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Radiation Heat Transfer Analysis in High Emissivity Baking Oven Using Network Representation Method

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Abstract

In an oven, the hot air flows by natural or forced convection while heat is distributed from the heating element by radiation. During baking process, heat is also transfer by conduction from the baking metal container to the baked product. High emissivity oven have an emissivity above 0.5 that enhance the thermal radiation exchange. Radiation is considered as the main process of heat transfer occurred in the oven. Use of network representation method provides a useful tool for visualizing radiation exchange. However, not many papers have been published in using this technique. This paper presents the application of network representation technique to analyze radiation heat transfer. The network is built based on identifying nodes associated with radiosities of each surfaces in the oven.

Keywords: radiation heat transfer, baking oven, network representation method

1. Introduction

In baking oven, typically there is a heating element, a heat transfer medium such as a pan or tray and the food itself. The heat moves from the heating element through the medium to the food. Temperature and heat are often used interchangeably, but they are not the same thing. Temperature is the driving force for heat transfer. Like gravity moves masses, temperature moves heat. Heat moves from high temperature to the lower temperature. In other words, a temperature difference causes the heat to move. Heat transfer plays a

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significant role during baking process. It consists of conduction, convection and radiation modes. Thermal radiation is considered one of the main processes of heat transfer occurred in the oven during baking process. According to Zheleva and Kambourva [1], the top surface of the product in the oven is heated mainly by radiation and only little part of the heat is transferred by convection which is less than 10%. To analyze the individual mode of heat transfer during baking process is very complicated. Several studies have used heat flux meters or h-monitors to measure the heat flux inside the oven [2], [3]. But, the disadvantage of using this tool is that it could not measure the individual mode of heat transfer. Network representation method seems to be useful to analyze radiation in an enclosure such as oven and furnace. It was first introduced by Oppenheim [4] in year 1956. A few study has been accomplished using this technique in this field of research [5], [6], however not many papers have been published on the radiation heat transfer especially for oven analysis. The objective of this paper is to apply the network method in the baking oven to calculate the net radiation heat transfer. The network is developed from radiation properties including view factors, reflectivites, emissivities and radiosities.

Nomenclature

q_i	radiation rate at surface i
A_i	area of surface i
J_i	radiosity at surface i
J_j	radiosity at surface j
G_i	irradiation energy at surface i
ε_i	emissivity of surface i
E_{bi}	emissive power of surface i
F_{ij}	view factor between surface i and j

2. Methodology

2.1. Wall surface temperature measurement

Heating process in the baking oven under natural convection mode was conducted for 30 minutes at 220°C. Six thermocouples were placed at each surface inside the oven. Data logger was used to record the temperature during the heating process. The experiment was repeated two times. Fig. 1 shows the thermocouple placement inside the oven with top surface as surface 1, back surface as surface 2, left surface as surface 3, front surface as surface 4, right surface as surface 5 and bottom surface as surface 6.

2.2. Radiation heat transfer analysis

Radiation heat transfer rate was calculated using network representation method. The analysis of radiation inside the oven was carried out by assuming the walls of the oven are modelled as diffuse, opaque and gray surfaces [7]. Each surface of the oven is assumed isothermal and uniform radiosity. The medium within the space inside the oven is taken to be non-participating. Conduction and convection effects during heating process are negligible and no heat loss from the oven is assumed. The net radiation heat transfer per unit surface area, q_i, is determined from each surface. Radiosity, J, is the radiation heat transfer energy that leaves a surface and irradiation, G, accounts for all of the radiation heat transfer energy received by a surface.

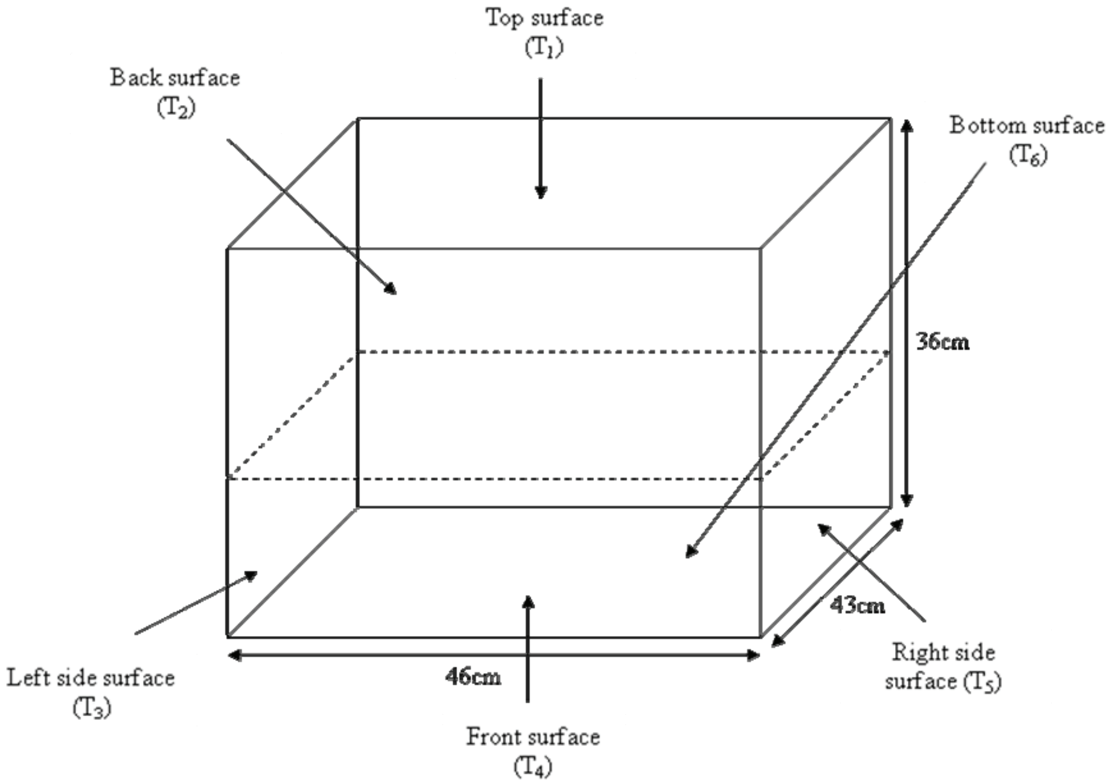

Fig. 1. Thermocouple placement in the oven

The net rate at which radiation leaves surface i, q_i, is equal to the difference between the radiosity and irradiation of surface i:

$$q_i = A_i\left(J_i - G_i\right) \tag{1}$$

For an opaque surface, the radiosity, written as:

$$J_i = \varepsilon_i E_{bi} + \left(1 - \varepsilon_i\right)G_i \tag{2}$$

Substituting equation *(2)* into equation *(1)*, it follows that:

$$q_i = \frac{E_{bi} - J_i}{\left(1 - \varepsilon_i\right)/\varepsilon_i A_i} \tag{3}$$

Using the reciprocity relation for view factors ($A_iF_{ij} = A_jF_{ji}$), an alternative expression can be obtained for the net radiation heat flux from surface i:

$$q_i = \sum_{j=1}^{N} A_i F_{ij} \left(J_i - J_j \right) \tag{4}$$

where N is the total number of surfaces in the oven. Combining equations (3) and (4):

$$\frac{E_{bi} - J_i}{\left(1 - \varepsilon_i\right) / \varepsilon_i A_i} = \sum_{j=1}^{N} \frac{\left(J_i - J_j\right)}{\left(A_i F_{ij}\right)^{-1}} \tag{5}$$

To calculate radiation exchange of in an enclosure of N surfaces, a total of N^2 view factors is needed. Therefore, for six surfaces inside the oven, a total of 36 view factors need to be determined.

2.3. Network representation

The radiative energy balances can be represented in a network. Compared with an electric network, E_b and J_i are analogous to the potential; q_i and q_{ij} are analogous to the current and resistances, respectively. The network analogy provides a useful way for visualizing radiation exchange in an enclosure and is a convenient tool for calculating the radiative exchange in an enclosure consisting of two or more surfaces. The network representation is as shown in Fig. 2. Defining the following variables to simplify the notation:

$$c_i = \frac{1 - \varepsilon_i}{\varepsilon_i A_i} \tag{6}$$

$$b_{ij} = A_i F_{ij} \tag{7}$$

Note that $A_iF_{ij} = A_jF_{ji}$. Therefore,

$$b_{ij} = A_i F_{ij} \tag{8}$$

Substituting equation (6) and (7) into equation (5), the following equation will be obtain:

$$\frac{E_{bi} - J_i}{c_i} = \sum_{j=1}^{N} \left(J_i - J_j \right) b_{ij} \tag{9}$$

Expanding and rearranging equation (9) for surface 1gives:

$$J_1 = \frac{\frac{E_{b1}}{c_1} + b_{12} J_2 + b_{13} J_3 + b_{14} J_4 + b_{15} J_5 + b_{16} J_6}{\left(b_{12} + b_{13} + b_{14} + b_{15} + b_{16} + \frac{1}{c_1} \right)}$$

The radiosity equations (J_1 to J_6) were solved simultaneously using Gauss-Seidel iteration method. Once radiosity value is obtained, the radiation heat transfer at surface i (q_1 to q_6) can be calculated using equation *(4)*. Net radiation heat transfer rate, q_i was computed by adding the radiation rates for each surface, q_{ij}. For example, to calculate net radiation rate for top surface (surface 1), equation *(4)* is used to determine the radiation rates between surface 1 and other surfaces inside the oven. Table 1 represents the values of view factor, radiosity and radiation rate for between surface 1 and other surfaces.

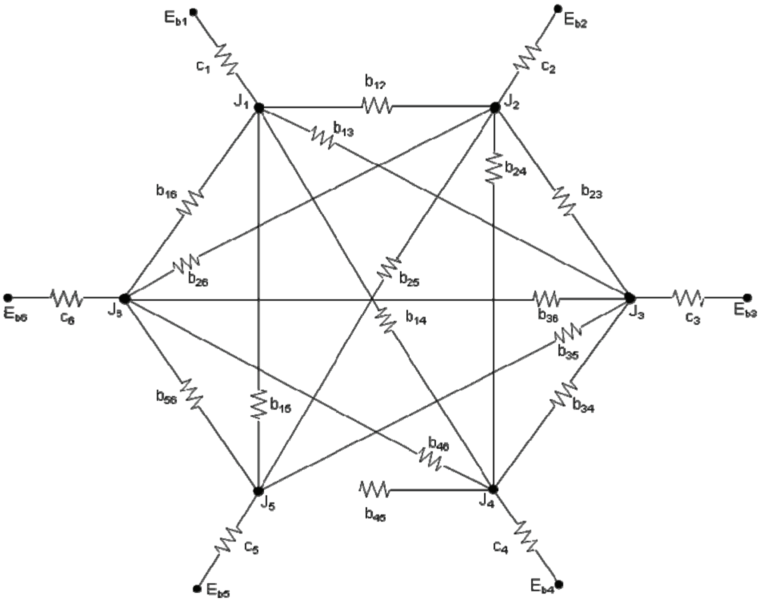

Fig. 2. Network representation diagram for all oven surfaces

Table 1. Radiation rate values

Surfaces, ij	View factor, F_{ij}	Radiosity, J_i (W)	Radiation rate, q_{ij} (W)
11	0	$J_1 = 4210.36$	0
12	0.192	$J_2 = 3568.25$	24.36
13	0.179	$J_3 = 3410.21$	28.30
14	0.192	$J_4 = 2397.62$	68.78
15	0.179	$J_5 = 3317.90$	31.57
16	0.259	$J_6 = 3943.48$	12.68
		Net radiation rate, q_1	165.7

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