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A Thesis Submitted to AAIT for the Fulfillment of Master of Science in Mechanical Engineering (Thermal Engineering).

Experimental and Numerical Study of Heat Transfer Characteristics in Traditional and Modern Cook-pot.

(A Case Study on Ethiopian Cookware)

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OCTOBER – 2018

Declaration

I, the under signed, declare that this MSc thesis is my original work, has not been presented for the fulfillment of a degree in this or other university, and all sources and materials used for the thesis work is acknowledged.

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This thesis work has been submitted for examination with my approval as a university advisor.

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Thesis Approval

Title: ***Experimental and Numerical Study of Heat Transfer Characteristics in Traditional and Modern Cook-pot.***

(A Case Study on Ethiopian Cookware)

- Submitted by ***Achamyeleh Muche*** for the partial fulfillment of the requirements for the Degree of Master of Science in Mechanical Engineering (Thermal Engineering),
- Submitted to ***School of Mechanical and Industrial Engineering***, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia.

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Abstract

The development in the design of cooktops and cookware with an increasing energy cost needs a research. This study was taken up to research the heat transfer characteristics of different cookpots on electric coil and identify the most appropriate pots. Experimental analysis and numerical simulations on different cookpots apply for determination of cookpot's thermal behavior. Clay and metal made cookpots have been considered for the analysis. Both experimental and numerical study made separately for a clay pot and metal pot, those contains water as cooking material (water boiling test).

In this paper, a methodology for evaluating the thermal efficiency of a pot on an electric stove using experimental methods and numerical simulations in Ansys transient thermal were presented. The numerical simulations and experimental tests corresponded well with one another.

The experimental data were collected using commercial Ethiopian cookpots (metallic and clay made '*shekla*'). From the experimental work, the cookpot's actual heating property and thermal efficiency had been determined. for the case study, the experiments were done using only an electrical stove, and all the tests were carried out at a power input level of 1500 W. The corresponding constant heat flux is applied directly through the bottom surface of the pot.

By modeling similar cookpots with the experimental one, transient thermal simulation gives the result, that shows the existing heat transfer properties, like; heat transfer pattern, heat flux distribution, temperature gradient and overall efficiency of the cookpot throughout the pot surface, graphically and numerically. The numerical results then compared with experimental measurements to set the difference.

From this result, the convection and radiation losses are less in case of optimum height to diameter ratio so thermal efficiency is highest among the cooking pots hence the large amount of heat energy has to be saved during cooking process. The effects of the parameters like stove to pot contact area, bottom flatness, body shape, filling amount, thickness, handle and ratios of diameter vs depth also addressed. Then after, the study extended to recommend the cookpot that have relatively good heat transfer behavior than the existing one.

Keywords: Cookpot; Heat transfer; Thermal efficiency; Energy saving; Ansys transient thermal.

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Nomenclatures

η	Cooking pot's thermal efficiency, dimensionless.
m_1	Water's mass at beginning of the test, kg.
m_2	Water's mass at end of the test, kg.
c	Specific heat, J/kg.K.
c_p	Specific heat at constant pressure, J/kg.K.
c_v	Specific heat at constant volume, J/kg.K.
$c_{p,w}$	Water's specific heat at constant pressure, kJ/kg.K.
$T_{1,w}$	Water's beginning temperature, K.
$T_{2,w}$	Water's boiling temperature or its highest temperature during the test, K.
h_{fg}	Water's latent heat of evaporation at atmospheric pressure, kJ/kg.
Q_{tot}	Total amount of heat transferred through bottom of the pan from the cooktop surface to water, kJ.
h -	The height of the pot (which is measured from the pot bed without considering the bottom thickness),
E_{tot}	total energy, J.
h	Convection heat transfer coefficient, W/m^2 K.
h_{fg}	Latent heat of vaporization, J/kg.
D -	Pot diameter (which is measured at its opening),
r -	External edge radius,
R -	pot's bottom curvature
A	Area, m^2.
θ –	wall slope (which is positive when the opening diameter is greater than bottom diameter).
V_{occ} -	the occupied volume percent of the pot volume (the ratio of the water volume to the pot's total volume at the beginning of test).

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Nowadays, an enormous amount of energy is wasted in different forms. Therefore, conservation of energy is necessary for all, especially for developing countries, like Ethiopia. Recently, using an electrical stove for cooking is dramatically increasing. But it is not efficient. Hence, here is way of conserving energy by optimizing the efficiency of cooking pots during the process of cooking.

Cooking is an inevitable part of daily life for many obvious reasons such as to reduce food-born illnesses, to enhance taste, texture, palatability, digestibility and shelf-life in commercial and residential settings. According to FAO [1], food-related energy demand for cooking and preparation of food is 75%, whereas the rest is for primary production (10%), transportation and processing (15%) of food.

It is true that cooking habits are different between countries and even in every country ethnical or geographical issues. Databases on energy consumption of cooking pots are necessary thing for one country. In Ethiopia, it is unavailable. This is because the availability and transparency of information is very difficult to assess and many technical or cultural and bureaucratic barriers tend the data gathering very unreliable.

Several studies about energy efficiency in cooking have focused primarily on the stove type and the type of fuel used. However, cook pot’s designs have greater influence on energy efficiency of cooking. [2]to date, small numbers of studies have attempted to improve cook pot’s thermal efficiency in urban or rural areas with access to an electrical grid with low-income and poor social conditions.

The significant parameters in improving cookware’s performance are, temperature and its distribution on the surface of the pot that contacts the food. Heat capacity of utensil material and its inertness to the contents are also important.

1.2. Problem Statement

Cookware for domestic and commercial food preparation has been relatively unchanged for the past many years in Ethiopia. Nevertheless, food preparation personnel continue to require cooking utensils which prevent or reduce the chances of over cooking, scorching, or burning food by evenly distributing the heat across the entire cooking surface of the utensils and by thermostatically controlling the cooking temperature thereof.

In Ethiopian traditional cooking culture, clay made cooking utensils have been applicable for many years. But now, in the recent years especially in the urban areas, metallic made cooking utensils are dominating it. This is because, no any improvements have been made on traditional clay made utensils for a long time.

The metallic made cooking utensils however have greater heat losses through its surface, in addition when the utensils are large scale the heat loss will increase with great amount. So, cooking utensils and food-serving containers with an improved ability of retaining heat are required. to provide this kind of utensils, first of all, the heat transfer characteristics (amount of heat loss) of cookpots must be known definitely.

Today different kinds of modified cooking utensils with good heat transfer property have been imported to our country. However, they are very costy and they are not available with the desired different capacity. and also, they are not designed by considering Ethiopian traditional cooking trend, so mostly compatibility issue has been a problem.

In Ethiopia, the energy comes mainly in two forms: burning natural gas and electrical resistivity. In both methods, the source of the heat is not uniformly spread over the pan. The heating elements of an electric range are designed to cover as much area as possible, but still have patterns (usually spirals) where there is no heat. So, this problem should be compensated with either cooking technique or through cookware design.

A metal made thin bottom pot, conducts heat quickly but unevenly. In contrast, a thick-bottomed clay made cooking utensils conducts heat slower, but more evenly, reducing hot spots. The thicker the bottom material, the more heat retained, and the greater the possibility of even cooking performance. In addition, it is also known that the food (‘*wett’ ወጥ or stew*) prepared by the traditional clay made cookpots have a good taste. So, if some improvement were done on these pots, Ethiopians prefer this one without any complain.

Consumers are demanding energy efficient appliances that translate into cost savings. In order to mitigate climate change, international legislation is forcing manufacturers to reduce their carbon footprint. Therefore, investments in energy efficiency are a sound and key business strategy in today's manufacturing environment.

Cooking is a daily activity, in Ethiopia every person eats and/or drinks at least two times per day. That means, a minimum of one time of cooking is necessary for a person per day. So, when we consider this as country level millions of cookpots are on stove at a time. But most of the stoves and cookpots used are not efficient, these results huge amount of energy loss as well as economical disturbance.

Presently, more than 90% of energy consumed in Ethiopia is derived from biomass fuels and is almost entirely used for cooking. The use of these fuels has resulted in massive deforestation and soil erosion, [3]. In Ethiopia, up to 90% of the electricity generated is supplied by hydroelectric stations. Currently on average Ethiopia's electric power distribution cost is about 0.55 ETH cents/kWh. Thus, it is necessary to find ways to improve the thermal efficiency of residential cooking systems, because the cost of electricity affects the economy of a significant segment of Ethiopia's urban population.

There are several reasons which have made it initiate to make study on clay pot.

i. ***Availability and cost:*** clay pots are easily available and very cheap compared to others and also more environmentally friendly. The cheapest and most durable of all the traditional pot is the clay pot.

ii. ***Clay pot can be re-used:*** we can use the old discarded broken clay pots for production of new one.

iii. ***Durability:*** Clay pots last long unless they are purposely or accidentally broken. They can last as long as one can think. it is a better option with less financial investment.

1.3. Objectives

1.3.1. General objective

- The principal objective of this thesis is to experimentally and numerically analyze the heat transfer characteristics of traditional and modern cookpot according to Ethiopian environment.

1.3.2. Specific objectives

- to perform experimental investigation on existing cookpot.
- to quantify the heat transfer characteristics of cookpots.
- to experimentally measure the temperature distribution throughout the pot body.
- to predict and simulate the temperature distribution and heat transfer behavior during cooking and validate the model predicted results with the experimental data.
- to account the amount of heat loss in the existing cooking utensils.
- to simulate and validate the recommended cooking utensil using ANSYS.
- to simulate and predict the optimum cooking efficiency.
- to quantify the effects of different parameters of cookpot and stoves on the pot’s thermal efficiency.
- to identify an energy efficient cookpot.

1.4. Methodology

The aim of this study is to investigate and to reach the optimum efficiency of cooking using electrical stove, by testing in laboratory four sample pots with different specification and, investigating the efficiency of the pots using software simulation. The study considers different parameters; physical parameter (like diameter and height) and other parameter (like conductivity) to reflect the range of heat transfer during cooking.

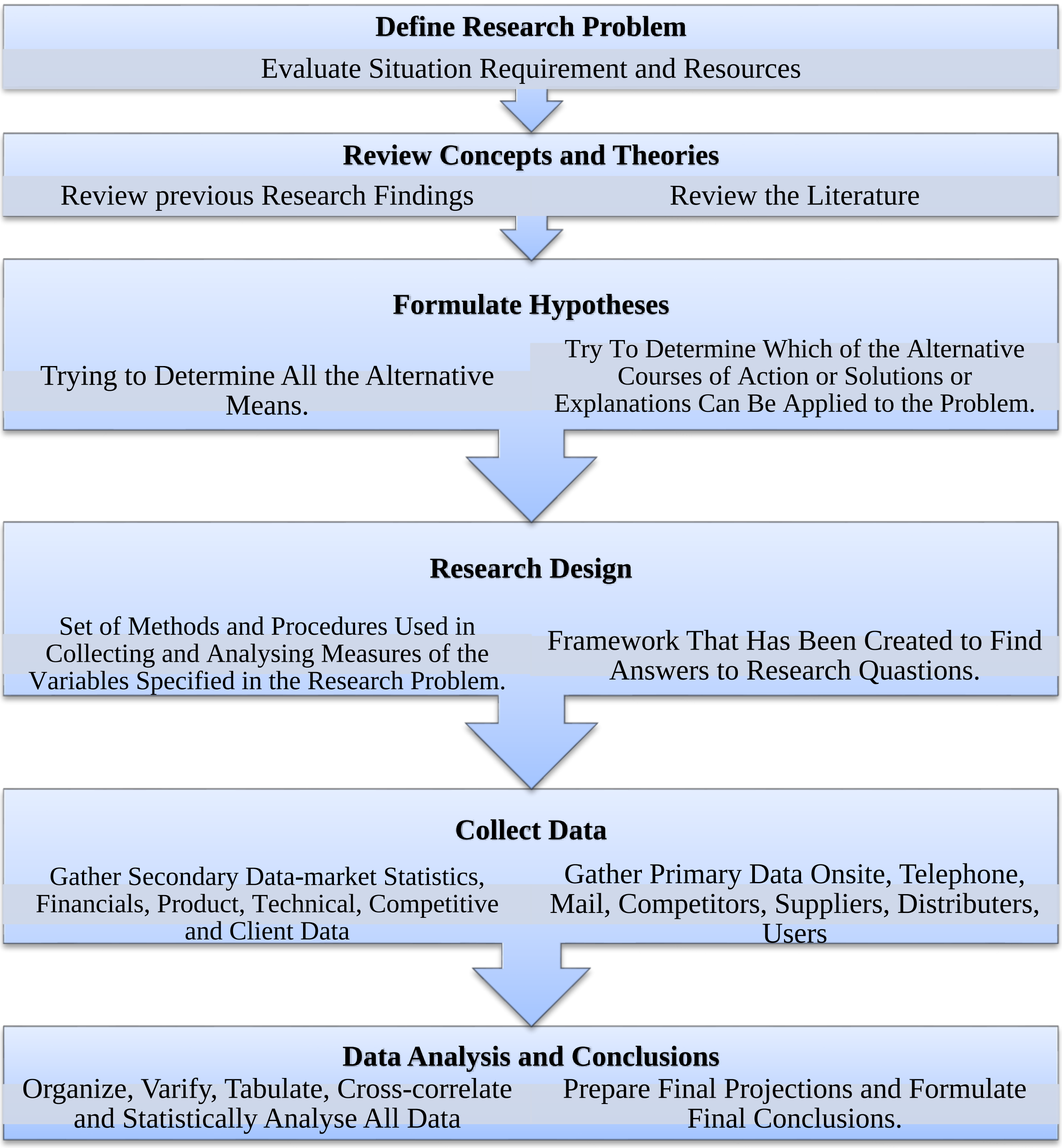

Figure 1. 1: Methodology of the research

1.5. Scope of the Study

The complete heat transfer behavior of a commercial cookpots analyzed experimentally and using numerical simulation software. Using the simulation results, the study extended for the selecting optimized type of cooking utensil that have good heat transfer behavior than the conventional one.

The experimental validation of both metal and clay pots were done using an actual prototype of the cookpot. The selected clay and metal pots performance were simulated based on the validated result for existing clay and metal pots. i.e. the project does not include the mechanical manufacturing of pots.

CHAPTER TWO
LITERATURE REVIEW

2.1. Heat Transfer Basis

Temperature is associated with the motion of molecules within a material, being directly related to the kinetic energy of the molecules, including vibrational and rotational motion. Whenever a temperature gradient exists within a system, or whenever two systems at different temperatures are brought into contact, energy is transferred. The process by which the energy transport takes place is known as heat transfer. The thing in transit, called heat, cannot be observed or measured directly. However, its effects can be identified and quantified through measurements and analysis. The flow of heat, like the performance of work, is a process by which the initial energy of a system is changed. Heat can be defined as the quality of being hot. Heat is fundamentally transported, or “moved,” by a temperature gradient; it flows or is transferred from a high temperature region to a low temperature one [4].

2.2. Modes of Heat Transfer

The literature of heat transfer generally recognizes three distinct modes of heat transmission: conduction, radiation, and convection.

Conduction: Whenever a temperature gradient exists in a solid medium, heat will flow from the higher-temperature to the lower-temperature region. The rate at which heat is transferred by conduction, q_k, is proportional to the temperature gradient dT/dx times the area A through which heat is transferred. The actual rate of heat flow depends on the thermal conductivity k, which is a physical property of the medium. for conduction through a homogeneous medium, the rate of heat transfer is then:

$$q_k = -kA\frac{dT}{dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

In this relation, $T(x)$ is the *local temperature* and x is the *distance in the direction of the heat flow*. [5].

Convection: This mode of heat transfer is met with in situations where energy is transferred as heat to a flowing fluid at the surface over which the flow occurs. This mode is basically conduction in a very thin fluid layer at the surface and then mixing caused by the flow. The energy transfer is by combined molecular diffusion and bulk flow. The heat flow is independent of the properties of the material of the surface and depends only on the fluid properties. The heat-transfer rate is related to the overall temperature difference between the wall and fluid and the surface area *A*. The basic equation of convection heat transfer is Newton's law of cooling:

$$q = hA(T_w - T_\infty) \text{ ....} 2.2$$

Where: ***h*** is *convection heat-transfer coefficient,* ***Tw*** *is temperature of the plate, and* ***T∞*** *is temperature of the fluid* [4].

Radiation: All electromagnetic radiation is classified as radiation heat transfer. Infrared, ultraviolet, visible light, radio and television waves, X rays, and so on are all forms of radiation heat transfer. The radiation heat transfers between two objects situated in a non-absorbing or emitting medium is given by the Stefan-Boltzmann law:

$$q_r = A_1\sigma(T_1^4 - T_2^4) \text{ ....} 2.3$$

Where: ***q_r*** *is heat flow rate in watts,* ***A*** is *surface area in square meters,* ***T_1*** is the *surface temperature in kelvin*; **σ** is a *dimensional constant with a value of 5.67 * 10^{-8} (W/m^2 K^4)* and ***T_2*** *is the surface temperature of the enclosure in kelvin.*

2.3. What is Cooking?

Cooking or cookery is the art, technology and craft of preparing food for consumption with or without the use of heat. Cooking techniques and ingredients vary widely across the world. from grilling food over an open fire to using electric stoves, to baking in various types of ovens, reflecting unique environmental, economic, and cultural traditions and trends. The ways or types of cooking also depend on the skill and type of training an individual cook has. Cooking is done both by people in their own dwellings and by professional cooks and chefs in restaurants and other food establishments. Preparing food with heat or fire is an activity *unique to humans*.

There are three main reasons for cooking food:

- to improve its digestibility, that is, to make it easier to eat, break down and absorb,

- to increase its palatability, which means to make it more attractive by improving the taste, smell and color, and
- to make it safe to eat, in relation to food poisoning and food spoilage micro-organisms.

Cooking food requires the transfer of heat to the food or the generation of heat with in the food, both of which can be achieved in many ways. In fact, most of the common cooking methods, such as boiling, frying, roasting, involve one of the types of heat transfer which are conduction, convection and radiation.

Most ingredients in cooking are derived from living organisms. Vegetables, fruits, grains and nuts as well as herbs and spices come from plants, while meat, eggs, and dairy products come from animals. Mushrooms and the yeast used in baking are kinds of fungi. Cooks also use water and minerals such as salt. Cooks can also use wine or spirits. Naturally occurring ingredients contain various amounts of molecules called proteins, carbohydrates and fats. They also contain water and minerals. Cooking involves a manipulation of the chemical properties of these molecules.

2.4. Cooking Heat Transfer

Cooking of food usually uses a combination of three methods. Conduction transfers the heat using direct contact; food is heated directly in a metal pan, in a liquid, or surrounded by air. Convection heat transfer occurs faster than conduction. Convection occurs by the movement of air, liquid, or steam around the food. Stirring the pan redistributes the heat due to convection from the bottom of the pan throughout the other ingredients.

Figure 2. 1: Convection role in heat transfer inside pot of water [6].

Convection plays an important role in heat transfer inside this pot of water (Figure 2. 1). Once conducted to the inside, heat transfer to other parts of the pot is mostly by convection. The hotter water expands, decreases in density, and rises to transfer heat to other regions of the water, while colder water sinks to the bottom. This process keeps repeating.

2.4.1. Boiling and evaporation

Boiling and evaporation are often used interchangeably to indicate phase change from liquid to vapor. Although they refer to the same physical process, they differ in some aspects. Evaporation occurs at the liquid–vapor interface when the vapor pressure is less than the saturation pressure of the liquid at a given temperature. Note that evaporation involves no bubble formation or bubble motion

Figure 2. 2: .Evaporation [7]

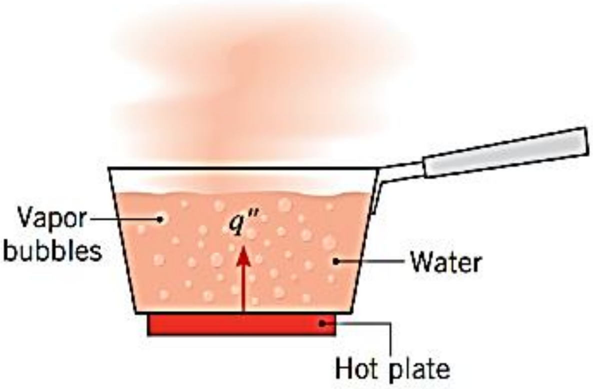

Figure 2. 3: Evaporation and boiling [7].

Boiling, on the other hand, occurs at the solid–liquid interface when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid. At 1 atm, for example, liquid water in contact with a solid surface at 110^{0}C boils since the saturation temperature of water at 1 atm is 100^{0}C. The boiling process is characterized by the rapid motion of vapor bubbles that form at the solid–liquid interface, detach from the surface when they reach a certain size, and attempt to rise to the free surface of the liquid. When cooking, we do not say water is boiling unless we see the bubbles rising to the top (Figure 2.2.)

Radiation heat transfer occurs when microwave (light waves) or infrared energy (heat waves) are spread into the food. As the microwaves penetrate the food, they bump into molecules of water and fat, causing them to vibrate rapidly. This vibration creates friction, which creates heat that cooks the food. The larger the piece of food, the more unevenly the microwaves penetrate, so microwave cooking has some limitations.

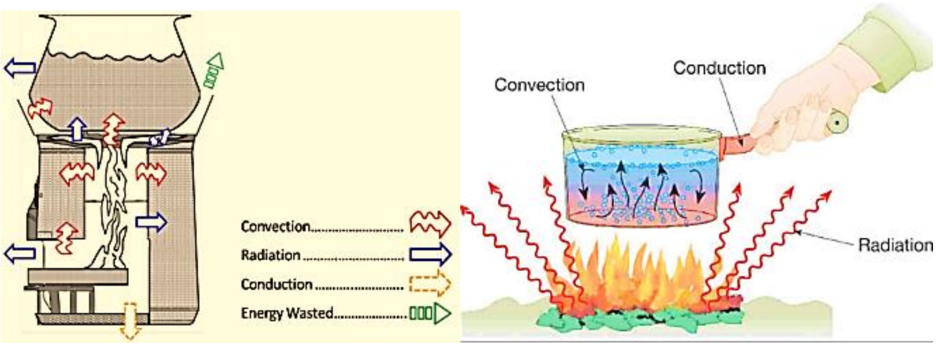

Figure 2. 4: heat transfer modes [7]

Figure 2. 5: Schematic of heat transfer modes in cooking. [7]

2.5. Review of Related Literatures

The analysis and optimization of cookpot's thermal efficiency is not a new idea. The mathematical modeling, experimental verifications and software simulations to know the heat transfer characteristic of cookpot has been done by many researchers.

Francisco J.Cadavid Presents a methodology for calculating the thermal efficiency of a pot on an electric stove using numerical simulations in Ansys Fluent by assuming steady state conditions. The study also evaluates the effect of pot's geometry variation on heat transfer to the load. The amount of heat loss increases with increasing height and decreasing diameter of the pot. and also, the heat flux distribution is more uniform at larger diameter. [8]

It was determined that the heat transfer to the pot was mainly caused by conduction between the heating element and the pot surface, representing 85.7% of the total energy going into the system. Heat transfer by convection and radiation represented 13% and 1.3% of the total incoming energy, respectively. The initial value of the contact resistance between the electrical resistance and the pot was approximated based on experimental tests. Three different aluminum pots were considered for simulation and experimentation.

The numerical simulations and experimental tests corresponded well with one another, with a difference of no more than 15% for all geometries analyzed. Finally, two substantial stove improvements were proposed. An insulating material is used to fill the area between the electrical resistor and the reflection shield reduces the heat losses to the surroundings from 15.19% to 6.64%. i.e. around 18.5 % increase in thermal efficiency. Next recommendation is polishing the surface of the electrical resistor and expanding the contact area will reduce the contact resistance between the electrical resistor and pot.

Dardashti Numerically assess the dependence of cookware performance on the number of layers and materials. It quantifies cookware's temperature distribution by varying of the number of layers and thermal properties by using a finite element model of heat transfer. 625 types of composite cookware filled with water at boiling temperature were compared in terms of thermal performance. The results show that a higher thermal conductivity material (Cu and Al) yields a more uniform surface temperature profile than a lower thermal conductivity material (Stt). Bilayer plates of Cu/CrNi and Cu/Stt gives best thermal performance for cookware. Single layer stainless steel is unsuitable for cook ware due to its poor conduction. [2]

Several studies have been carried out to determine the performance of cooking pots using natural gas/LPG stove as heat source. [9] Uses the experimental pot that have a larger area of heat transfer compared to normal pot. Testing was done in different phases comparing the standard cook pot with the experimental cook pot. The first phase brought five liters of water to boiling and then the pot is experimented in the simmering phase. Results shows that the energy saved using the experimental cook pot is higher than the standard pot with reduced energy of cooking. This would reduce large carbon emissions and other factors polluting atmosphere thereby reducing the global warming.

S.K. Hannani Applies experimental and statistical methods to analyze the influence of pot parameters, like diameter, height, material thermal conductivity, and wall inclination on the thermal performance. Pots with flat or bulgy bottom surfaces have higher efficiency than concave bottom. Variation of edge radius up to 20 mm has negligible effect on efficiency, but above 20 mm lowers the efficiency. Increasing the ratio of pot diameter to flame diameter yields higher efficiency. But increasing pot's height to pot's diameter ratio decreases the efficiency. The occupied volume percentage has no effect on efficiency. [10]

It is true that cooking habits are different between countries and even in every country ethnical or geographical issues should be taken into consideration. In Ethiopia databases on energy consumption of cooking pots are rare and perhaps unavailable. The availability and transparency of information is very difficult to assess and many technical or cultural and bureaucratic barriers tend the data gathering very unreliable.

The purpose of this thesis is to simulate and evaluate the heat transfer and overall thermal efficiency of a pot on electrical resistance heating. We evaluate the effect of many factors on the heat transfer to the load experimentally and through numerical simulations in Ansys transient thermal. The numerical results are compared with experimental measurements to make the prediction level more precise.

2.6. History of Ethiopian's Cooking Methodology

The various methods and materials used for cooking have shaped civilizations, as well as cultures, since as far back as the Stone Age. During the time of the Aksumite Empire, Ethiopia artisans created exquisite pottery using proper firing techniques and kilns. Although much of this technique and finesse has been lost, artisans continue to create both decorative and functional pottery items around the country. [11]

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Figure 2. 6: Different application of clay in Ethiopia [12] [11].

Injera is the staple flatbread food for most Ethiopian and Eritrean households [13]. It accounts for over 50% of all energy consumption in Ethiopia, and over 90% of all household energy consumption [14].

Figure 2. 7: Long standing Ethiopian traditional pots on a three-stone fire [15]

for long years, the stove type biomass fire unchanged. But now in recent years, different kinds of stove, electrical, fuel/gas, and modified biomass have been developed. Electricity is mainly used for lighting and small appliances, rather than cooking, and represents a small share of total household consumption in energy terms [16].

In Ethiopia, there are cooking vessels of two different types with regard to the form of the bottom: those with a rounded (convex) bottom (

Figure 2. 7) and those with a plain (level, flat) bottom (Figure 2. 9).

ii. In the south and southwest of Ethiopia, there is a wide variety of pottery styles. Many potters use molds to make medium to large sized pieces like water pots and cooking pans. Molds are made from baskets, leather, or even large holes dug in the ground. The molds often form the bottom half of the large pieces while the potters then build the top halves by hand. Small and simpler pieces are made by hand and do not need molds. Once the pieces have been shaped and dried, potters will often decorate the pots with their fingers or pieces of straw as shown in Figure **2. 8** below.

Figure 2. 8: Decoration the pots with fingers and pieces of straw.

Decoration usually includes straight lines in V-shapes or horizontal series or a ring of small bumps around the pot. Pottery is tested/sealed by fired twice, once by the potter and then once by the buyer at his home. The most common type is called a *shakla dist*, and some *Ethiopians will swear that the food tastes better when it simmers in earthenware.*

Figure 2. 9: Round pots of various sizes with lids [15].

2.2.1. Pottery Making Techniques

Figure 2. 10: Manufacturing process of clay pots in Ethiopia (Gondar).

Traditional Ethiopian pottery is made from three types of clay collected by hand. The clay is pulverized into a powder and mixed with water to create a flexible paste. Most potters do not use a potter's wheel but rather a flat, round plate which supports the piece of pottery and also indicates size and shape of the piece. In recent years, some potters have received help from development programs which provide them with pottery wheels and training on modern pottery making techniques. Those working without a wheel build pots using either the spiral coiling technique or a traditional method of moving around the pots.

Most Ethiopian pottery is either natural clay colored or black. The black color is created by coating the object in oil and then firing it in the kiln. After, the objects are left to cool under a mound of dried eucalyptus leaves giving them a black patina. Although most pottery is unglazed, some potters in the South will waterproof pots (Figure 2. 11) by heating them and then pouring cold milk into the pot or using the residue of local beer or coffee to seal it. Alternatively, a small group of potters use a simple resin glaze made from the leaves of the *ketketa* bush or from the sap of the euphorbia.

Figure 2. 11: Waterproof pots [11].

Occasionally, artisans will paint pottery after it has been fired to add further decoration. Recent efforts have been made to improve Ethiopian pottery and a few cooperatives located near Addis Ababa have successfully worked with women to create high quality pottery products.

2.6.1. Stages of firing

The most common stages of firing clay products are: ***Dehydration, Oxidation, Vitrification, Flashing and Cooling*** [17]

Dehydration: In this stage of firing, removal of water occurs. Burning out and breaking down of the carbonaceous matter and carbonates, as well as the "combined water", occur during the dehydration stage. [17] An endothermic reaction is observed at this stage due to further release of water and carbonaceous matter.

Oxidation: Burning of carbonaceous material takes place. Oxidation in the kiln may commence at temperatures as low as 300 ^{0}C and may extend as high as over 900 ^{0}C, depending on the rate of heating, the quantity of carbon present in the clay, the amount of excess air available in the combustion chamber, the density and area to volume ratio of the clay pots. [17]

Figure 2. 12: Firing of clay products

Vitrification: Vitrification usually commences at about 900 ^{0}C, when all the carbonaceous matter has been fully oxidized, and extends up to the highest temperature the pots can withstand without damage. The strength of the fired pots is developed during vitrification, by sintering of clay particles and melting of the clay mass. The solid particles become coated with liquid which upon cooling solidifies mainly as a glass and binds the particles together. [17]

Flashing: Holding the peak or finishing temperature for a period in order to impact the required colour to the pots by the addition of "un-combusted fuel" to the kiln.

Cooling: This is the decrease of kiln temperature from peak to ambient temperature.

2.6.2. Kinds of Pots

Ethiopians use different kinds of pots for cooking, which are classified into four categories: *tila*, *aksh*, *dist*, and *jebena* [18]. *Tila* pots have a rounded bottom, and a handle. They are used to steam root crops, hold water, and brew alcoholic beverages. *Aksh* pots are used to roast coffee beans and cereals and bake *injera*. *Disti* pots are used to cook side dishes, and *jebena* are coffee pots.

2.6.3. Potters

Pottery making consists of four components: digging clay, forming pots, firing pots, and selling them in local markets. Potters are responsible for all four components. In Ethiopian tradition forming pots is considered women's work, and men believe that grim consequences could occur if they were to assist with that task.

2.7. Food Contact Materials

Every kitchen, whether domestic or professional, has its utensils, pots and pans for creating delicious recipes. In fact, the regulation concerning materials and articles which come into contact with foodstuffs, which has a broader scope than the food safety law, is made up of continuously evolving laws.

The underlying principle of all of these measures clearly states how materials or articles (e.g. kitchen utensils, cutlery, cookware, containers, and plastic, rubber, paper or metal packaging) that come into direct or indirect contact with foodstuffs must be manufactured in accordance with good manufacturing practices and, in normal or predictable conditions of use, must be sufficiently inert to exclude the transfer of substances to food products in quantities that could endanger human health, modify the composition of food products to an unacceptable degree, or provoke the deterioration of the foodstuff.

2.7.1. Properties of metallic food contact materials

Food contact materials are materials that are intended to be in contact with food. During the contact of the food contact materials with the food, molecules can migrate from the food contact material to the food. Because of this, countries' regulations are made to ensure food safety. Metals and clays used as food contact materials play a role as a safety barrier between the food and the exterior. It may not allow the migration of deleterious substances or impart colors, odors, or tastes to food. Under normal use conditions it shall be:

- ✓ Safe;
- ✓ Durable, corrosion-resistant, and nonabsorbent;
- ✓ Sufficient in weight and thickness to withstand repeated ware washing;
- ✓ Finished to have a smooth, easily cleanable surface; and
- ✓ Resistant to pitting, chipping, crazing, scratching, scoring, distortion, and decomposition

2.7.1.1. Aluminum

Aluminum is the third most abundant element in the earth crust and is found widespread in minerals. Aluminum does not occur in nature in a free element state because of its reactive nature. Pure aluminum has good working and forming properties and high ductility, its mechanical strength being low. Therefore, aluminum is often used in alloys [19].

More than half of all cookware sold today is made of aluminum. Aluminum cookware is often coated with nonstick finishes or treated to harden the surface and make it more scratch-resistant. The acid in these foods may cause more aluminum than usual to enter the food and can cause pitting on the pot's surface.

Anodized aluminum has been processed to harden the cookware surface. This process creates a nonstick, scratch-resistant and easy to clean product. An anodized surface prevents reactions with acidic foods. Manufacturers claim that during the final stage of anodization the aluminum is sealed to prevent leaching of aluminum into food. Aluminum is a lightweight material which makes the pots and pans easy to handle. Storing highly acidic or salty foods in aluminum pots is not recommended. Thin-walled aluminum pots and pans easily get dents and scratches and become deformed [19].

2.7.1.2. Copper

Copper is found at a concentration of 70 mg/kg in the earth’s crust [3]. Copper exists in two oxidation states: Cu(I) (cuprous) and Cu (II) (cupric). Copper can also occur in a trivalent state due to certain chemical reactions.

Copper is an excellent conductor of heat and especially good for range-top cooking. Cooks often prefer copper cookware for delicate sauces and foods that require cooking at precisely controlled temperatures. Copper cookware is usually lined with tin or stainless steel [19].

The level of contamination of copper observed does not constitute a safety problem. It is recommended to avoid direct food contact with copper utensils when unacceptable organoleptic effects could take place. There is no recommendation or restriction for the use of copper coated with tin, stainless steel or another appropriate covering material. The general recommendation should be considered when evaluating individual food items in contact with copper utensils. The intentional migration of copper into for instance cheese, where copper is used as an active component, is considered elsewhere.

2.7.1.3. Stainless steel

Stainless steels are widely used in food contact applications. This is largely because of the corrosion resistance of stainless steels coupled with their strength and durability, their ability to be readily cleaned and sterilized without deterioration using a wide range of cleaning/sterilizing systems, and the fact that they impart neither color nor flavor to foodstuffs and beverages.

Stainless steel is a combination of iron and other metals. It contains chromium, and may contain nickel, molybdenum or titanium, which contribute a hardness that resists damage at high temperatures, scratching and corrosion. Stainless steel is regarded as a durable cookware choice because it will not permanently corrode or tarnish and its hard, nonporous surface is resistant to wear. Stainless steel cookware does not conduct heat evenly; therefore, it is commonly constructed with copper or aluminum bottoms. Manufacturers caution against allowing acidic or salty foods to remain in stainless steel for long periods. Although there are no known health hazards from leaching of the metal, undissolved salt can pit steel surfaces [19].

“Steel” is an alloy of iron and carbon (less than 2% carbon) which contains other elements (such as manganese, silicone and sulfur) for control of, or improvements in, properties. Such steel is often called “carbon steel”. Other elements can be added to develop special properties (e.g. up to 3% nickel, chromium and/or molybdenum) to give “alloy steels” for engineering purposes. Stainless steels1 comprise a group of special steels with an even higher alloy content, to impart the corrosion resistance which renders them “stainless”. They are steels with a wide variety of compositions but always containing a high percentage of chromium (a minimum of 10.5%) as this is the alloying element of prime importance for conferring the typical corrosion resistance of stainless steels. In practice, the majority of the stainless steels used in food contact applications contain around 18% of chromium as this has been found to be the optimum concentration for corrosion resistance in a wide range of food and beverage media.

It is also a concentration which is ideal in terms of cost and ease of fabrication. There are over 200 types (grades) of stainless steel, but only about 100 types are in regular commercial production and fewer than 10 types account for the bulk of usage.

2.7.1.4. Cast Iron

Cast iron cookware is a classic. It is strong, inexpensive, and an even conductor of heat. Cooking with cast iron provides a source of iron, which is an important nutrient. Cooking foods in unglazed cast iron may double the amount of iron in foods. Cast-iron cookware requires special handling. to prevent rust damage: Frequently coat the inside of cast iron cookware with unsalted cooking oil, do not scour or wash with strong detergents, Dry immediately after rinsing [19].

2.7.1.5. Ceramic/Enamel

Metal cookware is often coated with a ceramic or enamel coating to add color and resistance to stains, scratches and food odors. Domestically manufactured ceramic and enamel cookware, including slow-cookers and crockpots, is generally considered safe.

Finally, when we came to Ethiopians cooking culture, almost all the society uses an aluminum pot for cooking purpose, unless they are using clay pots. This is because as described earlier, aluminum has a property of an excellent thermal conductivity, light weight, scratch resistance and strong. and also, Al pots are Non-reactive and non-porous, it allows cooking with less fat, to cook delicate foods such as fish or eggs won't stick to the pan or break apart.

Due to the above reasons, to analyze the heat transfer properties of cookpots, all the experimental works and software simulations study were done by using an aluminum made and clay made cookpots.

2.7.2. Properties of clay, food contact materials

Clay pot are made from clay soil. This is rich old traditional knowledge passed from generation to generation. However, this culture of life is in very much longer of dying a natural death because of modernization. The use of clay item has been in use for long time. The Bible mention many time the use of clay pots in social as well religious life. In Ethiopia clay pots have been in use for time immemorial. Pot have been very essential in day-to-day life for cooking [20]. There are three essential properties that make clay different from dirt. These are ***plasticity, porosity,*** and the ability to ***vitrify*** [21]**.**

Plasticity: has to be our first consideration. we can't begin to make pottery without it. to be usable, clay has to have the ability to hold its form while at the same time be pliable enough to be moved by the potter's hands. This is plasticity, and it is determined by the size and shape of very fine grains or particles of clay called ***platelets***.

Porosity: is the second necessary property that clay must have. Clay has to dry without cracking. Remember, some clays are too plastic, like bentonite. The platelets are too fine and smooth and closely squeezes together to let the water of plasticity evaporate without cracking the pot.

Vitrification: is the third important property of clay. Vitrification is the process of becoming glasslike. Although clay products never become absolutely vitrified or glasslike, it is necessary that the clay become hard (or almost vitrified) at a reasonable temperature. Any substance will melt at some temperature. Most materials tend to become soft and deform before they melt. The ability of clay to hold its shape and not sag or slump in the primary melting stages sets it apart from other materials. Vitrification is not less important than plasticity or porosity. It is mentioned last only because it is the last stage in pottery construction.

There are several reasons which have made it possible to make study on clay pot.

- ***Availability and cost:*** clay pots are easily available and very cheap compared to others and also more environmentally friendly. The cheapest and most durable of all the traditional pot is the clay pot.
- ***Clay pot can be re-used:*** we can use the old discarded broken clay pots for production of new one.
- ***Durability:*** Clay pots last long unless they are purposely or accidentally broken. They can last as long as one can think. it is a better option with less financial investment.

2.8. Characteristics of Quality Cookware

2.8.1. Good conductivity

to work effectively, cookware should be made of a material that conducts heat quickly and evenly. Many believe a material's ability to conduct heat quickly is one of the most important considerations in choosing cookware. This bar graph (Figure 2. 13) shows copper to be the fastest conductor of heat; aluminum is second. Glass-ceramic and heat-resistant glass are the slowest conductors of heat.

Copper cookware should be lined with another material, such as stainless steel or tin so the food will not meet the copper. Copper cookware is lined because some foods interact with copper to form toxic substances.

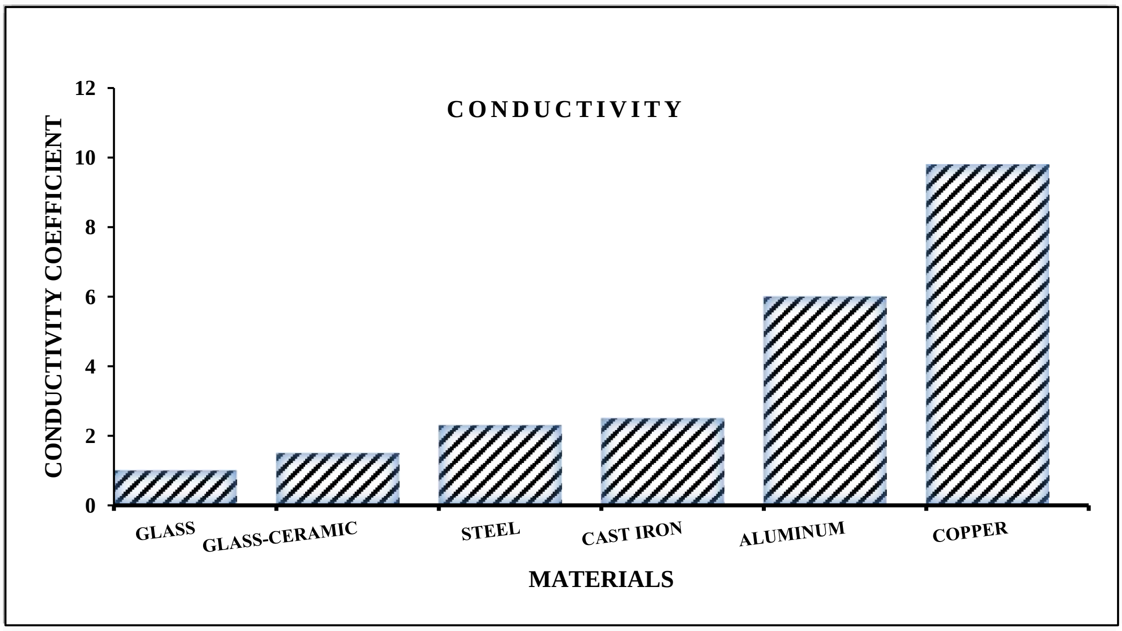


Figure 2. 13: Conductivity of Metals [22]

Aluminum is considered a fast conductor of heat. Although its conductivity is only half that of copper, it is four times that of iron or steel. Aluminum cookware is made by stamping, drawing, or casting and comes in a variety of gauges (thin, medium, and thick). Cast-iron cooking utensils have been around for a long time. Iron is heavy, brittle, and rusts unless protected. It is a slow conductor of heat. However, once heated, it tends to retain heat evenly for some time after the heat source is turned off.

Steel cookware is iron with carbon dissolved in it. It is lighter and stronger than iron but still rusts. Steel is an uneven conductor of heat. Stainless steel cookware is created by adding chromium and nickel to steel. Stainless steel will not rust. Generally, stainless steel cookware is not magnetic unless some magnetic material has been added during production. While stainless steel is easy to clean, durable, and resistant to corrosion, it can warp and develop hot spots [22].

Glass-ceramic cookware is made by transforming glass into a crystalline material, that can withstand sudden temperature changes. As cookware, it is a poor conductor of heat. Like heat-resistant cookware, glass-ceramic cookware has the advantage of not reacting with food acids and alkaline. of all cooktop materials, heat-resistant glass, which may be transparent or translucent is the slowest conductor of heat.

2.8.2. Uniform heat distribution

Generally, a thin bottom conducts heat quickly but unevenly. In contrast, a thick-bottomed cooking utensil conducts heat slower, but more evenly, reducing hot spots. The thicker the bottom material, the more heat retained, and the greater the possibility of even cooking performance.

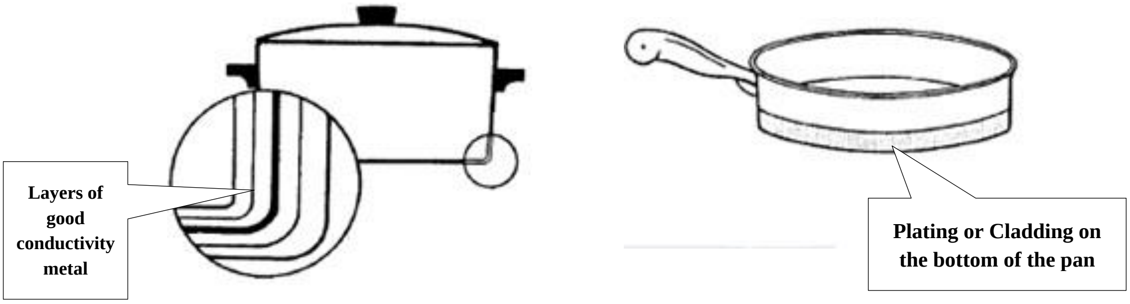
2.8.3. Proper thickness/Gauge

Along with the conductivity of the materials used in the cookware, the gauge or thickness of the material is another feature that determines the quality of cookware and cooking performance. When looking at the gauge or weight of a cooking utensil, the thickness of its bottom is most important.

2.9. Methods of Improving Cooking Performance

2.9.1. Sandwiching metals

The one way to improve the conductivity of cookware is sandwiching the metals that are good conductors of heat with other metals (Figure 2. 14(a)**)**. This can be done so there are as many as five layers of metals.



(a) **(b)**

Figure 2. 14: Methods of improving cooking performance (a) Metals sandwiched together. (b) plating [22]

2.9.2. Cladding the bottom of the pan

Another way of how metals can be combined to improve conductivity is to plate or clad a good heat-conducting material onto the bottom of cookware see Figure 2. 14(b). An example is copper clad onto the bottom of stainless-steel cookware.

2.9.3. Smoothing bottoms of the pan

Smooth, flat-bottomed cookware is important to good cooking performance and is recommended by all cooktop manufacturers. The flatter the cookware’s bottom surface when heated, the better it will receive heat from the element and conduct it to the food [22].

Some types of high-quality cookware are not flat until they are heated; otherwise, they are concave. Shorter cooking times and energy savings can be realized when cooking with flat rather than non-flat cookware.

2.9.4. Increasing the contact area between stove surface and pan

for good cooking performance, the diameter of the cookware should closely match the size of the heating area. Cookware should not extend more than 1 inch beyond the heating area. If cookware is too large, the heat is distributed unevenly, cooking time is increased, and more energy is used. Also, heat can be trapped under the heating element, causing the element to build up heat (Figure **2. 15**).

This build-up of heat may shorten the element's life or damage the surface around the element. When a cooking system is thermally limited, a too-large cooking utensil will cause the unit to cycle off and on, reducing the cooking speed and the life of the heating element. on glass-ceramic cooking surfaces, a cooking utensil that is too large in diameter can cause the glass to overheat and break.

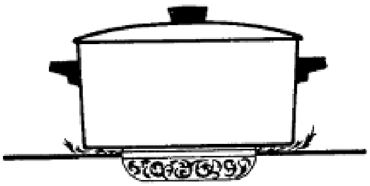


Figure 2. 15: Cookware too large for heating element [22].

Cookware that is too small for the heating element can waste energy because heat is lost into the kitchen. Small cookware also increases chances of spill-overs.

2.9.5. Good surface finish

Some of the most common finishes of cookware are natural metal, fused porcelain enamel, and anodized aluminum, which can influence cooking performance and ease of cleaning. Fusing porcelain enamel onto steel or iron makes it more attractive and easier to clean. Cookware fused with porcelain enamel will not rust unless chipped.

Anodizing aluminum can enhance aluminum's good performance. The dark-colored, anodized surface absorbs radiant heat and makes the cooking utensil harder. Fluorocarbons, under such names as Teflon II and Silverstone give a smooth, anti-stick finish to the inside of cookware. If not scratched, these finishes make cleaning easier. The color and texture of the finish also have some influence on cooking performance and speed. Dark-colored, rough textured cookware absorbs more radiant heat than highly polished cookware. However, the color of the cooking utensil is more important in the oven than on top of the range.

2.9.6. Tight-fitting lids

Lids should fit firmly and snugly. Some lids interlock with cooking utensils and some sit flat on the lips of cookware. (Figure 2. 16) Lids that sit flat must be heavy enough to provide a good seal. Tight-fitting lids hold in steam; thus, less water and energy are used during cooking.

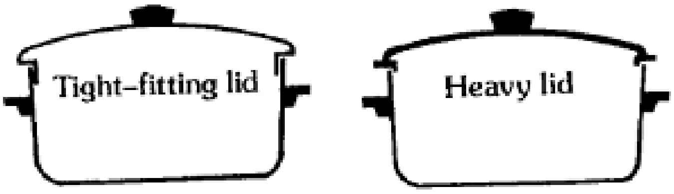


Figure 2. 16: Types of Lids [22].

2.9.7. Durable handles

Cookware handles should also be considered. If a handle is made of a material that will melt, look for a flame guard between the handle and the cookware Figure 2. 17. This guard will protect the handle from the heat of the cooking element. Metal handles may be oven-safe but they can get too hot to pick up without using a potholder.

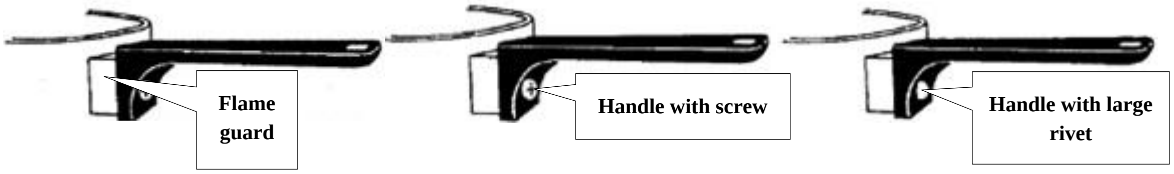


Figure 2. 17: Types of Handles [22]

Check to see that handles are securely fastened. Handles that are bolted or screwed may loosen but can be easily tightened (Figure 2. 17). Rivets on inexpensive cookware are often weak spots, but large rivets provide long-lasting attachments. A handle should be secure enough to easily lift a cooking utensil full of food. It should also fit the user’s hand comfortably, especially on large, heavy utensils. The handle weight should not cause an empty cooking utensil to tip toward the handle.

CHAPTER THREE

EQUIPMENT AND METHODS

The pots used in the study are standard pots used in the evaluation of various cook stove designs. They are pictured in Figure 3. 1. Four different sizes of pots with two materials have been used as sample for experiments. The most typical and relevant cooking processes in households are: [23]

- Boiling water (representing hot drinks, soups and parboiling process);
- Brewing coffee (representing automated brewing processes);
- Cooking potatoes (representing the cooking process itself);
- Boiling eggs (representing automated boiling processes).

Each process was carried out with various different approaches that are commonly used in households. Variations are made especially in the prepared amount and, where applicable, in the final state that is being aimed at. Since boiling water is the easiest, quickest, and cheapest to conduct, all the experiments done using it.

The aim of the test consists in comparing the thermal efficiency of different pots of boiling water. Efficiency is determined for different amounts of hot water that are common in households. Experimental validation consists of emulating a normal cooking process using a commercial electric stove as the heat source and water as the substance to be heated.

3.1 Appliances for Experiment

The basic appliances necessary for the experiment are:

i. ***Standard cookpots:*** A pot that are used in our region and have a volume of about 2.5 liters (for 2.25-L tests), 3.14 liters for 2.83 L test aluminum made pots and, 2.5 liters (for 2.25-L tests), 3.14 liters for 2.83 L test clay made pots. See Figure 3. 1.

Figure 3. 1: Pots for experiment

ii. ***Water:*** Initial temperature of water, by taking repetitive measurements at a time of testing, an average of 17.6°C was taken.

Figure 3. 2: Water at an atmospheric temperature.

iii. **Measuring instruments**

Figure 3. 3: Thermometer (contact and infrared) and mass balance,

iv. ***Electrical stove:*** A cook-top it has a coil that heats up due to resistance when current passes through it. It uses electricity to generate heat and cook food. The stove typically pulls around 1,500 Watts when turned on.

Figure 3. 4: Electric resistance stove.

Experimental validation consisted of emulating a normal cooking process using a commercial electric stove as the heat source and water as the substance to be heated. Series of experiments were performed for each pot. Each test had a duration of 310-450 min, within which the boiling temperature and steady-state conditions were reached. The experimental tests were conducted at an average atmospheric temperature of 17.6 ^{0}C and average atmospheric pressure of 85.2 kPa (Addis Ababa, March 24/2017). The test room was free from air conditioning currents.

Table 3. 1 presents the geometrical properties and characteristics of the pots used for experiment. The pots are classified according to the height, diameter, and type of construction material.

Table 3. 1: Geometrical properties and other characteristics of the pots

S.N.	**Diameter** ***(mm)***	**Height** ***(mm)***	**Thickness** ***(mm)***	**Material**	**Bottom curvature radius** ***(mm)***	**Lid condition**	**Grove height from bottom** ***(mm)***	**Area of contact (%)**	**Wall gradient (deg.)**	**Occupied volume** ***(%)***	**Conductivity (W/m.K) [24]**
1	170	110	1	Al	100	Open	100	95	0	85	204
2	200	100	1	Al	100	open	80	88	0	85	204
3	169	110	7	Clay	100	open	No	98	0	85	0.964
4	200	98	9	Clay	100	Open	No	90	0	85	0.964

3.2 Material Properties and Specifications

The local altitude of the laboratory where the tests were made is approximately 2400 m. above sea level. The boiling point for water at this mean altitude is ~89.60 ^{0}C. Thermophysical properties of experimental materials are listed in Table 3. 2 below.

Table 3. 2: Thermophysical properties of experimental materials

<table>
<tr><th colspan="7">Thermophysical properties of Aluminum (Al) at 300 K</th></tr>
<tr><td>Melting point</td><td colspan="2">Density/ ρ</td><td colspan="2">Specific heat /c_p</td><td>Thermal conductivity /k</td><td>Thermal diffusivity /α.</td></tr>
<tr><td>933 K</td><td colspan="2">2702 kg/m^3</td><td colspan="2">903 J/kg.K</td><td>204 W/m.K</td><td>97.1*10^6 m^2/s</td></tr>
<tr><th colspan="7">Thermophysical properties of water at 300 K [25]</th></tr>
<tr><td>Boiling point at 85.2 kPa</td><td>Density/ρ</td><td>Latent heat of evaporation/h_{fg}</td><td>Specific heat /c_p</td><td>Thermal conductivity/k</td><td>Thermal diffusivity/α</td><td>Molar mass/M</td></tr>
<tr><td>88.974 K</td><td>997.1 kg/m^3</td><td>2030 kJ/kg</td><td>4.183 kJ/kg.K</td><td>0.5948 W/m.K</td><td>0.143 *10^6 m^2/s</td><td>18.01 g/mol.</td></tr>
<tr><th colspan="7">Thermophysical properties of fired clay at 300 K [26]</th></tr>
<tr><td>Maximum temp</td><td colspan="2">Density/ρ</td><td>Specific heat/c_p</td><td>Thermal conductivity/k</td><td colspan="2">Thermal diffusivity/α</td></tr>
<tr><td>1316 K</td><td colspan="2">2124 kg/m^3</td><td>2920 J/kg.K</td><td>0.964 W/m.K</td><td colspan="2">0.046 m^2/day</td></tr>
</table>

3.3 Basic Definitions and Experimental Assumptions

In this section, the basic terms and the main assumptions employed to quantify the performance of cooking pots are described. Our final goal is to obtain a rational procedure that can assign to every cooking pot a dimensionless number called ‘‘thermal efficiency’’.

It is true that in an ideal situation, any proposed test method should be universal and mimic all features of cooking habits of the society. However, such a perfect cooking test method is far from being practical, and the proposed method should rely largely on statistical data obtained from the residential energy consumption survey of each country, unless using simple assumptions. Consider the above assumptions, the cooking habit is simulated by the following test method.

The total cooking procedure is divided in two parts. In the first part, a given mass of water (to be clarified later) is heated to its boiling point, while in the second part the given mass is kept free to atmosphere till it reaches room temperature.

3.3.1. Cookpot

Simply stated, Cookpot is the physical delivery system for transferring heat from the source such as, electrical coil, natural gas, and induction, to the contact surface of the food in which is intended to be cooked. Conduction of thermal energy via the food contact surface determines the behavior of how the food cooks. The conduction of heat is a combination of heat transfer through the pan materials, as well as heat transfer from the heat source (cooktop) to the base of pan. The construction materials of the pan largely determine how the thermal energy is transferred from the pan to the food. Considering the above points, this study investigates heat transfer characteristics of pans differing in composition and shape.

3.3.2. Thermal conductivity

This describes how readily a material will give or take heat through conduction. A material with high thermal conductivity will transfer heat quickly, while a low conductivity material will transfer heat more slowly. Moving heat rapidly does not necessarily mean rapid temperature change.

3.3.3. Heat capacity

The other important aspect of moving heat is how much the temperature of a material changes when we move a certain amount of heat into it. Heat capacity refers to how quickly a material's temperature changes with the addition of heat. As we add heat to a material with high heat capacity, it will increase temperature more slowly than a material with lower heat capacity.

3.3.4. Mass of water

to obtain the required mass of water for a given cook pot, different Ethiopian foods energy consumption of the cooking for residential sector must be employed. It is assumed that the mass of food is proportional to the mass of water. In addition, the mass of food is proportional to the number of persons the food is prepared or the so-called capacity of the cooking pot. Finally, the mass of water is related to the capacity of cooking pot.

Based on simple observations, only 45–85% of cooking-pot volume is filled with cooking material, and the required mass of water for different cooking pot are defined and shown in Table 3. 3 below.

Table 3. 3: number of users (Persons) and mass of water in cookpots

Persons	Minimum (cm^3)	Maximum (cm^3)	Mass of water(gram)
1	0	850	450
2	850	1600	890
3	1600	2500	1250
4	2500	4500	2200
6	4500	6600	3420
10	6600	8000	5130

3.3.5. Cookpot efficiency

Efficiency is calculated by the following formula: [27, 28]

$$\eta = \frac{m_1\, c_p\, (T_2 - T_1) + (m_1 - m_2) h_{fg}}{Q_{tot}} * 100\% \quad \text{3.1}$$

where:

- η is the cooking pot's thermal efficiency (dimensionless),
- m_1 is water's mass at beginning of the test in kg,
- m_2 is water's mass at end of the test in kg,
- c_p is water's specific heat at constant pressure (4.186 kJ/kg.K),
- T_1 is water's beginning temperature,
- T_2 is water's boiling temperature at local pressure during the test (K),
- h_{fg} is water's latent heat of evaporation at local atmospheric pressure (2030 kJ/kg),
- Q_{tot} is total amount of heat transferred from electrical stove surface through bottom of the pan to water. (kJ)

3.3.6. Contact resistance

Contact resistance between the electrical resistors and pot surface is a parameter that depends on many factors, such as the type of pot coating, pot surface texture, and electrical resistor deterioration level. Thus, the contact resistance often varies between pots and cannot be measured directly or indirectly in a reliable manner when no empirical correlations are available. The contact resistance in the cooking pot was quantified by carrying out an experimental test.

3.3.7. Other assumptions

The additional assumptions and measured values taken for the experimental test are:

- The Cookpot used for experiment made from aluminum (Al),
- One – directional heat flow,
- No internal heat generation,
- Thermal conductivity is constant throughout the surface,
- In addition, it is also assumed that the pot is filled with water at an atmospheric temperature,
- The ambient temperature has been taken as 290.6 K,
- The coefficient of heat transfer between the pot and the water is 95 W/m².K.

Figure 3. 5 presents the configuration and location of thermometer in the pots. The minimum temperature is located in the top center surface of the load to be heated (water).

Figure 3. 5: Temperature measuring setup

3.4 Experimental Procedure

The Water Boiling Test is a simplified method to analyze the heat transfer behavior of cooking process. It is intended to measure how efficiently a stove uses the input power to heat water in a cooking pot. The water boiling test for efficiency can be performed with simple equipment. Its primary benefits are: provide initial or laboratory assessments of stove performance in a controlled setting and to compare the effectiveness of different designs by performing similar tasks.

The following experimental procedure was employed for each test:

- Determine the cook-pot's capacity using Table 3. 3.
- Measure the weight of the empty pot (without water).
- According to Table 3. 3 fill the cook pot with suitable mass of water
- Measure the weight of the pot with water.
- Place a thermometer in the center of cook pot and measure the initial water temperature.
- Turn on the electric stove for 3 min before mounting the pot.
- Place the cook pot on the cook top and wait until the temperature reaches local atmospheric temp. At this moment, test is started.
- Record the water temperature at 2-5 minutes intervals (it depends).
- Record the time until the water reaches the boiling point (89.9 ^{0}C) and wait three-five additional minutes after boiling starts and then remove the pot from the stove.
- Record the water temperature at 2-5 minutes intervals until the water cool down to initial atmospheric temperature and immediately weigh the cook pot.
- Record the maximum water temperature during test procedure.
- Calculate the difference in weight to determine the amount of water evaporated.

3.5 Experimental Analysis

The experimental analysis includes determination of the parameters those are helpful to determine the thermal efficiency of the cookpots. Those parameters are: the heat transferred to the pot, input heat flux, cooking efficiency and time variation of temperature. All these parameters are calculated for all four experimented pots. In the following sections the sample procedural calculation for pot 1 and the final results for other pots are described. Complete procedures for others are given in Appendix 1.

cooking takes longer at high altitudes since boiling point of water is lower at higher altitudes due to the decreased atmospheric pressure. The effect starts to become relevant at altitudes above approximately 2,000 feet (610 m). At sea level, water boils at 100 °C (212 °F). for every 500-foot (150 m) increase in elevation, water's boiling point is lowered by approximately 0.5 °C. At 8,000 feet (2,400 m) in elevation, water boils at just 92 °C (198 °F). Appendix 2.2 [29].

3.5.1. Heat transferred to the pot

3.5.1.1.POT 1 heat transfer analysis

The detail geometrical and experimental parameter specifications of pot 1 is described in Table 3. 4.

Table 3. 4: All Pots parameter specifications

	Pot 1	**Pot 2**	**Pot 3**	**Pot 4**
Material:	**Aluminum**	**Aluminum**	**Clay**	**Clay**
Diameter:	170 mm	160 mm	181 mm	160 mm
Height:	110 mm	96 mm	100 mm	80 mm
Thickness:	1 mm	1 mm	9 mm	7 mm
Radius of curvature:	100 mm	100 mm	100 mm	100 mm
Bottom flatness:	Flat	Flat	Flat	Flat
Lid type:	Heavy weight	Heavy weight	Heavy weight	Heavy weight
Wall gradient:	0 degree	0 degree	0 degree	0 degree
Stove type:	Electrical stove	Electrical stove	Electrical stove	Electrical stove
Contact area percentage:	95 %	95 %	95 %	95 %
Surface condition:	Grove 80 mm from bottom	Grove 100 mm from bottom	Smooth	Smooth
Occupied volume percentage:	90 %	85 %	85 %	85 %
Height/Diameter ratio	0.63	1.74	0.55	0.55
Mass of empty pot:	0.3 kg	0.3 kg	3.5 kg	1.0 kg
Mass of water:	2.25 kg	2.0 kg	3 kg	1.8 kg
Mass of evaporated water:	0.1 kg	0.11 kg	0.12 kg	0.08 kg

It is assumed that the pan surface and the water are always at the same temperature. When we put the pan on the stove, the temperature of the water and the pan is increased. We use the equation for the heat transfer for the given temperature change and mass of water and aluminum.

Because water is in thermal contact with the aluminum, it is assumed that the pan and the water are at the same temperature. The theoretical energy required to heat 3050 ml of water by 72.3° C in 1800 seconds can be calculated using following procedures (By assuming no any heat and mass transfer interactions with the surrounding).

1. Calculate the temperature difference:

$$\Delta T = T_2 - T_1$$

$$= 89.9 - 17.6 = \mathbf{72.3\ {}^{0}C}$$

2. Calculate the mass of water:

Because the density of water is 999.97 kg/m^3, one liter of water has a mass of ~1 kg, and the mass of 2.83 liters of water is m_w = ***2.83 kg***.

3. Calculate the heat transferred to the water. Use the specific heat of water in Table 3. 2:

$$Q_w = m_w * c_{p,w} * \Delta T$$

$$Q_w = 2.83\,kg * 4186\frac{J}{kg.K} * 72.3\,K = 923075.79\,J = \mathbf{923.1\ kJ}$$

4. Calculate the heat transferred to the aluminum. Use the specific heat for aluminum in Table 3. 2:

$$Q_{Al} = m_{Al} * c_{p,Al} * \Delta T$$

$$Q_w = 0.45\,kg * 903\frac{J}{kg.K} * 72.3\,\mathrm{K} = 29379.11\,J = \mathbf{29.4\ kJ}$$

5. Compare the percentage of heat going into the pan versus that going into the water. First, find the total transferred heat:

$$Q_{Total} = Q_w + Q_{Al}$$

$$= 923.1\,kJ + 29.4\,kJ = \mathbf{952.5\ kJ}$$

Thus, the amount of theoretical energy required to heat 2830 ml of water by 72.3° C in 1800 seconds is 952.5 kJ.

6. Therefore, the theoretical power required to heat 2830 ml of water by 72.3° C in 1800 seconds is given by:

$$\frac{952.5\,kJ}{1800\,sec} = 0.529\,kJ/\mathrm{sec} = \mathbf{529.2\ Watts}$$

Thus, the amount of heat going into heating the pan is:

$\frac{29.4}{952.5} * 100\,\% = \mathbf{3.1}\,\%$ of heat going into the pan

and the amount going into heating the water is:

$\frac{923.1}{952.5} * 100\,\% = \mathbf{96.9}\,\%$ of heat going into water

These values indicate that, the heat transferred to the container is a significant fraction of the total transferred heat. The specific heat of water is over four times greater than that of aluminum. Therefore, it takes a bit more than twice the heat to achieve the given temperature change for the water as compared to the aluminum pan.

All the above parameters calculated for pot 1 can be evaluated for other three pots using similar methods (complete analysis includes in Appendix A1-A3). The final results are written below.

3.5.1.2. POT 2 heat transfer analysis

- The heat transferred to the water: $Q_w = 453971.7\,J = \mathbf{453.97\ kJ}$
- The heat transferred to the aluminum: $Q_{Al} = 28630.8\,J = \mathbf{28.63\ kJ}$
- The total transferred heat:

$$Q_{Total} = Q_w + Q_{Al} = 453.97\,kJ + 28.63\,kJ = \mathbf{482.6\ kJ}$$

- Thus, the amount of theoretical energy required to heat 2250 ml of water by 72.3° C in 1100 seconds is 482.6 kJ.

- Therefore, the theoretical power required to heat 2250 ml of water by 72.3 °C in 1100 seconds is given by:

$$\frac{482.6\,kJ}{1100\,sec} = 0.4387\,kJ/\text{sec} = \mathbf{438.7\ Watts}$$

- The amount of heat going into heating the pan is:

$$\frac{28.63}{482.6} * 100\,\% = \mathbf{5.93}\,\% \text{ of heat going into the pan}$$

- The amount going into heating the water is

$$\frac{453.97}{482.6} * 100\,\% = \mathbf{94.1}\,\% \text{ of heat going into water}$$

3.5.1.3. POT 3 heat transfer analysis

- The heat transferred to the water: $Q_w = 544800\,J = \mathbf{544.8\ kJ}$
- The heat transferred to the clay: $Q_{clay} = 152600\,J = \mathbf{152.6\ kJ}$
- The total transferred heat:

$$Q_{Total} = Q_w + Q_{clay} = 544.8\,kJ + 152.6\,kJ = \mathbf{697.4\ kJ}$$

- Thus, the amount of theoretical energy required to heat 2250 ml of water by 72.3° C in 2700 seconds is 697.4 kJ.

- Therefore, the theoretical power required to heat 2250 ml of water by 72.3 °C in 2700 seconds is given by:

$$\frac{697.4\ kJ}{2700\ sec} = 0.258\ kJ/\sec = \mathbf{258.3\ Watts}$$

- The amount of heat going into heating the pan is:

$$\frac{152.6}{697.4} * 100\ \% = \mathbf{21.9}\ \% \text{ of heat going into the pan}$$

- The amount going into heating the water is

$$\frac{544.8}{697.4} * 100\ \% = \mathbf{78.1}\ \% \text{ of heat going into water}$$

3.5.1.4. POT 4 heat transfer analysis

- The heat transferred to the water: $Q_w = 907900\,J = \mathbf{907.9\ kJ}$
- The heat transferred to the clay: $Q_{clay} = 533900\,J = \mathbf{533.9\ kJ}$
- The total transferred heat:

$$Q_{Total} = Q_w + Q_{clay} = 907.9\ kJ + 533.9\ kJ = \mathbf{1441.8\ kJ}$$

- Thus, the amount of theoretical energy required to heat 2830 ml of water by 72.3° C in 4500 seconds is 1441.8 kJ.

- Therefore, the theoretical power required to heat 2830 ml of water by 72.3 °C in 4500 seconds is given by:

$$\frac{1441.8\ kJ}{4500\ sec} = 0.3204\ kJ/\sec = \mathbf{320.4\ Watts}$$

- The amount of heat going into heating the pan is:

$$\frac{533.9}{1441.8} * 100\ \% = \mathbf{37.03}\ \% \text{ of heat going into the pan}$$

- The amount going into heating the water is

$$\frac{907.9}{1441.8} * 100\ \% = \mathbf{62.9}\ \%\ \text{of heat going into water}$$

3.5.2. Heat flux

The heat flux (W/m^2) is the heat transfer rate in one direction per unit area perpendicular to the direction of transfer, and it is proportional to the temperature gradient, in this direction. The heat flux represents the rate of heat transfer through a section of unit area, and it is uniform (invariant) across the surface of the wall. The heat flux values for all experimental pots are listed in Table 3. 5.

Table 3. 5: Heat flux values for experimental pots

POT NO.	Diameter m	Bottom surface Area, m^2	Boiling time sec.	Heat gain W	Heat flux W/m^2
Al POT-1	0.17	0.0226	2040	1500	66,371.68
Al POT-2	0.20	0.0314	2712	1500	47,770.70
Clay POT-3	0.169	0.02602	3000	1500	57,657.87
Clay POT-4	0.20	0.03597	3588	1500	41,701.42

3.5.3. Heat transfer efficiency

The cooking efficiency is the ratio of the energy entering the load (water) and the energy supplied by the stove.

Thermal/cooking Efficiency (η) is calculated by using equation 3.1 above.

$$\eta = \frac{Theoretical\ heat\ input}{Actual\ heat\ input} = \frac{m_1\, c_p\, (T_2 - T_1) + (m_1 - m_2)h_{fg}}{Q_{tot}} * 100\%$$

for pot 2:

m_1 is water’s mass at beginning of the test = 2.83 kg,

m_2 is water’s mass at end of the test = 2.63 kg,

c_p is water’s specific heat at constant pressure = 4.186 kJ/kg.K,

T_1 is water’s initial temperature = 17.6 ^{0}C,

T_2 is water’s boiling temperature or its highest temperature during the test = 83.8 ^{0}C,

$\boldsymbol{h_{fg}}$ is water’s latent heat of evaporation at atmospheric pressure = 2256 kJ/kg,

$\boldsymbol{Q_{tot}}$ is total amount of heat transferred from electrical stove surface through bottom of the pan to water = 3492.2 kJ [30]

Therefore:

$$\eta = \frac{2.83\ kg * 4.186\ \frac{kJ}{kg}.K * (357.1 - 290.6)K + (2.83\ kg - 2.63\ kg) * 2256\frac{kJ}{kg}}{3492.2\ kJ}$$

$$\eta = \mathbf{0.379 = 38}\ \%$$

Table 3. 6: Thermal efficiency Summery

	m_1(kg)	m_2(kg)	m_w(kg)	$c_{p,w}$(J/kg.K)	T_1(K)	T_2(K)	h_{fg}(J/kg)	q_{input}(J)	Efficiency
Pot 1(Al)	2.25	2.15	**0.1**	4186	290.6	357.0	2256000	2290000	46 %
Pot 2(Al)	2.83	2.63	0.2	4186	290.6	357.1	2256000	3492250	38 %
Pot 3(Clay)	2.25	2.14	0.11	4186	290.6	357.6	2256000	2061000	30 %
Pot 4(Clay)	2.83	2.61	0.22	4186	290.6	356.2	2256000	3435000	37 %

As shown in Table 3. 6,wall heat losses, i.e. the heat that is not transferred to the water, represent 54 %, 62 %, 70 % and 63 % of the total heat input for POT-1, 2, 3, and 4 respectively.

3.5.4. Time variation of temperature

3.5.4.1 POT 1

Equipment:	Cookpot-1	
Diameter:	170 mm	
Height:	110 mm	
Material:	Aluminum	
Heat input:	66371.68 W/m^2	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Full temperature data recorded for metal pot 1 is tabulated in Appendix 2.1

Time (Sec.)	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**
Temp.(^{0}C)	17.6	82.4	61.4	51.9	40	32.4	28	25.2	21.3	17.9	17.6

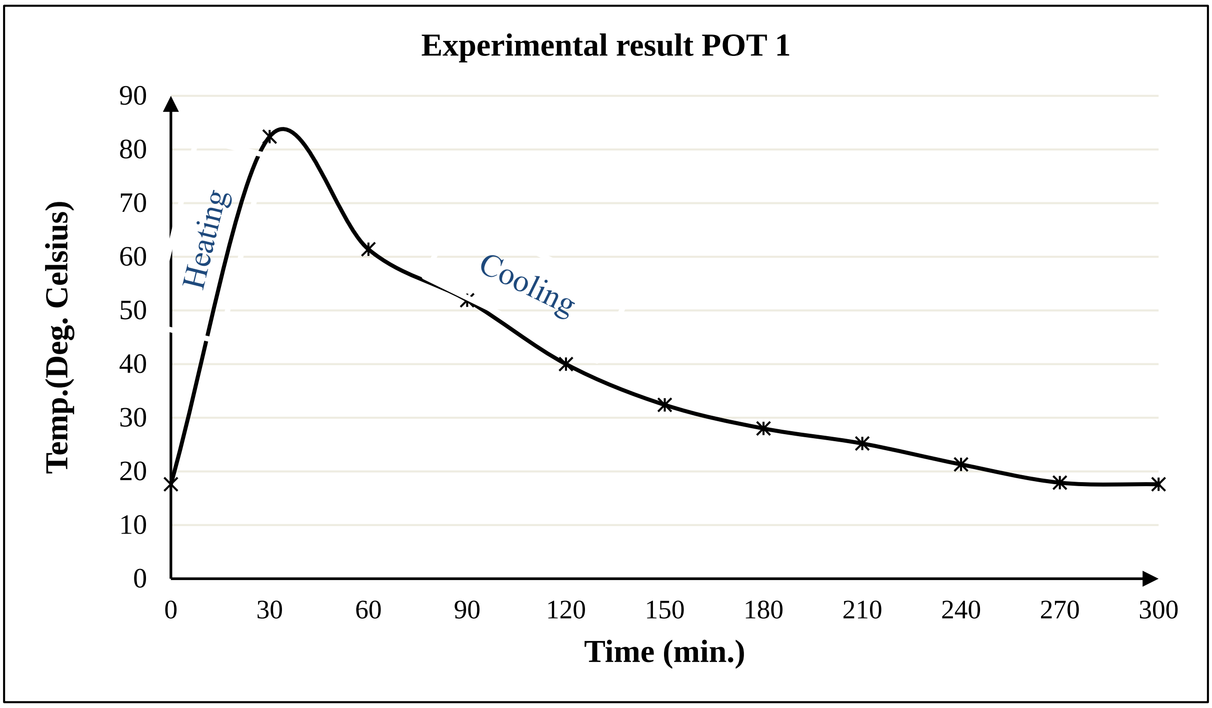


Figure 3. 6: Temperature variation with time metal pot 1

As we observe from the experiment, the water reaches the boiling point temperature 84.0 ^{0}C, after 34 minutes of heating. It takes 266 minutes to cooldown to local atmospheric temperature. The amount of water evaporated is 0.10 kg.

3.5.4.2 POT 2

Equipment:	Cookpot-2	
Diameter:	200 mm	
Height:	100 mm	
Material:	Aluminum	
Heat input:	47.7 KW/m^2	
Initial(atmospheric) temperature:	19.07 ^{0}C	

Full temperature data recorded for metal pot 2 is tabulated in Appendix 2.1

Time(min)	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**
Temp.(0C)	19.07	65.00	75.00	50.00	38.23	32.06	27.76	24.58	22.13	20.16	18.55	17.21	16.07

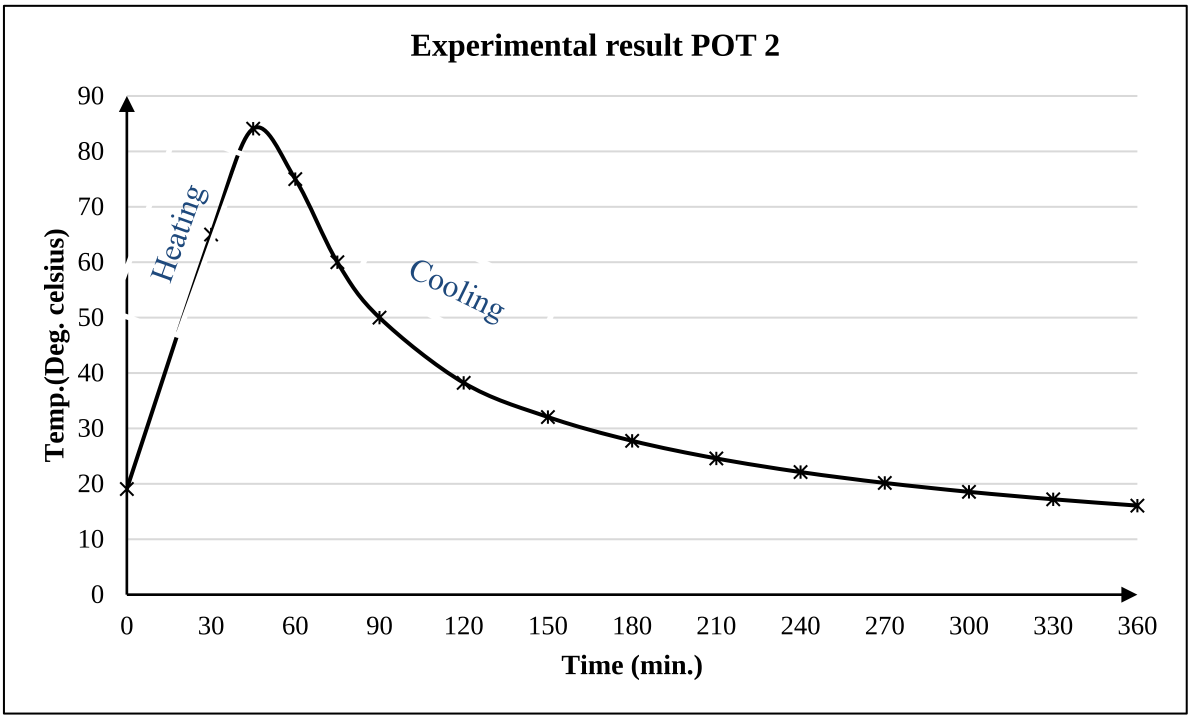


Figure 3. 7: Temperature variation with time metal pot 1

As we observe from the experiment, the water reaches the boiling point temperature 84.1 ^{0}C, after 45.2 minutes sec. of heating. It takes 314.8 minutes to cooldown to local atmospheric temperature. The amount of water evaporated is 0.11 kg.

3.5.4.3 POT 3

Equipment:	Cookpot-1	
Diameter:	170 mm	
Height:	110 mm	
Material:	Aluminum	
Heat input:	57.6 KW/m^2	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Full temperature data recorded for metal pot 3 is tabulated in Appendix 2.1

Time	**0**	**15**	**30**	**45**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**
Temp.(^{0}C)	17.6	50	70	83.4	82.00	68.00	55.50	47.00	41.00	37.00	34.00	31.00	29.00	26.86	25.34	24.02	22.86

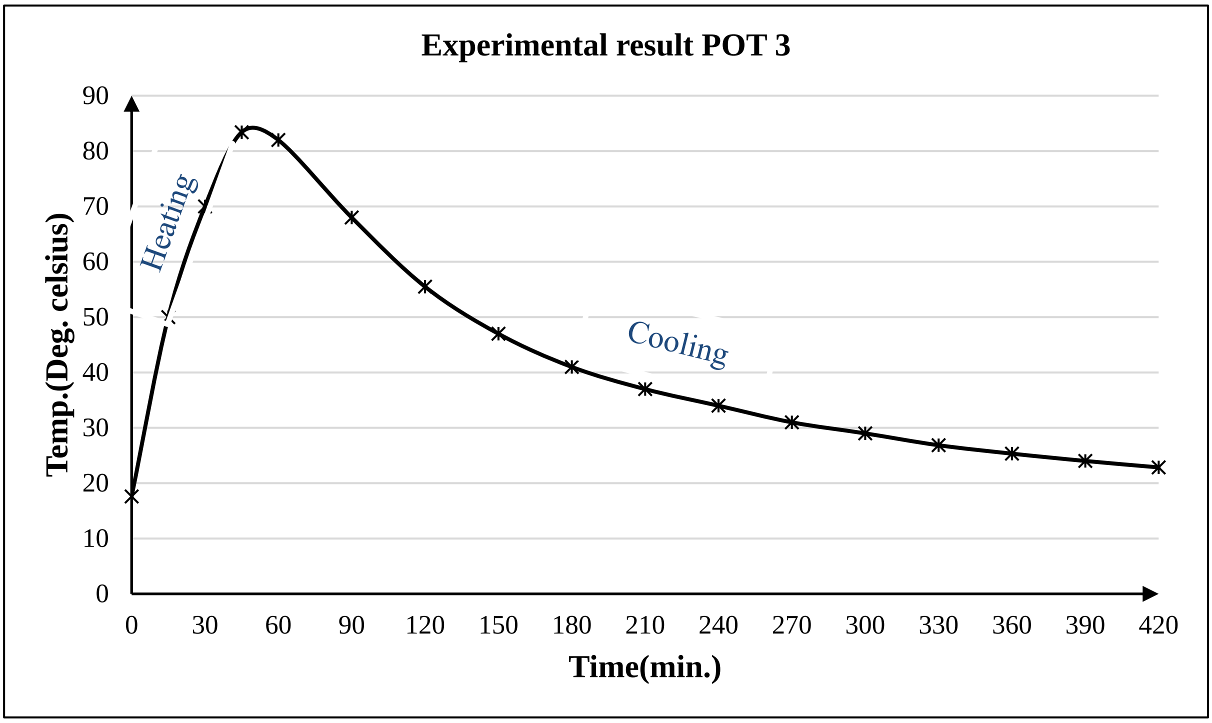


Figure 3. 8: Temperature variation with time clay pot 3

As we observe from the experiment, the water reaches the boiling point temperature 84.6 ^{0}C, after 50 minutes of heating. It takes 370 minutes to cooldown to local atmospheric temperature. The amount of water evaporated is 0.11 kg.

3.5.4.4 POT 4

Equipment:	Cookpot-1	
Diameter:	200 mm	
Height:	100 mm	
Material:	Clay	
Heat input:	41.7 KW/m^2	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Full temperature data recorded for pot 4 is tabulated in Appendix 2.1

Time	**0**	**30**	**40**	**50**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**	**450**	**480**	**510**
Temp.(^{0}C)	**17.60**	**63.00**	**73.00**	**81.00**	**83.00**	**74.00**	**62.00**	**51.00**	**44.00**	**38.00**	**34.00**	**30.00**	**28.00**	**26.00**	**25.00**	**23.50**	**22.00**	**20.00**	**19.17**	**18.42**

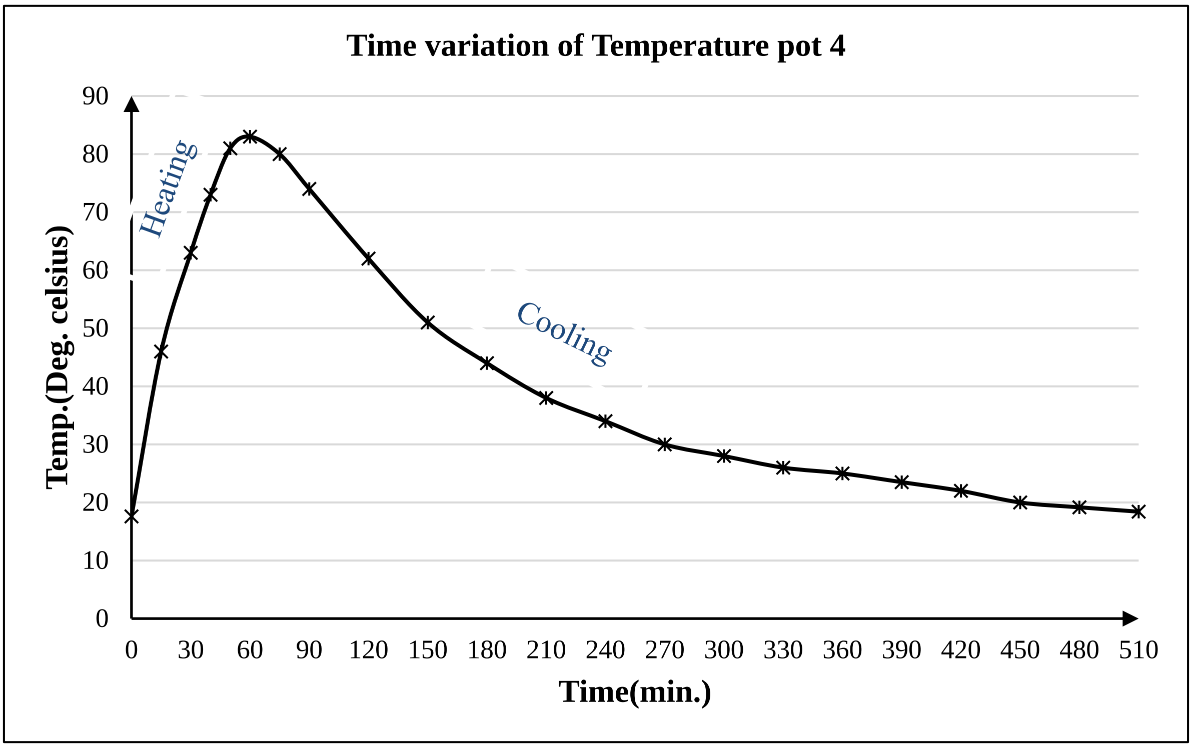


Figure 3. 9: Temperature variation with time clay pot 4

As we observe from the experiment, the water reaches the boiling point temperature 83.2 ^{0}C, after 60 minutes of heating. It takes 450 minutes to cooldown to local atmospheric temperature. The amount of water evaporated is 0.22 kg.

CHAPTER FOUR

MODELING AND SIMULATION

In this section, numerical modelling for the pots' energy consumption is described. The model is developed for the purpose of incorporating experimental results into the simulation. At first, ten independent parameters are postulated. Those are: occupied volume percentage, pot diameter, pot height, bottom wall curvature, edge radius, wall slope, conductivity, stove top surface area, and lid condition.; however, two parameters could be neglected or assumed as the ratio of two parameters leading to the definition of a new parameter.

4.1. Thermal Analysis

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interests are:

- ✓ The temperature distributions,
- ✓ The amount of heat lost or gained,
- ✓ Thermal gradient,
- ✓ Thermal fluxes, and
- ✓ Thermal efficiency.

Thermal simulations play an important role in the design of many engineering applications, including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components. [31].

4.2. Transient Thermal Analysis

Transient thermal analyses determine temperatures and other thermal quantities that vary over time. The variation of temperature distribution over time is of interest in many applications such as heat treatment problems, electronic package design, nozzles, engine blocks, pressure vessels, fluid-structure interaction problems, and so on involve transient thermal analyses. Transient thermal analyses can be performed using the ANSYS, Samcef, or ABAQUS solver.

The thermal analysis of our modeling of cook-pot was performed by using an ANSYS solver for Transient thermal analysis. we can use Transient thermal analysis to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that vary over time. Such loads include the following:

- ✓ Convections
- ✓ Radiation
- ✓ Heat flow rates
- ✓ Heat fluxes (heat flow per unit area)
- ✓ Heat generation rates (heat flow per unit volume) and
- ✓ Constant temperature boundaries

A transient thermal analysis can be either linear or nonlinear**.** Temperature dependent material properties (thermal conductivity, specific heat or density), or temperature dependent convection coefficients or radiation effects can result in nonlinear analyses that require an iterative procedure to achieve accurate solutions. [31] The thermal properties of most materials do vary at higher temperature variations, but for this study the temperature variation is up to boiling point of water, so the pot analysis was evaluated by assuming linear condition.

The basis for thermal analysis in ANSYS is a heat balance equation obtained from the principle of conservation of energy. The finite element solution performed via Mechanical APDL calculates nodal temperatures, then uses the nodal temperatures to obtain other thermal quantities. The ANSYS program handles all three primary modes of heat transfer: conduction, convection, and radiation.

4.2.1. Governing Equations

ANSYS Thermal solves the ***Energy equation*** in the following form:

$$\frac{\partial}{\partial t}(\rho E) + \nabla * (\vec{v}(\rho E + p)) = \nabla * \left(k_{eff}\nabla T - \sum_j h_j \vec{J}_j + \left(\overline{\tau_{eff}} * \vec{v}\right)\right) + S_h \quad \ldots\ldots\ldots\ldots 4.1$$

Where:

- k_{eff} is the effective conductivity (**k+k_t**, where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used).
- $\vec{J}_j$ is the diffusion flux of species ***j.***
- The first three terms on the right-hand side of Equation 4.1 represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively.
- S_h includes the heat of chemical reaction, and any other volumetric heat sources we have defined.

In equation 4.1 $$\boldsymbol{E = h - \frac{p}{\rho} + \frac{v^2}{2}} \qquad \text{……………………………………….4. 2}$$

where sensible enthalpy h is defined for ideal gases as

$$\boldsymbol{h = \sum_j Y_j h_j + \frac{p}{\rho}} \qquad \text{…………………………………….4. 3}$$

and for incompressible flows as

$$\boldsymbol{h = \sum_j Y_j h_j} \qquad \text{…………………………………………..4. 4}$$

In Equation 4.3 and Equation 4.4, $\boldsymbol{Y_j}$ is the mass fraction of species j and

$$\boldsymbol{h_j = \int_{T_{ref}}^{T} c_{p,j} dT} \qquad \text{………………….........……………….4. 5}$$

The value used for T_{ref} in the sensible enthalpy calculation depends on the solver and models in use. for the pressure-based solver T_{ref} is 298.15 K. for the density-based solver T_{ref} is 0 K except when modeling species transport with reactions in which case T_{ref} is a user input for the species.

4.2.2. Solving steps

Typically, Transient thermal analysis includes following several steps to solve the given problem.

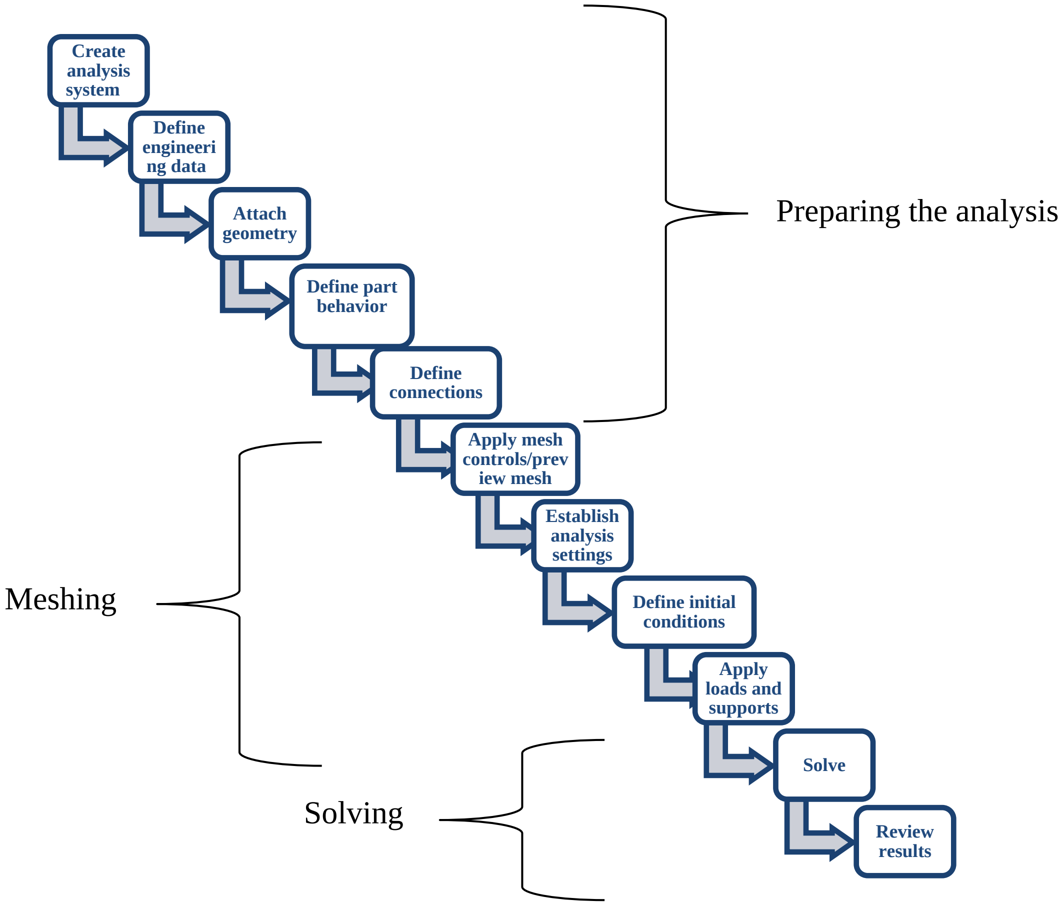


Figure 4. 1: Simulation Steps

4.3. Define Engineering Data

Thermal Conductivity, Density, and Specific Heat must be defined for Transient thermal analysis. These properties will be constant or temperature-dependent, but for this study all these properties were taken to be constant.

Table 4. 1: Thermophysical properties of materials for simulation.

<table>
<tr><th colspan="7">Thermophysical properties of Aluminum (Al) at 300 K</th></tr>
<tr><td>Melting point</td><td colspan="2">Density
ρ</td><td colspan="2">Specific heat
c_p</td><td>Thermal conductivity
k</td><td>Thermal diffusivity
α.</td></tr>
<tr><td>933 K</td><td colspan="2">2702 kg/m^3</td><td colspan="2">903 J/kg.K</td><td>204 W/m.K</td><td>$97.1*10^6$ m^2/s</td></tr>
<tr><th colspan="7">Thermophysical properties of water at 300 K [25]</th></tr>
<tr><td>Boiling point at 85.2 kPa</td><td>Density
ρ</td><td>Latent heat of evaporation
h_{fg}</td><td>Specific heat
c_p</td><td>Thermal conductivity
k</td><td>Thermal diffusivity
α</td><td>Molar mass
M</td></tr>
<tr><td>88.974 K</td><td>997.1 kg/m^3</td><td>2030 kJ/kg</td><td>4.183 kJ/kg.K</td><td>0.5948 W/m.K</td><td>$0.143 *10^6$ m^2/s</td><td>18.01 g/mol.</td></tr>
<tr><th colspan="7">Thermophysical properties of fired clay at 300 K [26]</th></tr>
<tr><td>Maximum temp</td><td colspan="2">Density
ρ</td><td>Specific heat
c_p</td><td>Thermal conductivity
k</td><td colspan="2">Thermal diffusivity
α</td></tr>
<tr><td>1316 K</td><td colspan="2">2124 kg/m^3</td><td>2920 J/kg.K</td><td>0.964 W/m.K</td><td colspan="2">0.046 m^2/day</td></tr>
</table>

4.4. Creating Model Geometry and Mesh

The object we want to model is a circular cookpot filled with water as shown in Figure 4. 2.

(a) ***(b)***

Figure 4. 2: Sample cookpots to be modeled, (a) Aluminum (b) Clay

4.4.1. Model geometry

In the current work, many different types of circular pots have been modelled. for all modelling the following five geometrical parameters shown in Figure 4. 3 are common.

i. ***D*** - Pot diameter (which is measured at its opening),

ii. ***h*** - The height of the pot (which is measured from the pot bed without considering the bottom thickness),

iii. ***r*** - External edge radius,

iv. ***R*** - Pot’s bottom curvature (equal to the 1/R and its sign is positive when its concave surface is on upward side, see Figure 4. 3, and it is negative when the concave surface is on downward side) and

v. θ – Wall slope (which is positive when the opening diameter is greater than bottom diameter).

vi. V_{occ} - The occupied volume percent of the pot volume (the ratio of the water volume to the pot’s total volume at the beginning of test).

It must be noted that if pot’s bottom surface is flat, then its curvature will be equal to zero and its radius of curvature will tend to infinity. to circumvent this problem, the radiuses of curvature of flat bottom pots have been assumed equal to 100 m [10].

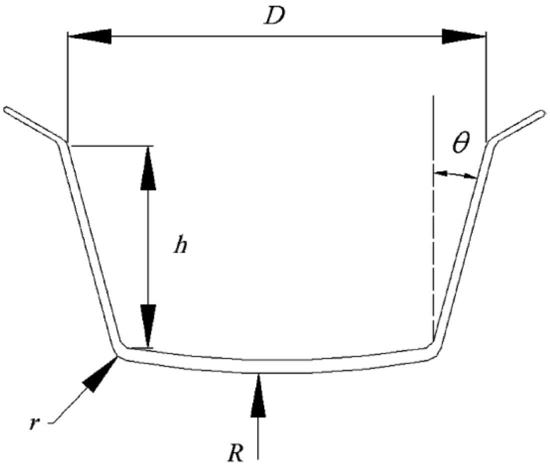


Figure 4. 3: Schematic of a cookpot and its parameters

According to the analysis type, the modeling process considers the different diameters and heights of pots that are commercially available in Ethiopia. to set the difference between the experimental and simulation results, modeling of the pots that are used for the experimental study were considered. geometrical characteristics of these pots are listed inTable **4. 2** below**.**

Table 4. 2: Geometrical properties and other characteristics of the pots

S.N.	**Diameter** ***(mm)***	**Height** ***(mm)***	**Thickness** ***(mm)***	**Material**	**Bottom curvature radius** ***(mm)***	**Lid condition**	**Grove height from bottom** ***(mm)***	**Area of contact (%)**	**Wall gradient (deg.)**	**Occupied volume** ***(%)***
1	250	160	1	Al	100	Open	100	103	0	85
2	160	100	1	Al	100	open	60	88	0	85
3	181	100	9	Clay	100	open	No	93	0	85
4	155	83	7	Clay	100	Open	No	78	0	85

4.4.2. Define Connections

In a thermal analysis, only contact is valid. Any joints are ignored. With contact the initial status is maintained throughout the thermal analysis, that is, any closed contact faces will remain closed and any open contact faces will remain open for the duration of the thermal analysis. Heat conduction across a closed contact face is set to a sufficiently high enough value (based on the thermal conductivities and the model size) to model perfect contact with minimal thermal resistance.

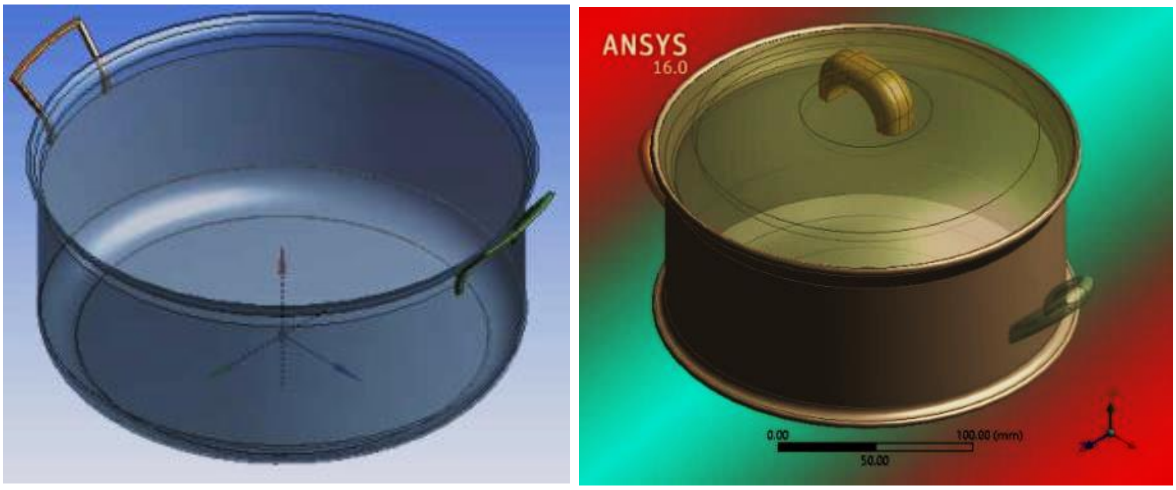


Figure 4. 4: 3D modeling samples a) metal pot 1 b) clay pot 3

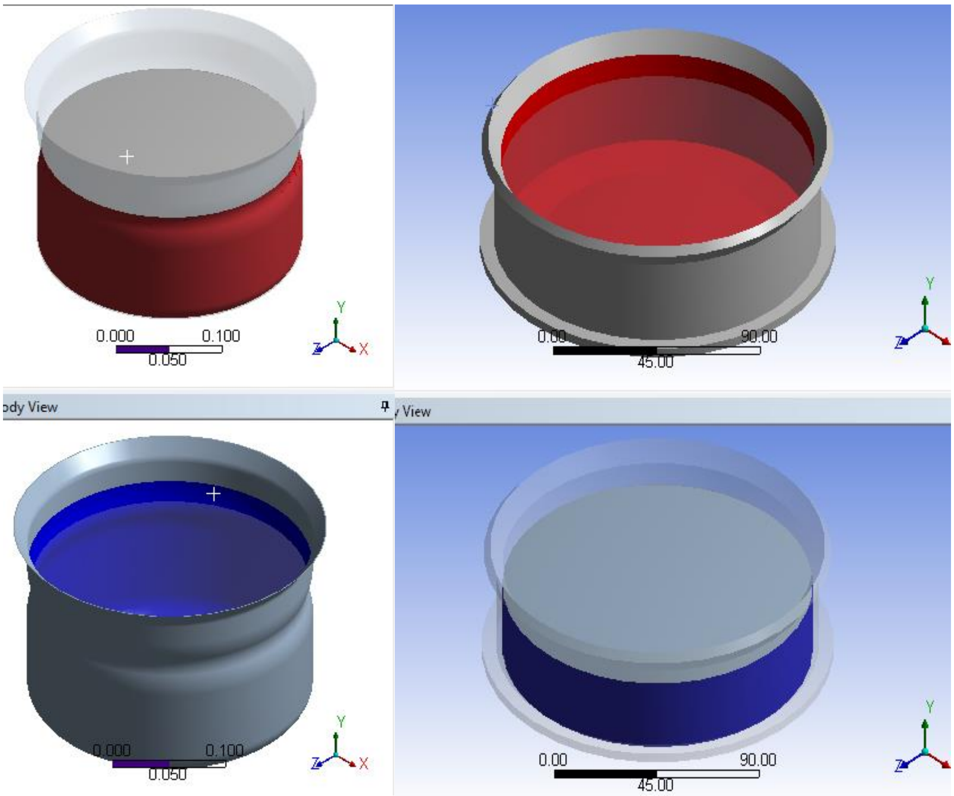


Figure 4. 5: Thermal contact areas

4.4.3. Meshing

ANSYS Transient Thermal uses unstructured meshes in order to reduce the amount of time spend to generating meshes, to simplify the geometry modeling and mesh generation process, to enable modeling of more complex geometries than can handle with conventional.

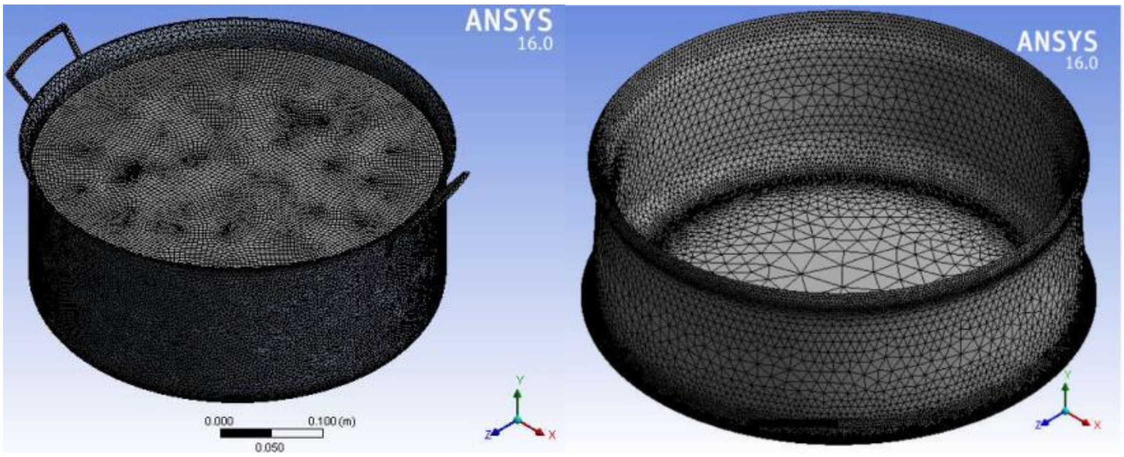


Figure 4. 6: Model Meshing (a) metal pot 1 model, b) clay pot 3 model

4.5. Setting Up the Solver and Physical Models

4.5.1. Boundary Condition and Geometry

Boundary conditions:

- Heat flux at the bottom surface: it depends on pot geometry.
- Free convection air temperature: 291 K
- Free convection coefficient of air: 7 W//m^{2}K
- Initial water temperature: 290 K

In addition, it is also assumed that the pan is filled up by water, and the coefficient of heat transfer between the pan and the water is assumed to be 90 W/ (m^2. K).

4.5.2. Establish Analysis Settings

for a transient thermal analysis, the basic analysis settings include:

Step Controls: Step Controls enable to control the rate of loading which could be important in thermal analysis if the material properties vary rapidly with temperature. When such nonlinearities are present it may be necessary to apply the loads in small increments and perform solutions at these intermediate loads to achieve convergence.

Output Controls: Output Controls enable to specify the time points at which results should be available for postprocessing. In a nonlinear analysis, it may be necessary to perform many solutions at intermediate load values. However, it not be interested in all the intermediate results and writing all the results can make the results file size unwieldy. In this case we can restrict the amount of output by requesting results only at certain time points.

Nonlinear Controls: Nonlinear Controls enable to modify convergence criteria and other specialized solution controls. Typically, it will not need to change the default values for this control. Nonlinear Controls are exposed for the ANSYS solver only. [31]

4.5.3. Define Initial Conditions

for transient thermal analysis we specify an initial temperature value of 17.6 deg. Celsius. This uniform temperature is used during the first iteration of a solution to evaluate temperature-dependent material properties. and used as the starting temperature value for constant temperature loads.

4.5.4. Apply Loads and Supports

The following loads are supported in a transient thermal analysis: Temperature, Convection, Radiation, Heat Flow, Perfectly Insulated, Heat Flux, Internal Heat Generation, Imported Convection Coefficient and Fluid Solid Interface. However, we use only two thermal loads, heat flux and convection for our model.

- Heat flux = 1500/A W/m^2
- Outside Convection heat transfer coefficient = 7 W/m^2

4.5.5. Solve

The Solution Information object provides some tools to monitor solution progress. Solution Output continuously updates any listing output from the solver and provides valuable information on the behavior of the structure during the analysis. Any convergence data output in this printout can be graphically displayed as explained in the Solution Information section.

4.6. Review Results

4.6.1. Temperature distribution

Applicable results are all thermal result types. Once a solution is available we can contour the results or animate the results to review the response of the structure. As a result of a nonlinear analysis we may have a solution at several time points. we can use probes to display the variation of a result item over the load history. Also, of interest is the ability to plot one result quantity (for example, maximum temperature on a face) against another results item (for example, applied heat generation rate). We can use the Charts feature to develop such charts, which are also useful to compare results between two analyses of the same model.

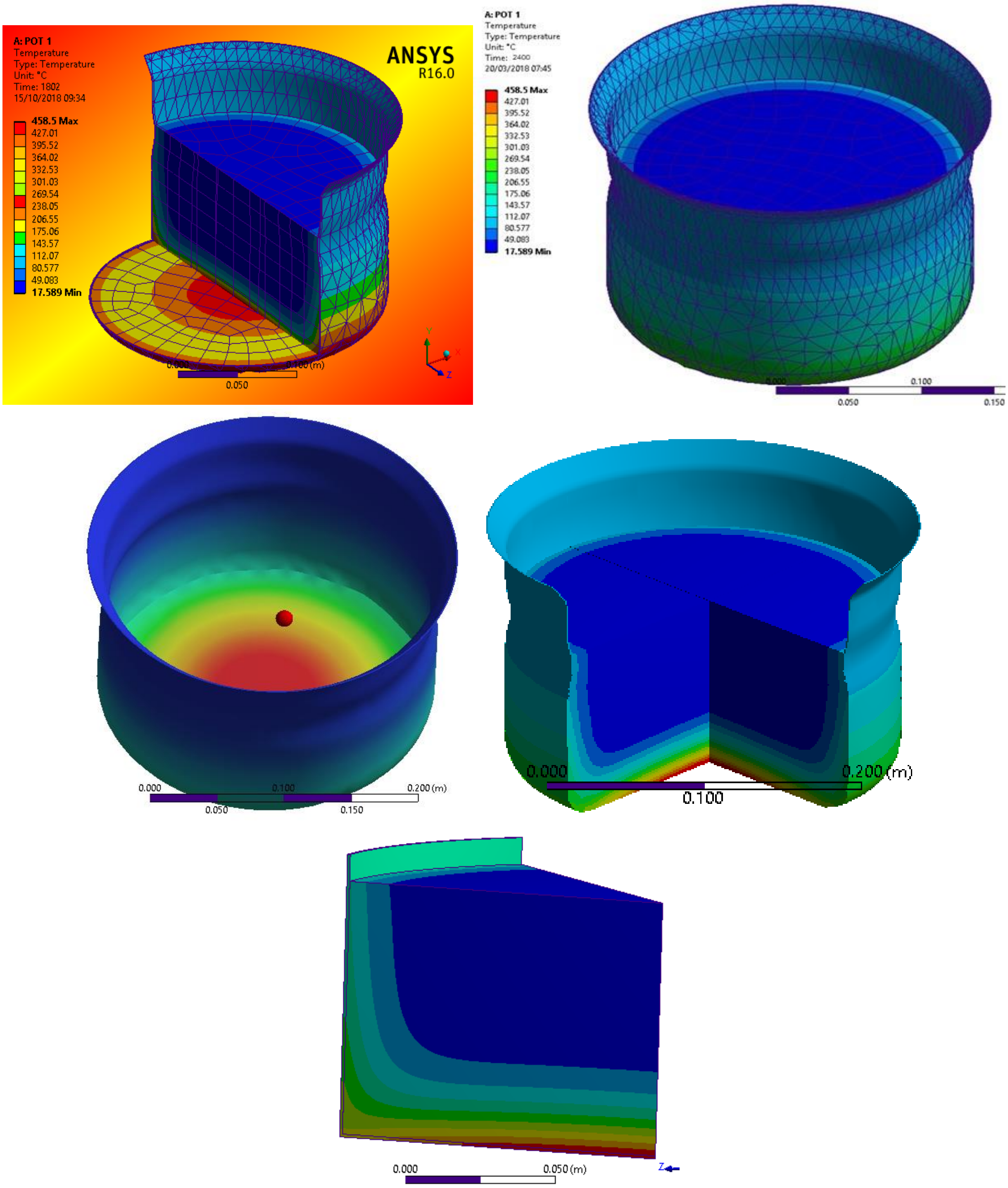
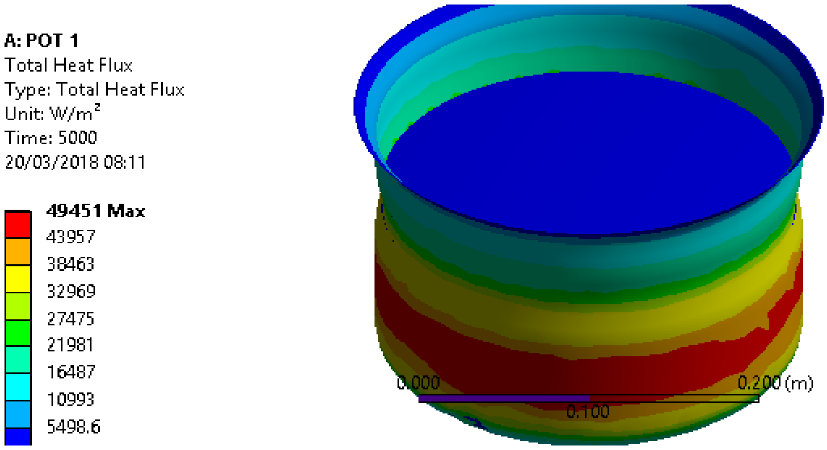


Figure 4. 7: Temperature distribution pot 1

4.6.2. Heat Flux Distribution

Figure 4. 8: Heat flux distribution Pot



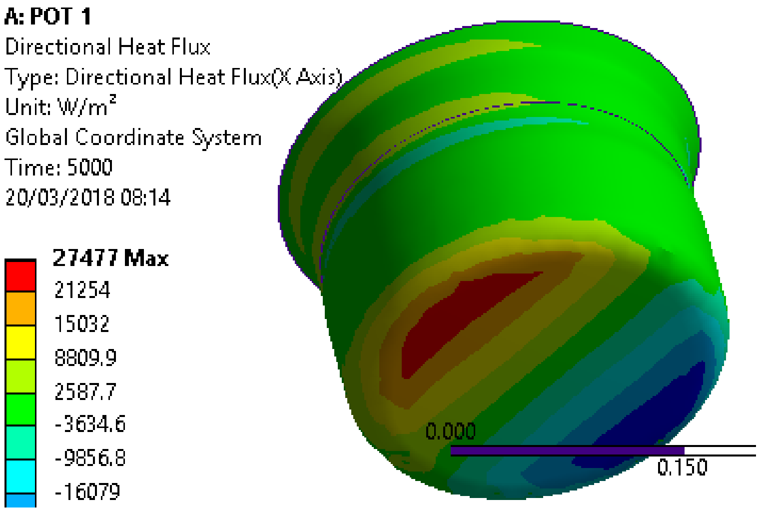


Figure 4. 9: Directional Heat flux Pot 1

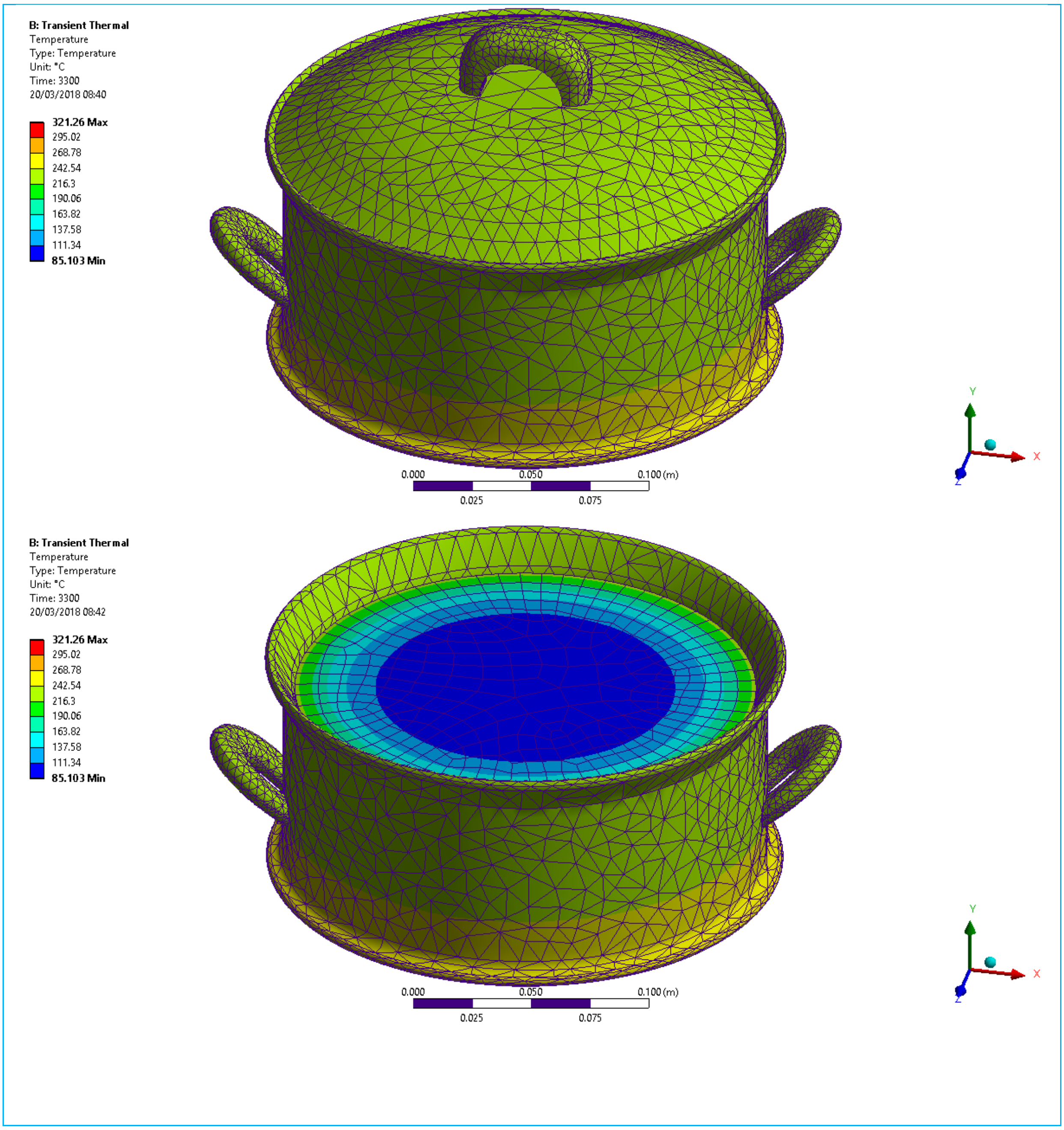


Figure 4.10

4.6.3. Scaling (Grid Independence) Test

Grid convergence is the term used to describe the improvement of results by using successively smaller cell sizes for the calculations. A calculation should approach the correct answer as the mesh becomes finer, hence the term grid convergence. The normal CFD technique is to start with a coarse mesh and gradually refine it until the changes observed in the results are smaller than a pre-defined acceptable error.

There are two problems with this approach. Firstly, it can be quite difficult with other CFD software to obtain even a single coarse mesh result for some problems (particularly when time is pressing). Secondly refining a mesh by a factor of 2 can lead to an 8 fold increase in problem size so even more time is needed. This is clearly unacceptable for a piece of software intended to be used as an engineering design tool operating to tight production deadlines.

These and other issues have added greatly to the perception of CFD as an extremely difficult, time consuming and hence costly methodology. However, we have developed an algorithm that diverges very little as the cell size is increased making it much easier to obtain the necessary accuracy, even on coarse grids. We have termed this ability to retain consistency across varying cell sizes as ‘grid independence’ or ‘scaling’, as the algorithm is attempting to find the same fundamental solution independent of either grid size or scale factor.

In this section 14 runs of the same problem but on very different grids. These show how well the software copes with a changing scale and how very close it is to having grid independence.

TABLE 4. 3: Temperature variation for cooling at diferrent mesh size

Time(Sec.)	30.00000	40.00000	50.00000	60.00000	70.00000	80.00000	90.00000	100.00000	110.00000	120.00000	130.00000	140.00000	150.00000	160.00000	170.00000	180.00000	190.00000	200.00000	210.00000	220.00000	230.00000	240.00000	250.00000	260.00000	270.00000	280.00000	290.00000	300.00000
Temp	85.51492	76.60540	69.69465	64.04815	59.27410	55.13864	51.49089	48.22788	45.27612	42.58138	40.10246	37.80733	35.67062	33.67187	31.79432	30.02413	28.34966	26.76111	25.25008	23.80935	22.43268	21.11461	19.85036	18.63569	17.46687	16.34057	15.25379	14.20386
more fine mesh	79.66492	72.10042	66.02563	60.94925	56.58896	52.76747	49.36616	46.30171	43.51336	40.95546	38.59280	36.39768	34.34790	32.42540	30.61531	28.90519	27.28458	25.74457	24.27753	22.87685	21.53679	20.25231	19.01900	17.83292	16.69059	15.58891	14.52507	13.49657
mesh-3	79.66492	72.34396	66.42698	61.46116	57.18265	53.42410	50.07273	47.04886	44.29416	41.76459	39.42612	37.25190	35.22035	33.31390	31.51804	29.82062	28.21143	26.68174	25.22406	23.83191	22.49966	21.22237	19.99568	18.81572	17.67908	16.58268	15.52378	14.49988
mesh-4	79.66492	72.18138	66.15884	61.11895	56.78559	52.98480	49.59989	46.54876	43.77145	41.22283	38.86809	36.67981	34.63599	32.71875	30.91330	29.20734	27.59046	26.05382	24.58984	23.19194	21.85443	20.57230	19.34115	18.15707	17.01660	15.91664	14.85441	13.82741
mesh-5	79.66492	72.58943	66.83359	61.98168	57.78794	54.09496	50.79580	47.81449	45.09515	42.59543	40.28249	38.13035	36.11809	34.22864	32.44787	30.76395	29.16688	27.64815	26.20043	24.81737	23.49344	22.22380	21.00416	19.83074	18.70016	17.60941	16.55577	15.53679
mesh-6	79.66492	72.34396	66.42698	61.46116	57.18265	53.42410	50.07273	47.04886	44.29416	41.76459	39.42612	37.25190	35.22035	33.31390	31.51804	29.82062	28.21143	26.68174	25.22406	23.83191	22.49966	21.22237	19.99568	18.81572	17.67908	16.58268	15.52378	14.49988
mesh-7	74.66492	68.33773	63.08648	58.59787	54.67823	51.19939	48.07217	45.23196	42.63048	40.23069	38.00356	35.92589	33.97890	32.14709	30.41761	28.77962	27.22394	25.74267	24.32903	22.97711	21.68174	20.43838	19.24303	18.09209	16.98241	15.91111	14.87564	14.40008
mesh-8	69.66492	64.40798	59.91523	55.99242	52.51110	49.38186	46.53999	43.93712	41.53615	39.30800	37.22945	35.28167	33.44918	31.71908	30.08054	28.52436	27.04264	25.62859	24.27629	22.98058	21.73691	20.54125	19.39005	18.28011	17.20858	16.17288	15.17071	14.17413
mesh-9	64.66492	60.33649	56.53950	53.15759	50.10890	47.33362	44.78670	42.43342	40.24639	38.20367	36.28739	34.48281	32.77760	31.16141	29.62539	28.16197	26.76459	25.42755	24.14585	22.91509	21.73138	20.59125	19.49161	18.42968	17.40295	16.40918	15.44630	14.82062
mesh-10	59.66492	55.97133	52.67168	49.68999	46.97032	44.47033	42.15715	40.00480	37.99237	36.10276	34.32185	32.63780	31.04062	29.52179	28.07397	26.69083	25.36682	24.09711	22.87741	21.70393	20.57329	19.48248	18.42879	17.40977	16.42322	15.46712	14.53966	14.25246
mesh-11	54.66492	51.68502	48.96684	46.46811	44.15601	42.00460	39.99298	38.10410	36.32382	34.64035	33.04368	31.52532	30.07792	28.69517	27.37152	26.10213	24.88273	23.70952	22.57915	21.48858	20.43511	19.41630	18.42995	17.47404	16.54675	15.64642	14.77153	13.92067
mesh-12	49.66492	47.28143	45.06835	43.00292	41.06666	39.24437	37.52337	35.89300	34.34417	32.86913	31.46116	30.11443	28.82383	27.58486	26.39356	25.24639	24.14020	23.07217	22.03974	21.04062	20.07273	19.13417	18.22322	17.33831	16.47797	15.64089	14.82585	14.03170
mesh-13	44.66492	42.81167	41.06309	39.40798	37.83686	36.34160	34.91523	33.55166	32.24561	30.99242	29.78797	28.62861	27.51110	26.43250	25.39021	24.38186	23.40531	22.45861	21.53999	20.64784	19.78067	18.93712	18.11594	17.31597	16.53615	15.77548	15.03305	14.30800
more coarse mesh	39.66492	38.25236	36.90143	35.60697	34.36446	33.16987	32.01966	30.91064	29.83997	28.80507	27.80365	26.83359	25.89300	24.98013	24.09340	23.23136	22.39266	21.57608	20.78048	20.00480	19.24808	18.50941	17.78794	17.08291	16.39356	15.71923	15.05926	14.41307

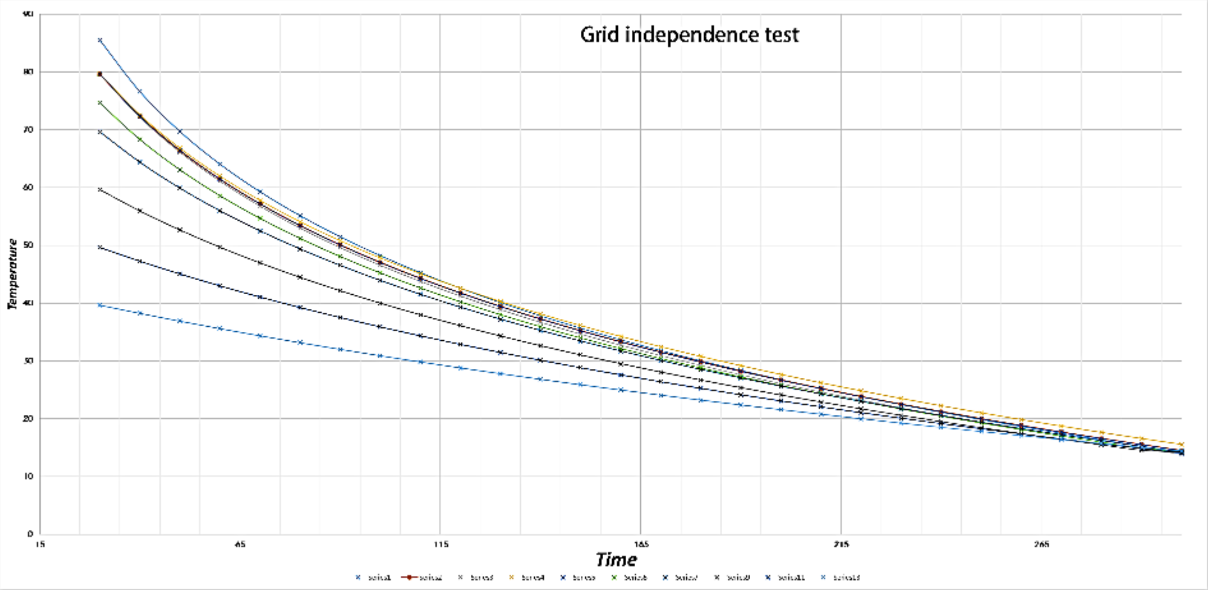
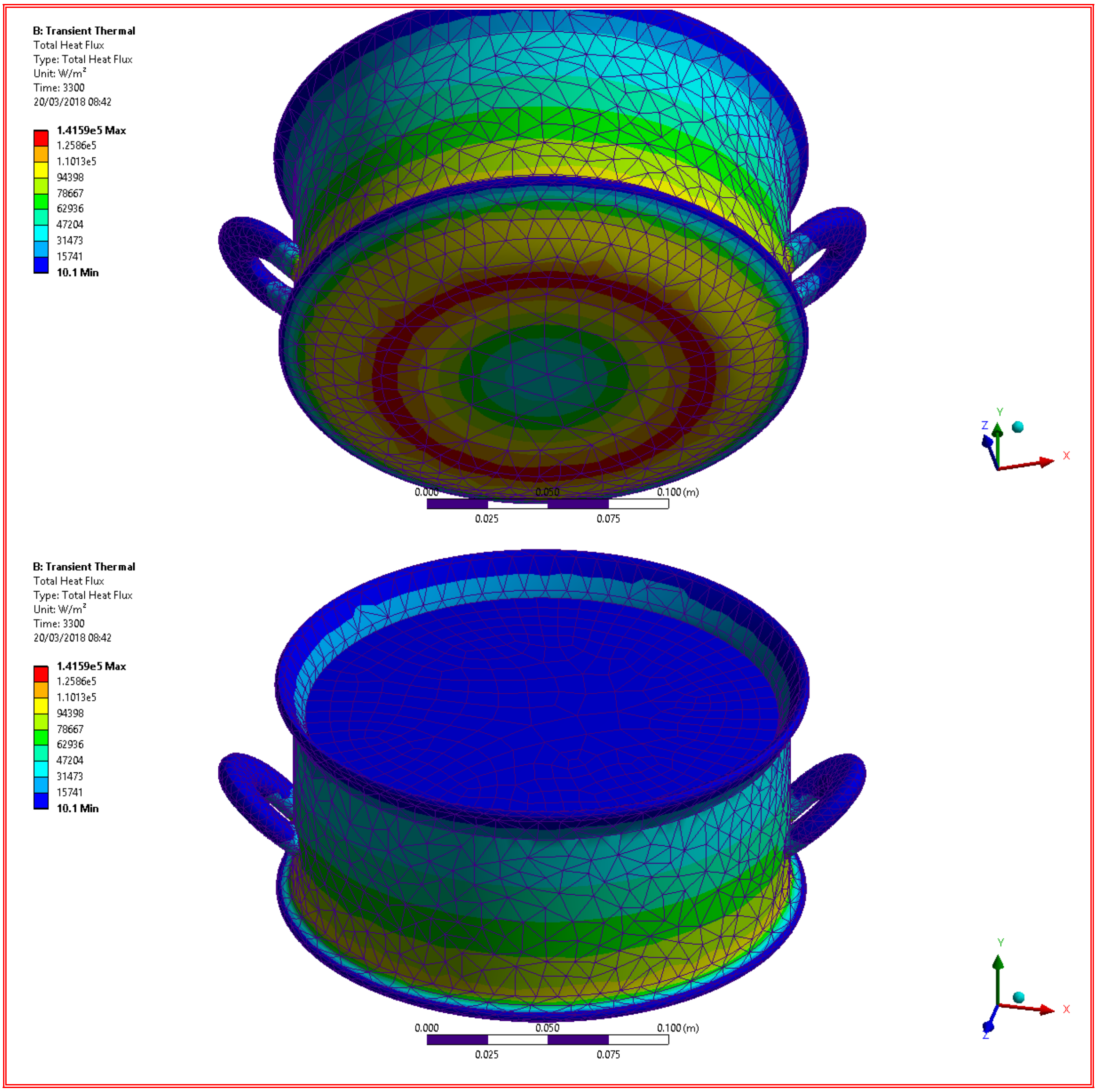


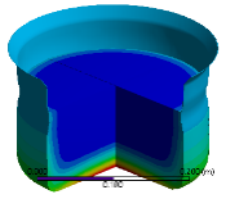
Figure 4.10: mesh independence test graph

4.6.4. Directional heat flux



4.6.4. Heating and Cooling Time

4.6.4.1. POT 1

Equipment:	Cookpot-1	
Diameter:	170 mm	
Height:	110 mm	
Material:	Aluminum	
Heat input:	66,371.68	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Ansys transient thermal simulation result sample temperature variation with time data displayed in simulation for metal pot 1 is tabulated below.

Time	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**
Temp.(0C)	17.6	93	76	50	37	30	25	21	18	16	15.1

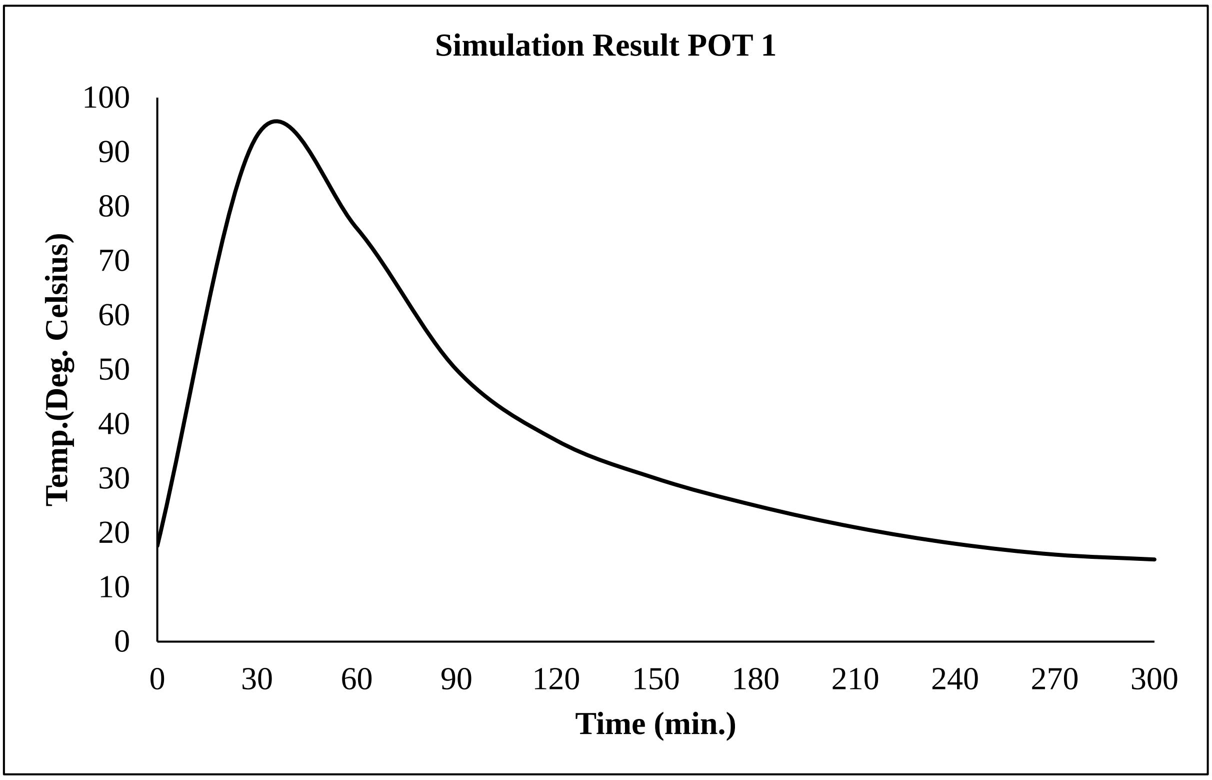
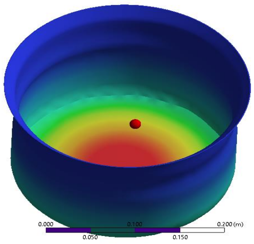


Figure 4. 10: Temperature variation with time metal pot 1

As we observe from the above Figure 4. 10, the water reaches the boiling point temperature 95.5 ^{0}C, after 35 minutes of heating. It takes 265 minutes to cooldown to local atmospheric temperature.

4.6.4.2. POT 2

Equipment:	Cookpot-2	
Diameter:	200 mm	
Height:	100 mm	
Material:	Aluminum	
Heat input:	47.7 KW	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Ansys transient thermal simulation result sample temperature variation with time data displayed in simulation for metal pot 2 is tabulated below.

Time(min)	**0**	**30**	**45**	**60**	**75**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**
Temp.(0C)	17.6	71	93	86	72	58	40	31	26	22.5	20	18	16	15.1	15

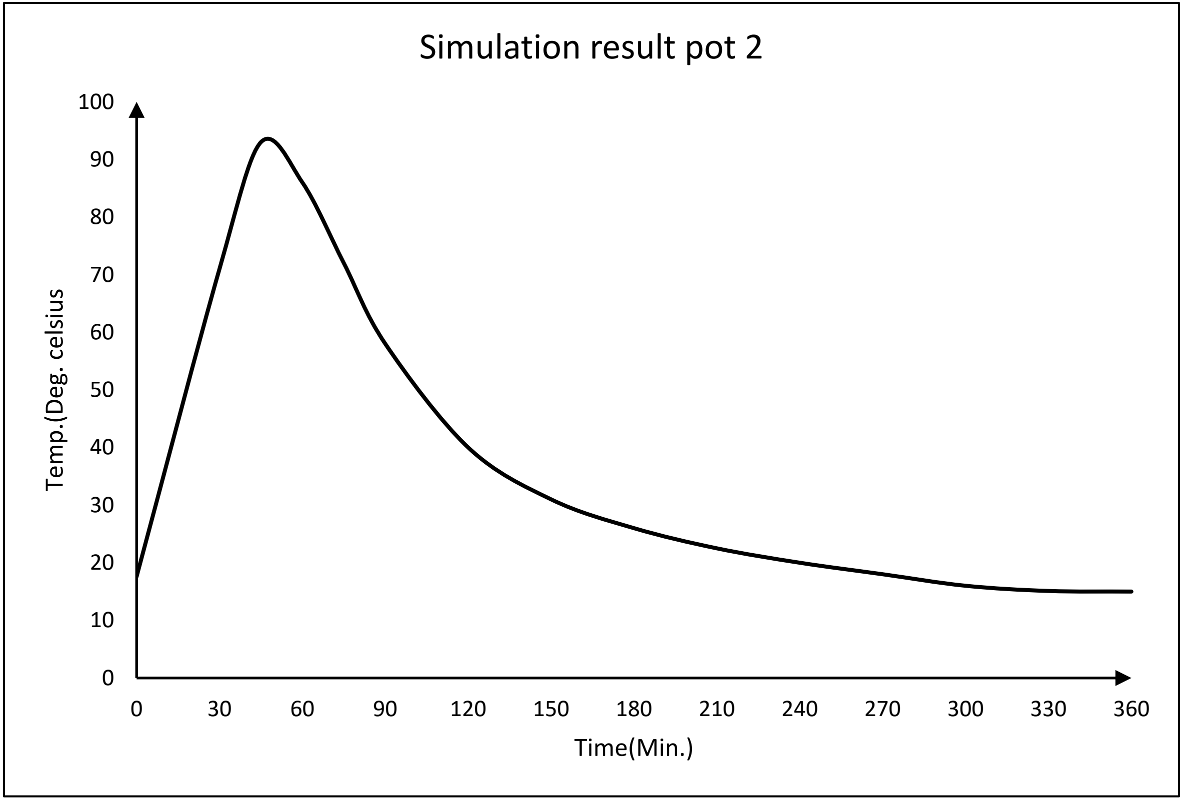
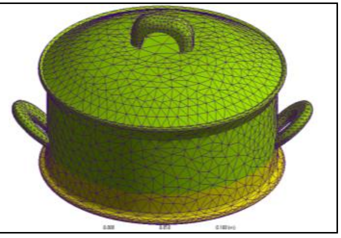


Figure 4. 11: Temperature variation with time metal pot 1

As we observe from Figure 4. 11, the water reaches the boiling point temperature 94.01 ^{0}C, after 47.5 minutes of heating. It takes 312.5 minutes to cooldown to local atmospheric temperature.

4.6.4.3.POT 3

Equipment:	Cookpot-1	
Diameter:	170 mm	
Height:	110 mm	
Material:	Clay	
Heat input:	57.6 KW/m^2	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Ansys transient thermal simulation result sample temperature variation with time data displayed in simulation for metal pot 3 is tabulated below.

Time	**0**	**15**	**30**	**45**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**
Temp.(^{0}C)	17.6	50	70	83.4	82.00	68.00	55.50	47.00	41.00	37.00	34.00	31.00	29.00	26.86	25.34	24.02	22.86

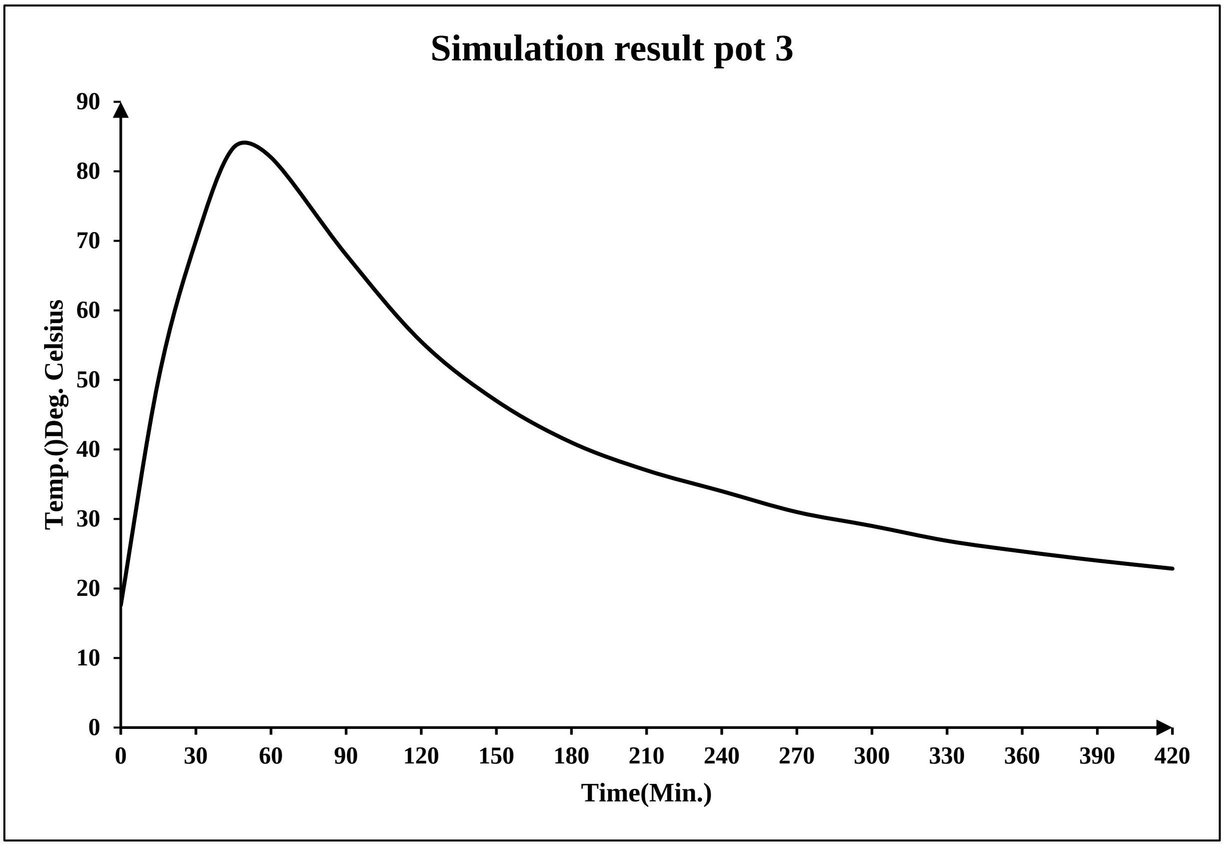
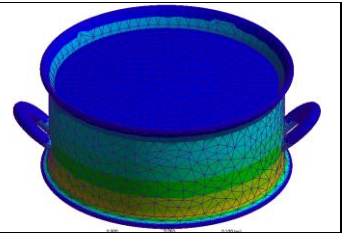


Figure 4. 12: Temperature variation with time clay pot 3

As we observe from Figure 4. 12, the water reaches the boiling point temperature 90.6 ^{0}C, after 44.7 minutes of heating. It takes 375.3 minutes to cooldown to local atmospheric temperature.

4.6.4.4.POT 4

Equipment:	Cookpot-1	
Diameter:	200 mm	
Height:	100 mm	
Material:	Clay	
Heat input:	47.7 KW/m^2	
Initial(atmospheric) temperature:	17.6 ^{0}C	

Ansys transient thermal simulation result sample temperature variation with time data displayed in simulation for metal pot 4 is tabulated below.

Time	**0**	**30**	**40**	**50**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**	**450**	**480**	**510**
Temp.(^{0}C)	**17.60**	**63.00**	**73.00**	**81.00**	**83.00**	**74.00**	**62.00**	**51.00**	**44.00**	**38.00**	**34.00**	**30.00**	**28.00**	**26.00**	**25.00**	**23.50**	**22.00**	**20.00**	**19.17**	**18.42**

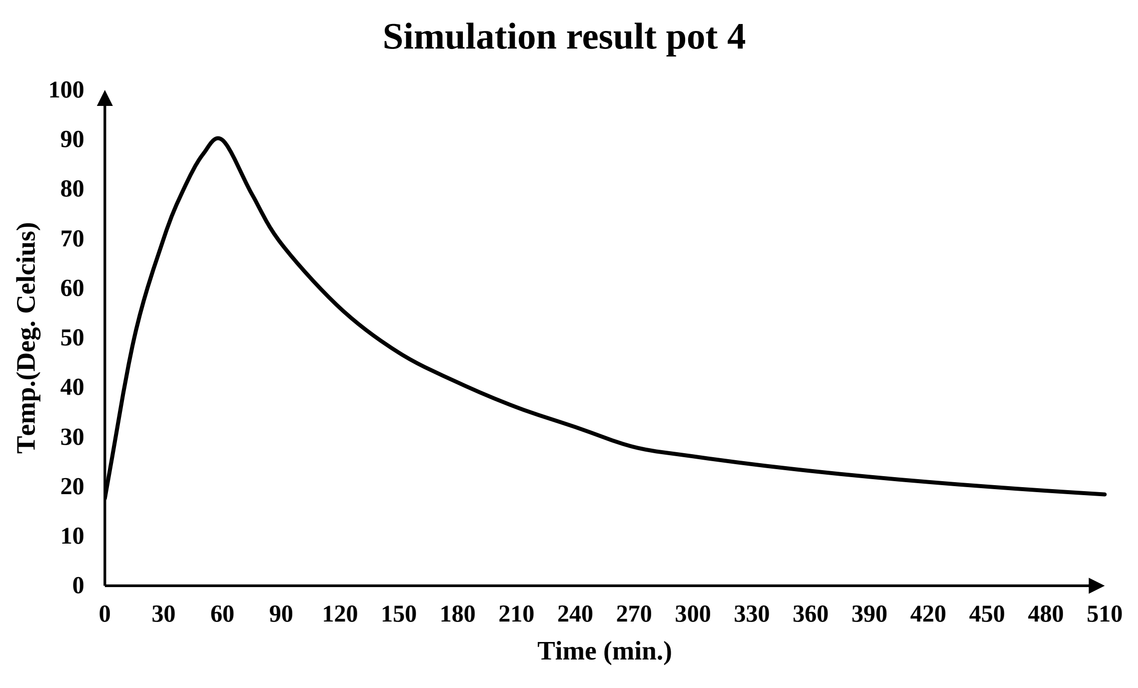


Figure 4. 13: Temperature variation with time clay pot 4

As we observe from the experiment, the water reaches the boiling point temperature 90.4 ^{0}C, after 57 minutes of heating. It takes 453 minutes to cooldown to local atmospheric temperature.

As we can see from the above results, the water heating process is taken smaller time than the cooling one. This is an important thing on energy usage as well as cost of the cooking process.

CHAPTER FIVE

RESULT AND DISCUSSION

5.1. Experimental result

Table 5. 1: All Pots experimental specifications

POT 1(Al)	**Diameter * Height:**	170 mm * 110 mm
	Heat input:	66,371.68 W/m^2
POT 2(Al)	Diameter * Height:	200 mm * 100 mm
	Heat input:	47770.70 W/m^2
POT 3(Clay)	Diameter * Height:	170 mm * 110 mm
	Heat input:	57657.87 W/m^2
POT 4(Clay)	Diameter * Height:	200 mm * 100 mm
	Heat input:	41701.42 W/m^2
Heat source:		Electrical stove
Initial(atmospheric) temperature:		17.6 ^{0}C

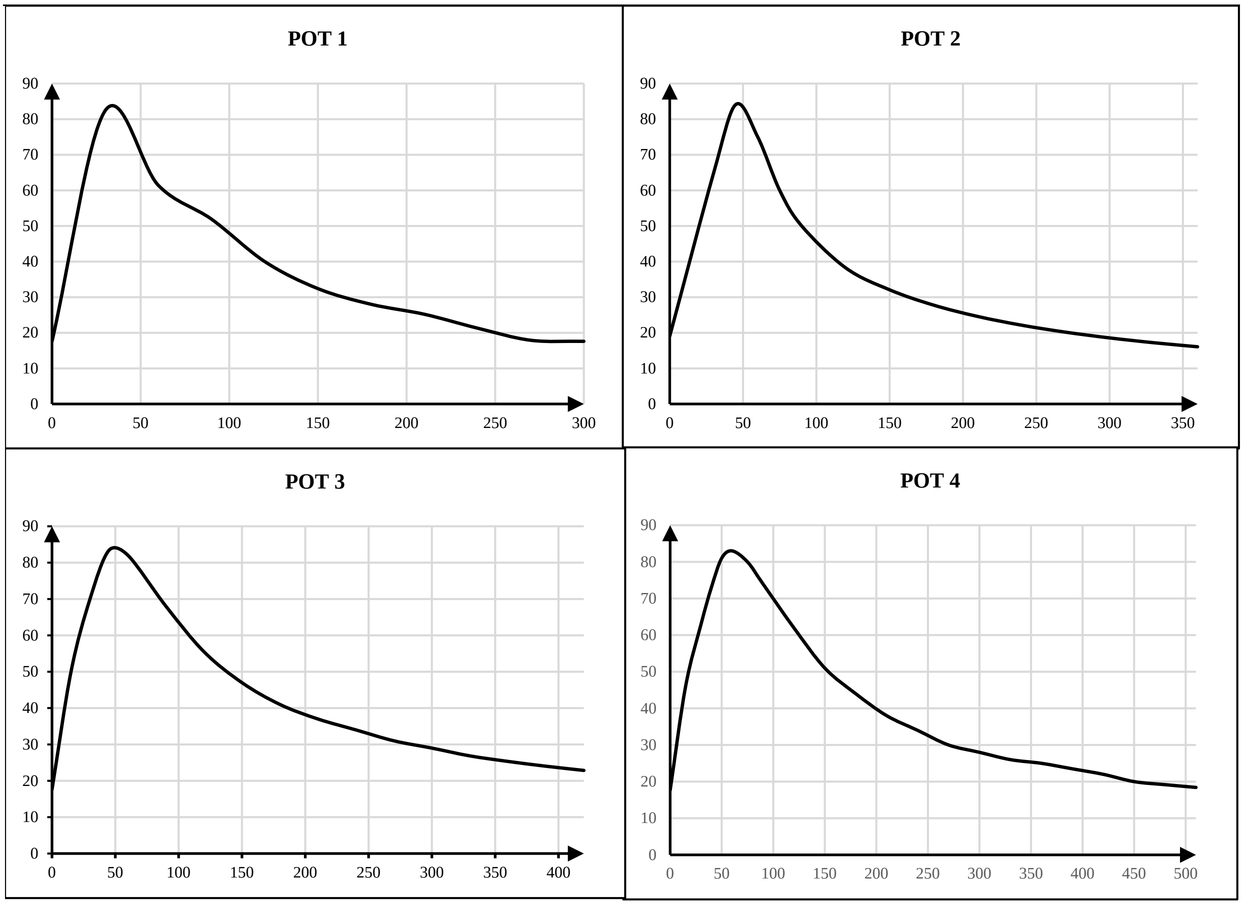


Figure 5. 1: Summery of experimental results for all pots

5.2. Simulation results

Table 5. 2**:** All Pots numerical specifications

POT 1(Al)	Diameter * Height:	170 mm * 110 mm
	Heat input:	66,371.68 W/m^2
POT 2(Al)	Diameter * Height:	200 mm * 100 mm
	Heat input:	47770.70 W/m^2
POT 3(Clay)	Diameter * Height:	170 mm * 110 mm
	Heat input:	57657.87 W/m^2
POT 4(Clay)	Diameter * Height:	200 mm * 100 mm
	Heat input:	41701.42 W/m^2
Simulation Software:		ANSYS TRANSIENT THERMAL
Initial(atmospheric) temperature:		17.6 ^{0}C

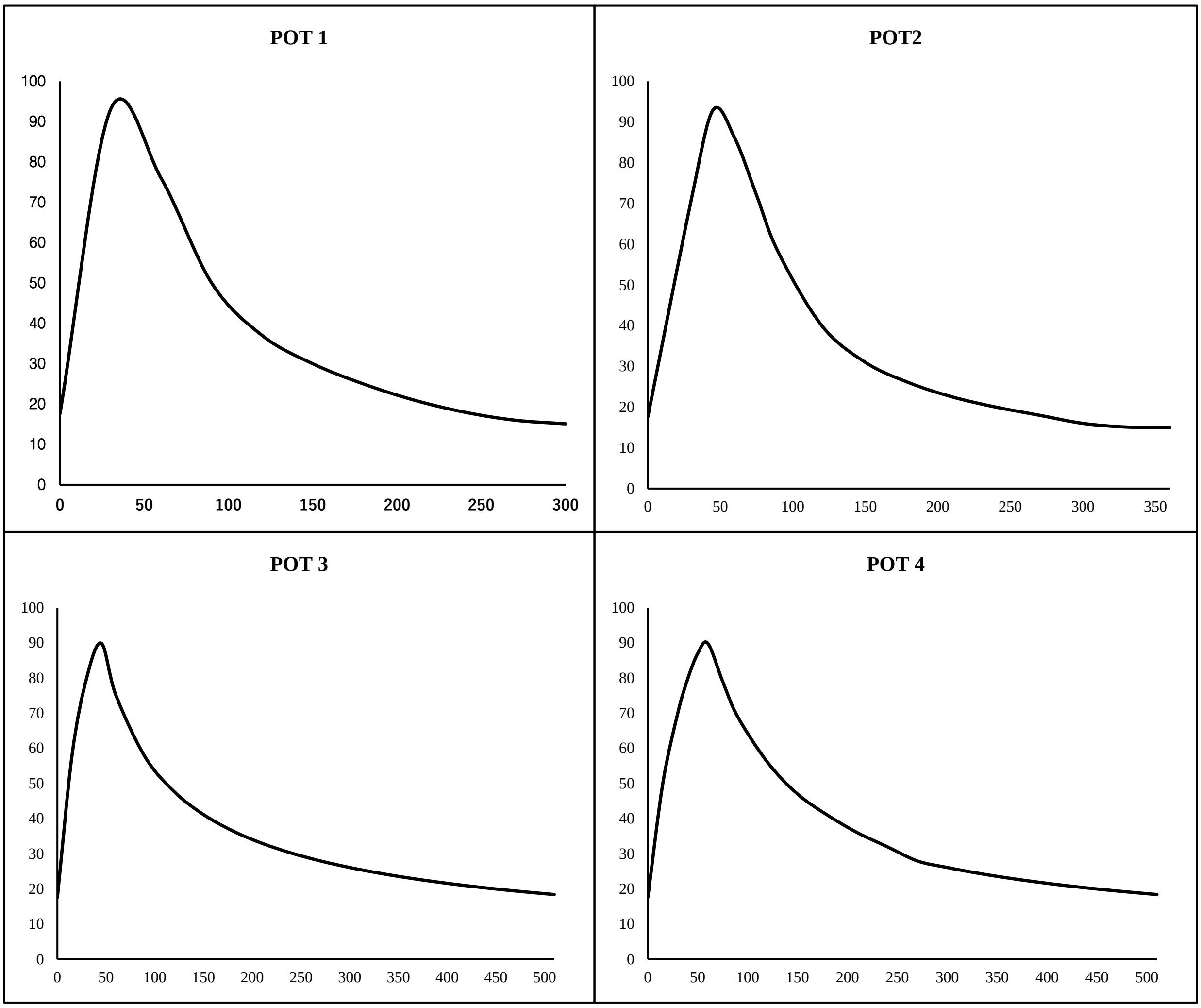


Figure 5. 2: Summery of simulation results for all pots

5.3. Comparison of experimental and simulation results

POT-1: Al POT

Table 5. 3: Pot 1 experimental and simulation results

Time	0	30	60	90	120	150	180	210	240	270	300
Experiment	17.6	82.4	61.4	51.9	40	32.4	28	25.2	21.3	17.9	17.6
Simulation	17.6	93	76	50	37	30	25	21	18	16	15.1

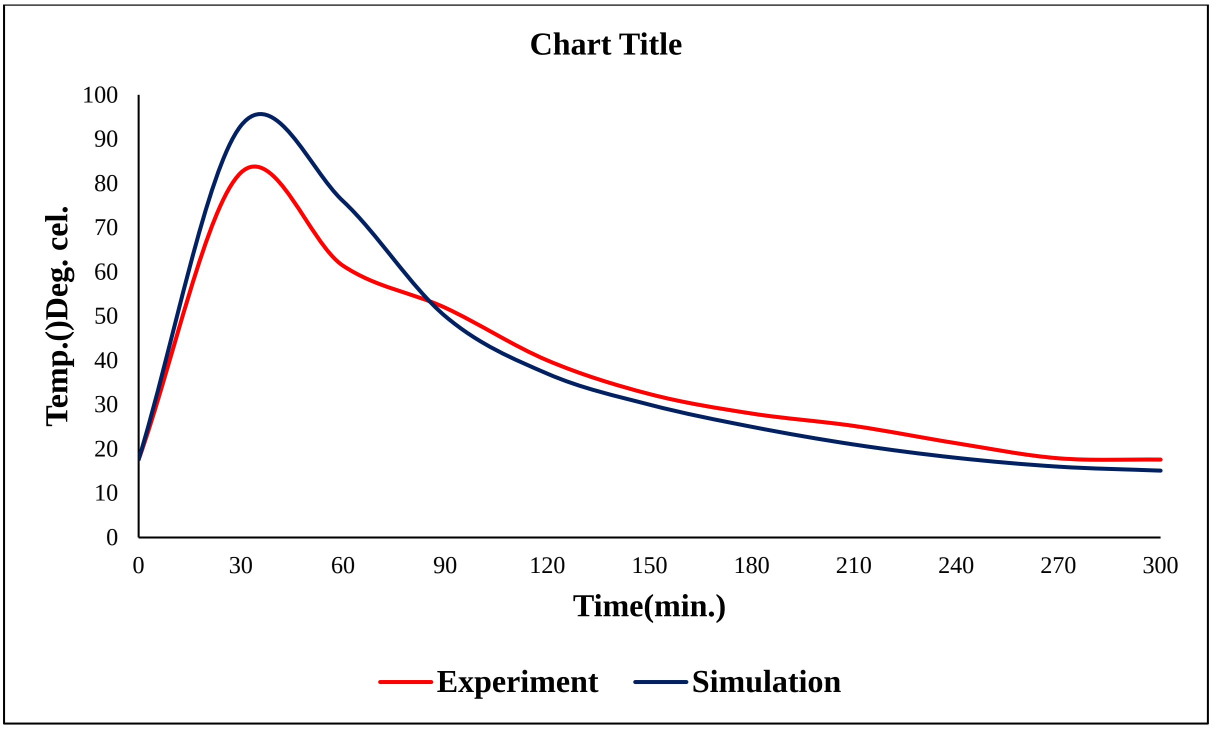


Figure 5. 3: POT-1 heating/cooling time coparison

As we can see from Figure 5. 3, the water reaches its boiling point (maximum temperature) 95.5 ^{0}C at a time of 35 minutes for simulation and 84.0 ^{0}C at a time of 34 minutes for experiment. This difference will be happened in different reasons like measurement errors, approximations, software limitation etc. But it is enough to do more on its further analysis.

Pot 2-Al Pot

Time(min)	**0**	**30**	**45**	**60**	**75**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**
Experiment	19.07	65	84.1	75	60	50	38.23	32.06	27.76	24.58	22.12	20.16	18.55	17.21	16.06
Simulation	17.6	71	93	86	72	58	40	31	26	22.5	20	18	16	15.1	15

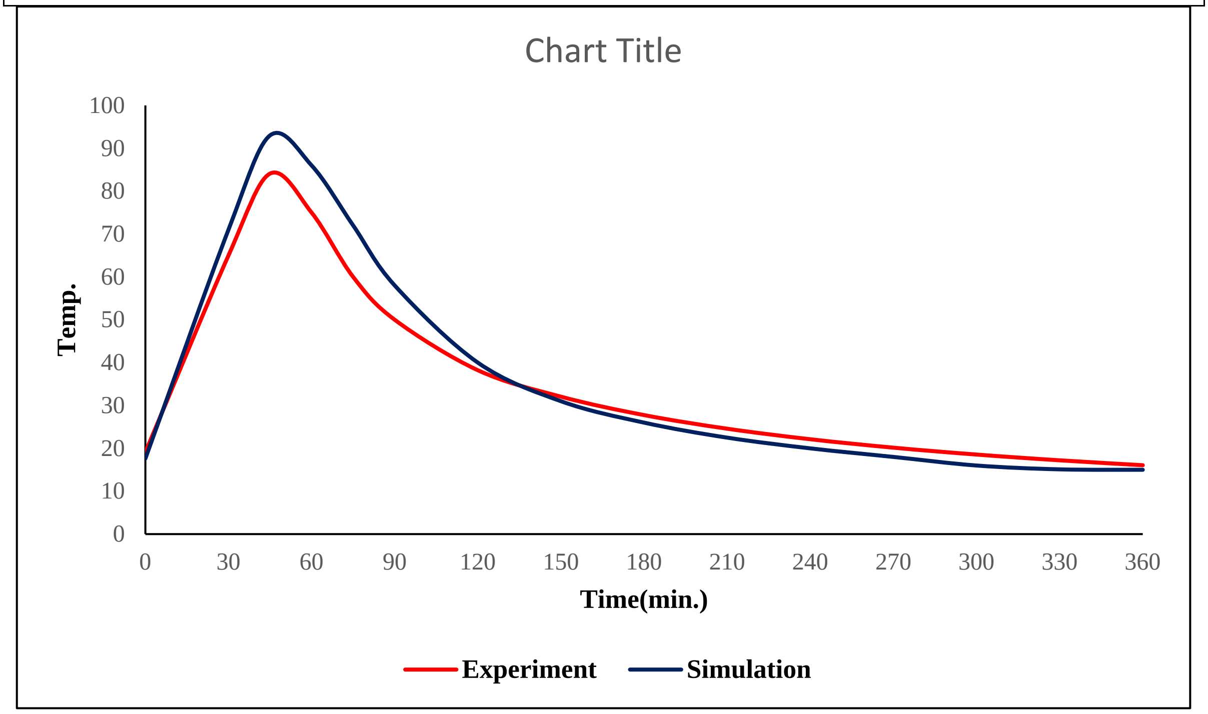


Figure 5. 4: POT-2 heating/cooling time

As we can see from Figure 5. 4, the water reaches its boiling point (maximum temperature) 93.5 ^{0}C at a time of 47.5 minutes for simulation and 84.1 ^{0}C at a time of 45.2 minutes for experiment. This difference will be happened in different reasons like measurement errors, approximations, software limitation etc. But it is enough to do more on its further analysis.

POT-3 (CLAY POT)

Table 5. 4: Pot 3 experimental and simulation results

Time	**0**	**15**	**30**	**45**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**
Experiment	17.6	50	70	83.4	82.00	68.00	55.50	47.00	41.00	37.00	34.00	31.00	29.00	26.86	25.34	24.02	22.86
Simulation	17.6	58	80	89.89	75.14	57.57	47.65	41.15	36.51	32.99	30.22	27.97	26.10	24.52	23.15	21.97	20.92

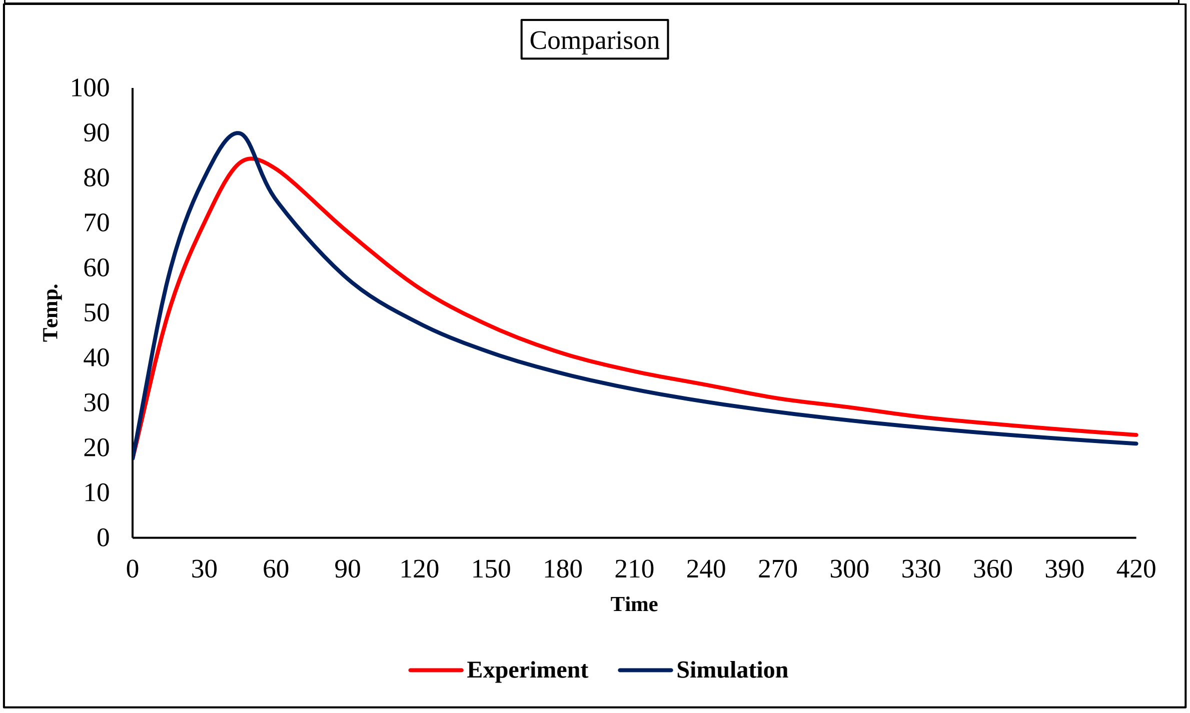


Figure 5. 5: POT-3 heating/cooling time

As we can see from Figure 5. 3, the water reaches its boiling point (maximum temperature) 90.01 ^{0}C at a time of 44 minutes for simulation and 84.6 ^{0}C at a time of 50 minutes for experiment. This difference will be happened in different reasons like measurement errors, approximations, software limitation etc. But it is enough to do more on its further analysis.

POT-4: CLAY POT

Table 5. 5: Pot 3 experimental and simulation results

	0	**15**	**30**	**40**	**50**	**60**	**75**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**	**450**	**480**	**510**
Experiment	17.6	46	63	73	81	83.00	80.00	74.00	62.00	51.00	44.00	38.00	34.00	30.00	28.00	26.00	25.00	23.50	22.00	20.8	20.1	19.6
Simulation	17.6	50	70	79.8	87	89.89	79.00	69.00	56.00	47.00	41.00	36.00	32.00	27.97	26.10	24.52	23.15	21.97	20.92	20.00	19.17	18.42

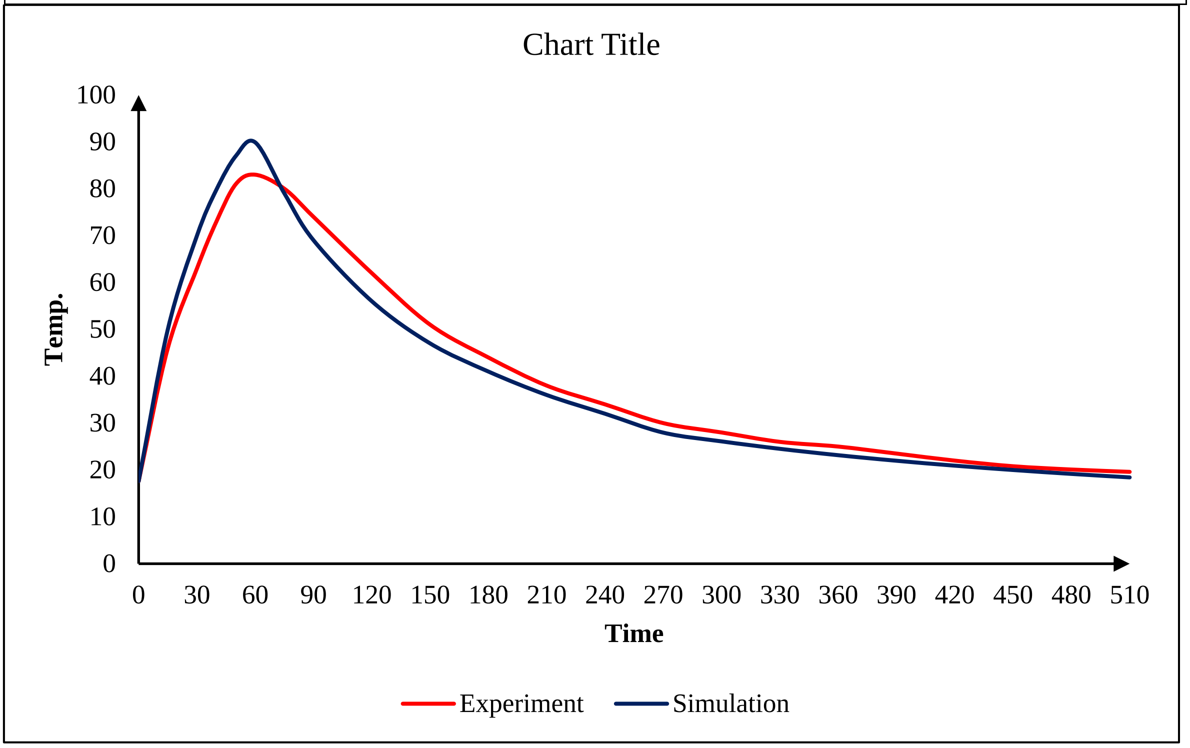


Figure 5. 6: POT-4 heating/cooling time

As we can see from Figure 5. 3, the water reaches its boiling point (maximum temperature) 90.3 ^{0}C at a time of 57.5 minutes for simulation and 83.2 ^{0}C at a time of 59.8 minutes for experiment. This difference will be happened in different reasons like measurement errors, approximations, software limitation etc. But it is enough to do more on its further analysis.

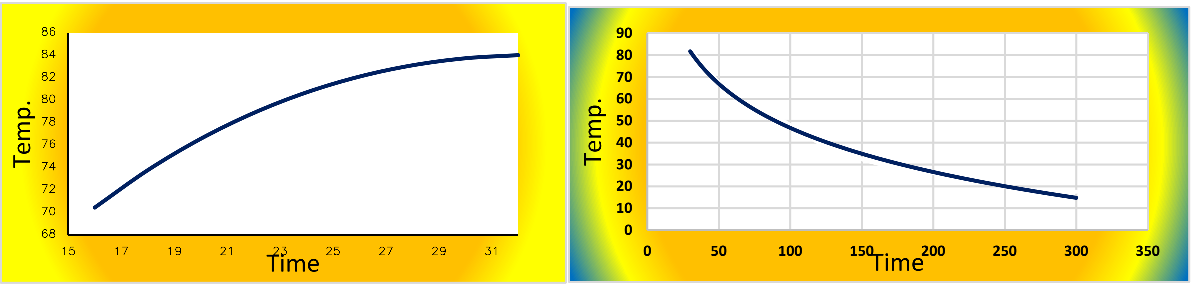


Figure 5. 7**:** *Heating and Cooling separate graph*

5.3.2. Thermal efficiency

for all of the pots tested, the heat flux was observed to be higher in locations where the electrical resistor is in contact with the pot's surface. Thus, the pot receives the greatest amount of energy at these locations.

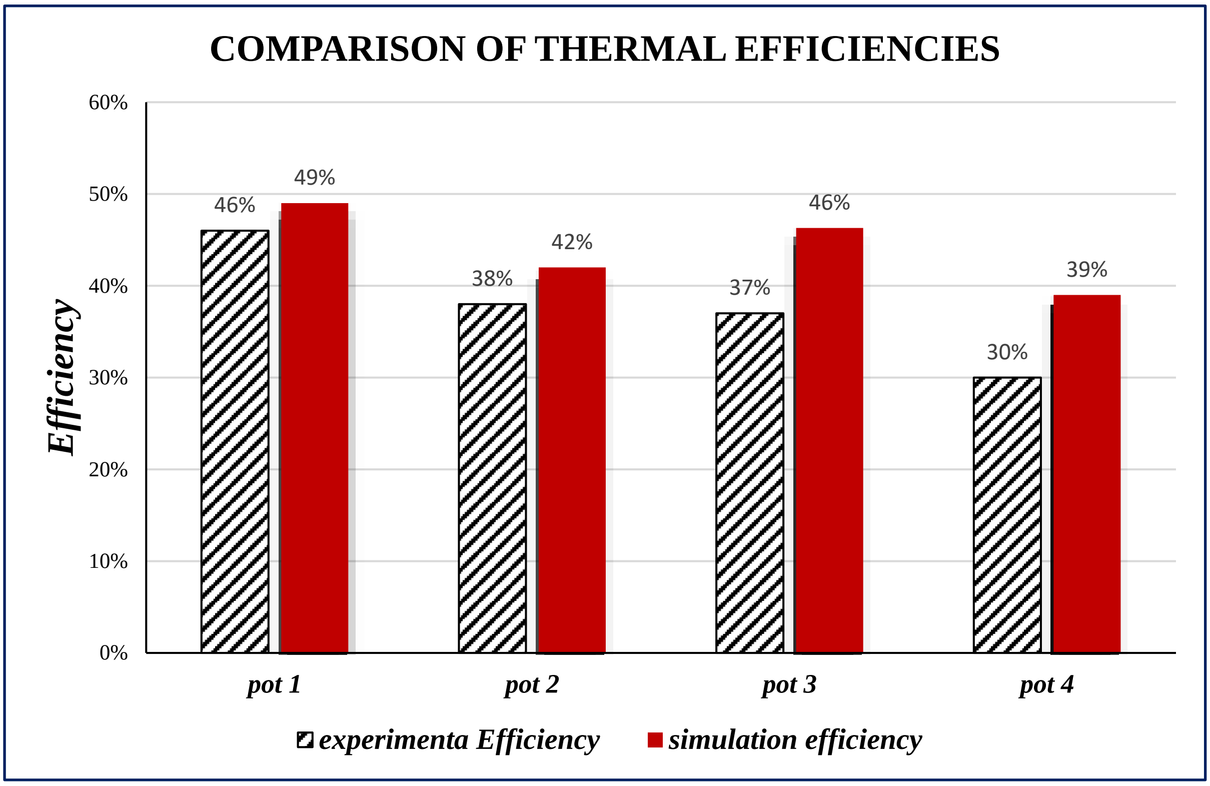


Figure 5. 8: Comparison of thermal efficiencies obtained by simulation and experimental tests

The simulations display good agreement with the experimental tests. The results confirm the usefulness of the proposed simulation methodology as a design and performance evaluation tool. The efficiency gap is approximately below 10 %. This variation is due to the assumption of the contact resistance, material property and geometry definition.

5.4. Comparison of metal and clay pots

5.4.1. Heating and cooling time

Using simulation results the heating and cooling property of the pots are compared.

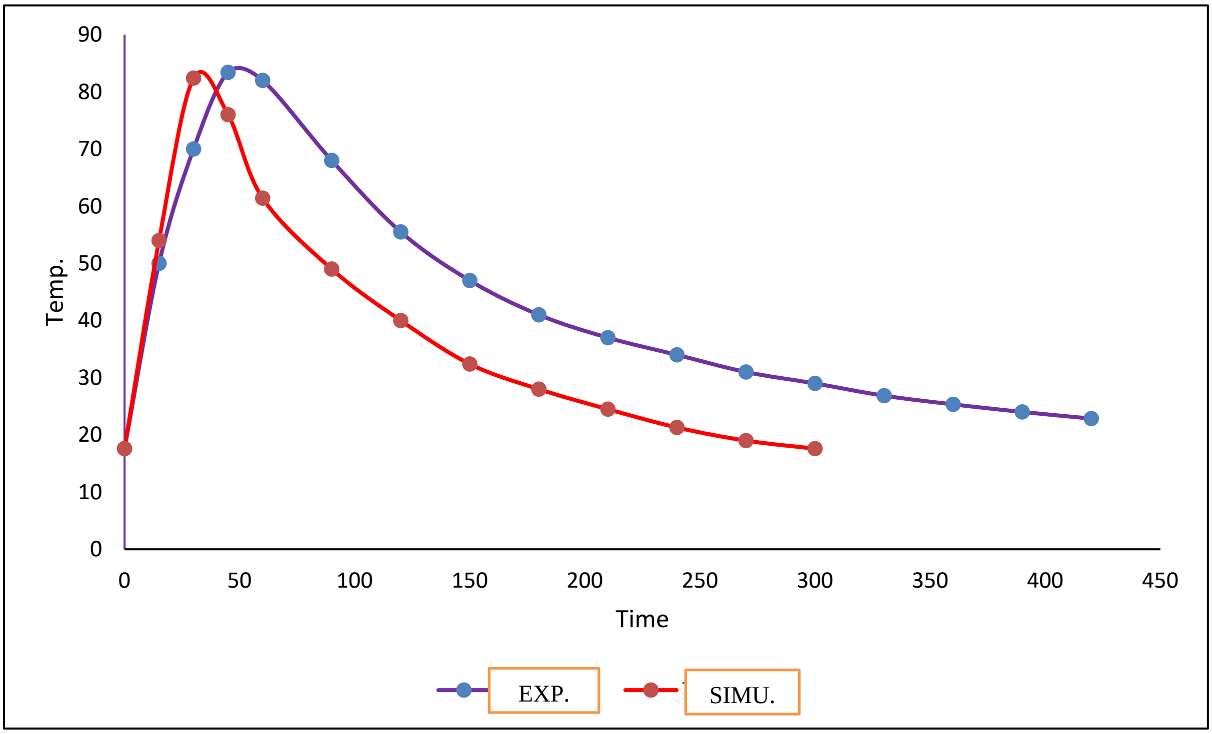


Figure 5. 9: comparison pot 1 and pot 3

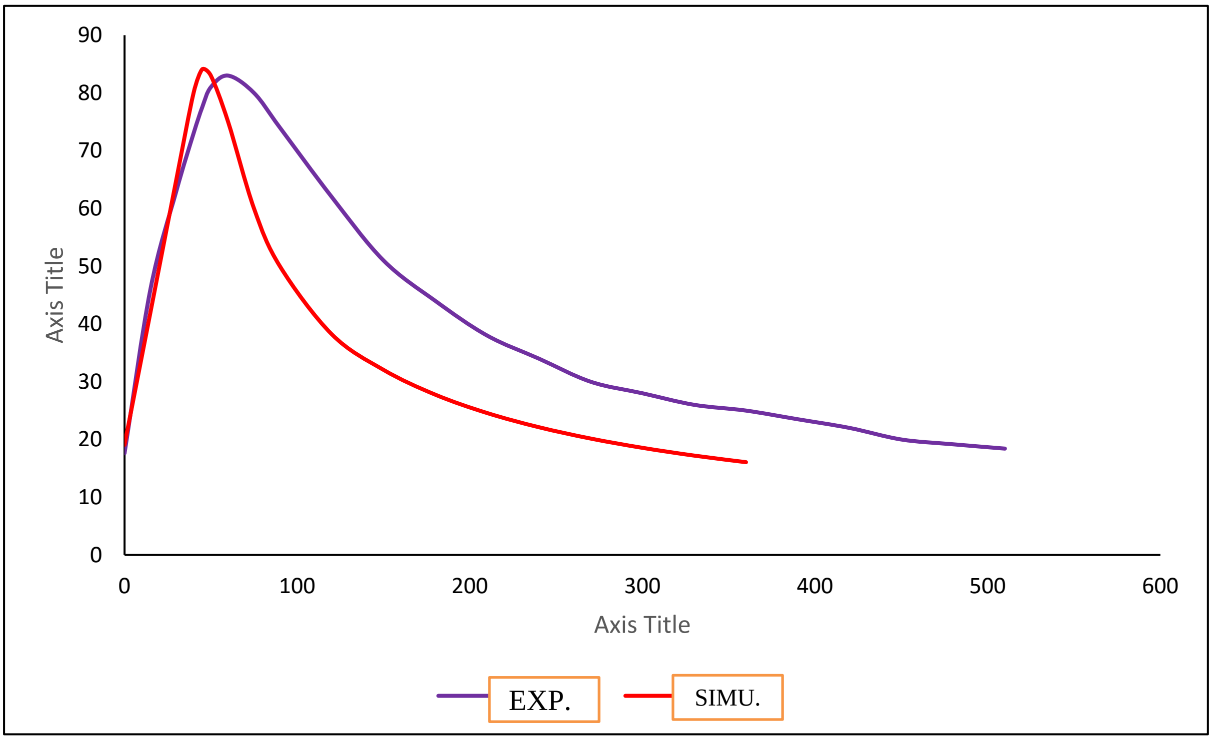


Figure 5. 10: comparison pot 2 and pot 4

5.4.2. Thermal efficiency

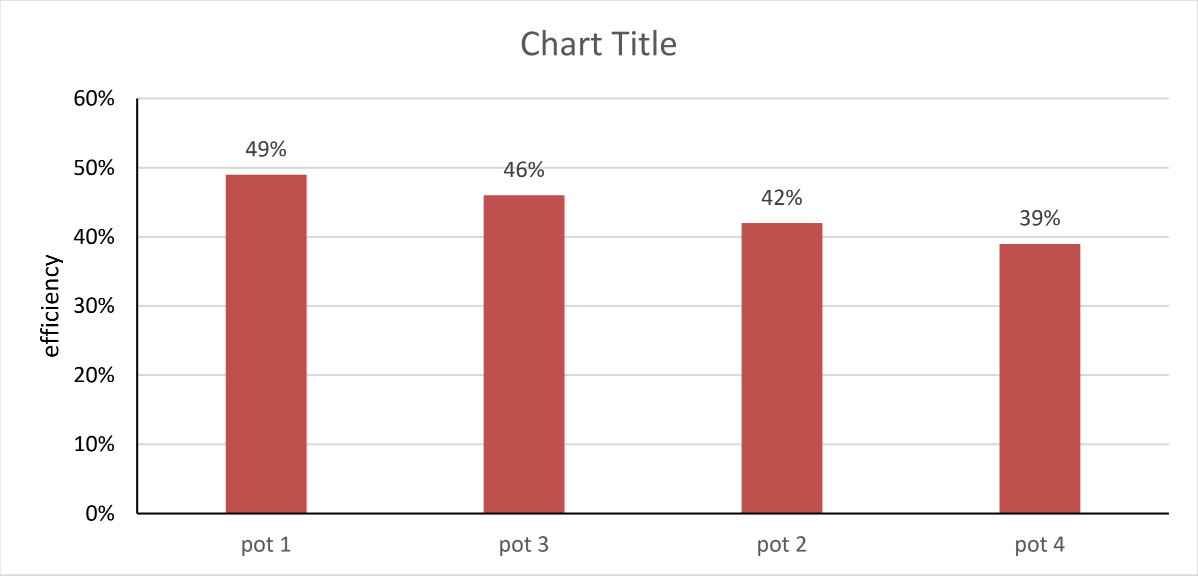


Figure 5. 11: Thermal efficiency comparison metal and clay pot

As we can see from **Figure 5. 11** metal pots are more efficient than clay pots.

5.5. Temperature variation at different nodes

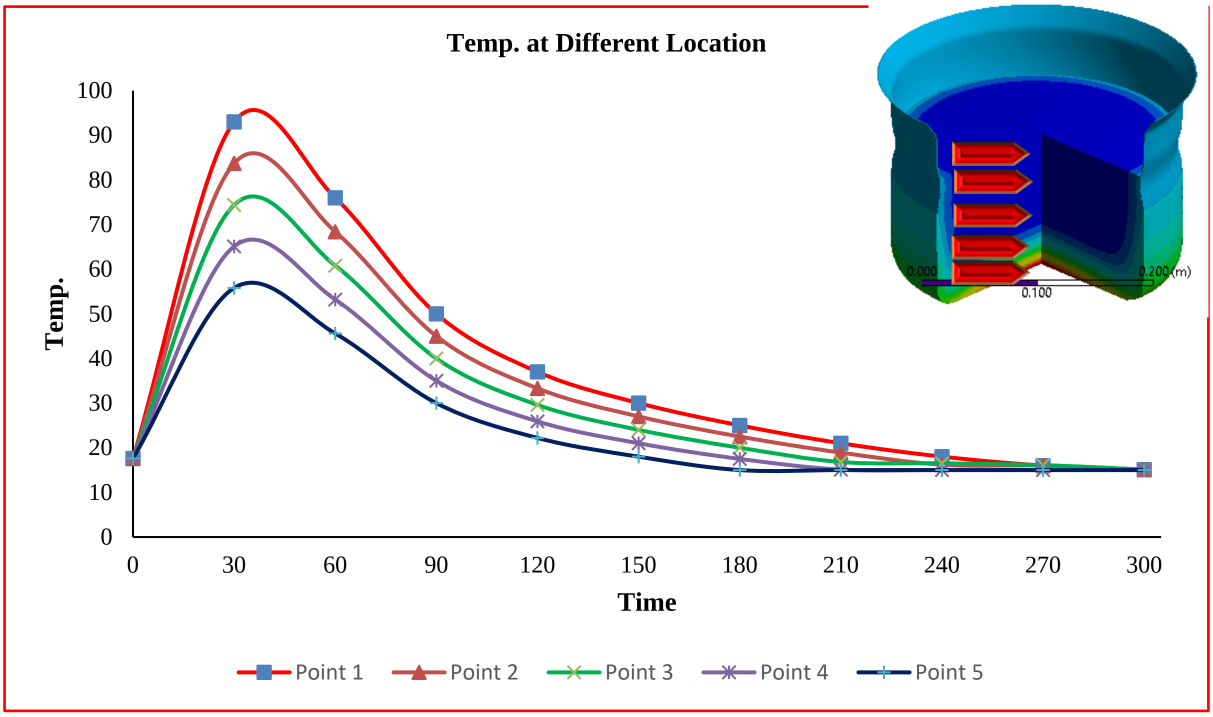


Figure 5. 12: POT-4 heating/cooling time

5.6. The Effects of Different Parameters on Efficiency

In this section a parametric study of different parameters on cook pot's efficiency is carried out. for the next sections, to identify the effect of selected parameter change on thermal efficiency, the selected model parameter varies between its limiting values and the other parameters have been remained unchanged.

5.6.1. Occupied volume percentage

In this part the effect of pot's occupied volume percentage on efficiency has been studied (Figure 5. 13). It can be seen that efficiency increases with increasing occupied volume percentage up to 0.66. If the occupied volume percentage exceeds this limit, efficiency decreases.

Table 5. 6: Occupied volume percentage versus efficiency

Test NO.	1.	2.	3.	4.	5.	6.	7.	8.
Occupied volume (%)	0.48	0.54	0.6	0.66	0.72	0.78	0.84	0.9
Thermal Efficiency	55.49	55.57	55.85	55.98	55.71	55.47	55.70	57.09

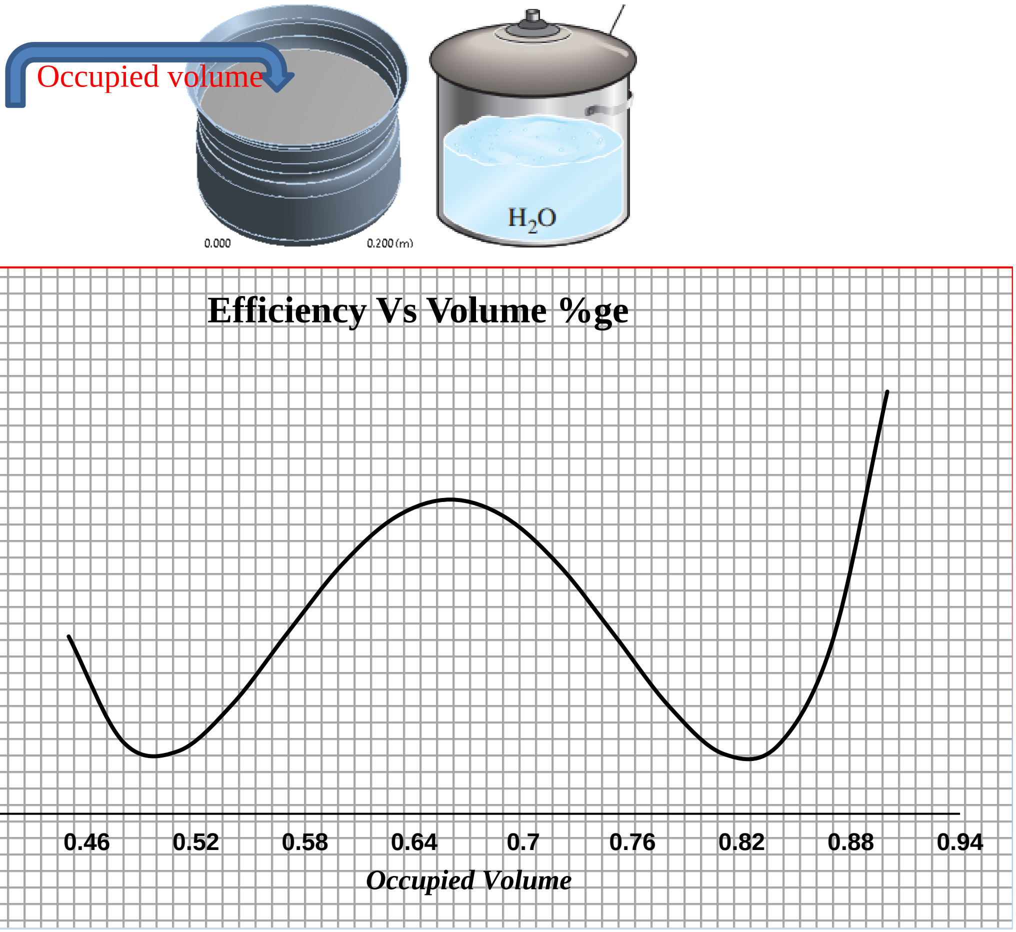


Figure 5. 13: Occupied volume percentage versus efficiency

According to this figure, the difference between maximum and minimum of efficiency value is less than 0.6%; this amount of variation is smaller than the conducted experimental tests repeatability error. Therefore, the sinusoidal shape reflects only the fluctuations of error. We can conclude that the efficiency is independent of occupied volume percentage.

5.6.2. Ratio of pot diameter to stove top

The efficiency vs. the ratio of pot diameter to contact area is presented in Figure 5. 15. As can be seen in this figure at lower ratios, increasing the ratio leads to greater efficiency. This behavior is due to the larger heat transfer surface. So hot gases, spreading out from the stove head, have more chance to interact with the bottom wall. This leads to higher heat absorption of the pot’s bottom. Therefore, high heat transfer efficiency is obtained.

The 16 _ 10-cm pot displays two heat flux peaks because the electrical resistance is not in contact within the pan, i.e., the pan is smaller than the resistor.

POT NO.	1.	2.	3.	4.	5.	6.
Ratio	1.55	2.05	2.55	3.05	3.55	3.8
Thermal Efficiency	-33.35	45.02	51.86	55.16	56.88	12.59

Figure 5. 14: area of contact

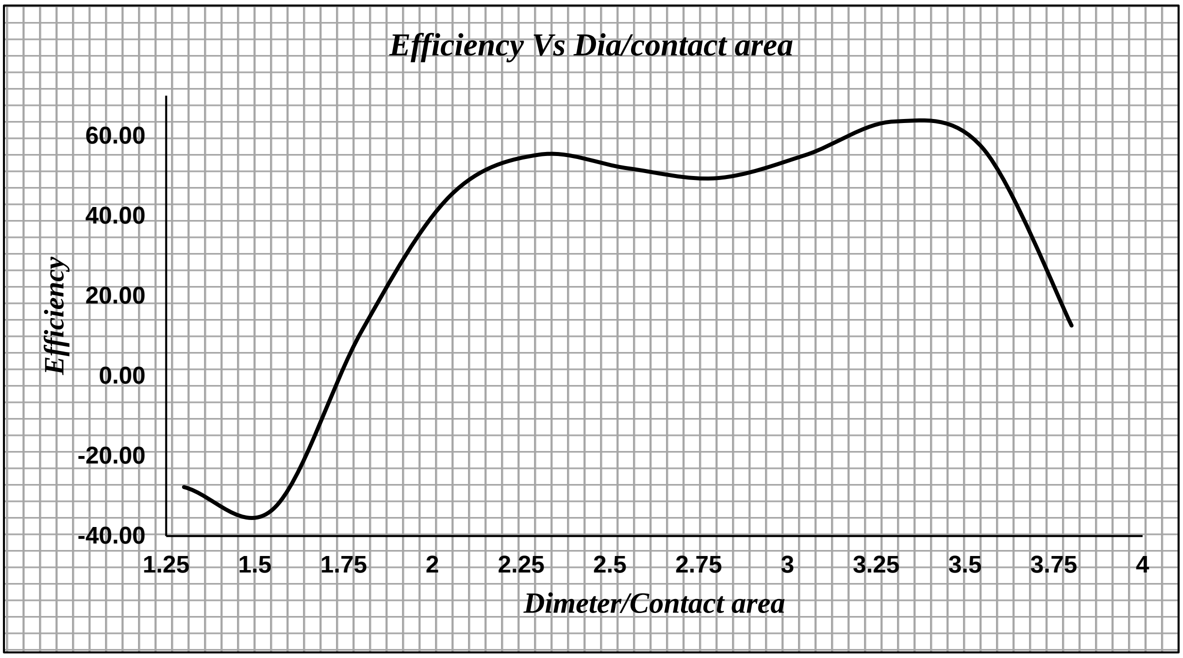


Figure 5. 15: Efficiency versus ratio of diameter to contact area

As can be seen from Figure 5. 15, for larger solid wall diameters, the increase of diameter does not play a dominant role in heat transfer efficiency. This is because of the lower temperature gradient over the pot's outer portion, which yields lower heat transfer rate.

for very small pot diameter to stove top diameter ratios, far away from tested pot dimensions, unphysical efficiency (negative efficiency value) is reproduced. This is obviously due to the lack of experimental values in the range of pot diameter to stove top diameter ratio less than 2–2.5. Further experiments should be conducted and the transient thermal simulation should be exploited to study the effects of variation of efficiency in this limit.

5.6.3. Pot height to pot diameter ratio

The effect of pot height to pot diameter ratio on heat transfer efficiency has been studied. As shown in Figure 5. 16, the efficiency decreases with increasing the above ratio, probably due to the separation of boundary layers on vertical walls.

Furthermore, the height variation does not significantly affect the radial heat distribution for pots of the same diameter, except at the periphery, where the variation of the flux is lower for lower pot heights. By varying the pot's diameter, the heat flux distribution was found to be more homogeneous at larger diameters.

The pot diameter has a significant influence on the overall heat transfer. Specifically, larger pot diameters lead to an increased heat transfer area and wet area (the surface in contact with water). Although the pot height does not affect the overall heat flux input, it does influence the energy lost by heat dissipation through the walls and thus affects the cooking efficiency.

The greatest efficiency of 84.5% was achieved for the pot with a diameter of 24 cm and a height of 5 cm, and the lowest efficiency of 60.5% was achieved for the pot with a diameter of 16 cm. This result verifies that the diameter affects the cooking rate. As can be seen from Fig. 9, for larger solid wall diameters, the increase of diameter does not play a dominant role in heat transfer efficiency. This is because of the lower temperature gradient over the pot's outer portion, which yields lower heat transfer rate. This behavior has been reported also by Jeddi et l. [28], although for the case of steady state computations.

Table 5. 7: Bottom curvature versus efficiency

POT NO.	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Ratio	0.2	0.27	0.47	0.54	0.56	0.62	0.65	0.84
Thermal Efficiency	57	55.05	55.05	55.1	55.05	55.02	55	53

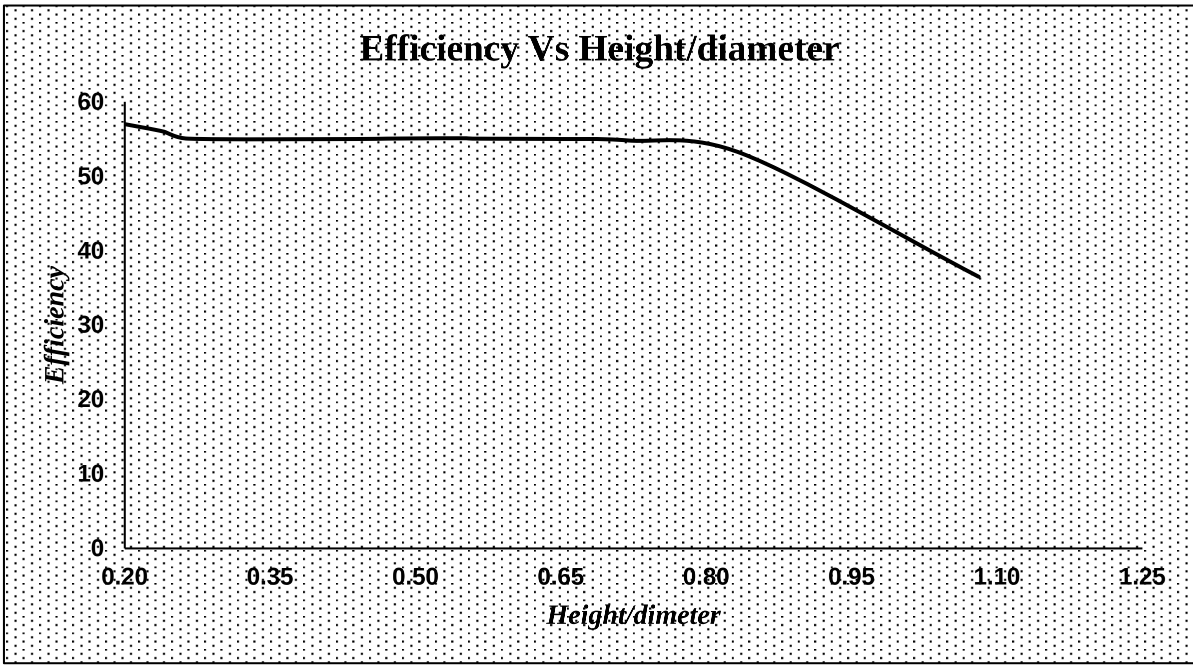


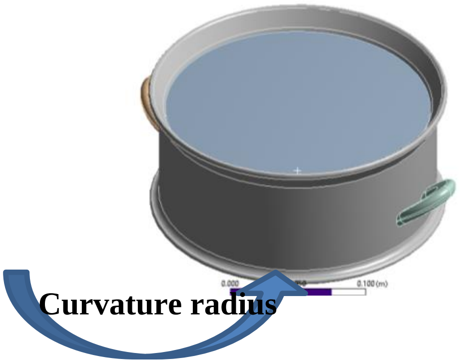
Figure 5. 16: pot height to diameter ratio versus efficiency

5.6.4. Bottom wall curvature

The effect of bottom wall curvature (bulgy and concave bottom surface) has been studied. Fig. 11 shows that pots with concave surface have lower efficiency but pots with flat or bulgy bottom surfaces have similar efficiency (greater than concave surfaces). This seems to be due to the fact that bulgy surfaces attract more hot gases to the bottom surface of cooking pots.

Table 5. 8***:*** Bottom curvature versus efficiency

POT NO.	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Bottom curvature radius (mm)	-0.08	-0.06	-0.04	-0.02	0	0.02	0.04	0.06
Thermal Efficiency	44	54	56	55.6	55.3	55.3	55.2	55.25



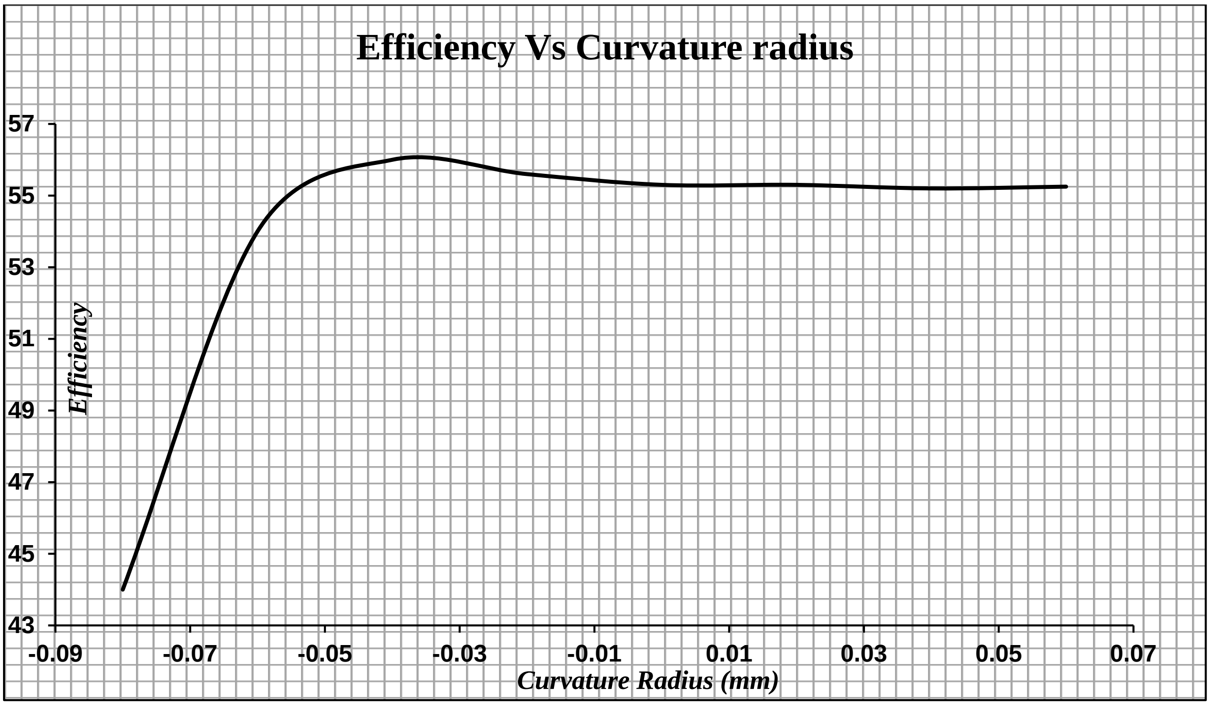


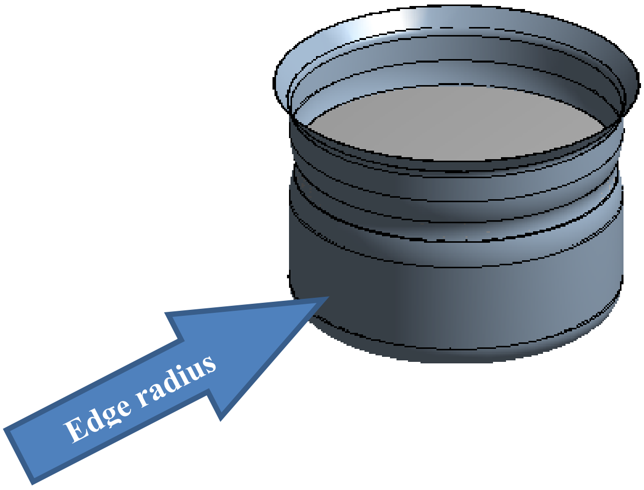
Figure 5. 17: Bottom curvature versus efficiency

5.6.5. Edge radius

In this section the effect of edge radius on efficiency has been studied (Figure 5. 18). Variation of the edge radius at regular pot's edge radius limit (up to 20 mm) does not have a dominant effect on efficiency. At greater edge radii increasing edge radius will result in lower efficiency.

Table 5. 9: Edge radius vs efficiency

POT NO.	1.	2.	3.	4.	5.	6.
Edge radius (mm)	5	10	15	20	25	30
Thermal Efficiency	55.5	54.5	55	55.2	53	40



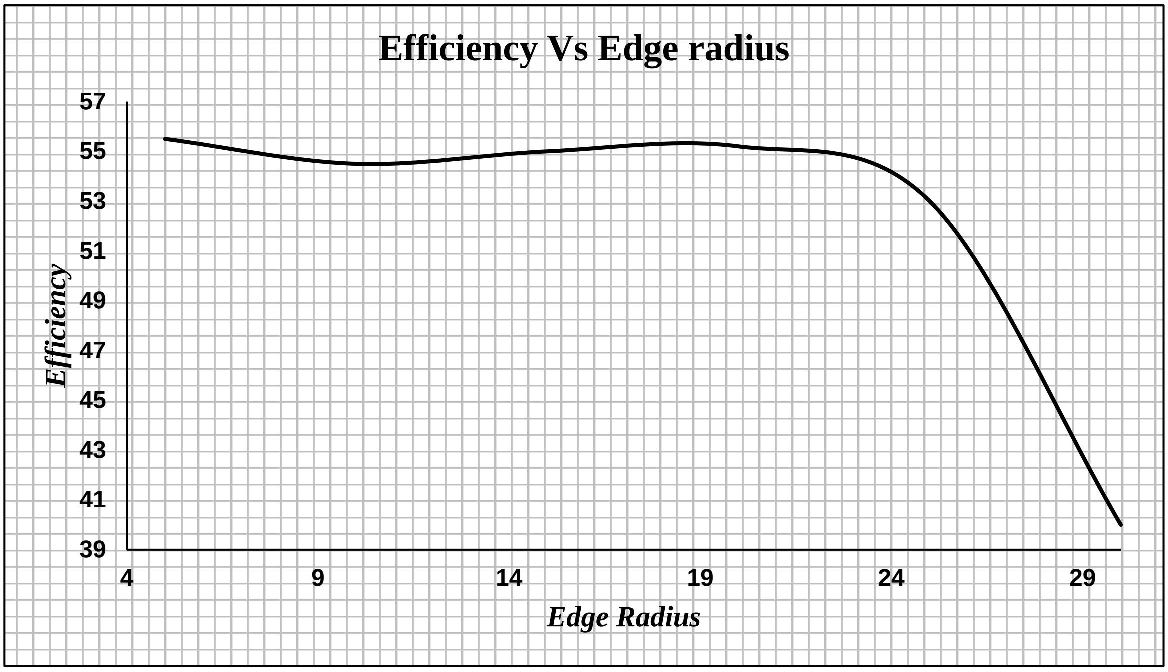


Figure 5. 18: Edge radius vs efficiency

5.6.6. Wall slope

The effect of wall slope on efficiency has been studied. As shown in Figure 5. 20 efficiency has increasing behavior with wall gradient. However, there is an asymptotic value for the efficiency. This seems to be due to the fact that for negative wall gradients hot gasses do not touch the walls of pot.

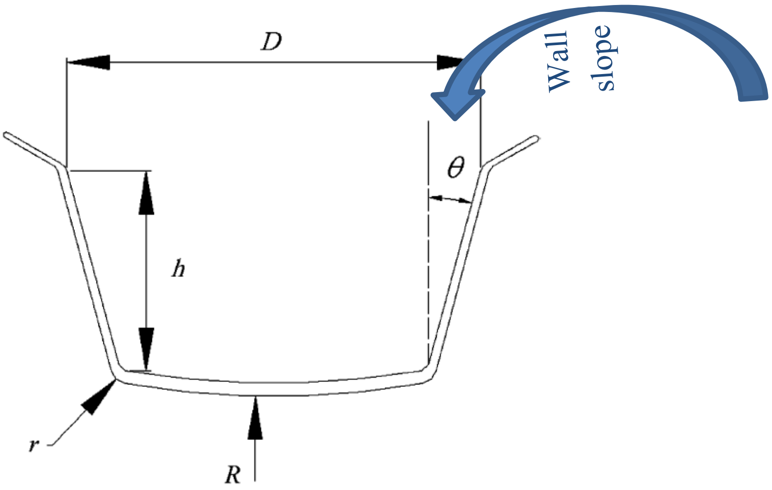


Figure 5. 19: Geometrical representation

Table 5. 10: Wall slope vs efficiency

POT NO.	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**	**11.**
Wall slope (deg.)	-30	-25	-20	-15	-10	-5	0	5	10	15	20
Thermal Efficiency		10	30	42	51	55	57	56.5	56	55.5	55

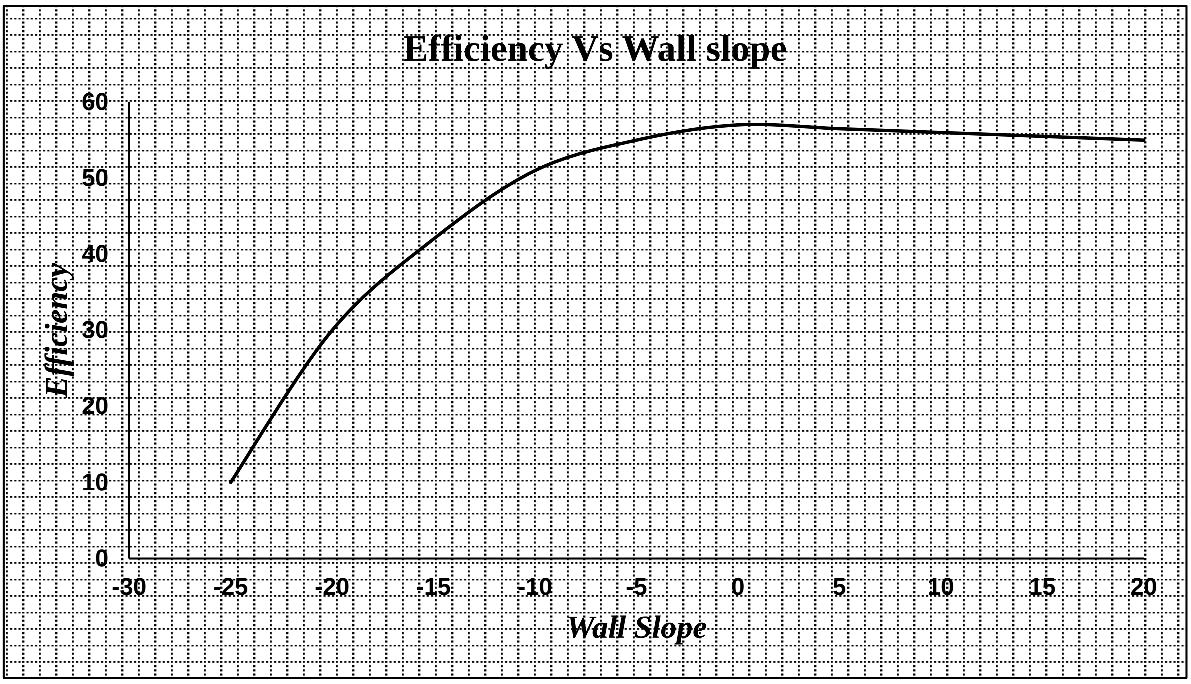


Figure 5. 20: Wall slope vs efficiency

5.6.7. Overall conductivity

As shown in Figure 5. 21 larger wall conductivities yield greater efficiencies, which is in consistence with the physical behavior of heat conduction. It must be mentioned that the variation of conductivity, for ordinary pot’s material conductivity, does not have a great effect on the pot’s efficiency. According to the results of current work, wall conductivity has a slight effect on pot’s efficiency. A similar conclusion has been reported by Mann et al.

Table 5. 11: Conductivity vs efficiency

Conductivity	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Thermal Efficiency	54.3	54.5	54.8	55.2	55.6	56	56.3	56.6	56.7	56.6

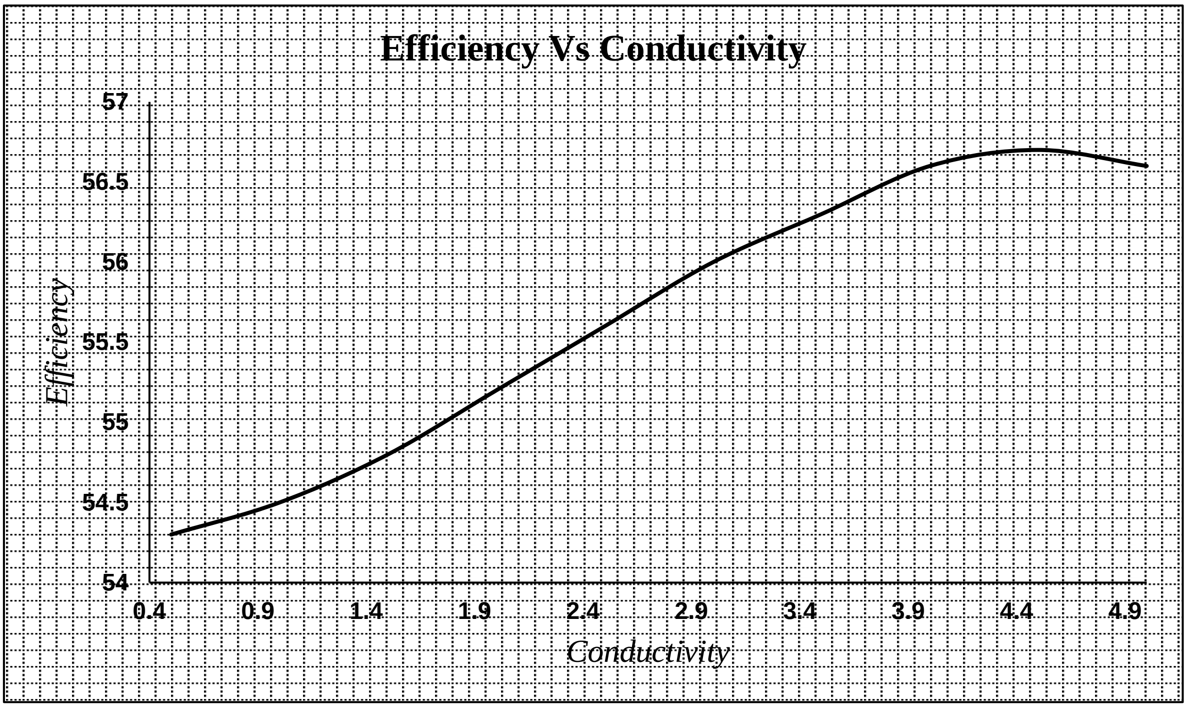


Figure 5. 21: Conductivity vs efficiency

5.6.8. Lid condition

As we know, evaporation does not require boiling at 100°C. Instead, it depends on the partial pressure of water vapor near the water surface. If the lid is on the pot, the partial pressure of water vapor under the lid is about equal to atmospheric pressure (slightly higher). If the lid is removed, the partial pressure of water vapor above the water is by approximation equal to the partial pressure in our kitchen. We can prove with simulation.is that water will get to a boil faster with the lid on, but it will boil away faster with the lid off.

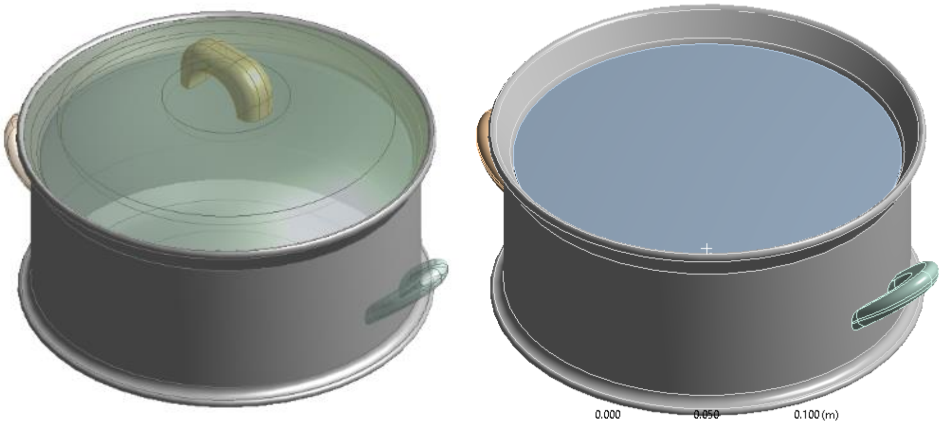


Figure 5. 22: Lid condition

Table 5. 12: Lid effect

POT NO.		**1.**	**2.**	**3.**	**4.**	**5.**	**6.**
Thermal Efficiency	*Open*	50.3	49.5	46.8	40.7	45.6	47.4
	closed	54.3	54.5	54.8	55.2	55.6	56
Boiling time							

With a lower partial water vapor pressure, the liquid will start evaporating more readily. This will lower the temperature of the evaporated water significantly: the enthalpy of evaporation is orders of magnitude more than the heat capacity of water. With a lower temperature, both heat losses due to convection and evaporation at the walls of the pan will lessen, and the heat source will be able to transfer heat more efficiently. So basically, with a lid, evaporation is a 'last resort' of keeping the water at 100°C, if 'normal' heat loss can't handle all of the incoming heat; without a lid, evaporation becomes the main way of losing incoming heat.

CHAPTER SIX
CONCLUSION AND RECOMMENDATION

6.1. Conclusion

This paper presents an experimental and numerical methods to simulate the thermal efficiency of cookpots on an electrical stove. The methods can be useful in the design and optimization of electrical stoves and cookware. It is useful to determining the parameters that increases heat transfer and reduces the cooking time when using electricity as a heating medium. This methodology allows to know the energy efficiency of the cooking process, create the incoming heat flux profile, and determine (and quantify) the heat transfer. In this thesis, the heat transfer characteristics of traditional and modern domestic pots and new modified cookpot were analyzed through computer simulations. Unlike field data analysis, simulations permit more variation concerning input data, external conditions and control parameters. Thus, the comparison of different system solutions will be facilitated.

Using experimental and simulation results, the variations of the efficiency with various parameters have been studied. Results show that efficiency increases with increasing bottom wall curvature, pot wall slope, and overall conductivity. and efficiency decreases with increasing edge radius and pot height to pot diameter ratio. Occupied volume percentage does not have a significant effect on efficiency.

Increasing the ratio of pot diameter to stove top diameter yields higher efficiency; however, for higher ratios, the efficiency remains almost constant. Flat bottom renders greater efficiencies than concave bottom surfaces. for ordinary edge radius heat transfer efficiency does not have a dominant role in efficiency but at greater values, with increasing edge radius, efficiency decreases. Efficiency increases with wall slope and overall conductivity; however, for ordinary pot material conductivities, the conductivity does not play a dominant role in efficiency.

In terms of thermal efficiency, the domestic cookpot and the recommended modified cookpot were compared using ANSYS Transient Thermal. The expected lower thermal efficiency of the traditional cookpot will overcome by using the improved one. The multiplication of the use of such systems will certainly be followed by the development of technologies in the country.

In this study, it has been state by simulation that electrical power used for cooking will be minimized. Especially for Ethiopia, shortage of power supply is the critical factor. So, the recommended technology is more advisable.

If the technology is addressed for small-scale and large-scale household and institutional utensils applications, this enables to use the technology as personal/family level. When this is happened huge amount of power will be saved as a country level and this will be show good way in cookpot technology in Ethiopia.
So, if we consider for a person, an average power of 0.7 kWh is used for one-time cooking (until boiling) [32], cost per hour = 0.825 ETH birr, cost per day = 0.825 ETH birr, cost per month =25.10 ETH birr: cost per year = 301.16 ETH birr, kWh per day = 1.50 kWh. for a number of 100,000 persons (one small city in Ethiopia) we use 150,000 kWh amount of power daily for one cooking. From this, if we minimize the energy usage for one person by 0.1 %. i.e. 0.15 kWh per day, we can save around 16,000 kWh per day. In cost, approximately 10,560 ETB can be saved per day. 6,854,400 ETB/year in one city. If we assume this in large scale cooking like university and camps, the power and cost saved will be doubled.

6.2. Important concluding remarks from the study

- The cooking efficiency can be increased by using the smallest oven for baking, using a pressure cooker, using an electric slow cooker for stews and soups, using the smallest pan that will do the job, using the smaller heating element for small pans on electric ranges, using flat-bottomed pans on electric burners to assure good contact, keeping burner drip pans clean and shiny, defrosting frozen foods in the refrigerator before cooking, avoiding preheating unless it is necessary, keeping the pans covered during cooking, using timers and thermometers to avoid overcooking, using the self-cleaning feature of ovens right after cooking, and keeping inside surfaces of microwave ovens clean.
- Area of contact: for good cooking performance, the diameter of the cookware should closely match the size of the heating area. Cookware should not extend more than 25 mm beyond the heating area. If cookware is too large, the heat is distributed unevenly, cooking time is increased, and more energy is used. Also, heat can be trapped under the heating element, causing the element to build up heat. Cookware that is too small for the heating element can waste energy because heat is lost into the kitchen.
- to extend the recommended small standalone units mechanical functionality to operate almost entirely in Ethiopia.

- ***Insulating material:*** The air currents that transfer heat from the resistors to reflector walls can be avoided if an insulating material is used to fill the area between the electrical resistor and the reflection shield.
- ***Contact resistance:*** Reduce the contact resistance between the electrical resistors and pot surface by polishing the surface of the electrical resistors also increase the effectiveness.
- ***Mixed materials:*** during manufacturing of cookware two and more materials are mixed to take advantage of the best properties of each material and avoid properties that may have a negative effect on the cooking.
- ***Consumer education***: Significantly more consideration is needed when selecting what type of cookware to purchase, as compared to years-past. The market is saturated with various pan compositions, shapes, thicknesses, and coatings. As a consumer, it becomes difficult to understand what really need and for what purpose. Consumers have found themselves overwhelmed with how many options are available and have resorted to purchasing based on looks, price, and/or the marketing appeal of the product. Considerations beyond price and aesthetics are needed when researching cookware to purchase. Therefore, consumer education would be the most valuable source of energy conservation.
- ***Speed of cooking:*** Metals of higher thermal conductivity, such as aluminum and copper, are commonly combined with those with lower values such as stainless steel. This allows the pan to have high heat transfer performance to increase speed of cooking, but also overall evenness of temperature for increased uniformity.
- ***Food safety regulations***: The choice of pots and pans should not solely be based on appearance and design. More important is that it is suitable for the food we prefer to cook and eat. Because of this, in many countries regulations are made to ensure food safety. Although cooking with pots especially clay made pots is a long history in Ethiopia, till now no any regulations were prepared on cookware manufacturing. So, it must be prepared for safety cooking of food.
- ***Material selection***: When man decided that between fire and food there must be a go between, he understood that this must have at least three fundamental characteristics: above all it had to be an impermeable material, secondly it had to resist fire and high temperatures and finally it had to be capable of transmitting heat to the food within, without it interacting chemically.

6.3. Recommendations for Future work

1. In Ethiopia till now no body or institution conducts a nationwide residential energy consumption survey. Next time it must be planned to do this by choosing a statistical sample household, distributed in different geographical regions of Ethiopia. The residential energy consumption survey results will be needed to categorize the cooking consumption and habits in more details.

2. Identifying the different types of clays in Ethiopia and carry out the mineralogical, geochemical and geotechnical evaluation of the clay for making cookpot is also needs deep research.

3. The effect of bottom surface grooves and shape of them are not considered in current modelling procedure. Work must be done to study the effect of pot's bottom grooves on efficiency.

4. Thermal analysis of bimetal plates with clay as cooking pots is also needs deep research.

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Appendices

Appendix 1: Experimental Data and Analysis

1.1. POT-2

1.1.1. Heat Transferred to the pot

Specifications

Table 6. 1: Pot 2 specifications

Material:	Aluminum
Diameter:	160 mm
Height:	96 mm
Thickness:	1 mm
Radius of curvature:	100 mm
Bottom flatness:	Flat
Lid type:	Heavy weight
Wall gradient:	0 degree
Stove type:	Electrical stove
Contact area percentage:	95 %
Surface condition:	Grove 100 mm from bottom
Occupied volume percentage:	85 %
Dia/height ratio:	1.74
Mass of empty pot:	0.3 kg
Mass of water:	2.0 kg
Mass of evaporated water:	0.11 kg

The pan and the water are always at the same temperature. When we put the pan on the stove, the temperature of the water and the pan is increased by the same amount. We use the equation for the heat transfer for the given temperature change and mass of water and aluminum.

Because water is in thermal contact with the aluminum, the pan and the water are at the same temperature. The theoretical energy required to heat 2000 ml of water by 72.3° C in 1180 seconds can be calculated using following procedures.

2. Calculate the temperature difference:

$$\Delta T = T_2 - T_1$$

$$= 89.9 - 17.6 = \mathbf{72.3}\ {}^{\mathbf{0}}\mathbf{C}$$

7. Calculate the mass of water.
   Because the density of water is 999.97 kg/m^3, one liter of water has a mass of ~1 kg, and the mass of 2.0 liters of water is m_w = ***2.0 kg***.
8. Calculate the heat transferred to the water. Use the specific heat of water in Table 3. 2:
   $$Q_w = m_w * c_{p,w} * \Delta T$$
   $$Q_w = 2.0\,kg * 4186\frac{J}{kg.K} * 72.3\,K = 605295.6\,J = \boldsymbol{605.3\,kJ}$$
9. Calculate the heat transferred to the aluminum. Use the specific heat for aluminum in Table 3. 2:
   $$Q_{Al} = m_{Al} * c_{p,Al} * \Delta T$$
   $$Q_w = 0.3\,kg * 903\frac{J}{kg.K} * 72.3\,\mathrm{K} = 19586.07\,J = \boldsymbol{19.6\,kJ}$$
10. Compare the percentage of heat going into the pan versus that going into the water. First, find the total transferred heat:
   $$Q_{Total} = Q_w + Q_{Al}$$
   $$= 605.3\,kJ + 19.6\,kJ = \boldsymbol{624.9\,kJ}$$

Thus, the amount of theoretical energy required to heat 2000 ml of water by 72.3° C in 1100 seconds is 624.9 kJ.

Therefore, the theoretical power required to heat 2000 ml of water by 72.3° C in 1100 seconds is given by:

$$\frac{624.9\ kJ}{1100\ sec} = 0.5680\ kJ/\sec = \mathbf{568.1\ Watts}$$

Thus, the amount of heat going into heating the pan is:

$$\frac{19.6}{624.9} * 100\ \% = \mathbf{3.14}\ \%$$

and the amount going into heating the water is:

$$\frac{605.3}{624.9} * 100\ \% = \mathbf{96.9}\ \%$$

These values indicate that, the heat transferred to the container is a significant fraction of the total transferred heat. since, the specific heat of water is over four times greater than that of aluminum. Therefore, it takes a bit more than twice the heat to achieve the given temperature change for the water as compared to the aluminum pan.

1.2.POT-3

1.2.1. Heat Transferred to the pot

Specifications

Material:	Clay
Diameter:	181 mm
Height:	100 mm
Thickness:	9 mm
Radius of curvature:	100 mm
Bottom flatness:	Flat
Lid type:	Heavy weight
Wall gradient:	0 degree
Stove type:	Electrical stove
Contact area percentage:	95 %
Surface condition:	Smooth
Occupied volume percentage:	85 %
Height/Diameter ratio:	0.55
Mass of empty pot:	3.5 kg
Mass of water:	3 kg
Mass of evaporated water:	0.12 kg

Because water is in thermal contact with the clay, the pan and the water are at the same temperature. The theoretical energy required to heat 3000 ml of water by 72.3° C in 4500 seconds can be calculated using following procedures.

2. Calculate the temperature difference:

$$\Delta T = T_2 - T_1$$

$$= 89.9 - 17.6 = \mathbf{72.3\ ^0C}$$

3. Calculate the mass of water.

   Because the density of water is 999.97 kg/m^3, one liter of water has a mass of ~1 kg, and the mass of 3.0 liters of water is m_w = ***3.0 kg***.

4. Calculate the heat transferred to the water. Use the specific heat of water in Table 3. 2:

$$Q_w = m_w * c_{p,w} * \Delta T$$

$$Q_w = 3.0\,kg * 4186\frac{J}{kg.K} * 72.3\,K = 907943.4\,J = \mathbf{907.9\ kJ}$$

5. Calculate the heat transferred to the clay. Use the specific heat for clay in Table 3. 2:

$$Q_{clay} = m_{clay} * c_{p,clay} * \Delta T$$

$$Q_{clay} = 3.5\,kg * 2110\frac{J}{kg.K} * 72.3\,\mathrm{K} = 533935.5\,J = \mathbf{533.9\ kJ}$$

6. Compare the percentage of heat going into the pan versus that going into the water. First, find the total transferred heat:

$$Q_{Total} = Q_w + Q_{clay}$$

$$= 907.9\,kJ + 533.9\,kJ = \mathbf{1441.8\ kJ}$$

Thus, the amount of theoretical energy required to heat 3000 ml of water by 72.3° C in 4500 seconds is 1441.8 kJ.

Therefore, the theoretical power required to heat 3000 ml of water by 72.3° C in 4500 seconds is given by:

$$\frac{1441\,kJ}{4500\,sec} = 0.3204\,kJ/\mathrm{sec} = \mathbf{320.4\ Watts}$$

Thus, the amount of heat going into heating the pan is:

$$\frac{907.9}{1441.8} * 100\ \% = \mathbf{62.9}\ \%$$

and the amount going into heating the water is:

$$\frac{533.9}{1441.8} * 100\ \% = \mathbf{37.03}\ \%$$

These values indicate that, the heat transferred to the container is a large fraction of the total transferred heat. since, the specific heat of water is over four times greater than that of aluminum. Therefore, it takes a bit more than twice the heat to achieve the given temperature change for the water as compared to the aluminum pan.

1.3.POT-4

1.3.1. Heat Transferred to the pot

Specifications

Material:	Clay
Diameter:	160 mm
Height:	80 mm
Thickness:	7 mm
Radius of curvature:	100 mm
Bottom flatness:	Flat
Lid type:	Heavy weight
Wall gradient:	0 degree
Stove type:	Electrical stove
Contact area percentage:	95 %
Surface condition:	Smooth
Occupied volume percentage:	85 %
Height/Diameter ratio:	0.55
Mass of empty pot:	1.0 kg
Mass of water:	1.8 kg
Mass of evaporated water:	0.08 kg

Because water is in thermal contact with the clay, the pan and the water are at the same temperature. The theoretical energy required to heat 1800 ml of water by 72.3° C in 2700 seconds can be calculated using following procedures.

2. Calculate the temperature difference:

$$\Delta T = T_2 - T_1$$

$$= 89.9 - 17.6 = \mathbf{72.3\ {}^0C}$$

3. Calculate the mass of water.

   Because the density of water is 999.97 kg/m^3, one liter of water has a mass of ~1 kg, and the mass of 1.8 liters of water is m_w = ***1.8 kg***.

4. Calculate the heat transferred to the water. Use the specific heat of water in Table 3. 2:

$$Q_w = m_w * c_{p,w} * \Delta T$$

$$Q_w = 1.8\,kg * 4186\frac{J}{kg.K} * 72.3\,K = 544766.04\,J = \mathbf{544.8\ kJ}$$

5. Calculate the heat transferred to the clay. Use the specific heat for clay in Table 3. 2:

$$Q_{clay} = m_{clay} * c_{p,clay} * \Delta T$$

$$Q_{clay} = 1.0\,kg * 2110\frac{J}{kg.K} * 72.3\,\mathrm{K} = 152553\,J = \mathbf{152.6\ kJ}$$

6. Compare the percentage of heat going into the pan versus that going into the water. First, find the total transferred heat:

$$Q_{Total} = Q_w + Q_{clay}$$

$$= 544.8\,kJ + 152.6\,kJ = \mathbf{697.4\ kJ}$$

Thus, the amount of theoretical energy required to heat 1800 ml of water by 72.3° C in 2700 seconds is 697.4 kJ.

Therefore, the theoretical power required to heat 1800 ml of water by 72.3° C in 2700 seconds is given by:

$$\frac{697.4\,kJ}{2700\,sec} = 0.2583\,kJ/\sec = \mathbf{258.3\ Watts}$$

Thus, the amount of heat going into heating the pan is:

$$\frac{152.6}{697.4} * 100\,\% = \mathbf{21.9}\,\%$$

and the amount going into heating the water is:

$$\frac{544.8}{697.4} * 100\ \% = \mathbf{78.1}\ \%$$

These values indicate that, the heat transferred to the container is somewhat large fraction of the total transferred heat. since, the specific heat of water is over three times greater than that of clay. Therefore, it takes a bit more than twice the heat to achieve the given temperature change for the water as compared to the aluminum pan.

Appendix 2: Necessary Tables

2.1. Recorded experimental data

Pot 1

Time	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	120	150	180	210	240	270	300
Temp.(°C)	17.6	28	42	54	67	76	82	84	81	76	70	65	62	59	57	56	55	53	52	40	32	28	25	22	18	17.6

Pot 2

Time	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	120	150	180	210	240	270	300	330	360
Temp.(°C)	17.6	26	34	42	50	57	65	72	80	84	83	79	75	70	64	60	56	52	50	38.23	32.06	27.76	24.58	22.13	20.16	18.55	17.21	16.07

Pot 3

Time	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	120	150	180	210	240	270	300	330	360	390	420
Temp.(°C)	17.6	28	39	50	57	64	70	75	80	83.4	84.1	83	82	80	77	75	73	70	68.00	55.50	47.00	41.00	37.00	34.00	31.00	29.00	26.86	25.34	24.02	22.86

Pot 4

Time	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	120	150	180	210	240	270	300	330	360	390	420			
Temp.(°C)	17.6	27	37	46	52	58	63	68	73	77	81	83	83.2	82.5	81	80	78	76	74.00	62.00	51.00	44.00	38.00	34.00	30.00	28.00	26.00	25.00	23.50	22.00	20.00	19.17	18.42

2.2. Boiling point of pure water at elevated altitudes

Based on standard sea-level atmospheric pressure (courtesy, NOAA):

Altitude, ft (m)	Boiling point of water, °F (°C)
0 (0 m)	212°F (100°C)
500 (150 m)	211.1°F (99.5°C)
1,000 (305 m)	210.2°F (99°C)
2,000 (610 m)	208.4°F (98°C)
5,000 (1524 m)	203°F (95°C)
6,000 (1829 m)	201.1°F (94°C)
8,000 (2438 m)	197.4°F (91.9°C)
10,000 (3048 m)	193.6°F (89.8°C)
12,000 (3658 m)	189.8°F (87.6°C)
14,000 (4267 m)	185.9°F (85.5°C)
15,000 (4572 m)	184.1°F (84.5°C)

Source: NASA.

2.3. Thermophysical Properties: Water vapor at 1 atm [33] [34]

T Temp.(K)	ρ density(kg/m^3)	cp specific heat (kJ/Kg-K)	µ viscosity(10-7N-s/m^2)	ν kinematic viscosity (10-6m^2/s)	k thermal conductivity (10-3W/m-K)	α thermal diffusivity (10-6m^2/s)	Pr Prandtl number
380	0.5863	2.060	127.1	21.68	24.6	20.4	1.060
400	0.5542	2.014	134.4	24.25	26.1	23.4	1.040
450	0.4902	1.980	152.5	31.11	29.9	30.8	1.010
500	0.4405	1.985	170.4	38.68	33.9	38.8	0.998
550	0.4005	1.997	188.4	47.04	37.9	47.4	0.993
600	0.3652	2.026	206.7	56.60	42.2	57.0	0.993
650	0.3380	2.056	224.7	66.48	46.4	66.8	0.996
700	0.3140	2.085	242.6	77.26	50.5	77.1	1.000
750	0.2931	2.119	260.4	88.84	54.9	88.4	1.000
800	0.2739	2.152	278.6	101.7	59.2	100.0	1.010
850	0.2579	2.186	296.9	115.1	63.7	113.0	1.020

Appendix 2: Photo Gallery