PERFORMANCE INVESTIGATION OF SOLAR POWERED INJERA BAKING OVEN FOR INDOOR COOKING

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Abstract

In Ethiopia there is a huge demand of thermal energy for domestic purposes. The energy needed for baking injera is almost obtained from fire wood and fossil fuel which are both the main causes for environmental pollution and depletion of forest resources. A new type of baking system is proposed where solar energy is used as a power source. The solar thermal energy is transferred to the kitchen by means of a circulating heat transfer fluid which is heated by a parabolic trough.

The aim of this study is to investigate the performance of the proposed system which can also be applied for baking of bread and Indian chapatti. A new type of baking pan made from ceramic is manufactured and used for baking injera. In order to heat the ceramic baking pan, a steel pan with fins is put underneath and the oil enters the cavity to transfer the heat to the steel and fins which further heats the baking pan. In order to simulate the daily solar radiation, an electric heater is used to heat the oil in a tank. The oil is pumped to the baking pan bottom and returns back after discharging heat to the steel pan and fins. Experiments were conducted for initial heat up and baking cycles. It takes approximately 1 hour to start circulating the oil and 40 minutes to reach the optimum baking temperature (~ 180°C – 220°C). 5 injera was baked at an interval of 2 minutes and idle time of 3 minutes between each injera. The preliminary study from the laboratory model shows encouraging results of the proposed system.

1 INTRODUCTION

Most of the developing countries are suffering from what many call the energy crisis, which is characterized by depletion of locally available energy resources and dependence on imported fuels. The energy crisis is increasing the food crisis by increasing the rate of deforestation and thereby causing degradation of farmlands. Furthermore, dependence on imported fuel is weakening the capacity of the concerned countries to buy food whenever the need arises. All these situations apply to Ethiopia.

Injera is spongy flat bread with a distinctive test and texture. It is predominantly eaten as a staple food item in Ethiopia and some parts of East Africa. It is similar to an Indian chapatti but with small bubbly structures on top. Injera baking requires temperatures ranging from 180°C – 220°C. In most households of Ethiopia, the energy demand for baking injera is largely met with bio-fuels such as fuel wood, agricultural residue and dung cakes. Whereas, electricity is used in some of the urban households.

In Ethiopia Currently three baking techniques are used for baking injera. These are:

1. Baking on Open fire method (three stone method)
2. Baking on Mirt-injera stove and
3. Baking on Electric baking pan

To improve health and general welfare, better cooking and heating facilities are important. Solar cooking can decrease the health hazards associated with indoor fire cooking and the economic burdens associated with fire-wood gathering or purchase [5].

While many designs exist for solar cooking in pots, relatively few exist for frying (Solar cooker internaltional, 2010; Fundacion Tierra, 2010). The existing systems are also limited to direct cooking technologies by illuminating the pots on the sides as well as the bottom. Whereas, for injera baking, the heating must be directed to the bottom of the baking pan.

Solar cooking with energy storage using phase change material [1], pressurized water vessel [9], box type solar cooker with auxiliary heating [7] and pebble bed thermal energy storage have been proposed , which require the cook to work outdoors in rural areas and on roof tops in urban areas [11]. The majority of these systems work below the baking temperature required for baking injera (180^{o}C-220^{o}C). Besides, they do not satisfy the general requirements for baking injera.

The solar fryer which is specifically designed for cooking injera was developed by Gallagher (2010). He used a 0.46 m diameter pan and 1.2m diameter mirror for his prototype, which was designed for cooking 0.42m diameter slices of injera. A mirror below the pan directs the radiation to the pan bottom, which is coated with a low-emissivity black absorber. The mirror uses flat, hexagonal panels of aluminized-Mylar to provide uniform illumination across most of the pan bottom. This system is mainly designed for cooking outdoors.

The other well-known solar fryer was developed by Devos (2006) by arranging an array of 0.15m square glass mirrors in a 1.54 m^2 rectangle, with each mirror tilted to fit an off-axis parabola. The array is placed near the ground just beyond a table that supports the fry pan, which sits at an opening in the table. Reflected sunlight is brought to a quasi-focus on the bottom of the pan, and a metal vane below the table is used to block part or all of the incident sunlight. The mirror angle is adjusted through the day and the seasons to direct focused sunlight to the pan [5].

Jorgen Lovseth (1997) proposed a concentrating solar thermal system with pebble-bed heat storage using air as heat transfer medium. Prassana and unanand (2010), proposed a hybrid solar cooking system where the solar energy is transported to the kitchen by means of circulating fluid. They proposed an option to maximize the sun energy by changing flow rate dynamically.

In this study, a solar powered injera baking system is proposed wherein the solar energy is transferred to the kitchen by means of a circulating heat transfer fluid. In conventional injera baking, there is a smoke emission from domestic fuels which is the major source of indoor pollution, especially in rural and poor urban communities. This smoke contains pollutants and particulates that adversely affect the health of women. The proposed system is free of smoke, hence, improves the health and safety of the user. A solar powered injera baking technology is expected to contribute considerably towards meeting domestic cooking energy requirement in a country blessed with abundant sunshine.

2 DESCRIPTION OF THE SYSTEM

The block diagram of the proposed solar powered injera baking system is shown in Fig. 1. The system consists: parabolic trough, pumps, heat storage tank and the injera baking mitad. The parabolic trough is used to collect solar energy and increase the temperature of the fluid.

The heat transfer fluid coming from the trough gives up its heat to the fluid coming from the baking pan, within the heat exchanger. The baking pan consists of a ceramic pan with steel plate underneath. Fin like structures are welded at the bottom of the steel plate to facilitate heat transfer and to hinder direct oil flow from oil gallery. Heat is transferred from the working fluid to the steel plate then to clay pan and finally to injera during baking. The injera mitad is placed in the kitchen where the baking is done. All other components are placed at intermediate levels according to the building requirements.

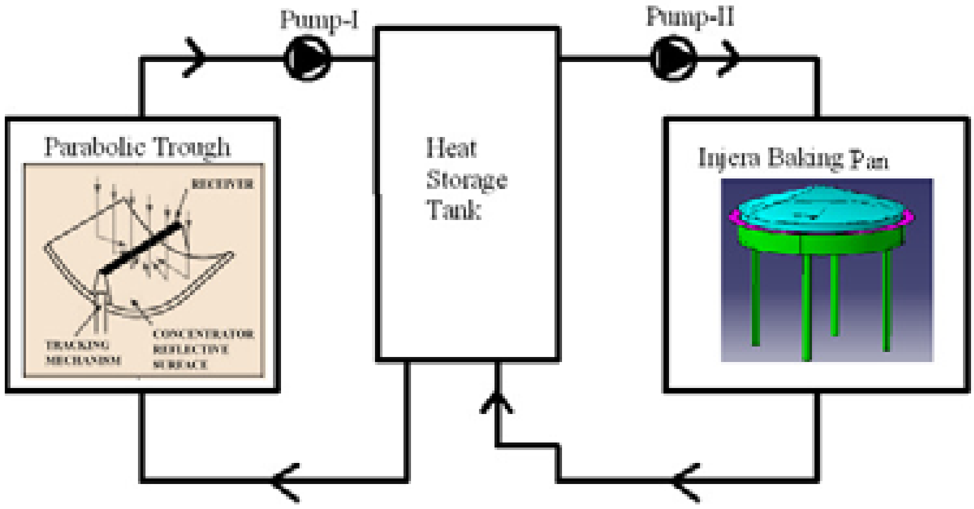

Fig. 1 Block Diagram of Solar Powered Injera Baking Oven

Pump-I is used to Pump the heat transfer fluid (Shell Thermia-B) between the parabolic trough and the heat storage tank (heat exchanger). The energy extracted from the sun is used to heat up the oil to the required temperature. Once the required temperature is reached (~ 300 ^{o}C), the heat energy is transferred to the baking pan using Pump-II. Oil is partly stored below the baking pan, in order to overcome sudden drop of surface temperature of the baking pan during baking.

For this study the part comprising the trough, Pump I and the piping line between the heat exchanger and the trough were replaced by a single unit, i.e., oil heating and storage tank. In order to simulate the daily solar radiation, an electric heater was used to heat the heat transfer fluid in the heating and storage tank. Then, it was pumped to the baking pan assembly. Thus, heat will transfer from the heated oil to the baking pan by convection and conduction heat transfer mechanisms. Once the energy is discharged to the baking pan, the heat transfer fluid returns from the oil gallery to the oil storage and heating tank through the return pipe line to get heated. The circulation of the heat transfer fluid will continue as long as Pump II is running.

3 MAIN COMPONENTS OF THE SYSTEM

The laboratory model adapted for this study consists of:-

- baking pan assembly (oil gallery, baking pan and baking pan support)
- Oil heating and storage tank (heat transfer oil storage tank and electrical heater)
- Heat transfer fluid piping and pump system (supply line, return line, check valve and pump II).
- Insulation and sealing sub-system (high temperature resistant gasket maker (~ 340 ^{o}C), ash insulation (for oil gallery and heating and storage tank) and fiber glass insulation for piping line).
- Baking pan cover (used to open and close baking pan surface during baking).

Layout out of the laboratory model is shown in Fig. 2 below

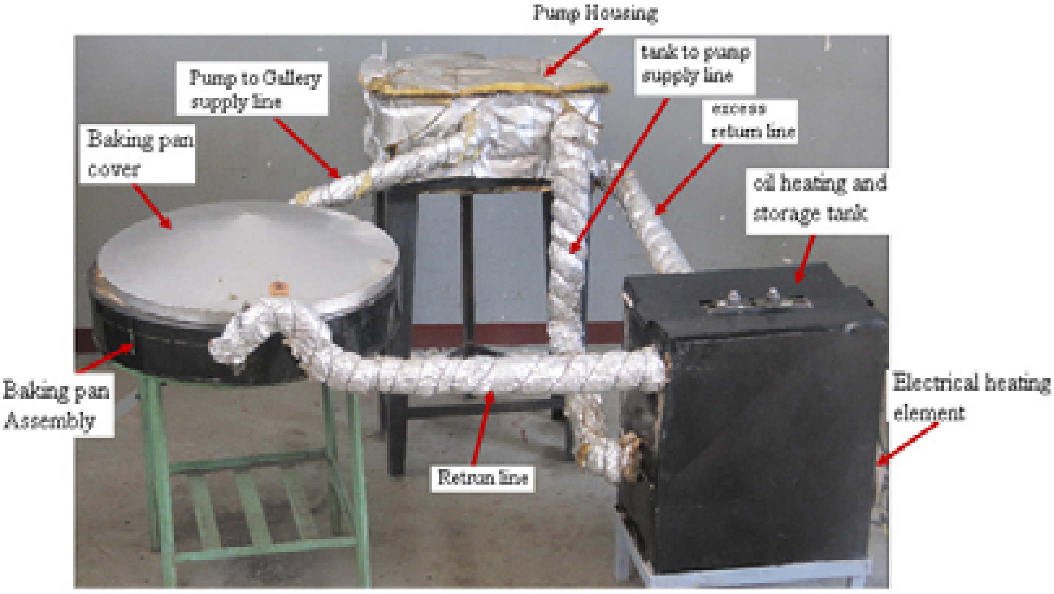

Fig. 2 Main components of the laboratory model

3.1 Baking Pan

Traditionally, flat and circular clay pans with diameter ranges of 500 mm to 600 mm and 20mm thick are used as baking pans. The baking pan used for the proposed system is 8 mm thick and 580mm in diameter. The diameter is kept similar to existing baking pans. This makes the system socially acceptable as the users are familiar with the injera size and a significant change in size may affect the acceptability of the system. The heat transfer from the oil to baking pan top is mainly by conduction. Hence, reducing baking pan thickness will result in saving a significant amount of energy. Therefore, the thickness of the baking pan utilized in this system is reduced to 8mm. Besides; the material of the pan is changed from clay to high conductivity ceramic pan. Direct contact of the pan with heat transfer oil can cause cracking of the baking pan. To avoid this problem 3mm conductive steel sheet metal is used to separate from the heated oil.

Fig. 3 Photograph of the ceramic pan in horizontal and vertical arrangement

3.2 Heat Transfer Fluid Gallery

In order to bake injera in the same way it is made now, the top surface of the baking pan should be kept in the temperate range of 180 ^{o}C – 220 ^{o}C for a long time. In order to overcome sudden drop of baking pan top surface temperature below this optimum temperature range, oil is partly stored below the baking pan in the heat transfer fluid gallery. The heat transfer fluid gallery is made with equal size to the baking pan. This helps to transfer heat energy to injera batter uniformly. The oil gallery is 60 mm high and 580mm in diameter. Galvanized steel pipes of ½ inch diameter are welded to inlet and outlet ports of the ½ inch diameter hole drilled on opposite sides of the housing of the gallery. The oil gallery has a total volume of 15.9 liters.

Fin like structures are welded inside the gallery to hinder direct oil flow from inlet to outlet and to enhance the heat transfer. To minimize heat loss, the oil gallery is insulated with ash insulation system which has 35mm thickness from below and the side of the wall.

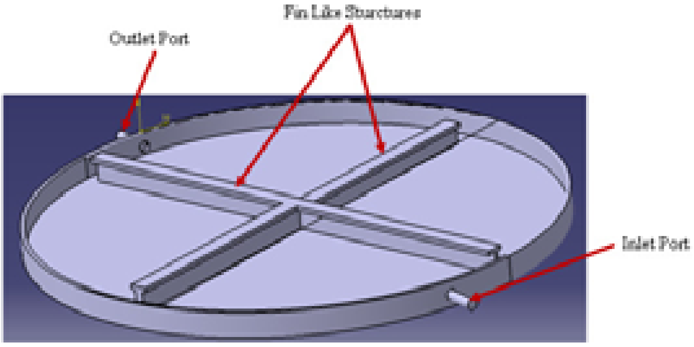

Fig. 4 Fin like structures on heat transfer fluid gallery

3.3 Oil Heating and Storage Tank

Shell Thermia B heat transfer oil is used as heat transfer medium. The oil expands by about 20% from the room temperature volume when it reaches temperatures of in the order of 300 ^{o}C. For the proposed system here, the expansion of the oil is taken care of by increasing the volume of the tank to handle more oil. The tank has dimensions of 400mm, 500mm and 230mm of length, height and width respectively. Therefore the tank has a total volume of approximately 46 liters excluding the volume occupied by the Electrical heater.

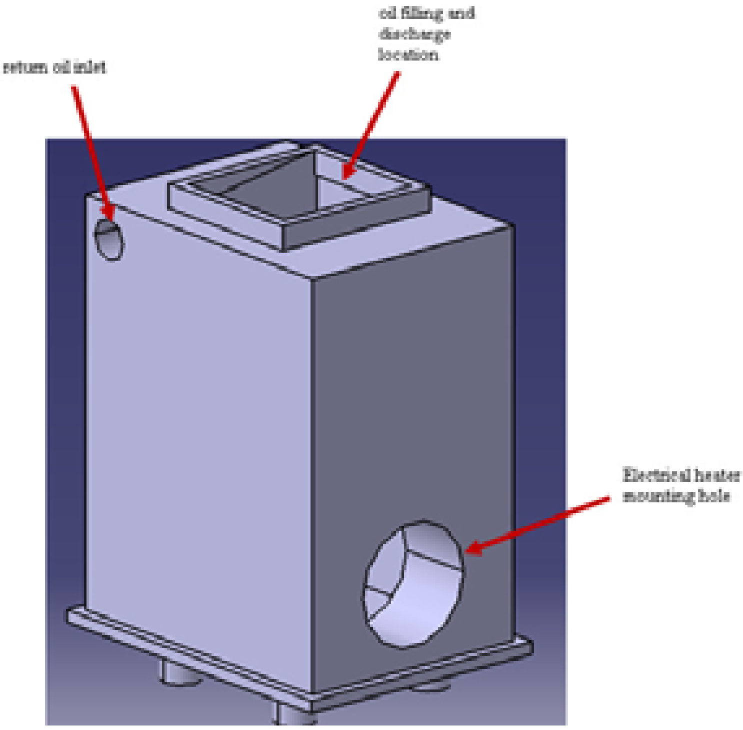

Fig. 5 Oil storage and heating tank

3.4 Piping System

The piping system comprises of supply line (from storage and heating tank to pump II and from Pump II to inlet port of the oil gallery), return line (from oil gallery to storage tank) and excess oil return line (from pump II to storage and heating tank). The heat transfer fluid is pumped from the storage tank to the inlet side of the baking pan assembly system using Pump II. All pipes lines are made of ½ inch galvanized steel pipe. The piping system has a total length of 4.5 m, with 2.1m supply line, 1.4 m return line and 1.0 m excess return line.

4 CAPACITY OF ELECTRICAL HEATING ELEMENT

Flanged type immersion heaters are commonly employed in oil and water heating systems. For this particular case also flanged type electrical immersion heater was selected as heating element. In order to determine the capacity of the heater the following assumptions were made;

- The electrical power is supplied continuously for approximately 1 hour
- The heat losses from the oil gallery are mainly by convection and conduction.
- Properties of the material of the tank and the oil remain constant during the process.

Based on the above assumption, the required input power can be calculated as:

$$(Q_{in} - Q_{loss})\Delta t = mc_p \Delta T \tag{1}$$

The heat loss (Q_{loss}) is given by:

$$Q_{loss} = \frac{T_f - T_\infty}{R_t} \tag{2}$$

The thermal Resistance (R_t) is given by:

$$R_t = \frac{1}{h_1 A} + \frac{t_1}{k_1 A} + \frac{t_2}{k_2 A} + \frac{1}{h_2 A} \tag{3}$$

Where: T_f is the average oil temperature (150 ^{o}C), T_∞ is the ambient temperature (20 ^{o}C), h_1 and h_2 are the convective heat transfer coefficients of heat transfer fluid (490 W/m^2.K) and ambient air (10 W/m^2.K) respectively. t_1 and t_2 are thicknesses of the housing sheet metal of the heat storage tank (3mm) and the insulating material (35mm) respectively, k_1 and k_2 are the thermal conductivities of heat storage tank material (43 W/m.K) and Ash (0.14 W/m.K) respectively and A is area of the tank (0.814 m^2). Assuming that the oil is heated to a temperature of 280 ^{o}C above ambient temperature, the required capacity of the heater is approximately 6 kW. Based on this result a commercially available 6 kW flanged immersion type heater was employed for the system.

5 EXPERIMENTAL RESULTS AND DISCUSSION

The Experiment was conducted at the Department of Mechanical Engineering work shop of Addis Ababa Institute of Technology. Different tests were performed to observe the performance of the system during initial heat up and baking. K- Type thermocouples were used to record the temperature variations in the heating and storage tank, baking pan inlet, baking pan outlet and on the surface of the baking pan. Injera baking experiments were also conducted successfully and the results of the experiment will be presented and discussed to show to what extent the basic design objectives and specifications can be met with this proposed system.

5.1 Heat up Time and Temperature distribution of oil in the heating and storage tank

The oil in the heating and storage tank is heated by a 6 kW Flanged immersion type electrical heater. The tank has approximately an oil volume of 42 liters. In order to avoid the reduction of the oil from the tank during pumping, the oil is first circulated to the oil gallery and the tank is refilled to the required volume. K- type thermocouples were attached to a National Instrument data logger and the result was recorded using Lab view software.

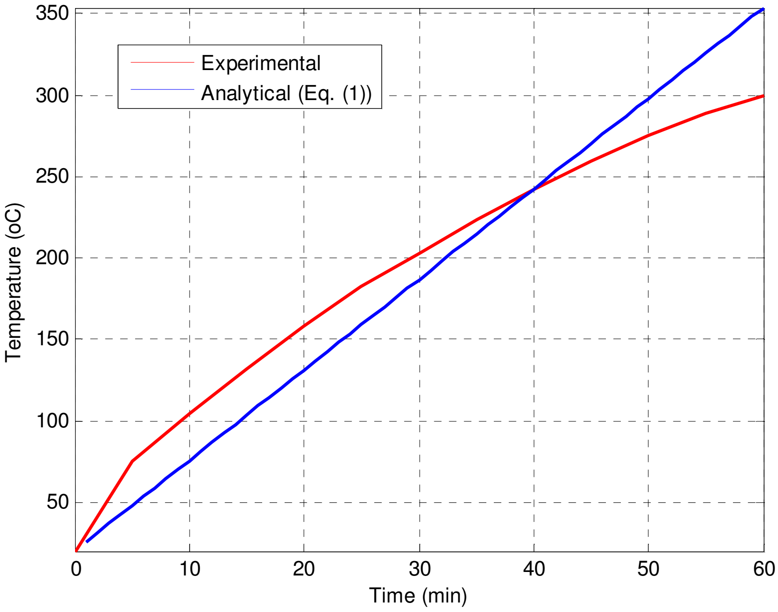

Fig. 6 Temperature distribution of oil in heat storage tank during initial heat up

As shown in Fig. 6 above, it takes approximately one hour to reach a temperature of 300 ^{o}C. The heat losses are roughly approximated for the analytical result. Hence there is a significant difference between the experimental result and Analytical result.

5.2 Heat up time and temperature distribution of baking pan surface.

Once the oil in the storage tank reaches the required temperature (~ 300 ^{o}C), Pump II starts working and the fluid is pumped to the oil gallery. The temperature of the baking pan top surface starts to rise. In order to bake successfully, the top surface of the baking pan is expected to be at a temperature of 180 ^{o}C to 220 ^{o}C. Fig. 7 shows the temperature distribution of the heat storage tank, baking pan inlet, baking pan surface and baking pan outlet during simultaneous heat supply and pumping. As shown in the figure, it takes approximately 40 minutes to reach the optimum baking temperature. Therefore baking can be started after 1 hour and 40 minutes including the heat up time for oil in heat storage tank. The oil leaving the heat storage tank suddenly drops in temperature during the first step of pumping. Gradually it regains its temperature during the pumping process. During the pumping, the temperatures at inlet and outlet of oil gallery were observed to be relatively higher than the tank temperature. This is due to non-uniform distribution of the heating of the electrical wire. The oil leaving the heat storage tank is relatively at higher temperature compared to the bulk oil in the tank.

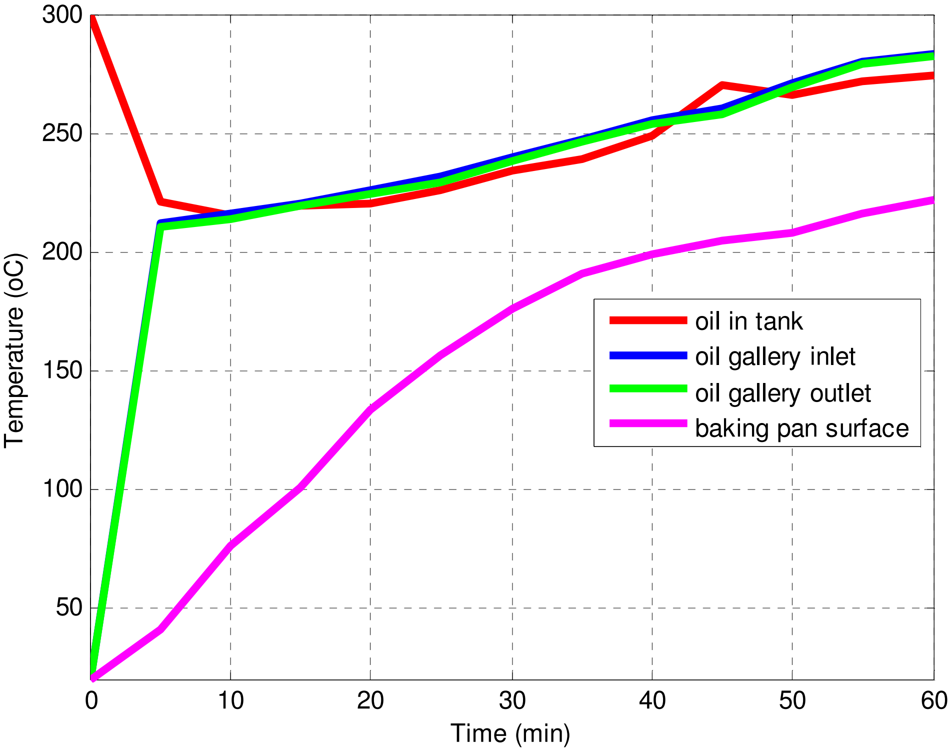

Fig. 7 Temperature distribution of oil in tank, oil inlet to gallery, exit from gallery and baking pan surface

5.3 Injera baking experiment

Experiments were conducted to bake an injera batter prepared from Teff flour. The dough used for this experiment is ~ 2/3 water and 1/3 Teff flour by weight. A full size injera ~ 56cm in diameter was baked successfully. Totally 5 injera was made and it took 2 minutes to remove each injera from the baking pan. An idle time of 3 minutes were recorded between each injera. The idle time is to recover to the baking surface temperature which was reduced during the cooking of injera. It is assumed that the injera is cooked at boiling temperature of water for the specific location.

In Addis Ababa where the experiment is conducted, the boiling point of water is nearly 92 ^{0}C. Thus, the injera is baked when the surface temperature reaches 92 ^{o}C. Generally it took 10 minutes of baking time and 12 minutes of idle time for baking five injera.

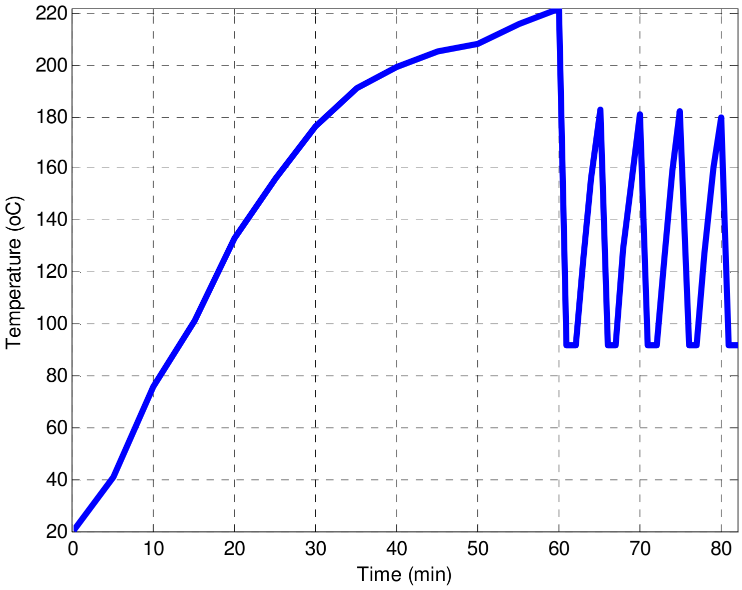

Fig. 8 Temperature distribution of baking pan top surface during initial heat up and cyclic baking

As shown in fig. 8 above, it took approximately one hour to start baking. Even though the injera is removed after 2 minures during the first baking, the injera is cooked sooner than estimated because of high initial temperature on pan surface. The remaining four injera was baked in approximately 2 minutes each. Due to the increase in specific heat of the oil with temperature, the oil retains the heat for longer periods. Thus, we observed that it is still possible to bake at least two injera after the electric power supply is shut-off. Besides, the baking pan looses heat very slowly which is also one advantage to maintain the baking surface temperature for longer periods.

Assuming that 20 injera is baked per day (based on average family size), it takes 100 minutes of heat up time, 40 minutes of baking time and 57 minutes of idle time. Thus, it takes approximately 3 hours and 28 minutes to bake 20 injera. The solar radiation can efficiently be collected for approximately four hours per day. Hence the proposed system can work efficiently with solar power.

Photograph of the injera baked during the first baking cycle is illustrated in fig. 9. The injera is similar in texture and taste with the one baked on conventional baking pans. It is also removed from the baking pan surface easily (with out sticking) and the small bubbly structures (eyes) were similar with those obtained in conventional baking pans.

Fig. 9 Photograph of injera baked using the laboratory model of the proposed system

5.4 Energy Utilized for baking Injera

The energy utilized for baking injera is defined as the energy required to raise the temperature of the dough (batter) to a particular temperature (sensible heat), plus the amount of energy necessary to boil the water which evaporates during the baking process (latent heat). The initial mass of batter and the mass of injera produced from the batter were measured to determine the energy required for cooking injera. Thus, the mass water vapor can be obtained by reducing the mass of injera produced from the initial mass of batter. It was assumed that, the heat capacity of the injera batter is the same as that of water during the sensible heating process. Therefore, the energy utilized for baking injera is given as:

$$Energy\ Utilized = m_{batter}c_{batter}(T_{boil} - T_{room}) + (m_{batter} - m_{injera})h_{fg}$$

(4)

Where; m_{batter} is the mass of the batter for one injera (0.4 kg), T_{boil} is the boiling temperature of water in Addis Ababa (~92°C), T_{room} is the room temperature (20 °C), c_p is the specific heat of water (4.187 kJ/kg.K), m_{injera} is the mass of the injera produced (0.32kg), h_{fg} is the latent heat of vaporization of water (2260 kJ/kg). based on these data the Energy utilized will be 301.4 kJ. For cooking time of 120 seconds, the power requirement during the cooking then becomes 2.51 kW.

5.5 *Heat Loss*

Heat is transferred from the heating and storage tank to baking pan assembly by circulating heat transfer fluid through the pipe. Since the temperature of the fluid is much higher than ambient temperature, the fluid losses heat energy to ambient.

Heat is first lost from the heat transfer fluid through the pipe wall by conduction [2] and given as:

$$P_{loss} = \frac{2\pi k_1 l}{\ln\left(\frac{D_o}{D_i}\right)}\left[T_f - T_{pipe}\right] \tag{5}$$

Where: D_i and D_o are the inner (17mm) and outer diameters of the pipe (21mm) and k_1 is the thermal conductivity (0.046 W/m^2.K) of the pipe material [25].

Heat from the pipe is lost through the insulation by conduction and radiation given by Cengel [12]:

$$P_{loss} = \frac{2\pi k_2 l}{\ln\left(\frac{D_o + 2t}{D_i}\right)}\left[T_{pipe} - T_{amb}\right] + A_o \sigma \varepsilon_o \left(T_{pipe}{}^4 - T_{amb}{}^4\right) \qquad 6)$$

Where k_2 *is* the thermal conductivity of the insulation material (0.046 W/m^2.K), t is the thickness of the insulation (3.5mm), A_o is the outer surface area of the pipe, D_o is the outside diameter of the pipe (21mm), l is length of the pipe (4.5m) , σ is the Stefan- Boltzmann constant, ε_o is the emittance of the outer surface of insulating material (0.04), T_f,T_{pipe} and T_{amb} are average Oil temperature (150 °C),Pipe outer wall temperature and (40°C) ambient temperature (20 °C) respectively. Based on these data the heat loss from pipe lines is 0.054kW.

The heat loss from the region insulated by Ash is ignored for this analysis. The Ash was found to be very effective insulator compared to fiber glass insulation. Hence the heat loss is calculated only for piping lines where fiber glass insulation was used.

6 CONCLUSION

In this paper, the performance of solar powered injera baking oven, where heat energy is transported to the kitchen by means of a heat transfer fluid is investigated. The laboratory model of the system, where solar energy is simulated by electrical heating gives encouraging results. Main components of the system and experimental results were described in detail with illustrations and graphs. The ash insulation used for most of the components is found to be a very effective insulator. It is cost effective as it can be obtained freely. From the experimental result, it was observed that it took approximately 1hour for heating oil to 300 ^{o}C and 40 minutes to reach the optimum baking surface temperature. Injera is removed from the baking pan every two minutes and it takes an idle time of three minutes between each injera to recover to optimum baking temperature. Based on average family size, 20 injera can be baked per day in approximately three hour and 28 minutes. In Ethiopia, high flux radiation can be collected efficiently at least for four hours. Thus, 20 injera can be baked per day efficiently using the proposed system; which is powered by solar energy.

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