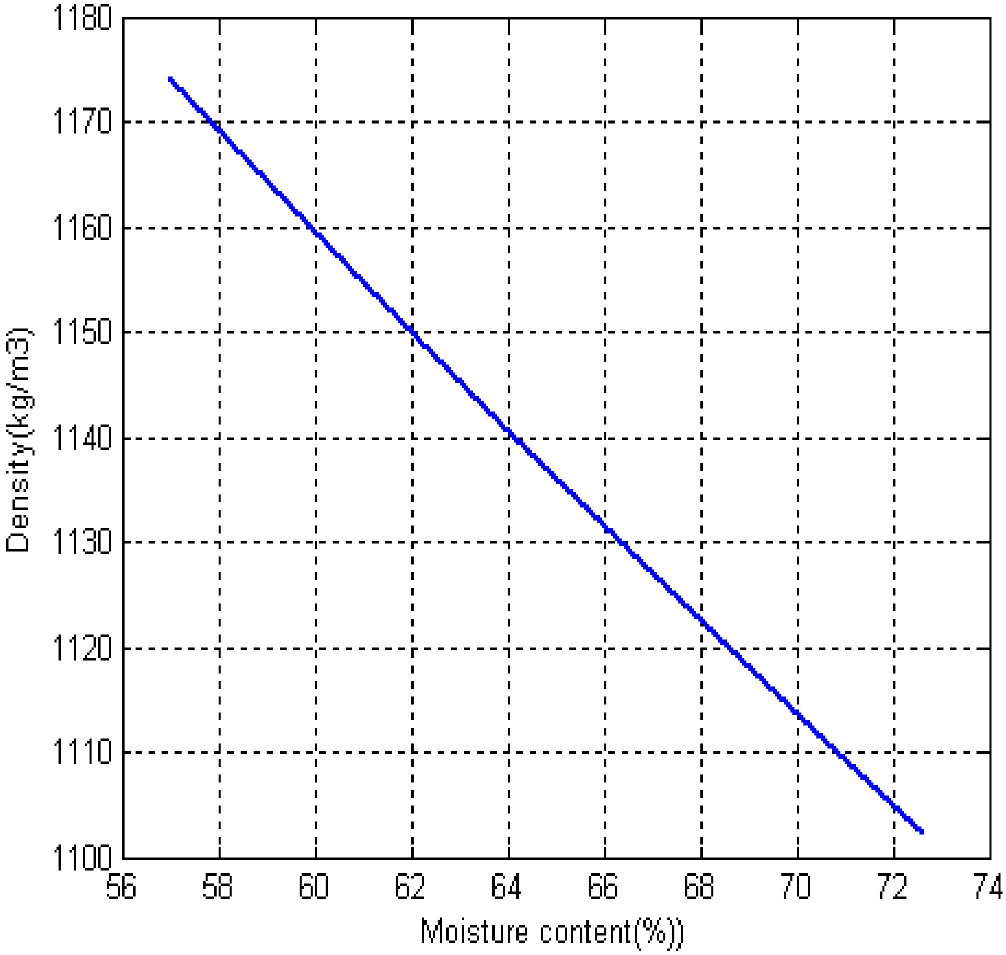


Figure 3.3: Density vs. moisture content of the product

3.2.3 Thermal Conductivity (k)

Enjera was baked on the hot plate by spreading a known amount of batter. Thermal conductivity of the product has a parabolic behavior (Figure 3.4). Thermal conductivity of the product increased when the moisture content decreased from the maximum (73%) to the medium (or 63.8%); and below this moisture content it decreased.

Thermal conductivity of teff batter and enjera was 0.53 W/m.K and 0.558 W/m.k respectively. The temperature of the product varied from ambient up to boiling temperature during baking time. Maximum thermal conductivity of the product, at 63.8% of moisture content and 92.3^{o}c temperature, was around 0.565 W/m.K.

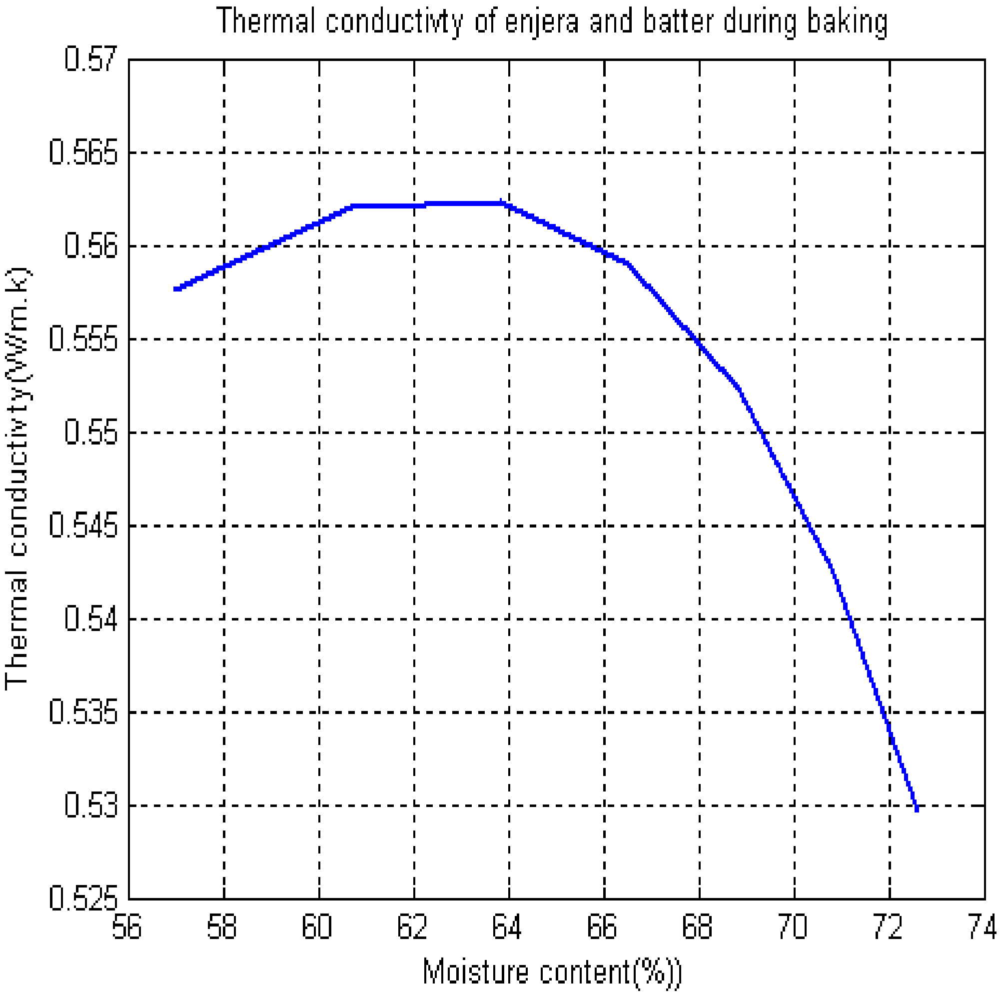


Figure 3.4: Thermal conductivty vs moisture content variation of the product

3.2.4 Thermal Diffusivity (α)

It defines the rate at which heat diffuses by conduction through an enjera and batter composite, and is related to thermal conductivity (k), specific heat (c_p) and density ρ [kg/ m^3] of the product as described in Equation (2.19). Thermal diffusivity of teff product varied from $1.85x10^{-4}$ m^2/sec of enjera up to $1.44x10^{-4}$ m^2/sec of batter, and it has a concave shape to wards the origin of the axis (Figure 3.5). But in general case, thermal diffusivity of the product increased when the moisture content decreased during baking time.

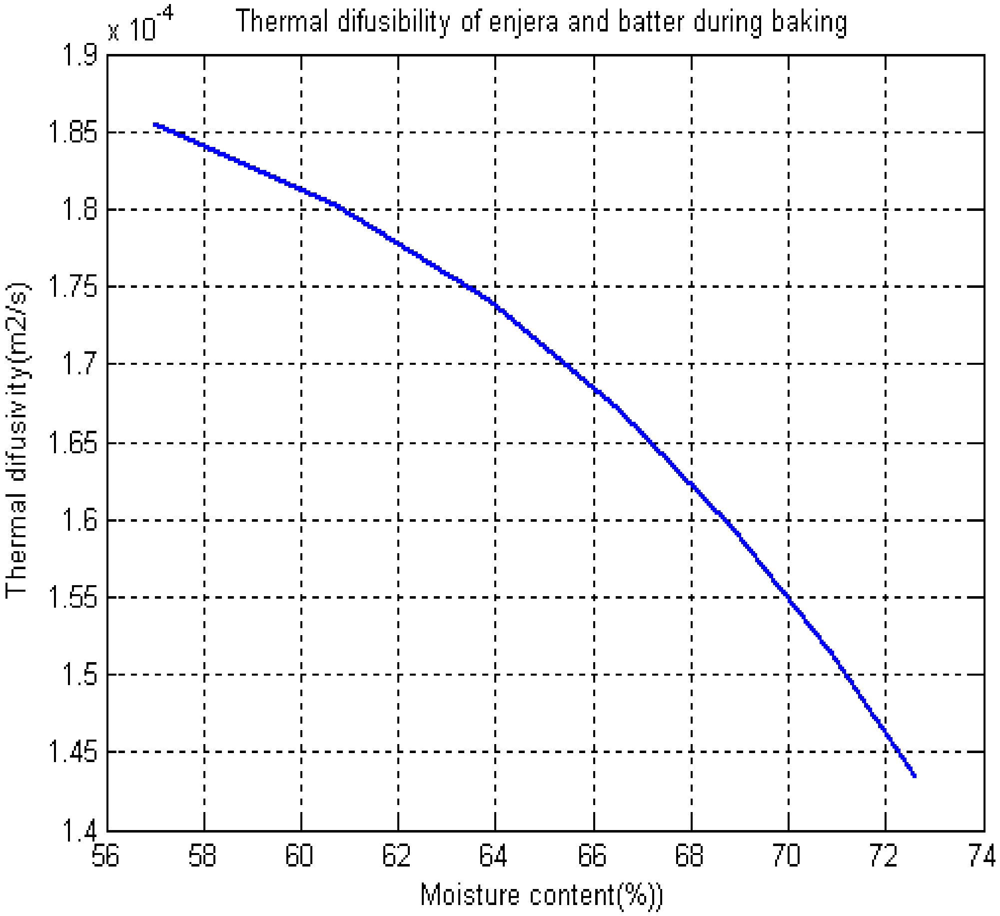


Figure 3.5: Thermal diffusivity of the product with variation of moisture content

3.3 Thermal Properties and Dimension of the Baking Pans

Thermal properties of the baking pans /‘mitad’/ consists of thermal conductivity, emissivity, specific heat capacity, and density. Thermal conductivity of the conventional and improved baking pan is approximately 0.5 W/m.K and 0.98 W/m.K respectively. Diameter and thickness of the pans are physical properties of conventional and improved electric ‘mitad’. Table 3.6 is applicable for all graphical simulations and also for heat transfer analysis of the baking pan. The standard parameters used in the numerical model for most analysis runs are summarized in this section. All simlutions of the model use these parameters unless otherwise specified.

Table 3.6: Thermo-physical properties of enjera, baking pan and its dimensions

Ethiopian Electric Cooking Appliance 'Mitad' Components	**Conventional Property**	**Improved Property**	**Unit**
Cooking plate thickness	0.020	0.008	(m)
Distance b/n plate surface & heating coils	0.015	0.008	(m)
Cooking plate diameter	0.580	0.580	(m)
Specific heat capacity of cooking plate	835	900	(J/kg.K)
Emissivity of upper surface of the plate	0.98	0.94-0.97	----
Conductivity of cooking plate	0. 5	0.98	(W/m.K)
Thickness of the contact b/n cooking plate &lateral sides	0.02	0.008	(m)
Diameter of plate-lateral sides contact	0.65	0.65	(m)
Thermal conductivity of plate-lateral sides contact	0. 5	0.98	(W/m.K)
Emissivity of each sides	0.25	0.24	----
Distance b/n cooking plate and lid cover	0.04	0.04	(m)
Emissivity of the lid cover	0.11	0.11	----
Heat capacity of lid cover	756	756	(J/kg.K)
Thermal conductivity of the product	0.56	0.56	W/m.K
Specific heat of the Enjera	2960	2960	J/kg.K
Density of the Enjera	1175	1175	kg/m^3
Thermal diffusivity of the Enjera	$1.85x10^{-4}$	$1.85x10^{-4}$	m^2/s
Dimention of Enjera	Φ(0.50-0.55) ×(0.005-0.008)	-----	(m)

Where; W – watts, J – Joules, m – meters, s –second, kg –killo gram and K – degrees Kelvin.

CHAPTER FOUR

ANALYTICAL STUDY OF HEAT TRANSFER CHARACTERISTICS OF THE BAKING PANS

Heat can be lost in three directions of the baking pans /'mitad'/. Those are bottom, lateral and top directions of the baking pans which energy dissipates to the environment (or surrounding). Ovens use all three fundamental heat transfer modes; convention, conduction, radiation, and in various combinations. The bottom surface of enjera is heated mainly through conduction and only a little part of the heat is transferred to its upper surface by means of convection and radiation mechanism.

4.1 Heat Loss Coefficient Analysis of the Baking Pans

Heat lost coefficients are the losses that take place by conduction, convection and radiation as shown in the thermal resistance circuit, in Figure 2.4. The heat source of the electric baking pan /'mitad'/ is the current flow through Ni–Cr coil (or wire) that inserted in the bottom side of the baking pan. This is heated due to the resistance and an electric current flow through the wire called ohmic heating.

4.1.1 Top Heat Transfer Coefficient

A. Convective Heat Transfer Coefficient

Heat transfer occurs across the baking pan lid cover by free convection to the sorounding. In many food processing applications, including cooling, transient convective heat transfer occurs between a fluid medium and the solid food item.

I. Heat transfer coefficient from the pan surface to the lid cover

$$h_{1c} = \mathrm{Nu}\frac{k}{L} \tag{4.1}$$

Where, Nu– is the Nusselt number ($\mathrm{Nu} = f$ (Ra, Pr, geometric shape, boundary conditions))

k – thermal conductivity of evaporated water fluid

L – pan to lid cover distance

In order to determine the convective heat transfer coefficient betwen the pan and lid cover, the air properties will be considered at mean temperature between them (Appendix A):

$$T_f = \frac{(T_{lc} + T_p)}{2}$$

$$= \frac{(60+180)}{2} = 120\ ^{o}C$$

Where, T_{lc}- temperature of lid cover (^{0}C) and T_p- temperature of baking pan surface (^{0}C). And this Nusselt number (Nu) is determined from the Rayleigh number (Ra) as follows:

$$Ra = GrPr = \frac{g\Delta T \dot{\beta} L^3}{v^2} Pr \tag{4.2}$$

$$= \frac{9.81 m/s^2 \times (120^{o} c)^{-1} \times 0.000858 \times 0.58^3}{(2.9\times 10^{-7})^2} \times 1.461$$

$$= 2.377\times 10^{8}$$

The Nusselt number (Nu) for horizontal plate (β=0) and uniform surface temperature, the recommended correlation for the heated upper surface is given as follows:

$$Nu = 0.14\times (Ra)^{1/3}, \text{for } 2\times 10^{7} < Ra < 3\times 10^{10} \tag{4.3}$$

$$= 0.14\times (2.377\times 10^{8})^{1/3}$$

$$= 86.729$$

$$h_{1c} = \frac{(86.729\times 0.68)}{0.1}$$

$$= 589.76\ w/m^2 .K$$

II. Heat transfer coefficient from the lid cover to the ambient. This is determined using convention heat transfer coefficient type, Equation(4.1), as given below:

$$h_{2c}=14.8 w/m^2.K$$

B. Radiative heat transfer coefficient

For the baking pans, it was assumed that, it have the same radiating, pan surface area, and also have a unit value of geometric factor. Therefore, the over all coefficients for radiation heat transfer (F_{pr}) are equal to the series emissivity (ε_{eff}) summation of the pan and lid cover.

I. Radiative heat transfer coefficient from the baking pan surface to the lid cover

$$h_{1r} = \varepsilon_{eff}\, \sigma \frac{(T_p + 273)^4 - (T_{lc} + 273)^4}{(T_p - T_{lc})}$$

Where; σ – Stefan Boltzmann constant [$5.67 x 10^{-8}$ $W/m^2.K$],

T_p – surface baking pan temperature

T_{1c} – temperature of lid cover of the baking pans from the appendix (B); and

The effective emissivity of the baking pans is given by:

$\varepsilon_{eff} = [1/\varepsilon_p + 1/\varepsilon_{lc} - 1]^{-1} = 0.11$for conventional baking pan; and

$= 0.099$, for improved baking pan.

The radiative heat transfer coefficients of conventional and improved pan are determined as:

$$h_{1r,Conventional} = 0.11 \times 5.67x10^{-8} \frac{(180 + 273)^4 - (61.15 + 273)^4}{(180 - 61.15)}$$

$=1.553 w/m^2K$, and

$$h_{1r,Improved\ pan} = 0.099 \times 5.67x10^{-8} \frac{(160 + 273)^4 - (59.15 + 273)^4}{(160 - 59.15)}$$

$=1.40 w/m^2K$

II. From lid cover to ambient or surrounding

The sky temperature or (temperature of the surrounding) (T_{sky}) given by:

$T_{sky} = Ta - 6 = 15^oc$

And the radiative heat transfer coefficient is expressed as:

$$h_{2r} = \varepsilon_{lc}\, \sigma \{\frac{(T_{lc} + 273)^4 - (T_{sky} + 273)^4}{(T_{lc} - T_a)}\}$$

$$= 0.11x\, 5.67 \times 10^{-8} \{\frac{(61.14 + 273)^4 - (15 + 273)^4}{(61.14 - 21)}\}$$

$= 0.866\ w/m^2K$

The total effective top heat transfer coefficient from pan surface to the ambient is given as:

$$U_t = [\frac{1}{h_1} + \frac{1}{h_2}]^{(-1)}$$

Where; $h_1 = h_{1c} + h_{1r}$ $=591.31\ W/m^2\ K$, and

$$h_2 = h_{2c} + h_{2r} = 15.866 \text{ W/m}^2 \text{K}$$

$$U_t = [\frac{1}{591.31} + \frac{1}{15.866}]^{(-1)}$$

$$= 15.45 \text{ W/m}^2\text{k}$$

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

$$\dot{q} = Ut\ (T_p - T_{lc})$$

$$= 1854.63 \text{ W/m}^2$$

For a given diameter of the baking pans has similar value as shown below:

$$\dot{q}_{\text{Loss,Top Side of Conventional}} = \dot{q}_{\text{Loss,Top Side of Improved}}$$

$$= 490.32\text{W}$$

This heat transfer rate (490.32W) might not be considered as energy loss from the baking pan completely because it includes an energy absorbed by the product (or latent energy evaporation from the product to the ambient). Hence, the heat loss occurs during the heating up and between consecutive baking cycles.

4.1.2 Bottom Heat Transfer Coefficient

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

$$U_b = \left[\sum \frac{t_{in}}{K_{in}} + \frac{1}{h_b}\right]^{-1}$$

And convection and radiation heat transfer coefficient from the bottom casing surface to the ambient is given as follows:

$$h_b = h_{r,b} + h_{c,b}$$

Where; $h_{2r} = \varepsilon_{lc}\, \sigma \{\frac{(T_{lc} + 273)^4 - (T_{sky} + 273)^4}{(T_{lc} - T_a)}\}$

$$= 0.10 \text{x}\ 5.67 \times 10^{-8}\ \{\frac{(120.18 + 273)^4 - (15 + 273)^4}{(120.18 - 21)}\}$$

$$= 9.624 \text{ W/m}^2\text{.K}$$

And, $h_{c,b} = 11.8\text{W/m}^2\text{.K}$, this is determined using Equation (4.1)

$$h_b = h_{r,b} + h_{c,b} \approx 20\ \mathrm{W/m^2.K}$$

Then the back loss coefficient formula and its analytical value as shown below:

$$U_{b,\text{conventional pan}} = \left[\frac{t_{\text{insulated}}}{K_{\text{insulated}}} + \frac{1}{h_b} + \frac{t_{\text{gyp}}}{K_{\text{gyp}}} + \frac{t_{\text{plate}}}{K_{\text{plate}}}\right]^{-1}$$

$$= \left[\frac{0.01}{0.3} + \frac{1}{20} + \frac{0.004}{0.13} + \frac{0.004}{40}\right]^{-1}$$

$$= 11.62\ \mathrm{W/m^2.K}$$

The thickness of improved baking pan is around 8 mm; and has 4 mm grooved conventional pan underneath it. Because ceramic pan was hard to groove in order to insert and hold an electrical resister. Since the two pans have different thermal resistance, then cooking plate with a low thermal resistance will deliver large amounts of heat to the baking pan surface. There fore, the insulation of material of improved baking pans is conventional pan and primitive dried mud.

$$U_{b,\text{improved pan}} = \left[\frac{t_{\text{insulated}}}{K_{\text{insulated}}} + \frac{t_{\text{conv. pan}}}{K_{\text{conv.pan}}} + \frac{1}{h_b} + \frac{t_{\text{plate}}}{K_{\text{plate}}}\right]^{-1}$$

$$= \left[\frac{0.02}{0.3} + \frac{0.16}{0.5} + \frac{1}{20} + \frac{0.006}{40}\right]^{-1}$$

$$= 6.8\mathrm{W/m^2.K}$$

4.1.3 Edge/Lateral heat Transfer coefficient

Energy lost from the lateral side of the baking pan casing may be taken to have similar value with the bottom side of the baking pan if the thickness and area of the edge insulation has the same to that of back (or bottom) insulation. But they have different thickness and area.

$$U_{e,\text{conventional pan}} = \left[\frac{t_{\text{in}}}{K_{\text{in}}}\ \text{clay} + \frac{t_{\text{in}}}{K_{\text{in}}}\ \text{insulation} + \frac{t_{\text{plate}}}{K_{\text{plate}}}\right]^{-1}$$

$$= \left[\frac{0.02}{0.5}\ \text{clay} + \frac{0.03}{0.3} + \frac{0.006}{200}\right]^{-1}$$

$$= 7.15\ \mathrm{W/m^2K}$$

$$U_{e,\mathrm{Improved}} = \left[\left[\frac{K_{in}}{t_{in}} \mathrm{clay} + \frac{K_{in}}{t_{in}} \mathrm{improved} \right]^{-1} + \frac{t_{in}}{K_{in}} \mathrm{insulation} + \frac{t_{plate}}{K_{plate}} \right]^{-1}$$

$$= \left[\left[\frac{0.5}{0.016} + \frac{0.98}{0.008} \right]^{-1} + \frac{0.03}{0.3} + \frac{0.004}{200} \right]^{-1}$$

$$= 9.25 \mathrm{W/m^2.K}$$

Where; t_{in}= 2cm and K_{in}= 0.5 W/m2.K for the conventional clay pan

t_{in}= 8mm and K_{in}= 0.98 W/m2.K for the improved pan

t_{in}= 6cm for bottom side, t_{in} =3cm for lateral side and K_{in}= 0.3 W/m^2.K for the primitive dried mud insulation

4.1.5 Over all Energy Transfer Coeficient of the Pans

Over all energy loss 'Q_L' is the sum of the top, bottom and edge energy lost. The over all heat loss percentage for 15 number of enjera baking per cycles of conventional and improved electric 'mitad' to the suorounding was arround 48% and 23%; and the energy lost was around 6.8 MJ and 2.85MJ respectivly. From the total energy loss, around 70% - 85% heat was dissipated by the bottom side of the baking pans. For electric 'mitad', the clay-plate type has an efficiency value about 25% lower than that of the ceramic plate. And the improved electric 'mitad' type used 30% less energy demand than the conventional 'mitad' type.

4.2 Energy Flow Diagram of the Baking Pans

Based on the experimental result, the energy flow diagram shows that the greatest energy loss of conventional and improved baking pans occur at the bottom of the system by 35.08% and 23% and the thermal efficiency of the enjera baking pans was estimated to be about 52 % and 75 % respectively. Even though the efficiency of improved electric 'mitad' had higher than the conventional one but still there was high energy loss due to poor insulation material as shown in the energy flow diagram (Figure 4.1 and 4.2). This diagram shows that energy flow for 15 numbers of enjera baking per cycle. The last enjera was baked with out power input; which helps to decrease the energy loss and retains (or accumlation) in the baking pans.

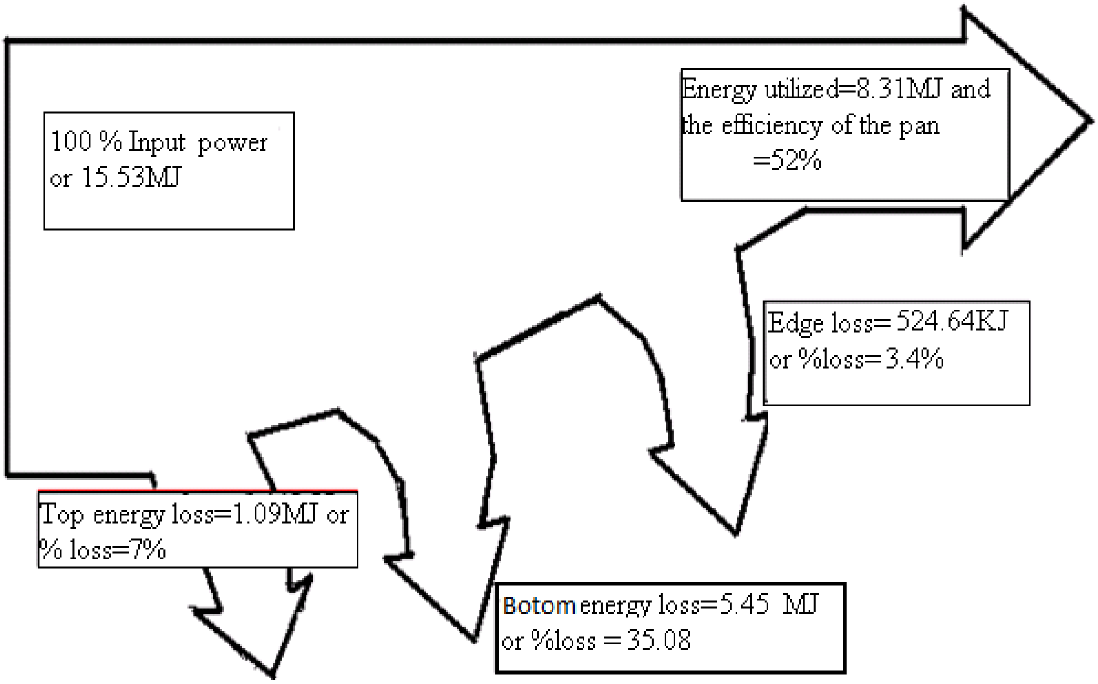


Figure 4.1: Energy flow diagram of conventional baking pan during 15 enjera baking per cycles

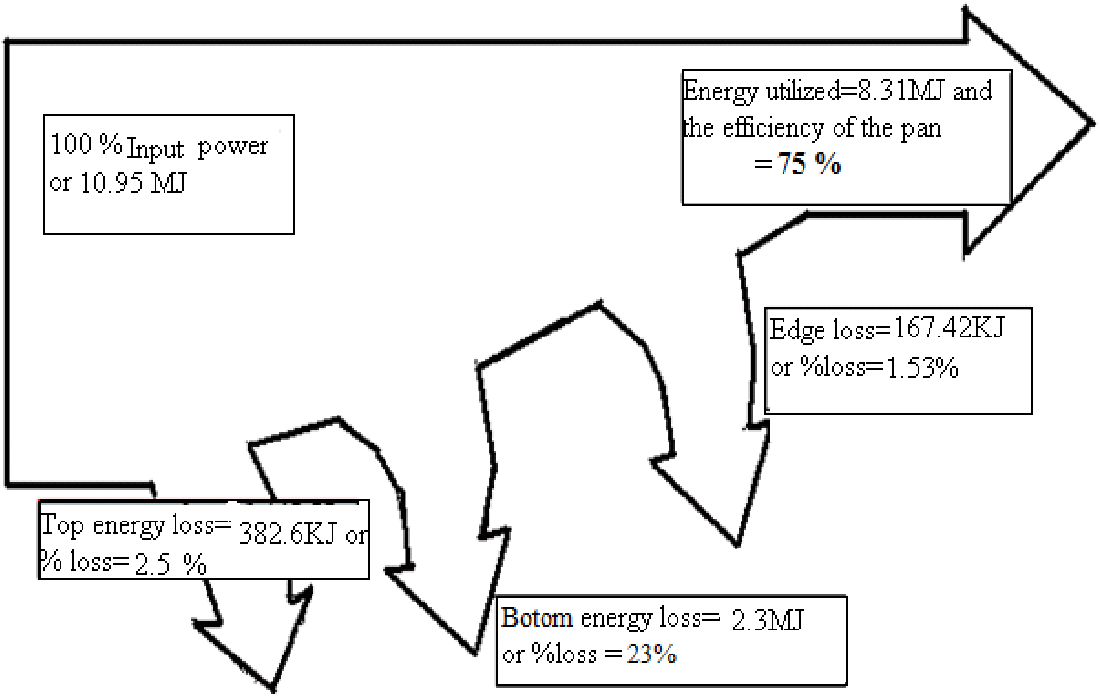


Figure 4.2: Energy flow diagram of improved baking pan during 15 enjera baking per cycles

4.3 Heat up Temperature Simulation of the Baking Pans Using FDM

A typical Finite Difference Method (FDM) during heat up simulation of the electric 'mitad' is given in the Figure (4.6 and 4.7).

4.3.1 Initial and Boundary Conditions

Initial Conditions:

The initial temperature of injera baking pan /'mitad'/ is uniform and equal to the determined initial value.

$$T_{(r,\, z,\, 0)} = T_{\text{Ambient}} = 20^0\text{C}$$

Boundary Conditions:

The general boundary conditions for the electric baking pan on the top, lateral and bottom surfaces are described as follows [9, 22].

- The amount of heat passing in to the body and the heat loss from (or to) the surface depending on the temperature gradient of the surface of the baking pan.

$$k\frac{\partial T}{\partial n} + h_c\,(T - T_a) + h_r\,(T - T_a) = 0$$

Where; h_c –is convective heat transfer, h_r –is radiation heat transfer,

k–is thermal conductivity of the pan, T –is pan surface temperature and

T_a– is ambient temperature.

The first term $(k.\partial T/\partial n)$ is the amount of heat passing in to the body (or pan), the second term $(hc(T - Ta))$ and the third term $(hr(T - Ta))$ are the heat loss from (or to) the surface.

- At the bottom and lateral surfaces of electric baking pan, the boundary condition is:

$$-(k\frac{\partial T}{\partial n})_{(r,0,t)} = h_{C2}\, x\, (T - T_\infty)$$

- The electrical heating coil is heat generation load at bottom side of the system.

Symmetry Conditions

- The temperature is axis symetric. Hence the temperature varies only in axial direction or along the thickness. The loading (heat flux from heating coil) is symetric.

4.3.2 Improved Baking Pan

Heat up temperature history of the improved electric baking pan /'mitad'/ shows that from ambient to pan surface temperature (or 180 ^{0}C, before it starts to bake). To achieve 160 ^{0}C –180 ^{0}C of the improved baking pan surface temperature it needs around 1080 –1200 second. And the electric power density was around 9.08 kW/m^2 of the pan surface area.

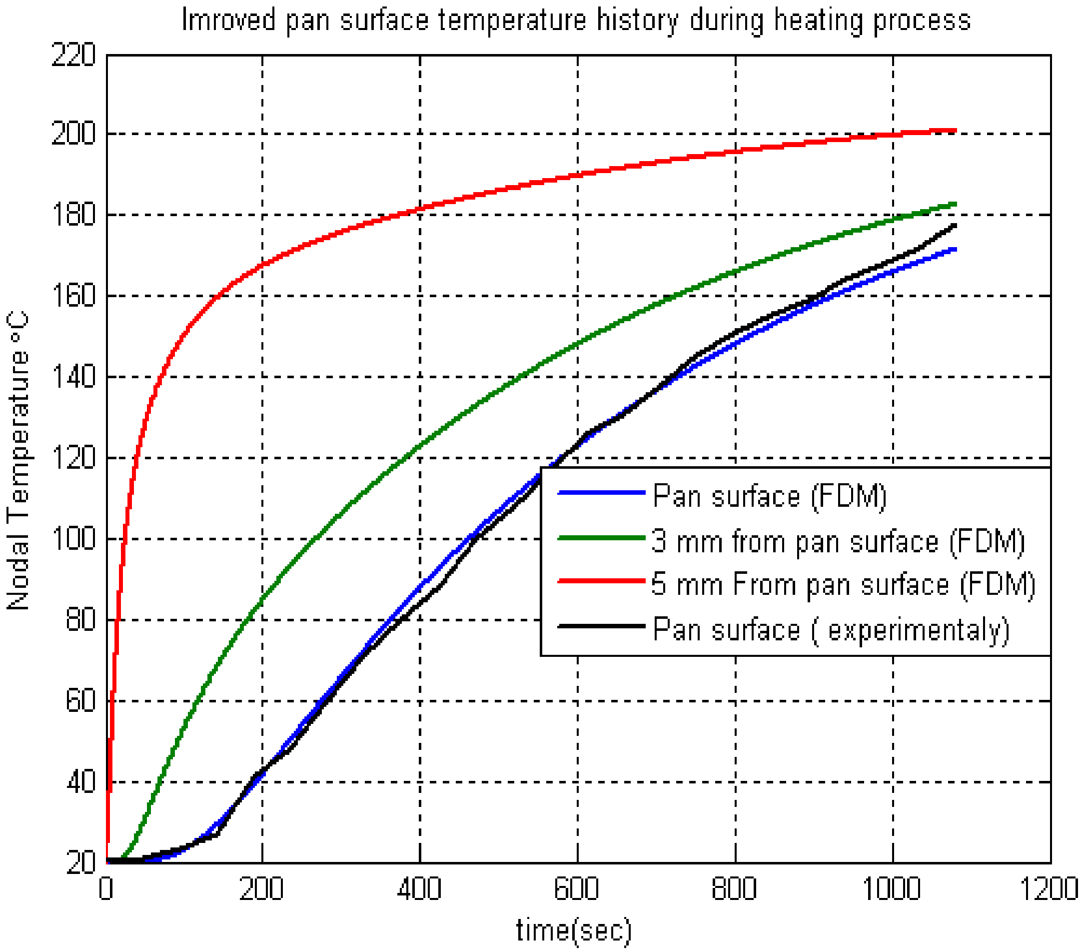


Figure 4.3: Heat up temperature history of improved baking pan using FDM

The effective surface temperature of the baking pan were compared using FDM (Finite Difference Method) and experimentally, as shown in Figure 4.3. So, the temperature variation at the surface during heat up was in a good agreement with the experiment. The temperature only varies in axial direction or along the thickness of the pan.

4.3.3 Conventional Baking Pan

Heat up temperature history of the conventional electric 'mitad' shows that from the ambient temperature to the baking pan surface temperature (180 ^{0}C - 200 ^{0}C), it takes around 760 - 850 second, as shown in Figure 4.7. The electric power density was 12.86 kW/m^2 of the pan surface area of the conventional electric 'mitad'.

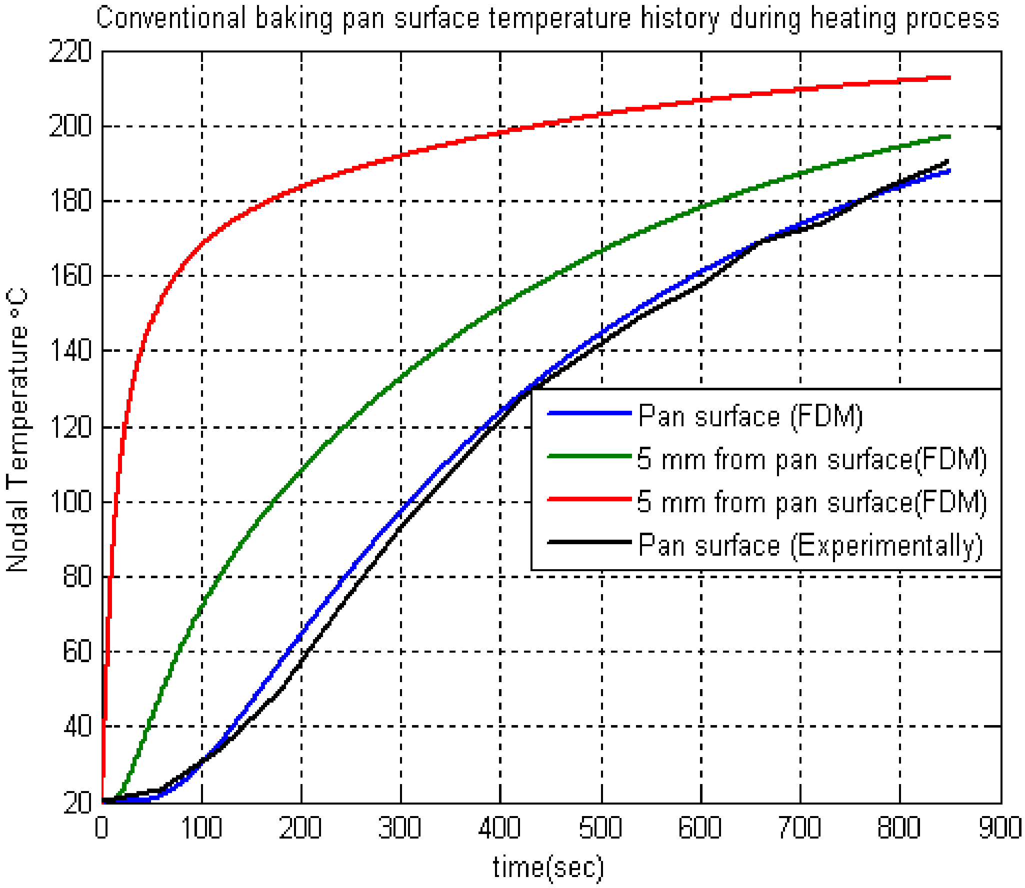


Figure 4.4: Heat up temperature history of conventional baking pan using FDM

Although the conventional electric 'mitad' heating time was lower than improved electric 'mitad', the power demand was greater by 30%.

4.5 Power Estimation and Distribution in Electrical Powered Baking Pan

By selecting the length of resistance wire 12m for R09, 11m for R08 and 10m for R07 we can estimate R and the respective power P as follows:

P_{R07}=1.86kW,

P_{R08}=2.2kW and

P_{R09}=2.5kW.

The power demand for R07 type is small and most of the time it is not used for locally manufactured electric injera baking pan. The power consumption in each loop using different resistances of the pans. The conventional and improved electric 'mitad' has 12 loops and the power density has 12.86 kW/m^2 and 9.08 kW/m^2 respectivly.

It is clear that the power is directly proportional to the length of the heating coil. Thus, the power supply for the ith loop represents as follows:

$$P_i \propto \text{length of wire loop}\text{ , and}$$

$$\text{length of wire loop} \propto r_i$$

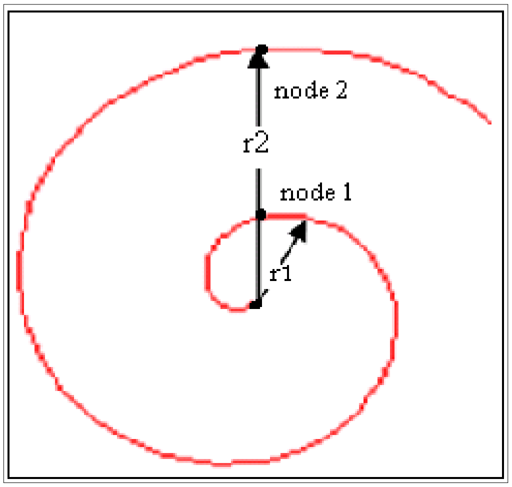


Figure 4.5: The image of helical coil that is inserted in the back side of the baking pan

The perimeter of the helical wire for one loop is calculated as follows (Figure 4.5):

$$\text{length of the loop} = \text{perimeter of the loop}$$

$$= 2\,\pi\,\frac{(r_1 + r_2)}{2}$$

There are 13 nodes or points to interconnect the 12 helical loops. There fore, the length of each loop depends on the radius of each node as follows:

$$\text{perimeter of each loop} = 2\pi \frac{(r_i + r_{(i+1)})}{2}$$

And the power of loops is as a function of radius of the nodes, as shown below:

$$P_j = \frac{2\pi P \frac{(r_i + r_{(i+1)})}{2}}{L_t}$$

Where; P_j – each power of the loops,

p – the power of the total wire length,

i=1, 2, 3...13, number of nodes in the connection of loops and

L_t – total length of the helical wire of the baking pan.

A. Power Distribution of Conventional Electric ‘Mitad’ Using Experimental Analysis For Each Loops

P1=23.61W;

P2=70.833W;

P3=118.056W;

P4=165.278W;

P5=212.5W;

P6=259.72W;

P7=306.944W;

P8=354.167W;

P9=401.389W;

P10=448.64W;

P11=495.833W;

P12=543.056W.

B. Power Distribution of Improved Electric ‘Mitad’ Using Experimental Analysis For Each Loops

P1=16.67W;

P2=50W;

P3=83.33W;

P4=116.67W;

P5=150W;

P6=183.33W;

P7=216.67W;

P8=250.0W;

P9=283.33W;

P10=316.67W;

P11=350W;

P12=383.33W;

CHAPTER FIVE

EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF CONVENTIONAL AND IMPROVED ENJERA BAKING PAN /‘MITAD’/

5.1 Experimental Test Equipments and its Procedure

The equipments used for the experimental tests in this paper are discussed as follows:

5.1.1 Digital Mass Balance

A mass balance was used for weight. Objects to be weighed were placed on the balance pan and the mass noted from the digital display. Buttons at lower right allow options such as zeroing the scale before weighing an object.

Figure 5.1: Digital mass balance

5.1.2 AMB Moisture Balance

The AMB moisture balance is a precision weighing scale for determination of moisture content in small samples of materials by drying the sample with halogen heaters. The test begins by pressing the button on/off switch. After a few minutes the moisture increases or decreases according the input mode. After some time the % of the moisture will become stable for a long period of time, terminate the test at this time.

(A) (B)

Figure 5.2: Moisture content measurement **(**A) AMB 310 moisture balance (B) sample holder

5.1.3 Multi meter and Infrared Thermometer

It can measure current flow, resistance and voltage. These parameters help us to determine the total power input of the baking pans. Infrared thermometer with ‘K’ type probe was used to measure the surface temperatures of injera baking pan and room temperature.

Figure 5.3: Multi meter current flow, resistance and voltage logger

5.1.4 PC with Microsoft Excel, Matlab, and Lab View

Lab View software program was stored and written in Excel program data sheet applications for printing data sheets, analyzing run data, and comparing runs by using Excel software. Its programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as thermocouple and multi meters. Lab View contains a comprehensive set of tools for acquiring, analyzing, displaying, and storing data, as well as tools to help us troubleshoot code we write.

Figure 5.4: Experimental set up of thermocouples during heating up and cyclic injera baking process

5.2 Heating up Time Taken, Power Consumption and Temperature of the Pans

A data logger supported by Lab View software was used for temperature logging while a multi-meter was used for power input measurement of the baking pans. The time requirement of the pans varies according the energy input, which were 850 seconds for high power input of the conventional pan and 1080 seconds for low power input of the improved baking pan.

5.2.1 Standard / Conventional/ Electric 'Mitad'

Based on the experiment, the time taken to heat up the conventional electric 'mitad' was varied from 13-15 minutes. Conventional electric 'mitad' had the heating rate of 15^0C/min during the heating-up time. The average surface temperature of the baking pan before the start of baking was around 180^0C-200^0C, as shown in the Figure 5.5.

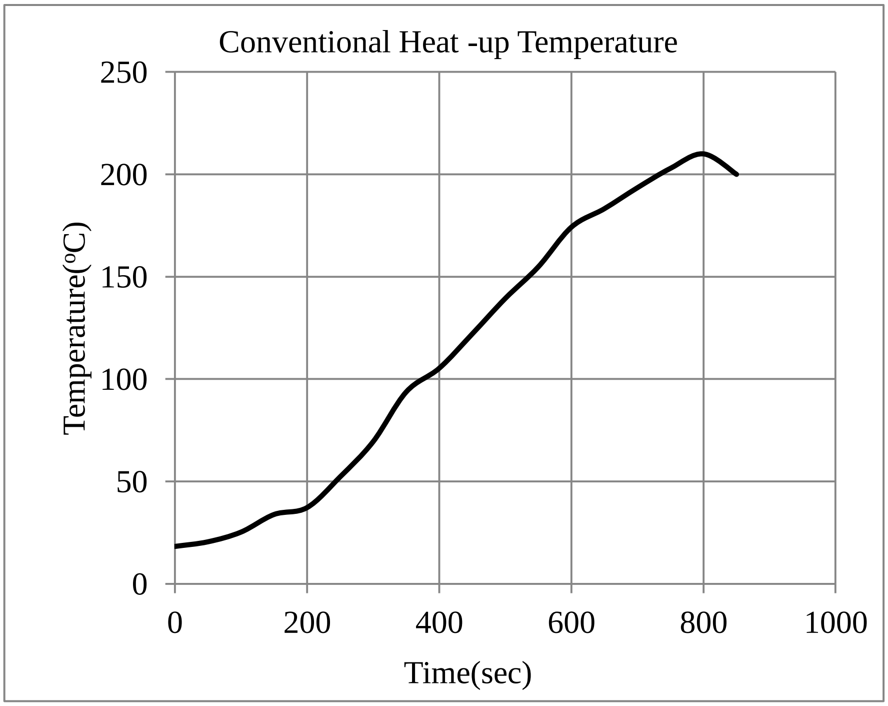


Figure 5.5: Heat up temperature profile of conventional baking pan /'mitad'/

The current flow in the conventional electric baking pan /'mitad'/ varies from the higher to lower value until the pan was heated up (Figure 5.6). According to the data logged (current versus time), the formula for heat up time using regression line is given as follows:

The variation was given by:

$$I(t) = 10^{(-0.000921 \times \log(t) + 1.24784)} \tag{5.1}$$

The average heating up power and energy requirement for the baking pan was around 3.5kW and 3.3MJ respectively. The current decreased from 17.55A to 16.32A within the 15 minutes (Figure 5.6). During the baking process, the current flow almost oscillated in one point.

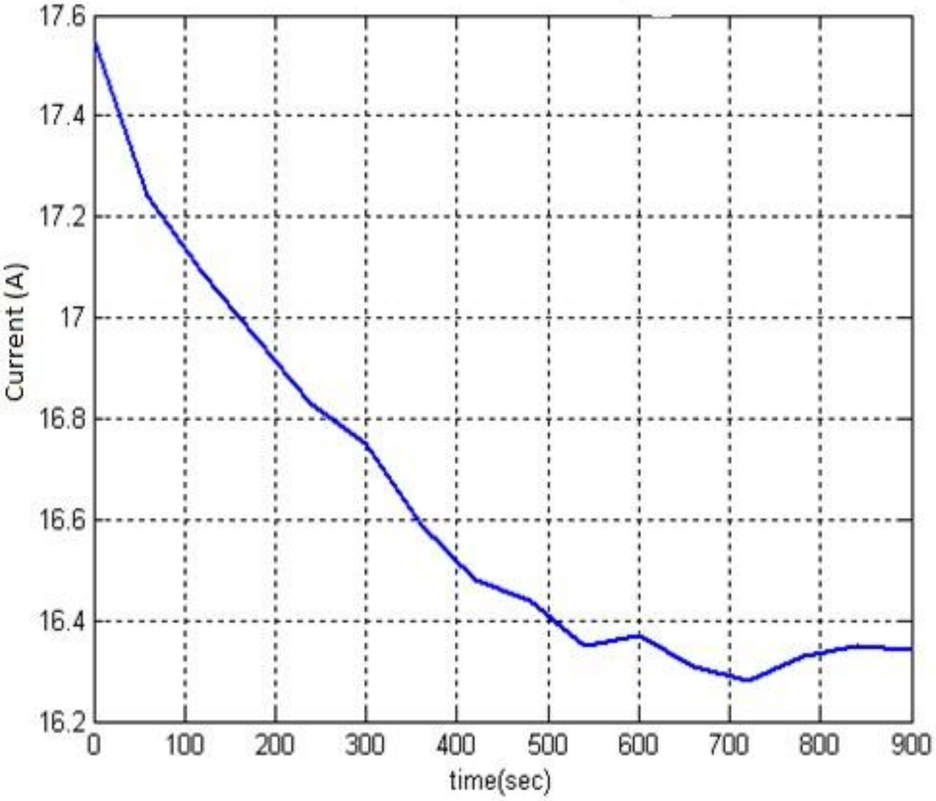


Figure 5.6: Current flow during heat-up of a conventional baking pan

The total electrical energy determination formula for conventional baking pan at the time (t) is:

$$E = V\,I(t)\,t \tag{5.2}$$

The power is the derivative of energy for the variation of current flow in the time of heat up,

$$P = \frac{dE}{dt}$$

$$P = (1 - 0.00921)\,V\; I(t) \tag{5.3a}$$

After the pan is heated up, there was almost a constant current flow from the power source; which means the power of baking pan is the product of current and voltage (220V).

$$P_{baking} = V \ I_{baking} \tag{5.3b}$$

Total energy and power consumption of the standard baking pan, 2cm thickness and 58 cm diameter, was determined as shown in Equations (5.5 and 5.6). Assuming in Ethiopian household an average of 15 enjera baked per cycle, the total time required was around 4260 sec as determined by equation:

$$t_{total}(sec) = t_{heatup}\ (sec) + n\, t_{baking}\ (sec) + (n-1)\, t_{gap}\ (sec) \tag{5.4}$$

$$= 860 \text{ sec} + 15\times 200 \text{ sec} + 14\times 30 \text{ sec}$$

$$= 4260 \text{ sec}$$

Where; $t_{heat\ up}$ – time taken during heat up

n– number of enjera baked

t_{baking} – time taken during one enjera baking (160-200 sec)

t_{gap}– time taken among two consecutive enjera baking (30 sec)

The total energy intensity (Q) required per one cycle /or period/ is as follows:

$$q_{total}(J) = q_{heatup}\ (J) + n\, q_{baking}\ (J) + (n-1)\, q_{gap}\ (J) \tag{5.5}$$

$$= 3.3\text{MJ} + 10.5\text{ MJ} + 1.73\text{MJ}$$

$$= 15.53 \text{ MJ}$$

Where; $q_{heat\ up}$ – energy cosumption during heat up

q_{baking} – time cosumption during one enjera baking

q_{gap}– time cosumption among two consecutive enjera

n– number of enjera baked

And an average power required for the conventional baking pan determined using the experimental result as follows:

$$P = \frac{(3.53\text{kW}\ t_1 + 220\text{V} \times 16.25\text{A}\ t_2)}{2\ (t_1 + t_2)} \tag{5.6}$$

$$= \frac{(3.53\text{kW} \times 850\text{sec} + 220\text{V} \times 16.25\text{A} \times 3420\text{sec})}{2 \times (850\text{sec} + 3420\text{sec})}$$

$$= 12.86\ \text{kW/m}^2$$

Where; t_1 - the time taken during heat up time

t_2 - the time taken during 15 enjera baking

For the given diameter of the baking pans, the power density varies from 12-14 kW /m^2. Even though the diameter of the pan was 58cm, the effective diameter of the pan was 55cm.

5.2.2 Improved Electric 'Mitad'

The time taken for the average heat up temperature (180^{o}C) of a new improved electric 'mitad' was around 18-20 minutes. Although the improved enjera baking stoves /'mitads'/ took long time to heat up, they retained heat well once they are heated. This property was useful for slow cooking food.

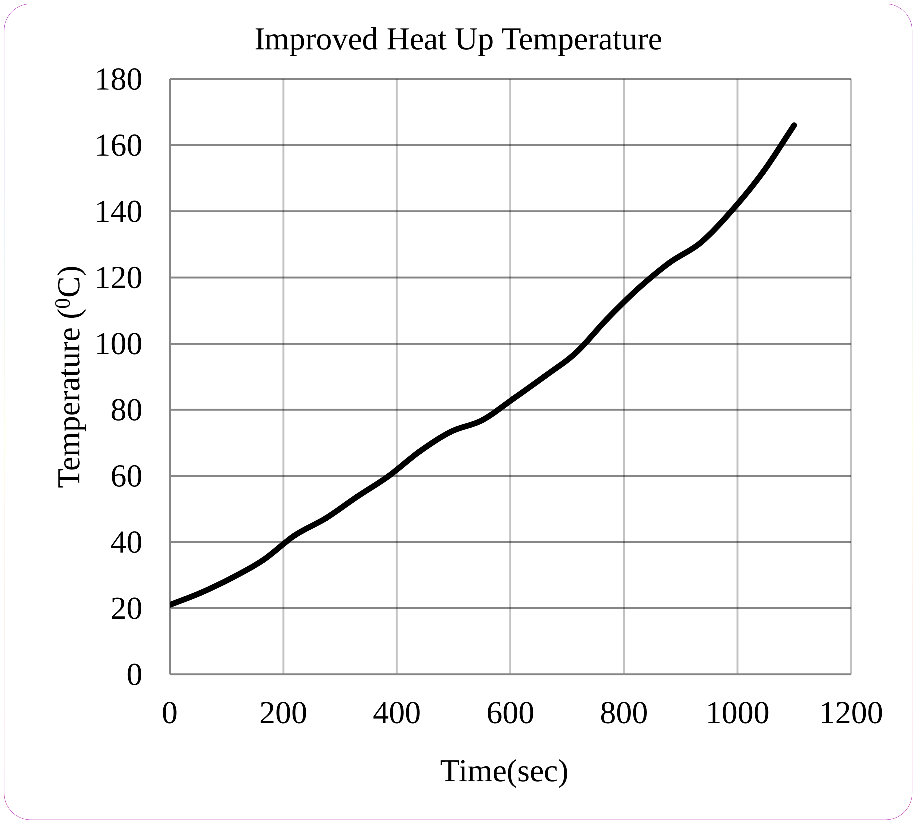


Figure 5.7: Heat up temperature logging of improved baking pan

Improved baking pan had the heating rate of 9.03^{0}C/min during heated up time. The power density, during heated up and baked enjera, was around 9.08 kW/ m^2. The current flow, during and after heated up, was almost constant as given in Figure 5.8. The average current flow and power consumption of the baking pan was 10.91A and 2.4kW respectively.

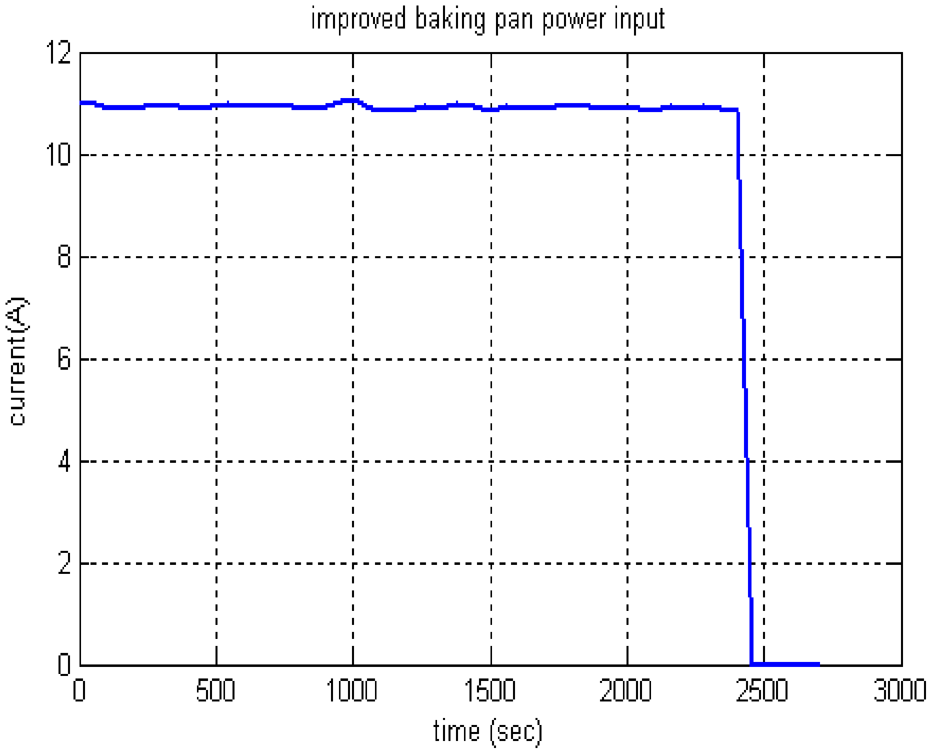


Figure 5.8: Current flow of improved baking pan during heat up and baking system

Based on the experiment, except the heated up time (ranges 1080-1200 sec), the time taken for each enjera baking and idle time were equivalent with conventional baking pan. Based on the Equations (5.4 and 5.5), total time taken and energy required for improved baking pan was around 4540sec and 10.92MJ respectively.

5.3 Performance Comparison of the Baking Pans

To compare the efficiency of each electric 'mitad' there are two key parameters, these are total and utilized energy intensities. In this baking experiment, the total energy consumption by different types of the baking pans was compared to the actual energy utilized intensity.

A. Total Energy Intensity

Energy intensity is the total amount of energy used to bake one kilogram of enjera. It includes both the actual energy utilized in baking enjera and the energy which is lost during baking. Total energy intensity or input energy of the baking system decreased as the solid content of batter increased (Figure 5.9).

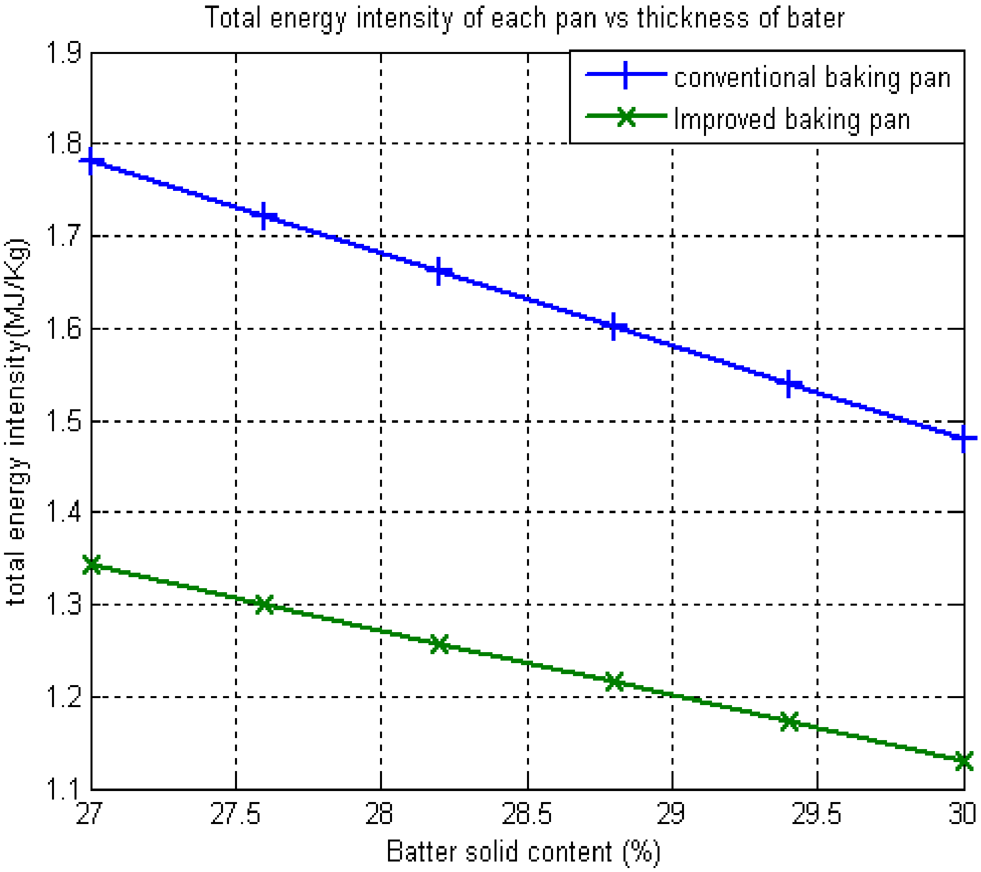


Figure 5.9: Total energy intensity of the product Vs solid content of enjera batter

Total energy intensity of conventional baking pan was higher than improved baking pan. The difference in energy intensity among the baking pans, at any solid content of the batter, was around 0.43 MJ/Kg; this value indicated that there was energy wastage in the conventional baking pan. The performance of the baking pan can be increased by 23%, for 15 numbers of cycles, if the energy consumption of conventional baking pan was minimized by 0.43kJ/gm.

B. Utilized Energy Intensity

The heat supplied to the enjera was used for raising the temperature of the batter from room temperature (20^0C to 25^0C) to the boiling point of water (in Addis Ababa, about 92.3^0C). Considering the gross temperature rise of the product (sensible heat increase) and the latent heat of vaporization of evaporated moisture content, the useful energy (q_{useful}) which was actually used for baked one kilogram of enjera can be expressed as follows:

$$q_{useful} = m_{batter}\ c_p\ (T_{pt} - T_b) + m_w\ h_{vaporization}$$

$$= 0.581\text{kg} \times 2960\text{J/kg.k} \times (92.3^{o}\text{C}-20^{o}\text{C}) + 0.167\text{kg} \times 2530\text{kJ/kg}$$

$$= 0.554\text{MJ /enjera}$$

Where; m_{batter} – is an average mass of the batter, kg; c_p – average heat capacity, kJ/kg k;

T_b – the teff fermented flour (or batter) temperature, ^{0}C;

T_{pt} – is the product surface temperature, ^{0}C;

m_w– the moisture loss during baking, kg; and

$h_{vaporization}$ – is the latent heat of water evaporation, kJ/kg.

The total energy used for 15 number of enjera per cycle:

$$q_{total} = n\, q_{useful} = 8.313\text{MJ}$$

C. Efficiency of the Baking Pans

Cooking energy efficiency is controlled by two prameters. Those are how heat is imparted to the food and how heat loss is controlled. The efficiency of improved eletric 'mitad' was higher than conventional enjera baking pan (Table 5.1).

$$\eta_{baking\ pan} = \frac{q_{total}}{q_{input}}$$

Where, q_{input} – total energy input to the electric mitad and

q_{Useful}- useful energy which absorbed to the product

Table 5.1: Performance experimental result of each electric 'mitad'/

Test no.	Efficiency of the baking pans %, (15 number of enjera)	
	Conventional cooking appliance	Improved cooking appliance
1	52.6	74.4
2	51.1	73.7
3	53.3	76.8
Average	52.0 %	75.0 %

The efficiency of improved enjera baking pan was given in Table 5.1 in comparision with conventional electic mitad. The results show the efficiency improvement was around 23%, which means the house hold energy consumption can be drastically reduced by 31-32%.

5.3.1 Performance Increment Options of the Baking Pans

I. Solid Content of the Batter

As the density of the batter increased, the energy required to baking the product decreased; because small amount of water evaporated during baking process. As a result, the efficiency of enjera baking pan also increased (Figure 5.10). However, the optimum solid content of the batter has to be determined from enjera quality.

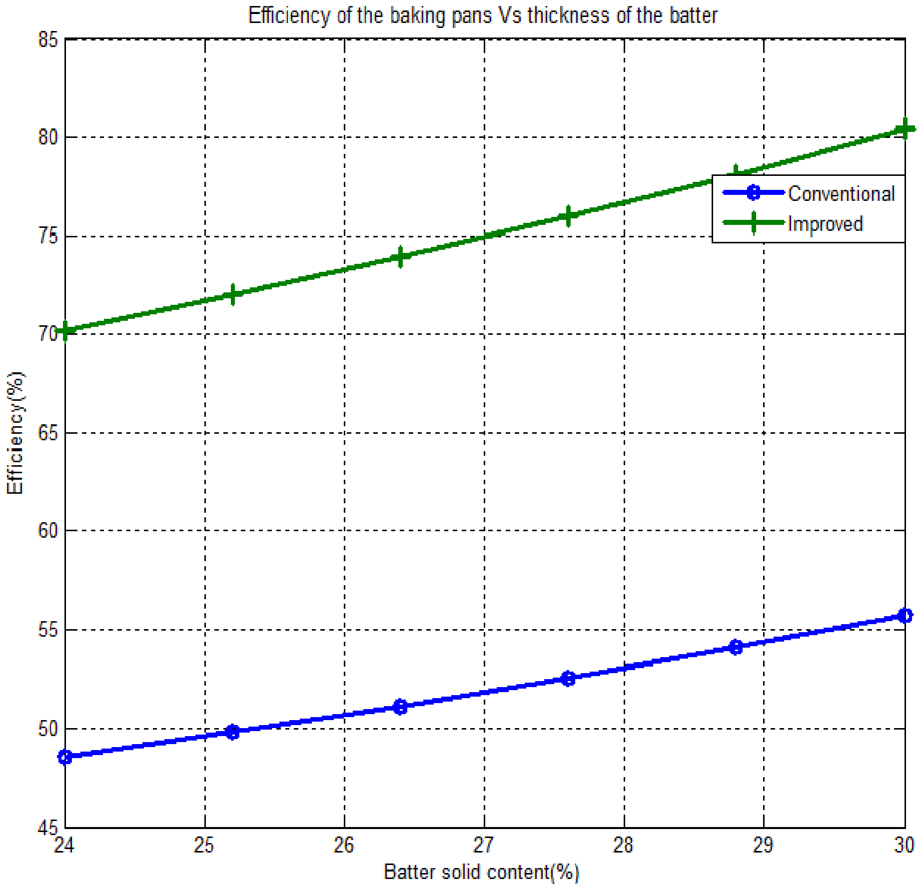


Figure 5.10: Efficiency of each electric baking pan /‘mitad’/ vs solid content of batter

II. Number of Enjera Baked per Cycle

The efficiency difference between the two pans has direct relation with the number of enjera baked per cycle. This means that, when the number of enjera baked per cycle increased from 5 to 20, and then the efficiency difference increased from 15% to 26% as shown in experimental simulation Figure 5.11.

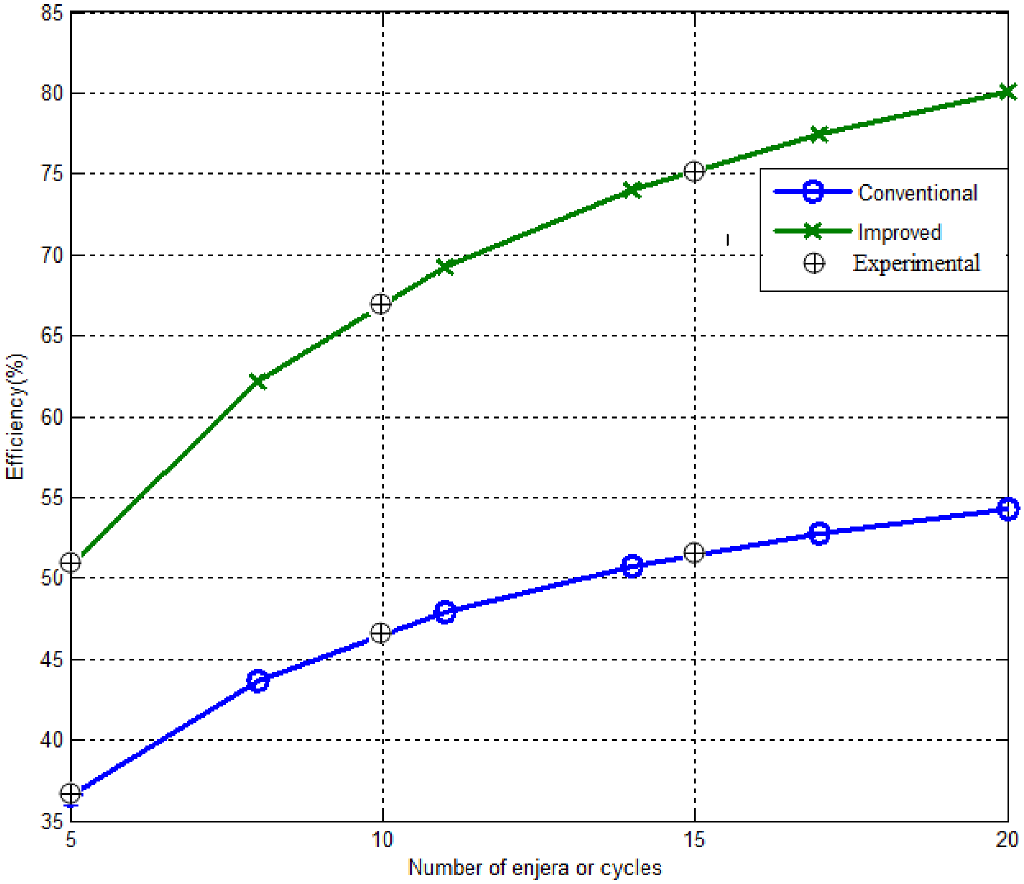


Figure 5.11: Efficiency of each electric baking pan /'mitad'/ Vs number of enjera

Preheat time is the time required to raise the pan surface temperature from room temperature to baking temperature. Preheat energy consumption of the baking pan was around 20-25% for 15 enjera baking per cycle. Therefore, in order to minimize the percentage of preheat energy consumption and to increase overall efficiency, it was better to bake more than 20 enjera per cycle. Finally, avoiding opening the lid covers while preheating the baking pans. If the lid cover was opened, the over all heat loss increased.

CHAPTER SIX

ECONOMIC ANALYSIS AND COMPARISON OF IMPROVED AND CONVENTIONAL ELECTRIC ‘MITAD’

6.1 Energy Economic Analysis

Energy economic analysis is used to compare the improved and conventional electric ‘mitad’; because they have different one-time (initial investment cost) and multiple-time (annual energy consumption) costs. Energy management in electric ‘mitad’ is typically justified in terms of keep away from energy costs. For improved electric ‘mitad’, expenses come at the beginning of the project, while saving/benefits occur later (Figure 6.1 and 6.2). Low energy consuming equipment has a greater initial investment than the higher energy consuming one. In order to compare them, time value of money and discounted cash flow analysis are important [8].

6.1.1 Present Worth Analysis of the Baking Pans

The most common techniques for comparing two or more alternatives using net present worth ‘PW’ method are present value, internal rate of return and life cycle costing.

A. Present Value (PV)

This is the value of ‘PV’ in the present received ‘A’ amount of money annually in ‘n’ year. Total present value is mathematically defined as follows:

$$PV = \frac{A}{(1+i)^n} \tag{6.1}$$

Where; i– interest rate on investments,

A – Annual operating cost

n – Number of year

B. Net Present Value (NPV)

Net present value (NPV) –is defined as the sum of the present values (PVs) of the individual cash flows of the same entity.

$$NPV = A\frac{(1+i)^n - 1}{i(1+i)^n} + CI \qquad (6.2)$$

Where; CI–Annual operating cost

i– interest rate on investments(for $i \neq 0$)

6.2. Cost Analysis of the Baking Pans

6.2.1 Initial Investment of Conventional and Improved Electric ‘Mitad’

Initial investment of the conventional and improved electric ‘mitad’, which includes the components and labor cost of the baking pans, are determined in Tables (6.1and 6.2).

Table 6.1: Initial investment analysis of conventional electric ‘mitad’

No	Type	Size (mm)	Req. No.	Cost (Birr)
1	Clay pan	Φ580	1	40
2	Lid cover	540x650	1	87.75
3	Side sheet metal	100x2041	1	36.738
4	Bottom sheet metal	Φ649	1	76.05
5	Heating coil	10000-12000	1	35
6	Switch OFF/ON	------	1	65
7	Vertical support Ferro	Φ16x650	4	58.50
8	Horizontal support Ferro	Φ8x650	8	32.50
9	Gypsum insulation	------	------	50
10	Circular pan seating	25x650	1	13.00
11	Labor cost	------	------	200
				Total Cost = 694.54 Birr

Table 6.2: Initial investment analysis of improved electric ‘mitad’

No	Type	Size(mm)	Req. NO	Cost(Birr)
1	Lid cover	540x650	1	87.75
2	Side sheet metal	100x2041	1	36.738
3	Ceramic pan	Φ580	1	200
4	Bottom sheet metal	Φ649	1	76.05
5	Heating coil	10000-12000	1	35
6	Switch OFF/ON	-------	1	65
7	Vertical support Ferro	Φ30x650	4	58.50
8	Horizontal support Ferro	Φ10x650	8	32.50
9	Gypsum insulation	-------	------	10
10	Circular pan seating	25x650	1	13
11	Labor cost	------	-----	200
12	Clay pan	Φ580	1	40
				Total Cost = 844.54 Birr

6.2.2 Annual Energy Consumption Cost of the Baking Pans

Assuming, an average 15 number of enjera was baked daily throughout the year of the Ethiopian house hold. Annual energy consumption cost of the baking pans can be found out as follows:

$$E_{ACC,i} = E_{el}\,\frac{\text{kWh}}{\text{day}}\ \text{x}\ 30\,\frac{\text{day}}{\text{month}}\ \text{x}\ 12\,\frac{\text{months}}{\text{year}}\ \text{x}\ P_{el}\,\frac{\text{birr}}{\text{kWh}}$$

Where; $E_{ACC,i}$ – Annual energy consumption cost of conventional and improved baking pan,

E_{el} – is the amount of kWh use per a cycle, (3.026 kWh and 4.023 kWh for Improved and conventional electric ‘mitad’ respectively), and

P_{el} – is the unit price of ellectricty per kWh

Therefore, the total annual electricity consumption cost of conventional and improved electric ‘mitad’ is around Birr 675.48 and Birr 320.31 respectively.

6.3 Cost Comparism of the Baking Pans

Th economic comparision of the baking pans was the electrical energy which delivers from EEPCO throughout the year. The present value of the baking pans and net benefit of improved electric ‘mitad’ is given in Figures (6.1and 6.2):

6.3.1 Present Value Comparison of the Baking Pans

According to Figure 6.1, from the beginning up to seven months, conventional electric ‘mitad’ has less life cycle cost than improved enjera baking pan.

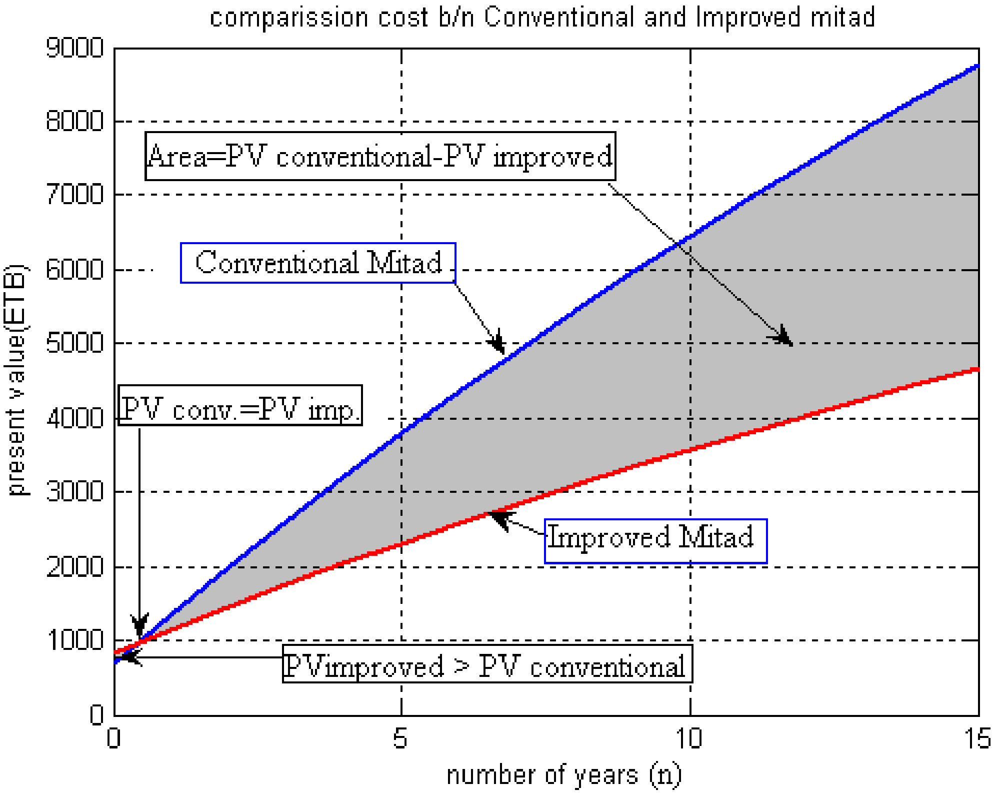


Figure 6.1: Present value of electric energy cost vs. number of years of the baking pans

After seven months, the improved electric mitad will become more economical. So, it is beter to use the ceramic plate electric mitad.

6.3.2 Net Benefit of Improved Baking Pan

Based on the Tables (6.1 and 6.2), initial investment of the conventional ‘mitad’ was lower than the improved ‘mitad’. But the uniform annual energy consumption cost is vise versa (Figure 6.2).

The saving from the improved 'mitad' due to lower electric energy consumption can be around Birr 2879.70 and Birr 4090.00 for the life time of 10 and 15 years respectively (Figure 6.2).

$$NB_i = TC_c - TC_i$$

Where, NB_i= Net benefit of improved electric 'mitad'

TC_i= Total energy cost of improved electric 'mitad'

TC_c= Total energy cost of conventional electric 'mitad'

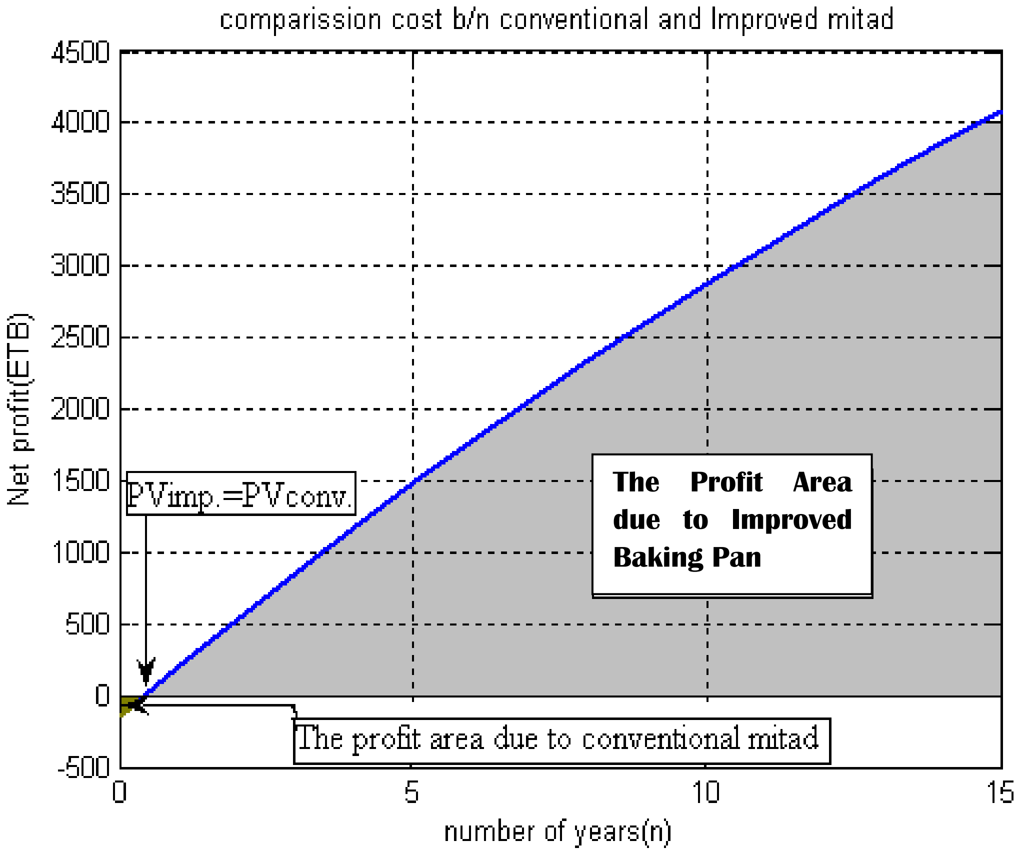


Figure 6.2: Net profit of improved baking pan vs. the 'n' number of years

The annual electrical energy saving by using improved electric mitad was around 360kWh. If one million conventional electric mitad are replaced by the impoved mitad, 360000MWh of electricity can be saved.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1. Conclusion

Based on the experimental results the following points were concluded:

- Moisture and solid content percentage of the batter was 72.68% and 27.32%, and enjera was around 57.67% and 42.33 % respectively.
- For electric baking pan, the batter was poured on the baking pan at a thickness of 1.8–2.5 liters/m^2.
- The average power consumptions of conventional and improved electric 'mitads' were 12.86 kW/m^2 and 9.08 kW/m^2 respectively.
- Heating up time required varies according the energy input of the baking pan which was 780 seconds for high power input of conventional electric 'mitad' and 1080 seconds for low power input improved 'mitad'.
- Improved and conventional electric 'mitad' had the heating rate of 9.03^0C/min and15^0C/min respectively and the optimum baking surface temperature of the baking pans was around 160^0C -200^0C.
- The maximum energy losses of conventional and improved baking pans were occurred at the bottom side of the baking system by 35.08% and 23% with the efficiency of 52% and 75% respectively.
- Performance improvement options of the electric 'mitad' were dependent on the idle time, quantity of food being baked, density of the product and combination of them.
- Brief economic comparisons suggested that while improved baking pans were more expensive to purchase, it was much more efficient in energy consumption, and would save money in the long run time. To conclude that, improved electric 'mitad' fulfill the needs of the Ethiopian household much better than the conventional one.

7.2 Recommendation

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

- Based on the experimental result, the efficiency for 8mm thickness of the baking pan was around 75%. So, it is important to investigate the efficiency improvement of the improved baking pan.
- Acording to the experiment, the ceramic improved baking pan had heighest heat-up time. This can be further reduced by using low thermal conductivity material for holding the resisters at the back of ceramic plate than using clay pan. Moreover, the durability of the pan has to be optimized by using different ceramic materials.
- Improved baking pan has difficulties in cooking good enjera if used directly without proper pan preparation. So that, surface preparation should be done before it starts to bake.

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APENDIXES

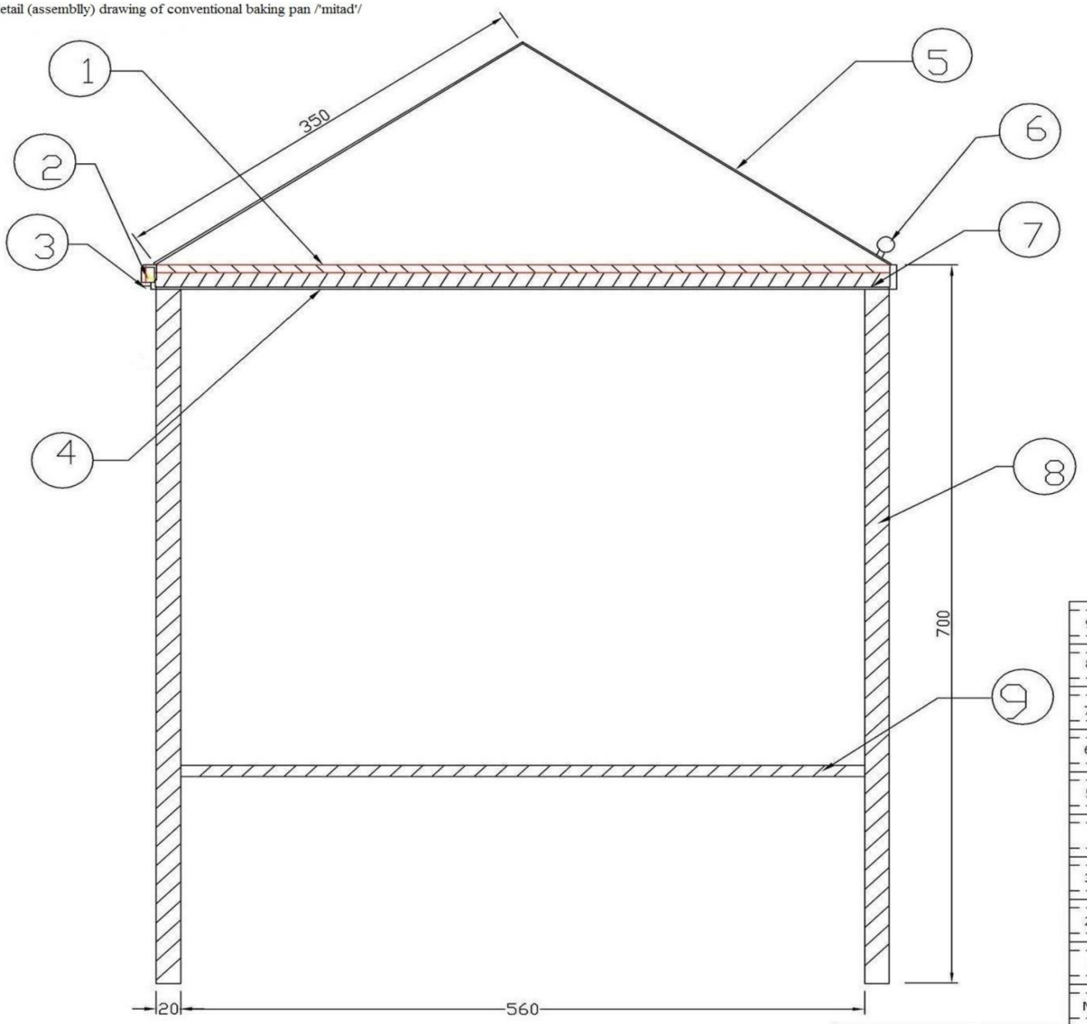
Appendix (A): Thermal property of the evaporated water fluid

T(oc)	**ρ(kg/m3**	**Cp(j/kg·K)**	**K(w/m.K)**	**α(m^2/s)x10^{-7}**	**V(m^2/s)x10^{-7}**	**pr**	**β(K-1)**
100	958.3	4216	0.6791	1.681	2.940	1.75	0.000751
120	942.89	4245.63	0.682433	1.704704	2.48963	1.4611	0.000858
127	937.5	4256	0.6836	1.713	2.332	1.36	0.000895

Appendix (B): The temperature of pan sides we will use in the heat loss coefficient

No.	**Name of parameter**	**Standard pan**	**Improved pan**	**Unit**
1	Average side temperature	66.66142	49.32	°C
2	Average Enjera upper surface temperature	68.48088	68.48	“
3	Average lid cover temperature	61.14793	59.15	“
4	Average bottom plate temperature	120.1801	68.8	“
5	Clay pan surface temperature	180	160	‘’
6	Clay pan surface temperature when dough poured	90	85.56	‘’

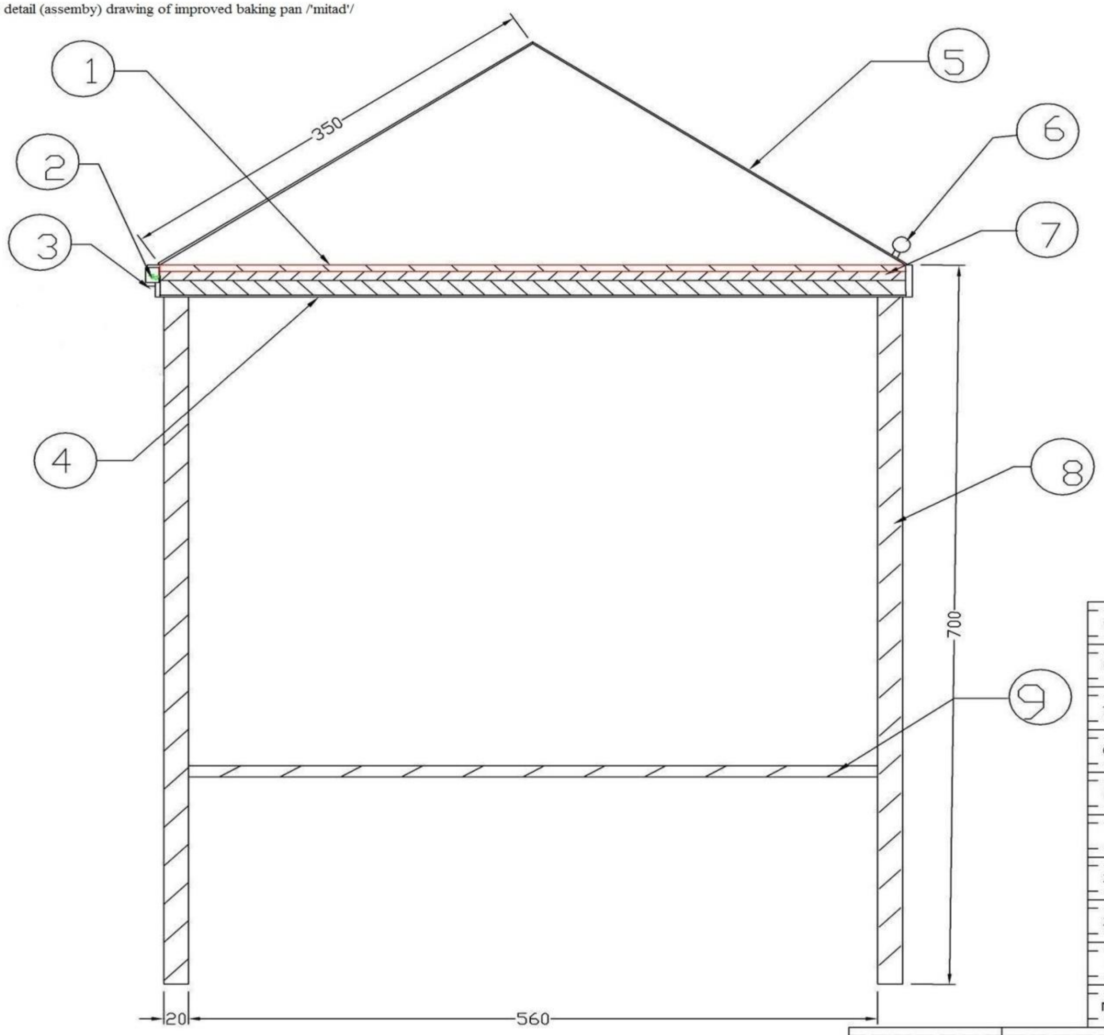
Apendix (C): 2D detail (assemblly) drawing of conventional baking pan /'mitad'/



9	FERO	Ø8 X 425	METAL	1
8	LEG HOLOW BAR	Ø20 X 650	METAL	1
7	GYPSUM			
6	LID COVER LIFT		PLASITIC/MET.	1
5	LID COVER	300∏x350	METAL	2
4	BOTOM CASING	Ø600	SHEET METAL	1
3	SIDE PLATE	600∏X100	SHEET METAL	1
2	SWITCH ON/OFF		----	1
1	CLAY PAN	Ø58X20	FIRED CLAY	1
NO.	PART NAME	DIMENTION	MATERIAL TYPE	QUANTITY

DRAWN BY	AWASH TEKLE		SCALE
DATE	APRIL-2011	ASSEMBLY DRAWING OF BAKING PAN/MITAD	1:4
NAME OF ORG.	ADDIS ABABA UNIVERSITY	DRAWING NUMBER	1

Apendix (D): 2D detail (assemby) drawing of improved baking pan /'mitad'/



9	FERO	ø8 X425	METAL	5
8	LEG HOLOW BAR	ø20X650	METAL	1
7	grooved clay pan	ø580X20		
6	LID COVER LIFT		PLASITIC/MET.	1
5	LID COVER	330Π×350	METAL	1
4	BOTOM CASING	ø600	SHEET METAL	1
3	SIDE PLATE	600Πx100	SHEET METAL	1
2	SWITCH ON/OFF		----	1
1	CERAMIC PAN	ø580 &10	FIRED CERAMIC	1
NO.	PART NAME	DIMENTION	MATERIAL TYPE	QUANTITY

DRAWN BY	AWASH TEKLE			SCALE
DATE	APRIL-2011	ASSEMBLY DRAWING OF BAKING PAN/MITAD		1:4
NAME OF ORG.	ADDIS ABABA UNIVERSITY	DRAWING NUMBER	1	

Appendix (E): Experimental temperature logging for the improved electric cooking appliance

Time (sec)	**T(°c)**	**Time (sec)**	**T(°c)**	**Time (sec)**	**T(°c)**	**Time (sec)**	**T(°c)**	**Time (sec)**	**T(°c)**
0	20.01	540	72.32	1080	133.5	1620	136.7	2160	89.53
60	24.70	600	75.84	1140	151.8	1680	151.4	2220	92.79
120	29.24	660	81.64	1200	166.0	1740	79.33	2280	106.01
180	34.63	720	88.44	1260	84.42	1800	79.67	2340	142.9
240	41.97	780	94.82	1320	89.53	1860	94.20	2400	84.42
300	47.26	840	101.3	1380	92.79	1920	97.04	2460	89.53
360	53.68	900	108.8	1440	94.08	1980	151.8	2520	92.79
420	58.75	960	117.0	1500	101.2	2040	166.0	2580	94.08
480	66.97	1020	125.5	1560	112.5	2100	78.15	2640	93.93

Appendix (F): Experimental temperature logging for the standard electric cooking appliance

Time(sec)	**T(°c)**	**Time(sec)**	**T(°c)**	**Time(sec)**	**T(°c)**	**Time(sec)**	**T(°c)**
0	19.40	540	67.59	1080	76.22	1620	152.3
60	20.13	600	75.43	1140	122.34	1680	79.00
120	22.58	660	86.30	1200	157.34	1740	81.25
180	27.22	720	98.47	1260	79.00	1800	76.48
240	33.51	780	111.74	1320	81.25	1860	81.61
300	40.63	840	145.35	1380	76.48	1920	166.6
360	48.17	900	76.83	1440	81.61	1980	78.66
420	57.50	960	77.21	1500	120.68	2040	79.86
480	19.40	1020	67.591	1560	76.22	2100	78.60

Appendix G: 3D Auto Cad drawing of electric baking pan / "mitad"/