Effect of Convection Mode on Radiation Heat Transfer Distribution in Domestic Baking Oven

Nur Hanim Hassan, Ruzitah Mohd Salleh, and Ummi Kalthum Ibrahim

***Abstract*—The aim of this study is to analyze on the effect of radiation heat transfer inside an oven under natural and forced convection modes using network representative method. This analysis is important to understand the fundamental principle of heat transfer occur in an oven. Most previous work focused on conduction and convection process in an oven instead of radiation which leads to this research. The experiment was conducted using the baking oven with temperature ranges from 180 ℃, 200 ℃ and 220 ℃. The oven was pre-heated 10 minutes prior taking the temperature reading for duration of maximum 20 minutes. The data collected were recorded in the data logger. Based on these data, analysis on the radiation exchanges that occurred inside the oven chamber were performed by the network representative method. The radiation rates of all surface involved were successfully determined. With the calculated radiation rate, analysis on the effects of radiation under natural convection and forced convection modes were performed. Based on the temperature profiles and radiation rate patterns, it was proven that the forced convection mode has more radiation effect compared to natural convection mode.**

***Index Terms*—Baking, forced convection, oven, radiation heat transfer**

I. Introduction

The basis of this study applies the heat transfer process. Heat transfer can be categorized into three main processes which are the conduction, convection and radiation of heat. It explains the energy transfer between surfaces and with different type of medium involved during the heating process [1], [2]. The analysis of heat transfer is important due to it applications within the daily usage and including the large scale implementations. This study focused on the radiation analysis to show the effect under the natural and forced convection in enclosure using network representative method. The radiation analysis is complicated than the conduction and convection process because the radiation behaviour depend on the radiative properties of materials [3], [4], [5]. Principle of this study can also be applied to any equipment that has radiation effects by increase the efficiency of the equipment.

In the natural convection process, the heat transfers from the oven heating element inside the oven to the surrounding chamber without using any external forces [6]. While for the forced convection process, the heat transferred from the oven heating element is applied with forced air (external forces) within the oven chamber [7], [8]. The forced convection process can be achieved by installing fan inside the oven chamber. The radiation analysis of heat transfer starting from the oven heating element to the surrounding chamber was analyzed in details by using the network representative method. This method based on the electrical network that shows the surface radiation exchange inside the oven chamber. Based from the radiation analysis under natural convection and forced convection process, this could help to improve a better implementation of heat transfer studies in designing an oven.

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II. Methodology

A. Temperature Range Selection

There are several temperature ranges that can be selected in determining the effects of radiation heat transfer inside enclosure depending on the suitability of the processes involved. In this research, the temperature are based on normal bread baking temperatures which were 180 ℃, 200 ℃ and 220 ℃. These values were selected based on the compatibility of the type of oven used in this project.

B. Time Intervals Selection

The total time required in this project is 30 minutes which includes 10 minutes for pre-heating the oven, followed by time requires for data collection (20 minutes). The time interval for recording the temperature is 2 minutes.

C. Thermocouple Placement

In order to obtain reliable temperature readings, the thermocouples were placed accordingly to each surface inside the oven. For both natural convection and forced convection mode, the thermocouples were placed at the same position. The data logger was placed firmly in the middle of the oven.

Following figure (Fig. 1) shows the real positions of thermocouples placed for all six surfaces involved.

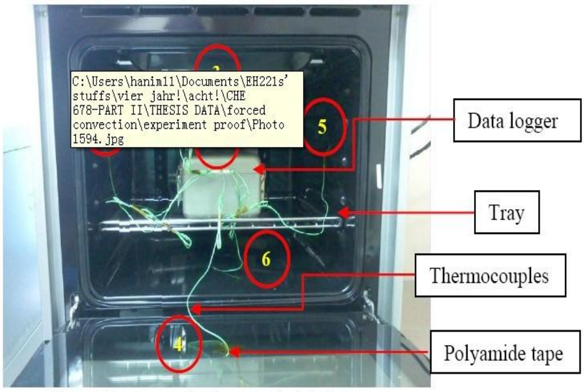

Fig. 1. Thermocouple placement inside the oven. 1-left, 2-back, 3-top, 4-front, 5-right, 6-bottom

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III. Result and Discussion

A. View Factor Calculation

The calculation of view factors applies three methods which were the aligned parallel rectangle, perpendicular rectangles with common edges and reciprocity rules [9]. The value of all view factors were shown in Table I.

TABLE I: VIEW FACTOR VALUES.

F_{ij}	1	2	3	4	5	6
1	0	0.1819	0.1774	0.1819	0.1774	0.1594
2	0.1819	0	0.1774	0.1633	0.1774	0.1777
3	0.2384	0.2384	0	0.2383	0.249	0.2384
4	0.1862	0.1672	0.1816	0	0.2383	0.1819
5	0.2384	0.2384	0.2490	0.3128	0	0.1774
6	0.1594	0.1777	0.1774	0.1819	0.1320	0

B. Radiosity Determination

The value of emissivity, ε for black surface was taken as 0.98 while ε for glass was taken as 0.93 [2]. The inverse matrix method was applied in determining all radiosity values of six surfaces. Sample of calculations for the values of J_1 – J_6 determination were shown at the temperature of 180 ℃ natural convection with $E_{b1} – E_{b6}$ values substitution at minute of 20.

The inverse matrix form;

$$\begin{pmatrix} 1 & -0.00358 & -0.00477 & -0.00372 & -0.00477 & -0.00313 \\ -0 & 1 & -0.00477 & -0.00328 & -0.00477 & -0.00358 \\ -0 & -0.00355 & 1 & -0.00366 & -0.00499 & -0.00355 \\ -0.01 & -0.011 & -0.017 & 1 & -0.022 & 0.013 \\ -0 & -0.00355 & -0.00499 & -0.00476 & 1 & -0.00266 \\ -0 & -0.0036 & -0.00477 & -0.0036 & -0.0036 & 1 \end{pmatrix} \begin{pmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \end{pmatrix} = \begin{pmatrix} 1860.3 \\ 2076.1 \\ 3722.1 \\ 803.97 \\ 1088.3 \\ 1873.3 \end{pmatrix}$$

Inverse values obtained from Excel spreadsheet;

$$\begin{pmatrix} 1.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 1.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 1.00 & 0.00 & 0.01 & 0.00 \\ 0.01 & 0.01 & 0.02 & 1.00 & 0.02 & -0.01 \\ 0.00 & 0.00 & 0.01 & 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 \end{pmatrix}$$

C. Radiation Analysis

Radiation analysis was performed using network representation method [10], [11], [12]. The radiation network was constructed by first identifying nodes associated with the radiosities of each surface. Within the six enclosure surfaces for the oven, there are six points that could be constructed in producing the network representation that indicates the radiation occurred between all six surfaces. The six nodes for all surfaces from surface 1 to surface 6 are shown in Fig. 2.

There are several steps required in determining the radiation rate values which include the requirements view factor for each surfaces, radiosity values and the radiation rate values. Assumptions made for calculation were; the surface is having grey surface, isothermal surface of enclosure, conduction effect is negligible and no heat loss from the oven [13], [14].

D. Radiation Rate Profile

After obtain all values of radiation rate, graphs of radiation rates versus time were plotted for both natural convection and forced convection modes to indicate the radiation rate profiles for temperature of 180 ℃, 200 ℃ and 220 ℃. As presented in Fig. 3, Fig. 4 and Fig. 5, the results show that the highest temperature reading was recorded at the top surface. This is due to the position of the heating coil located at the top surface inside the oven. All surfaces except the bottom and front surfaces experience fluctuating in temperature as indicated in the graph. It was clearly seen that there were four complete heating and cooling process that occurred on the surfaces. For top surface, the heating process took approximately for 4 minutes and about 9 minutes for the cooling before starting to heat up again. The cooling process took longer time to maintain the temperature of the oven by natural convection process.

As for the bottom and front surfaces, the temperature was lower and relatively stable compare to other surfaces, especially after 20 minutes of heating process. The lower temperature reading of the front surface was mainly contributed by the type of material used for the front surface which is it was made of thick glass. This was totally different compared to other four surfaces which were black surface metals that obviously having greater heat absorption and transmission abilities.

While for the left, right and back surfaces, the temperature pattern was almost similar to each other. The temperature profiles produced by these three surfaces may influence by the same origin of the material used and all of the surfaces were painted in black colour, where black surfaces properties that able to absorb and transmit heat efficiently. The bottom surfaces was also painted in black colour but due to the position of bottom plate is opposite of the heating coil located at the top surface; the heat took longer time to reach the bottom surface and this cause the temperature patterns to be lower as like the front surface.

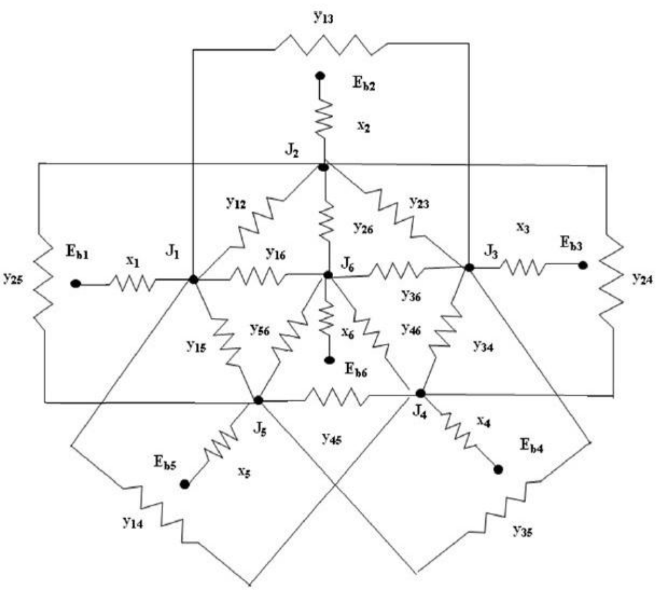

Fig. 2. Network representation approach

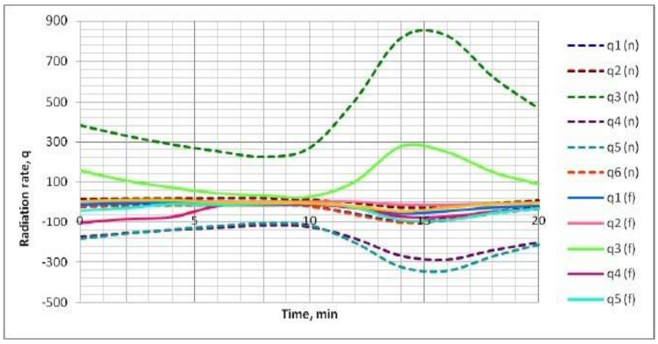

Fig. 3. Radiation rate profile at 180 ℃ (n-natural convection, f-forced convection)

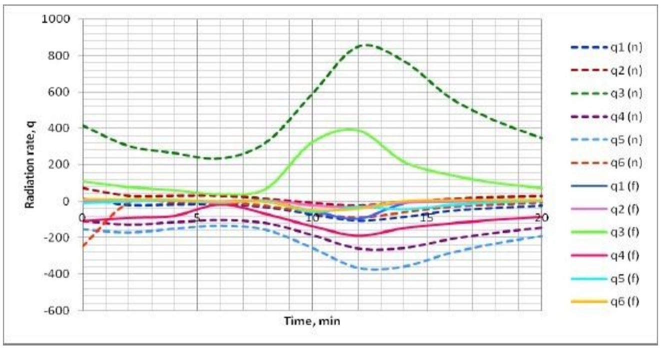

Fig. 4. Radiation rate profile at 200 ℃ (n-natural convection, f-forced convection)

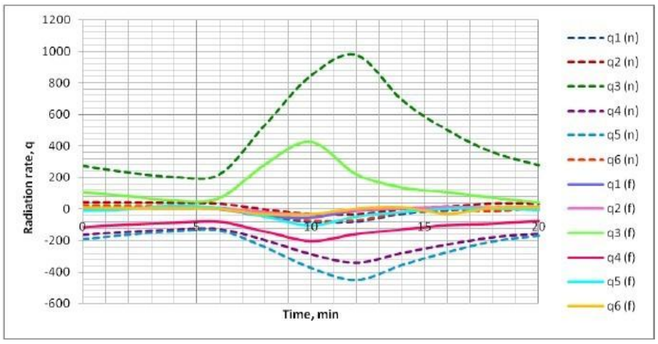

Fig. 5. Radiation rate profile at 220 ℃ (n-natural convection, f-forced convection)

IV. Conclusion

The results demonstrated that the temperature profile of the oven walls fluctuated indicating there was a heating and cooling process for all convection modes. The electrical network can be used to calculate the radiation rate for all enclosed surface of the oven. Furthermore, the network also allows identification possible paths for radiation process to take place. This indicates the potential direction of heat flow from the heat source by illustrating whether the modes of surfaces are emitting or absorbing the heat. The forced convection mode has higher calculated radiation rate compared with the natural convection mode.

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