American Journal of Management Science and Engineering
2024, Vol. 13, No. 3, pp. 42-51
https://doi.org/10.11648/j.ijepe.20241303.11

Research Article

Comparative Analysis of Different Burner Concepts in a Locally Manufactured Bread-Baking Oven

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Abstract

The supply and control of heat within an oven with minimal loss is an integral process in optimizing the bread-baking process. Research over the years reports on measures to control heat, however, there is limited data on optimizing burner designs for efficient heat supply. Challenged with enhancing the functionality of a bread baking oven made locally, three different burner concepts (i.e., U, H and Rectangular shaped) were designed, fabricated and evaluated in a locally manufactured bread baking oven. The study investigated the three burner configurations to enhance the locally manufactured ovens' environmental sustainability, cost-effectiveness, and efficiency. The study also assessed each burner design concept's performance in relation to heat distribution, fuel consumption, and emissions through thorough experimentation and analysis. Thermocouples were used to determine the temperature differences within the oven and outside the oven walls to verify heat losses. The results showed that the concept burner design can be used to bake bread with good quality parameters like colour, texture and taste within efficient baking time. Computational Fluid Dynamic (CFD) analysis performed on the proposed burner design concepts in relation to heat flow show that continuous flow of heat was assured during baking. Also, simulation performed on the baking trays show an acceptable stress and strain levels as well as favorable factor of safety, indicating that the designs proposed is suitable for the purpose. Data analysis performed on the heat generated within the oven chamber considering the lower and upper trays for all the burners evaluated can be ranked in terms of percentage as RB > HB > UB (41.39% > 30.72% > 27.89%). Based on the study conducted, the authors can suggest the best design concept for heat generation in locally manufactured ovens should be rectangular-shaped.

Keywords

Burner Design Concept, Bread-Baking Oven, Bread, Heat Transfer, Baking

1. Introduction

The bake oven is the most regularly used device in the pastry food service sector [4]. An oven is an enclosed thermally insulated chamber to heat, bake, or dry a product. Baking is a cookery that involves cooking flour-based foods

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Received: 23 April 2024; **Accepted:** 16 May 2024; **Published:** 30 May 2024

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over a long period. Baking is possibly as old as humanity [12]. The Egyptians and Mesopotamians, the first known civilizations, grew wheat [10]. They created the ability and craft of making bread after discovering that wheat kernels could be eaten in a pleasant form by grinding and turning them into flour, and then adding water to generate a paste that could be baked and consumed. Fire and physical labour were essential at the time for the development of early baking techniques. Egyptians were pioneers in baking, according to evidence going back to 2600 B.C. Egyptians were the first to employ yeast in bread baking. In 2014, the world's oldest oven, estimated to be approximately 6500 years old, was unearthed in Croatia [6]. The baking process involves the simultaneous transport of heat and mass. Heat moves from the surrounding air into the inside of the dough or batter. At the same time, moisture and other liquid components evaporatively travel/escape from the core to the outside or surrounding air. Literature shows that baking ovens have been developed and evaluated with efficient performance over the years. The oldest historical record of an oven being constructed dates back to 1490 in Alsace, France [2]. Count Rumford created a functional iron cooking stove for big working kitchens [2]. Stewart's Oberlin iron stove, invented in 1834, was a successful and small cast iron design [2]. The development of gas stoves was delayed until gas connections capable of supplying gas to residences became ubiquitous. Microwave ovens were created as a consequence of another technology. Researchers in recent times have analyzed diverse types of baking ovens. For example, Ploteau [9] and Khatir [16], focused on bread baking whereas Mirade [8] anticipated the air temperature in an industrial biscuit baking oven. Some research studies on the design and fabrication of baking ovens obtained good results for transient reactions [3]. Still, the high processing requirements of the numerical techniques make them unfeasible for processes requiring a large number of simulations. Some previous research publications focused on constructing basic thermal models for ovens, particularly for use in the construction of temperature regulators, such as Edgar [3], where elementary ideas were applied to produce models that represent the temperature dynamics of an oven cavity. While these models were useful, they did not address the entire thermal behaviour of the system because they were just concerned with the cavern temperature. Other research groups focused on the cooking load itself, developing exact models for various combinations of cooking load and heating technique. Abraham [5] projected a heat transfer model to a metallic load, whereas [7] developed models incorporating thermal diffusivity and mass transfer phenomena in cake baking processes. The environmental effects of traditional methods of baking are a growing concern. Consequently, some researchers have focused on improving burner designs in baking ovens. Domestic burners with reduced pollutant emissions are highly appealing because of society's growing concern for environmental protection, particularly for indoor air pollution. As a result, further research on residential gas-fired burners has been conducted to achieve improved thermal efficiency while conserving energy and lowering emissions [14]. Junus [11] investigated the influence of residential burner design parameters on pollutant emissions from natural gas hob burners. These variables include cap shape, cap material, cap mass, cap dimension, hob position, gate height, port spacing, and port shape. As a consequence of their research, they discovered that slit ports, no flame inserts, and no central secondary aeration resulted in decreased emission rates. Another research, [15] investigated the efficiency and emissions of natural gas-powered household burners. They discovered that the load height to flame length ratio and thermal input had an impact on the thermal efficiency and emissions produced by the burner. In similar research, Suvit [13] investigated the NOx and CO emissions from household cooktop burners powered by natural gas at various load heights and thermal inputs. The literature presented shows that there has been advancement in the design and fabrication of baking ovens and burners. However, there is still limited or no data on the effects of different burner design concepts and their effects on baking to optimize the baking process of bread. The study of baking ovens and burner design is essential because it has the potential to optimize and provide an efficient baking process for energy efficiency and product quality. Therefore, this research seeks to (1) develop a locally manufactured baking oven, (2) perform a comparative analysis on three different burner design concepts (Rectangular, H-shaped, U-shaped) to verify its effects in terms of performance, heat generation etc., (3) predict an efficient burner design for locally manufactured baking ovens.

2. Materials and Methods

2.1. Design and Construction of the Baking Oven and Experimental Burners

The baking oven was designed and modelled using computer-aided design software known as Solid Works with dimensions and details forming the basis for the experimental oven construction. Figure 1 shows three-dimensional (3D) views from the model.

Figure 1. *Oven front view.*

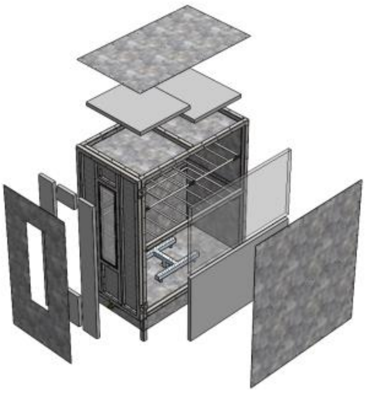

Figure 2. Exploded view.

The locally produced baking oven was built according to the standard design concept of an oven using a galvanized steel plate. The oven is made up of a housing unit, thermocouple ports, a gas nozzle outlet, and a heating gas burner. The housing unit forms the overall structural component of the oven and to enhance efficient heat conservation, the housing unit was made of three different layers: exterior galvanized steel plate of thickness 1. 2 mm with dimensions 450 x 380 x 350(length, width, height) mm respectively. The inner skeletalstructure comprises a rectangular galvanized tube with dimensions 1045 x 480 x 650 mm (height x breadth x Length) respectively and the middle layer of the oven is made of a thermally insulating material (fiberglass) that covers all four sides of the oven which serves as an insulator. As shown in Figure 1, the oven was fitted with two sets of baking racks: the lower tray is made of 10 mm round steel bars rectangularly made to fit in the oven and to hold small baking pans. The oven works using convection with the free flow of hot air from the burners to the upper rack. The lower rack is also made with the same dimensions and details as the upper tray. The spacing between the upper tray and the top of the oven was maintained at 280 mm. An even spacing of 280 mm was kept between the top and bottom trays.

Figure 3. Oven front view.

Figure 4. Oven insulation.

Figure 5. Fabricated oven iso-view.

Three different burner design concepts were considered to evaluate the baking oven burner design, namely U, H and rectangular-shaped burner, as illustrated in Figure 6 through 8. The fabrication of the burners was through the process of measuring, cutting, and welding. A hacksaw blade of 0.63 mm thickness was used to make incisional cuts on the burners for the flow of gas into flames. The three burner design concepts considered are presented below.

Figure 6. U-shaped burner.

Figure 7. *H-shaped burenr.*

Figure 8. *Rectangular burner.*

2.2. Computational Fluid Dynamics (CFD) Analysis of Baking Oven and Burners

Stress analysis, strain analysis, and factor of safety study on the bread tray were performed in the numerical analysis of the planned and constructed bake oven to validate its appropriateness for the design. The basic ideas of heat transfer can be used to develop the equations that control the flow of heat in a bake oven. To simulate temperature distributions inside the oven, these equations are usually numerically solved in the framework of Computational Fluid Dynamics (CFD). The heat conduction equation, which is the fundamental formula for heat conduction, can be written as follows for a transient process:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla * (k \nabla T) + Q \tag{1}$$

Where ρ is the density of the oven material, c_p is the specific heat at constant pressure, T is the temperature, t is the time, k is the thermal conductivity, ∇ is the del operator and Q represents any heat generation or absorption. Steady-state characteristics are often taken into consideration for a baking oven. The time derivative term on the left side of the equation becomes zero in this situation.

$$\nabla * (k \nabla T) + Q = 0 \tag{2}$$

The way heat is transferred between the various components of the oven is explained by this equation. Heat sources and sinks in the domain, such as food items that absorb heat or heating elements, are accounted for by Q. Due to fluid motion in the oven, the heat conduction equation is used in conjunction with the fluid flow equations (Navier-Stokes equations) and the convective heat transfer term as a result of significant airflow. The combined equation is expressed in equation 3, where U is the fluid velocity.

$$\rho c_p u * \nabla T = \nabla * (k \nabla T) + Q \tag{3}$$

2.3. Oven Capacity Estimation

The oven capacity is estimated by considering specific parameters such as (1) the area of the baking pan, (2) the spacing between the various oven racks and (3) the height of the oven. It is mostly estimated to determine the quantity of bread the oven can accommodate within a baking period. The number of bread loaves and the size of the baking pan (both the bread and the pan) are related to the oven's capacity. The total volume (V_T) of the oven is the sum of the bottom rack volume (V_1) + upper rack volume (V_2). The capacity of the locally manufactured oven is estimated as below:

$$A_c = B * L \tag{4}$$

Where, Ac = Area of a single spacing between oven racks.

$$A_c = 480 * 650 = 0.312 \text{ m}^2 \tag{5}$$

Where B, L and H represent breadth, length and height respectively.

$$V_1 = (B * L * H) \tag{6}$$

$$V_1 = (280 * 480 * 650 = 0.087 \text{ m}^3 \tag{7}$$

Since the racks are equally spaced,

$$V_T = 2 * 0.087 = 0.174 \text{ m}^3 \tag{8}$$

To determine the quantity of bread that the oven can accommodate, specific parameters were considered. These parameters are (a) the size of the baking pan, (b) spacing within the oven trays and (c) the number of oven trays present. The total volume (V_T) of an oven is the sum of the bottom rack volume (V_1) and upper rack volume (V_2). Estimated volume of a single bread baking pan (Vbp).

$$V_{bp} = 0.12 * 0.13 * 0.28 = 0.0044 \text{ m}^3 \tag{9}$$

Hence, given the specific pan size, the oven capacity = VT/

Vbp =0.174/0.004368 = 40 breads for the study. In baking ovens heat generation is a very important process, therefore the amount of heat within the burners was determined. The internal and external heat flows were determined using a REX-C700-FK07-M-AN temperature sensor and OM-HL-EH-TC thermocouple respectively. The total energy generated by the gas burner was calculated using the formula below [1]):

$$E_T = E_b + E_r + E_c \quad (10)$$

Where ET = the amount of heat generated by the gas burner; E_b = the amount of heat gained by the baked bread, E_r = the amount of heat radiated to the heating chamber; E_c = the amount of heat conducted through oven walls.

$$E_b = m_b * h_c * \Delta(T_1 - T_2) \quad (11)$$

$$E_b = 0.44 * 2890 * (453.95 - 409.15) \quad (12)$$

$$E_b = 56.97 \text{ KJ} \quad (13)$$

Where, m_b = mass of bread dough; h_c = specific heat capacity of the bread dough = 2890 J/kg/K); ΔT = Change in temperature. Both the heat transfer inside the oven and the heat loss (heat transfer from the inside of the oven to the outside) were determined using the thermocouple and temperature sensor to measure the temperature inside and outside the oven during the experiment. The equation below was used to estimate the energy radiated.

$$E_r = \varepsilon * \delta * A_c * (T_1^4 - T_2^4) \quad (14)$$

Where Er = the amount of heat radiated to the heating chamber per sec (KJ), δ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4); T_1= Initial absolute temperature in kelvin, T_2 = final absolute temperature in Kelvin, ε = emissivity (i.e., assume ε =1 for a perfect emissive surface).

$$E_r = 1.0 * 5.67 \times 10^{-8} * 0.312 * ((453.95)^4 - (409.15)^4) \quad (15)$$

The thermal conductivity of the baking chambers was calculated using the equation below [1].

$$E_r = 255.47 \text{ J/Sec} \quad (16)$$

For five (5) minutes heating Er = 76.64 KJ. The thermal conductivity of the baking chamber is given as,

$$E_c = C * A_c * (T_1 - T_2) / Length \quad (17)$$

where C = conductivity of steel (54 W/mK), Ac = Area of the baking chamber.

$$E_c = \frac{[54 * 0.312 * (453.95 - 409.15)}{0.65} \quad (18)$$

E_c = 348.4 KJ, for five (5) minutes heating duration.

2.4. Experimental Setup

In the process of evaluating the locally manufactured oven, three burner concepts were applied (U, H and Rectangular). The U-type burner was first fixed into the oven and lighted to determine the heat flow parameters in a baking setup. The pre-heat temperature within the oven was first recorded within five minutes before starting the actual baking to verify the heat flow from the burner. Data was recorded from four different points around the baking oven (P1- P4) within a time interval of 20 minutes. The internal and external heat flows were also recorded using a thermocouple (REX-C700-FK07-M-AN, OM-HL-EH-TC Thermocouple). The data was recorded twice to reduce the measurement error. The process was repeated for the H-type and rectangular-type burners. To verify the effect of the burner concept on baking, flour dough was prepared and baked within the oven for the different burner concepts. In the experiment the weight of the dough was taken before and after baking to determine the moisture loss as a result of heating.

Figure 9. *Pan weighing.*

Figure 10. *Data collection.*

To obtain an error-free data collection two different thermocouples were used to record the temperature both external (outer surface of the oven), semi-internal (4mm hole drilled within the insulation material) and internal section of the oven (4mm hole drilled to enter directly within the oven). The first thermocouple was used to record the temperature inside the oven through a blind hole of a diameter 4 mm. The recordings were taken at the top, back, right side and left side (P1 – P4). Similarly, the second thermocouple was used to record the temperature outside the oven. The recordings were done for 5 minutes at an interval of every 20 minutes for four (4) successive times and the average data was taken to reduce error. The flour dough for the experiment to evaluate the concept burners and the locally manufactured oven as a whole was prepared using the following ingredients, half a cup of white sugar, 1 spoon of salt, 1 teaspoon of yeast, 5 kg of flour, 1 litre of water, 1 litre of milk and 1 tablespoon of flavour. After being combined into a dough, the chosen components for bread production were put on baking pans to begin baking. When the oven reached a temperature that was confirmed to be suitable for baking, the processed dough was put inside. For the duration of baking, until the dough turned golden brown, the temperatures at the exterior and interior regions of the baking oven were noted. The experimental data was collected using a REX-C700-FK07-M-ANTemperature sensor, OM-HL-EH-TC Thermocouple, and 7 kg digital electronic weighing scale. The weighing scale was used to measure the weight of the dough before and after baking.

3. Results and Discussion

3.1. Computational Fluid Analysis

A computational fluid dynamics simulation was also performed on the tray to confirm the heat movement through the baking rack. This study assumes that heat transfer in a baking oven is accomplished by natural convection. Heat travels from the base of the oven via the mesh trays to various regions of the oven in a natural convection mechanism to provide a balanced supply of heat.

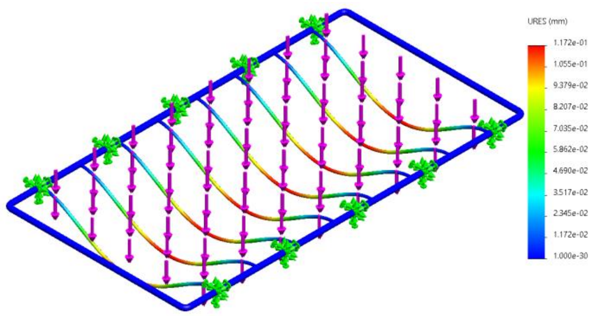

Figure 11. *Tray displacement plot.*

The stress analysis, strain analysis, factor of safety, and computational fluid dynamics research done reveal that the design is suitable for the purpose. Additionally, the rack design allows for simple heat movement through the oven. Figures 11 through 14 shows selected colour contour images from the simulation.

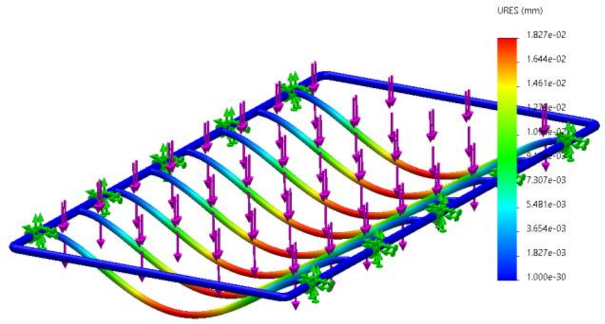

Figure 12. *Tray displacement plot.*

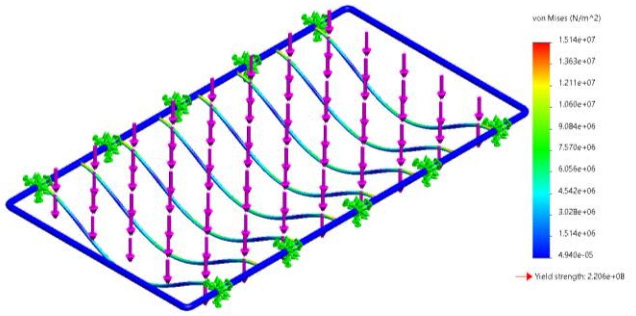

Figure 13. *Tray stress plot.*

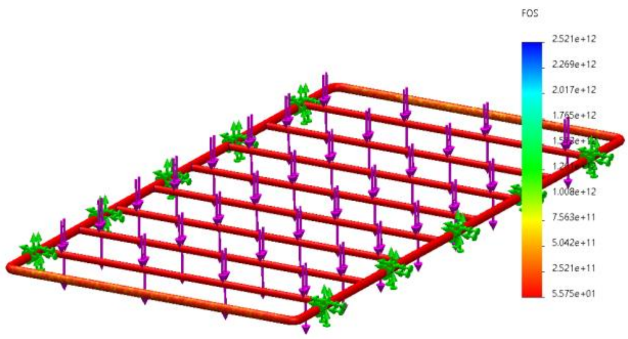

Figure 14. *Tray factor of safety.*

The heat flow sequence under computational fluid dynamics is presented below. The contour plots show an even distribution of heat within the oven during baking.

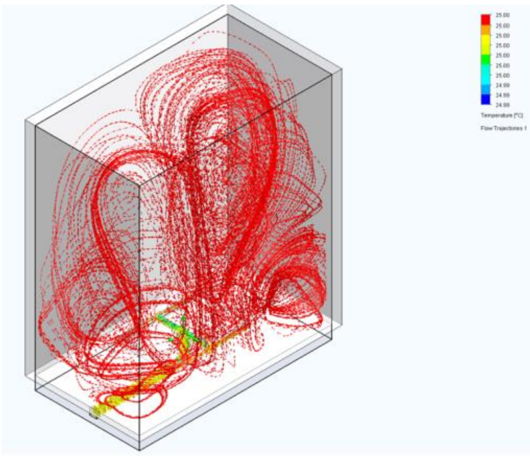

Figure 15. Rectangular burner heat flow trajectory.

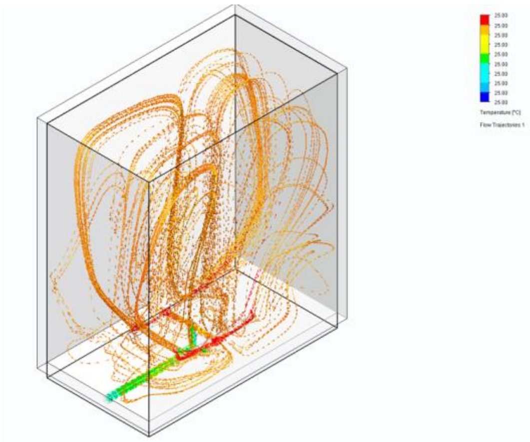

Figure 16. H-shaped burner heat flow Trajectory.

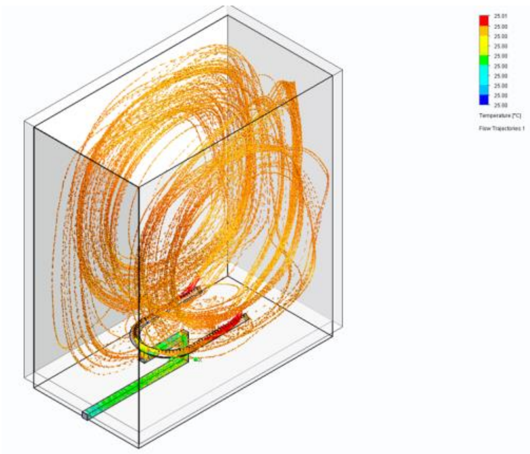

Figure 17. U-shaped burner heat flow trajectory.

3.2. Correlation Between Different Burner Designs and Heat Generation in the Oven

For each of the burner concepts, the internal heat distribution within the oven was recorded and plotted, as presented in Figure. 18. From the results, in terms of ranking the heat generation of the concept burners, it was noted that, RB > UB >HB. It's also important to note that the hob with the rectangular shape had a consistent rise in temperature. Throughout the recorded period, the temperature of the H-shaped burner changed less noticeably and stayed nearly constant. Similarly, as the plot Figure 18 illustrates, the temperature measured for the U-shaped burner was lower at first and eventually rose above the H-burner.

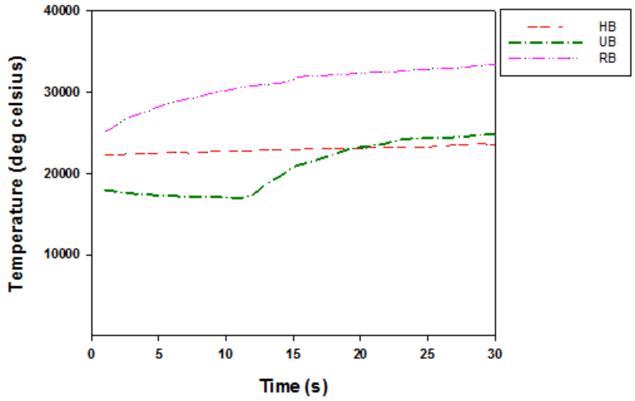

Figure 18. Burner types temperature generation plots.

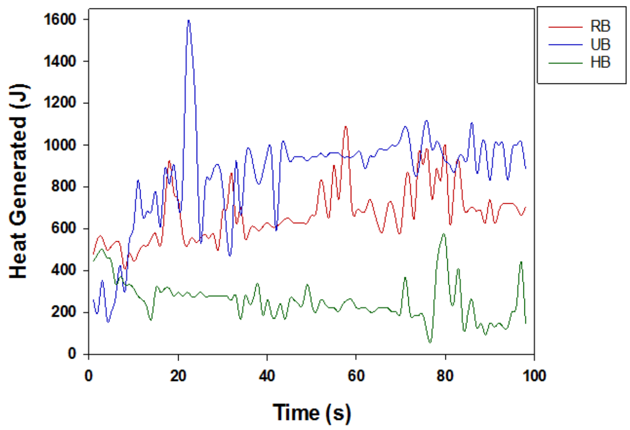

Figure 19. Heat generated between upper and lower trays.

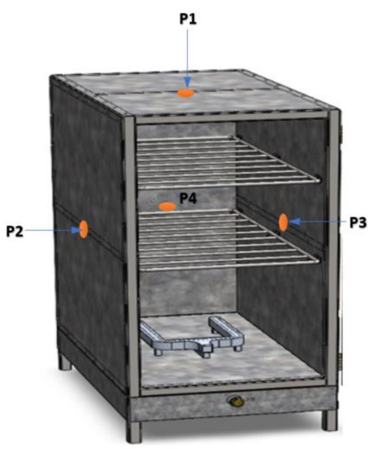

Figure 20. Temperature recording ports (P1-P4).

3.3. Effects of Tray Position (Upper and Lower) on Heat Generation Considering Ports 4 and 1

The amount of heat dissipated through the trays of the oven was monitored and recorded at port 4 and port 1 for the different burner designs. The least amount of heat was lost during the evaluation of the H-shaped burner, but the most heat was lost with the U-shaped burner, as shown in Figure 19. This demonstrates that although the hob with the rectangular form produced the most heat during the baking time, making it most efficient hob in terms of heat generation, the hob with the H shape produced the least heat loss, making it the most efficient hob in terms of heat generation. The quantity of heat generated, and the amount of heat lost to the environment are correlated in this way.

3.4. Effects of the Temperature Difference Across the Boundaries of the Oven (H-burner, U-burner and RB-burner)

The difference in temperature between the outer surface and within the insulating material was monitored at all four locations (i.e., P1 - P4) for all three types of burner designs used in the experiment. Analysis of the recorded data shows differences in temperature signifying heat differences between the insulation material and the outer surface of the oven.

Table 1. Average Temperature across oven boundaries.

Burner type	Temperature ℃				Difference Temp ℃	
	T_1-T_4		T_1-T_4		D_1	D_2
H	45	55	70	80	10	10
U	47	67	63	83	20	20
RB	35	60	56	66	25	10

Average temperature differences across the oven boundaries for all the burners are summarized in Table 1 and graphical plots presented in Figures 21 through 26, respectively.

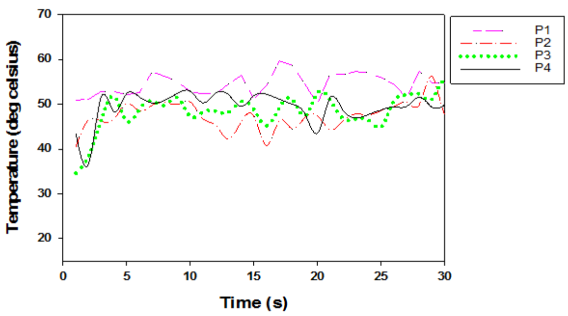

Figure 21. Heat loss at the outer surface of the oven using H-burner.

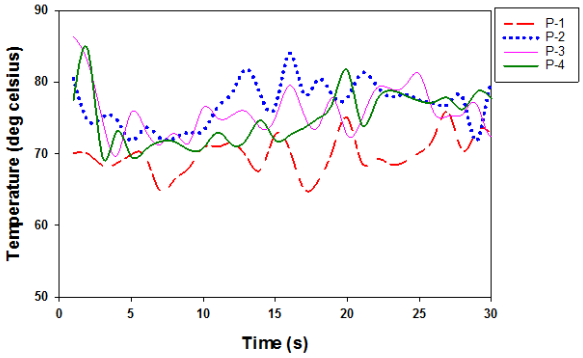

Figure 22. Heat loss through specific points on the insulation material using H-burner.

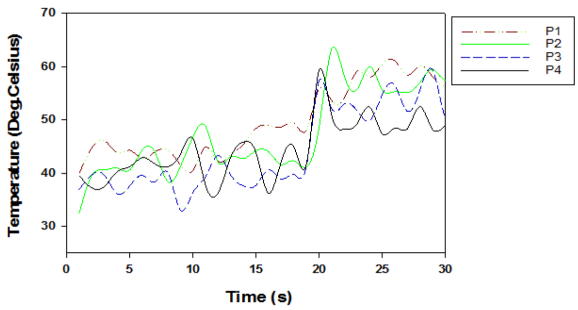

Figure 23. Heat loss at the outer surface of the oven using a U-burner.

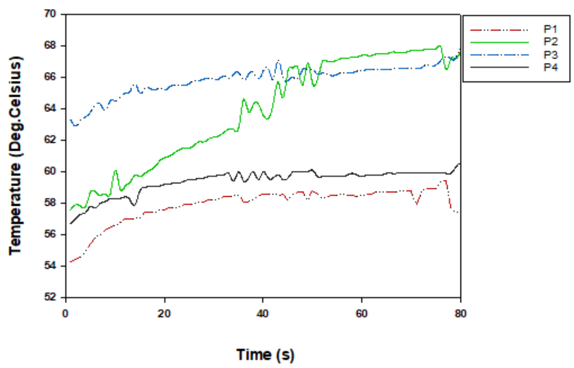

Figure 24. Heat loss through specific points on the insulation material using a U-burner.

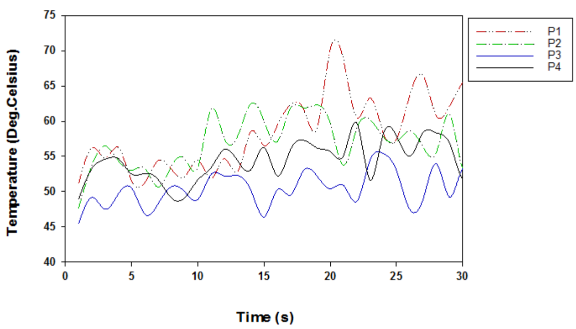

Figure 25. Heat loss through specific points on the insulation material using a RB – burner.

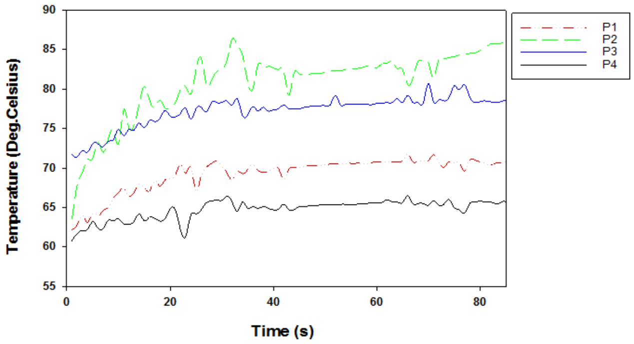

Figure 26. *Heat loss through specific points on the insulation material using RB-burner.*

The heat distribution pattern within the oven was also evaluated by assessing the amount of heat dissipation at all four port locations. For the H-shaped burner, a significant amount of heat loss was recorded on the sides of the oven (i.e., port 2 and port 3), while the back side (port 4) produced the least amount of heat loss. Figure24 presents the heat loss for the rectangular-shaped burner, a steady increase in temperature loss was noted at each of the four ports, with Ports 2 and 3 showing slightly higher temperatures. Port 1 records the least amount of heat loss. A similar pattern was observed for the U-shaped burner, however, port 4 (i.e., the back side of the oven), recorded the least amount of heat lost. Hence, it is apparent that the amount of heat loss was lesser at the top of the oven (port 1) as a result of the flour dough absorbing the generated heat from the burners through the trays.

3.5. Statistical Analysis of the Performance of the Burners (H and RB)

To statistically verify the significance of using the ports (P1 - P4) to determine the temperature difference at the outer section of the baking oven, multiple comparison procedure (Tukey Test) was applied to isolate the groups or groups that differ from the others.

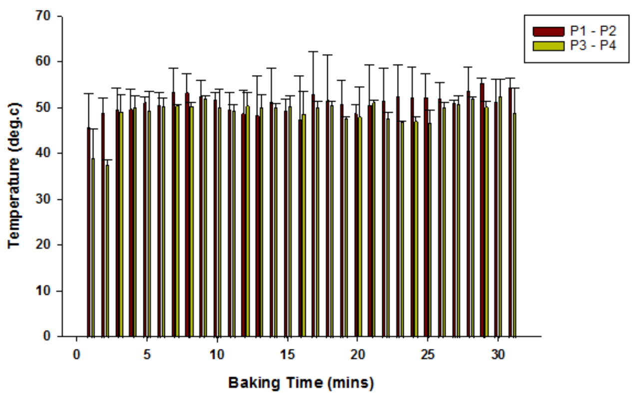

Figure 27. *Rectangular burner ANOVA error plot.*

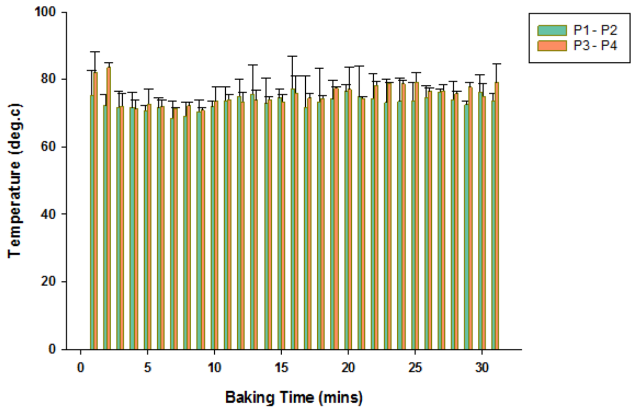

Figure 28. *H-shaped burner ANOVA error plot.*

The results of the grouped error bars are presented in Figure 12 and the corresponding P values are also presented in Table 2 (a and b) respectively. The differences in the median values among the treatment groups are greater than expected by chance; therefore, the data has a statistically significant difference of (P = < 0.001) as shown below. Analysis of the data shows that the application of the various burner concepts improves heat generation. Based on the data analysis the total heat generated within the oven chamber considering the lower and upper trays for all the burners evaluated can be ranked in terms of percentage as RB > HB > UB (41.39% > 30.72% > 27.89%).

Table 2. *P Values Rectangular Burner*

Comparison	P	P<0.05
$P_1 V_s P_2$	<0.001	Yes
$P_1 V_s P_3$	<0.001	Yes
$P_1 V_s P_4$	<0.001	Yes
$P_4 V_s P_2$	0.043	Yes
$P_4 V_s P_3$	0.473	No
$P_3 V_s P_2$	0.639	No

Table 3. *P Values H-Shaped Burner.*

Comparison	P	P<0.05
$P_2 V_s P_1$	<0.001	Yes
$P_2 V_s P_4$	0.141	No
$P_2 V_s P_3$	0.784	No significant difference
$P_3 V_s P_1$	<0.001	Yes
$P_3 V_s P_4$	0.626	No significant difference
$P_4 V_s P_1$	<0.001	Yes

4. Conclusion

In this study, three burner design concepts were developed and experimentally evaluated on a locally manufactured oven. The results showed that the concept burners can be used to bake bread with good quality parameters like colour, texture and taste within efficient baking time. The methodology applied in evaluating the oven and the burners has a statistically significant difference of (P = <0.001). The experimental evaluation shows that bread placed within the lower trays cooks faster than that on the upper trays. Based on thedata analysis the total heat generated within the oven chamber considering the lower and upper trays for all the burners evaluated can be ranked in terms of percentage as RB > HB > UB (41.39% > 30.72% > 27.89%) respectively. The study has shown that the rectangular burner design concept has the potential to generate a high amount of heat within the oven chamber which can lead to a reduction in baking time and improve baking efficiency.

Abbreviations

3D	Three-Dimensional
ANOVA	Analysis of Variance
CFD	Computational Fluid Dynamic
HB	H-shaped Burner
RB	Rectangular Burner
UB	U-shaped Burner

Acknowledgments

The authors wish to acknowledge that this research work was self-founded from their individual research funds.

Author Contributions

Samuel Darko Kofi: Conceptualization, Writing – original draft
Offeh Gyimah Kwabena: Supervision
Bismark Addai: Resources
Michael Anto: Resources

Conflicts of Interest

The authors declare no conflicts of interest.

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