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Experimental Investigation and Loss Quantification in Injera Baking Process

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Abstract

Electric Injera baking pans (Mitads) are the most prevalent and energy-intensive appliances used in Ethiopia and encounters bulk amounts of heat loss. However, only few and rarely published research and development were made to improve the thermal efficiency of the system and to quantify the amount of loss accounted. This study aims to make intensive experimental investigation to quantify the amount of heat loss accounted in the system and give the clue for the further research investigation to improve thermal performance of the system. Infrared thermometer was used to measure surface temperature of the bare plate and side and bottom enclosures, while K – type thermocouple was used to measure bottom temperature of clay plate and glass thermometer was used to measure surrounding temperature during Injera baking process. The results of experimental investigation were analytically analyzed and electric Injera baking process was encountered 46.15% heat loss. The value obtained from the analysis lies between the ranges (40 - 50%) of prediction made in previous studies.

Keywords: *Injera; baking pan; heat loss; porous media.*

Nomenclature

A	area (m^2)
T	temperature (°C)
m	mass (kg)
C_p	specific heat capacity (J/Kg.K)
h_c	convective heat transfer coefficient(W/m2K)
$\dot{q}$	Heat loss

Greek symbols

ϕ	Porosity
ρ	density (kg/m^3),
ε	emissivity

1. Introduction

Energy has become virtually important for household human activities like cooking, baking, lighting, and water heating [1, 2]. In Ethiopia, over 90% of energy consumed in household level is for cooking and from this 50-75% of energy is used for baking Injera – traditional pan cake like bread [3, 4]. Injera is the common staple food mostly served by Ethiopians, Eritrean and some parts of East Africans like, Somalia and Sudan [5], it is similar with Indian chapatti but, has small bubbly structures on top and requires temperatures ranging 180 °C – 220 °C for baking [6]. Its Baking demands significant amount of energy and time consuming. Two main types of baking

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stoves traditionally used for baking Injera are; Biomass and electric baking stoves [7]. In Biomass Injera baking stove, firewood is used as primary source of energy for baking [8]. However, use of such baking technologies has drawback like; indoor air pollution, rampart deforestation, low efficiency, gender inequality and high fuel consumption [4, 6]. Therefore, to reduce adverse environmental and health impacts of using biomass baking stove, shifting to electric Injera baking stove is primarily better choice in the urban area of the country [2, 9]. However, each existing electric Injera baking Stove (Mitad) consumes large quantity of electricity nearly about 3.0-3.5 kW for each baking with high-energy wastage encountered in the process [2, 3, 4]. Kemil et al. [4] presented that the average thermal efficiency of electric Injera baking stove is obtained as 50% for the clay plate and 60% for ceramic plate. Ezana et al. [10] analyzed that the efficiency of the better controlled electric Injera baking stove (mogogo) experiment is range from 43% to 55%, in which efficiency is slightly higher for the series of thinner Injera and lower for thickest Injera. He also presented the major factors affecting the energy intensity and efficiency of Injera production.

In almost all research done on electric Injera baking stove the amount of energy dissipated during the baking process, is not quantified and it's roughly predicted to vary from 40 to 50 percent [4, 10]. However, this research is aimed to make assessment of energy loss encountered in the electric injera baking process by making intensive experimental investigation. And, finally, the amount of energy loss quantified by making experimental investigation and analytical calculation during baking process is compared with the predictions made in previous researches.

2. Material and methods

For the evaluation of the loss accounted in the injera baking process, three series of baking experiments were performed by using the widely used existing electric injera baking pans (Mitads) with diameter of 58cm and plate thickness of 2cm. To make experimental investigation well calibrated temperature measuring instruments such as; K-type thermocouple, glass thermometer and infrared thermometer are used and, bottom temperature of clay plate was measured by using K-type thermocouple while, infrared thermometer was used to measure surface temperature of side enclosure, bottom enclosure, clay plate and cover. To obtain the correct reading from infrared thermometer, the emissivity of the material was adjusted to $\varepsilon = 0.11$, 0.95 and 0.98 for cover, side enclosures and baking plate respectively. Surrounding temperature was measured using glass thermometer. Finally, using data obtained from experimental investigation, heat loss from the electric baking stoves were calculated by considering convection and radiation heat loss from side enclosure, bare plate and lifting cover while, heat loss from the bottom insulation was calculated by conduction through saturated porous media that are combinations of stationary sandstone (solid) and air (fluid). Figure 1 (a), (b) and (c) shows experimental setup and Injera texture while, Figure 1(d) shows thermal circuit diagram representing heat loss encountered in the electric Injera baking pans.

3. Analysis of heat loss

In electric injera baking pans heat energy was lost from top, bottom and side directions of clay plate. Indeed, all three mode of heat transfer; conduction, convection and radiation are involved in the transfer of heat from electric Injera baking stove to the environment [11].

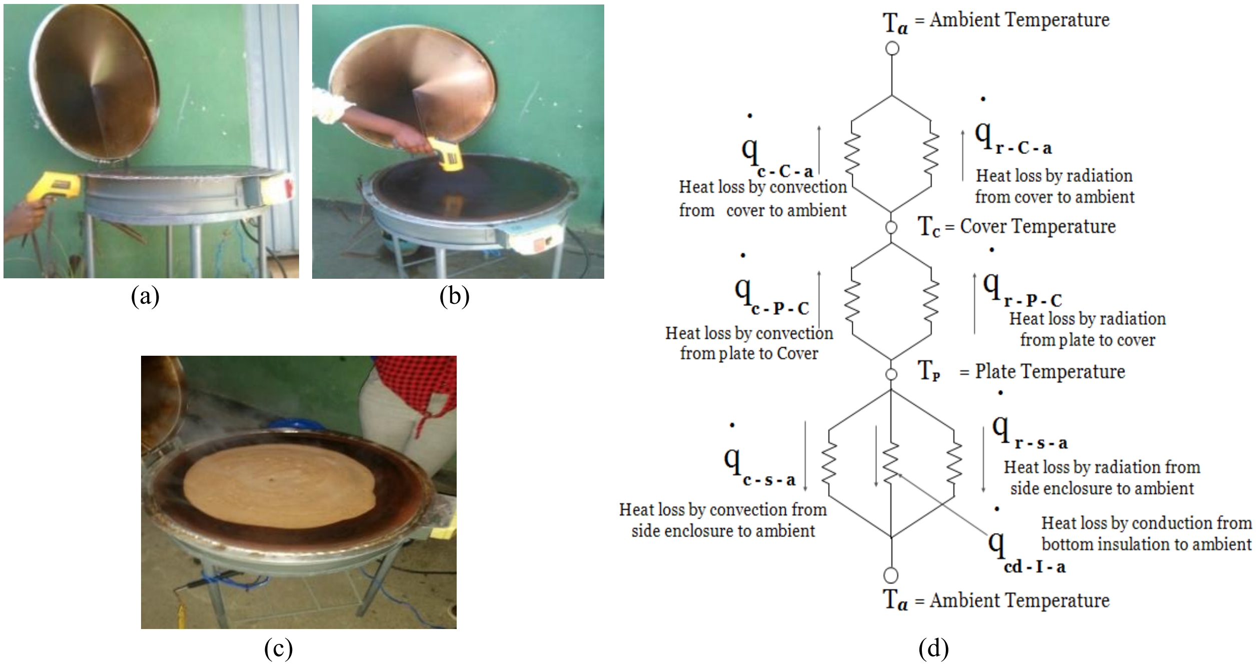

Figure1. (*a*) and (b) Experimental setup, (*c*) Injera texture (d) Thermal circuit diagram and heat loss in conventional Injera baking pan.

3.1 Heat loss from bare plate, cover and side enclosure

Heat energy was lost from the bare plate, cover and side enclosures of electric injera baking mitads through convection and radiation heat transfer modes. Therefore, heat energy lost at each baking of Injera was computed by using eqn. (1).

$$\dot{Q}_{loss} = [h_c A_p (T_{av} - T_\infty) + \varepsilon\sigma A_s (T_{av}{}^4 - T_{sur}{}^4)]180sec \quad (1)$$

where, convective heat transfer coefficient can be calculated by eqn. (2) [12 &13].

$$h_c = \frac{Nu\, K}{L} \quad (2)$$

The recommended correlations for the average Nusselt number over upper surface of hot plate were given by eqn. (3) [12].

$$Nu = 0.54 Ra_L{}^{1/4} \qquad (10^4 \le Ra_L \le 10^7), Pr \ge 0.7 \quad (3)$$

$$Nu = 0.15 Ra_L{}^{1/3} \qquad (10^7 \le Ra_L \le 10^{11}),\ all\ Pr$$

Average Nusselt number for natural convection over the horizontal enclosure (lifting cover) heated from below is determined from correlation proposed by Globe and Dropkin [12].

$$Nu = 0.069 Ra_L{}^{1/3} Pr^{0.074} \qquad for\ 3x10^7 \le Gr_L \mathrm{Pr} \le 7\,x10^{11} \quad (4)$$

Empirical correlations for the average Nusselt number for natural convection over side enclosure were given by eqn. (5) [12, 13].

$$Nu = 0.59 Ra_L{}^{1/4} \qquad (10^4 \le Ra_L \le 10^9) \quad (5)$$

$$Nu = 0.1 Ra_L{}^{1/3} \qquad (10^9 \le Ra_L \le 10^{13})$$

where, (Ra_L) is the Rayleigh number**,** which is the product of the Grashof (Gr_L) and Prandtl (Pr) numbers.

$$Ra_L = Gr_L Pr = \frac{g\beta(T_S - T_\infty){L_C}^3}{v^2} Pr \quad (6)$$

Convective and radiation heat loss from the bare plate, lifting cover and side enclosure were computed by eqn. (1), where surface emissivity (ε) of bare plate, cover (Aluminum) and side enclosure (Gray painted) were 0.98, 0.11 and 0.95, respectively.

3.2 Heat loss from bottom insulation

Thermal insulation commonly used to reduce heat loss at the bottom of electric injera baking mitads are sandstone and gypsum which has high thermal conductivity and increase the amount of heat loss via the bottom of clay plate. Therefore, heat energy was lost from the bottom insulation through saturated porous media, the combinations of stationary sandstone (solid) and air (fluid) [12].

Considering saturated porous medium that was subjected to surface temperatures T_1 at top and T_2 at bottom of insulation, the amount of heat energy lost at each baking of injera, after steady state was expressed [12] by eqn. (7).

$$q_x = \frac{K_{eff}A}{L}(T_1 - T_2)x \text{ 180sec} \quad (7)$$

where: $T_1 = 437K, T_2 = 391.9K$ and K_{eff} is an effective thermal conductivity which varies with the porosity (void fraction) of the medium(ϕ).

Considering only two conduction terms in the model with no convection ($h_1 = h_2 = 0$) maximum effective thermal conductivity can be obtained by eqn. (8) [12, 14].

$$K_{eff} = (\phi)K_f + (1 - \phi)K_s \quad (8)$$

Hence, heat loss from bottom insulation will be determined by using eqn. (7) considering the porosity of sandstone(ϕ) as 0.30.

3.3 Energy utilized for baking

Energy utilized is the amount of energy used for each baking of injera without including the loss accounted during baking process. It is the sum of energy required for raising the temperature of the dough to the boiling point of water, plus the energy required to vaporize the major part of the water in the dough. Therefore, the amount of energy utilized can be obtained from the following equation [11].

$$E_u = m_i C_{pi}(T_b - T_o) + h_{fg}(m_d - m_i) + (m_d - m_i)\ C_{pw}(T_b - T_o) \quad (9)$$

where, m_i is average mass of baked injera [$0.4135kg$], m_d is average mass of dough [$0.4995kg$], T_i is initial temperature of dough [$294K$] and T_b is boiling temperature of water in dough [$366K$].

4. Results and Discussion

In the experimental investigation, temperatures at bottom of clay plate, side enclosure, bare plate, and bottom enclosure were measured at the interval of four minutes during Injera baking process and shown in Figure 2. However, for analytical calculation of loss encountered in the Injera baking process average temperatures at each place was used. The average temperatures of bare plate, lifting cover, bottom enclosure, side enclosure and surrounding temperature were obtained as 477.5K, 356K, 391.9K, 374.5K and 299K respectively.

From experimental investigation it's recorded that cover was kept open for 25% of baking process (45seconds) to remove the Injera baked and pour the dough, from the total 180 seconds needed for Injera to be well baked. Therefore, to calculate total heat loss from cover and bare plate only 25%

of heat loss was considered from bare plate while lifting cover stay open and 75% of heat loss from lifting cover while it stays closed.

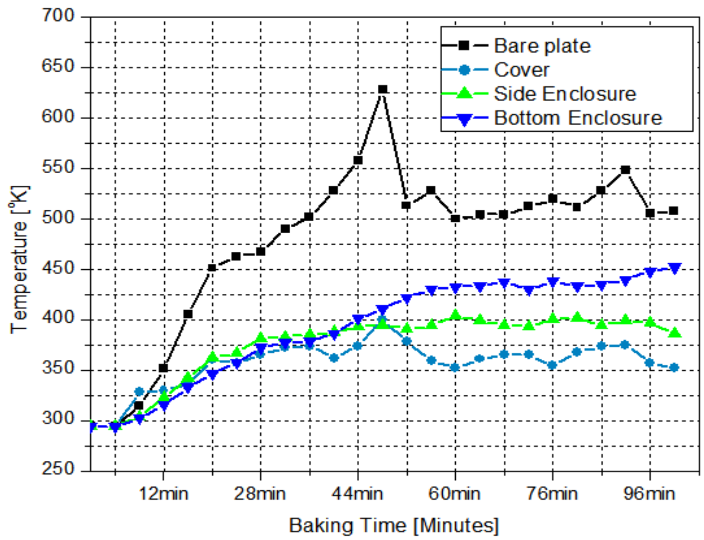

Figure 2. Surface temperatures obtained from experimental result.

From analytical calculation, heat loss encountered in the Injera baking pans (at each baking) from bare plate, cover, side enclosure and bottom insulation were obtained as 47.0KJ, 19.5KJ, 20.4KJ and 203.8KJ, respectively, as shown in Figure 3a.

This result shows total heat energy lost from electric pan (at each baking) was 290.74KJ which accounts 46.15% of heat loss from 630KJ input energy used for each baking. Bottom insulation accounts 70.1% of total heat loss accounted in system, while, bare plate, cover and side enclosure accounts 16.2%, 6.7% and 7.0%, respectively, as shown in Figure 3b. Thus, useful energy, the amount of energy utilized for baking injera (339.26KJ, 53.85%) was obtained by using eqn. (9).

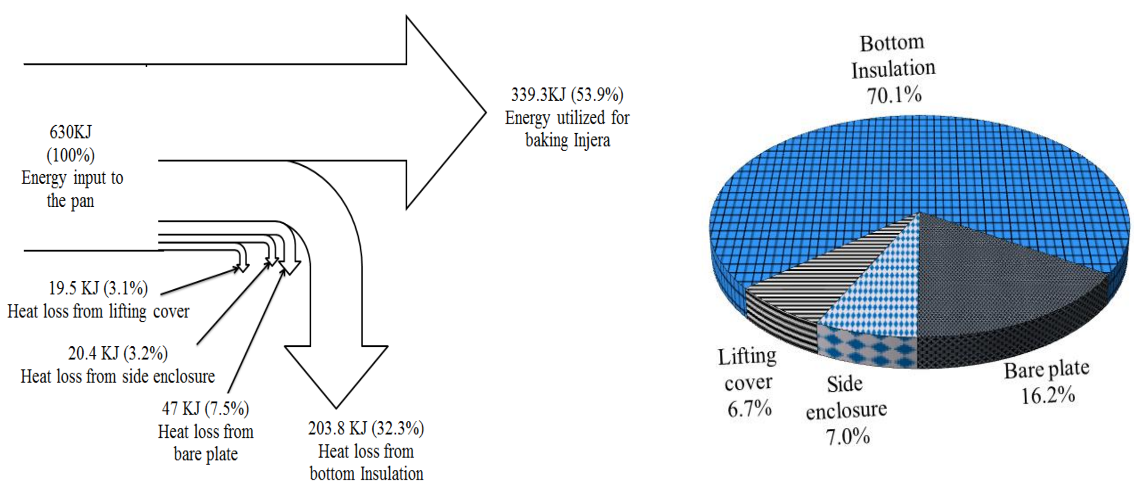

Figure 3. (a) Energy flow (Sankey) diagram of electric injera baking pan, (b) Percentage description of total heat loss accounted in the electric Injera baking Mitads.

5. Conclusions

In this study intensive experimental investigations were made to quantify the loss accounted in the electric Injera baking mitads. The experimental investigations and theoretical analysis shows that electric Injera baking mitads accounts 46.15% heat loss and this value lies between the ranges (40-50%) of predictions made in previous study. From, the total heat loss accounted in the electric mitads it's obtained that 70.1% of heat energy was lost through bottom insulation where, bare plate, cover and side enclosure account 16.2%, 6.7% and 7.0% respectively. Therefore, to reduce the major heat loss accounted in the electric Injera baking mitads further efforts on research and development will be required on selections and property improvement of bottom insulations.

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