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Heat and Mass Transfer in Industrial Biscuit Baking Oven and Effect of Temperature on Baking Time

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PAPER INFO

History:

Received 27 October 2013
Received in revised form 10 October 2014
Accepted 8 February 2015

Keywords:
Heat and mass transfer
Oven
Baking
Biscuit
Industrial

ABSTRACT

This research deals with heat and mass transfer in biscuit industrial baking ovens. In these ovens, heat reaches biscuits indirectly by radiation, convection and conduction. The method for numerical solution is that we first provide the related equations, then they are discretized by finite difference method (FDM), and finally, after encoding and writing a program for the computer, we run it. The Obtained results indicate that biscuit heat absorption occurs 69 % through radiation, 28% convection and 3 % conduction. This percent of conduction depends on the type of band conveyor. Baking time depends on temperature of the baking chamber. For example, it takes 7 minutes for biscuits to reach 4% of moisture in 200^0C.By increasing temperature of the baking chamber, the cooking time is decreased. Based on obtained results, there is a balance between heat and mass transfer rate. Results obtained from solving the equations indicates that maximum temperature of biscuits reaches 150^0C and the highest moisture of baking chamber is almost at the middle of the oven. Vapors generated by this procedure are sent out by several fans, installed inside the baking chamber at the same distance. Simulated data of heat and mass transfer equations are in good agreement with experimental results. Obtained results can be used to control baking time and to production good quality for biscuits.

1. Introduction

Baking biscuits at tunnel ovens have not been yet studied and controlled completely. Hence, by carrying out researches in this regard and providing appropriate composition of heat, moisture, and velocity, we can obtain appropriate baking time and high quality biscuits. Previous studies carried out on heat and mass transfer during biscuit baking time confirmed the simultaneous effect of moisture and temperature of the baking chamber on final product quality [1].These studies indicate that baking biscuit is not just drying; rather it is the result of series of physical and biochemical changes [2]. This is why we choose to study thermal properties of dough and obtained product [3, 4].Air velocity and temperature definitely influence heat transfer rate [5].in recent years there has been growing interest in modeling heat and mass transfer during the continuous baking of thin products (biscuit and cookies) between baked products and their environment within an oven[6,7]. Heat transfer mechanisms are consist of three forms of radiation, convection and conduction which radiation involves the highest percent [8, 9]. In past, biscuit baking processes were studied through general models [10]. After that, a very simple model of heat and mass transfer equations in baking chamber was analyzed and its results were compared to experimental results [11]. Most previous studies have been carried out Laboratory and the burners were distributed along the oven [12, 13], while this study has been implemented industrially, and a thermal

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resource has been used at the beginning of the oven. The aim of this study is to present a mathematical model of heat and mass transfer in an industrial biscuit baking oven, which is a combination of other models. In this model, in order to economize energy consumption we used a return channel. Meanwhile, there are other differences, e.g. in [14] dominant heat transfers are consist of in form of convection and conduction, While in this study, dominant heat transfer is radiation. Since the results for the current geometry are different for small devices compared to large devices, we decided to make and test a device in real industrial dimensions to solve this problem.

2. Methods and materials

For examining the structure of Biscuit baking model in tunnel ovens with indirect heat, first we indicate the simplified structure on tunnel ovens and then, in next section, we explain the used oven in this study.

2.1. Tunnel oven simplified representation

The model is designed in form of a simple and appropriate for the same tunnel ovens with indirect heat. According to fig.1, the model structure involves four main units.

Heat unit: Heat generated by a heat source is transferred to a baking chamber through two channels, one of which is installed under baking chamber and the other installed above it. The heat required is provided by a burner installed at the beginning of the oven.

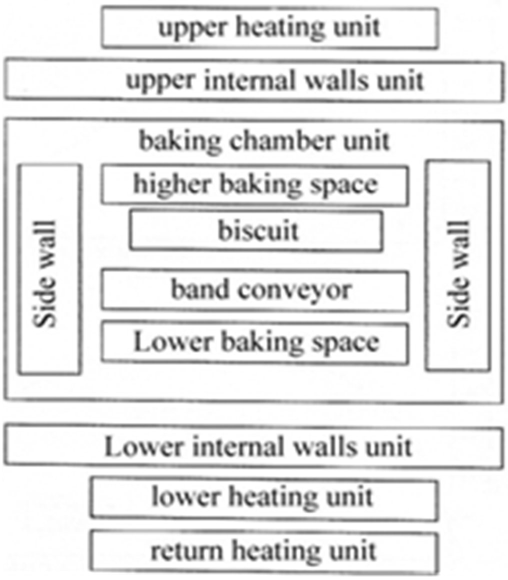

Figure 1. modular structure of the model of the baking oven

Internal walls unit: in this unit, heat is transferred from the heat unit to the baking chamber unit. It is divided into two parts, i.e. upper internal wall and lower internal wall.

Baking chamber unit: This unit includes band conveyor, side walls, internal space of baking chamber, and biscuits. Band conveyor carries biscuits with its movement inside this chamber. It absorbs and receives the heat needed for baking from the heat source through internal walls unit.

Heating return unit: In order to economize the energy consumption and to prevent heat losses, a channel was designed where the hot air could enter it from both sides from lower and upper, in such a way that the hot air may be used to preheat the air entered to combustion chamber.

2.2. Oven description:

Figure (2) show the oven along its length and its length is along the axis “x”. Oven length is almost 24 meters heated with indirect heat. In this model, a burner installed at the beginning of the oven is used to warm the oven. The burner is consists of gas or gasoil type. Band conveyor used in this oven is weaved with a wire grid in such a way that the air above and under the transporter is related to each other. The depth of the transporter is 0.8.

The Air of baking chamber including water vapor and other generated vapors is exhausted from baking area through 7 chimneys. As in figure (2), 7 vapor chimneys are installed along the oven in distances of 3 meters from each other, and the vapor resulting from drying process is exhausted from baking chamber. The rate of these fans is changeable. Several thermocouples are installed all over the oven to control and measurement baking chamber temperature.

Experiences of biscuit baking have indicated that it is influenced by different conditions including baking chamber temperature and air velocity inside the chamber. These different conditions are improved by modifying set points temperature in baking chamber and exhausted air of chimneys. In fig. 2, the arrows indicate the direction of hot air flow from the combustion chamber and return units.

3. Modeling equations

If we consider the baking of biscuits in an indirect fired oven with the biscuits supported directly on a band, then the important mechanisms of heat transfer to the biscuits include conduction from the band to the biscuit bottom, radiation from oven refractory surfaces to biscuit, and forced convection to biscuit top and sides.

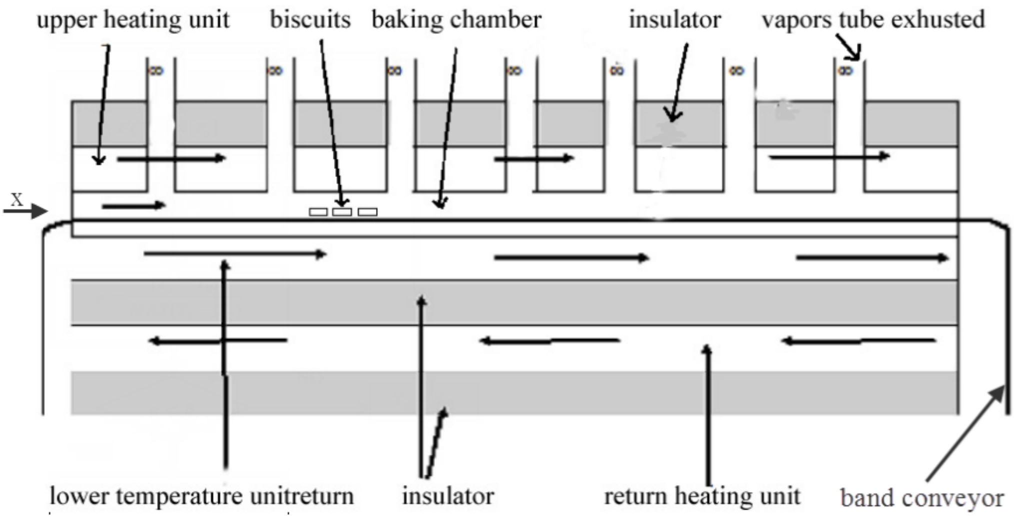

Figure 2. A simplified representation of the length of a tunnel oven

3.1. Radiation, heat transfer modeling

Because whole surface of the conveyor belt is not covered by biscuit, all radiation waves do not reach biscuits, so the shape coefficient factor of the wall's to biscuit is not 1. The amount of absorbed heat by biscuits in form of the radiation equals [7]:

$$q_{eb} = A_w F_b \sigma \left(T_W{}^4 - T_b{}^4 \right) \tag{1}$$

$$q_{et} = A_w F_t \sigma \left(T_W{}^4 - T_t{}^4 \right) \tag{2}$$

Where F_b and F_t are overall dimensionless coefficients for radiation heat transfer, [7, 9]:

$$F_b = \frac{1}{\frac{1}{F_{w-b}} + (\frac{1}{\varepsilon_w} - 1) + \frac{A_w}{A_b}(\frac{1}{\varepsilon_b} - 1)} \tag{3}$$

$$F_t = \frac{1}{\frac{1}{F_{w-t}} + (\frac{1}{\varepsilon_w} - 1) + \frac{A_w}{A_t}(\frac{1}{\varepsilon_t} - 1)} \tag{4}$$

Where A_W is the channel surface, Ab is the biscuit surface, and A_t is the surface of the conveyor belt, F_{w-b} The radiation shape factor of the wall's to biscuit, and ε is Emissivity of surfaces.

The expression for convection and conduction written as follows [9, 12]:

$$q_{cv} = A_w h_o (T_w - T_o) \tag{5}$$

$$q_{tb} = A_{tb} k_{tb} (T_t - T_b) \tag{6}$$

Where h_o is heat transfer coefficient inside the baking chamber, and k_{tb} is thermal conductivity coefficient between band conveyor and biscuits

3.2. Heat equilibrium in heat unit

Equation 5 is heat equilibrium in temperature unit, where $T_{a,\ i}$ is inlet hot air temperature, $T_{a,\ i+1}$ is the outgoing temperature in an element whose length is Δx through hot air channel, T_w is temperature of walls under specific conditions, h_i is heat transfer coefficient inside the channel, and A is the exchange surface between heat unit and baking chamber. Cp is the specific heat at constant pressure, hence we can write the energy equilibrium inside channels as follows [9]:

$$\dot{m} c_p (T_{a,i} - T_{a,i+1}) = h_i A (T_{a,i} - T_w) \tag{7}$$

It means that the energy waste inside channel is transmitted to the channel wall inform of convection with the temperature of T_W.

3.3. Heat equilibrium in baking chamber

Heat transfer among elements in the baking chamber is carried out in the forms of radiation, convection, and conduction thermal fluxes. Fig. 4 shows Thermal fluxes of each element.

3.4. Heat equilibrium on the channel internal wall

In all previous studies, temperature has been assumed as constant in width; and just temperature gradient exists along the oven, the length of the oven is along axis (x).

$$\left[k_W \, e_W \, A_W \, \frac{\partial^2 T_W}{\partial x^2} \right] = q_i - q_{cv} - q_e \tag{8}$$

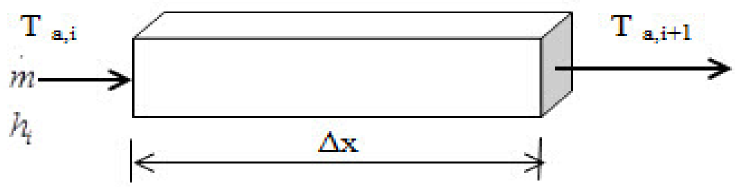

Figure 3. heat equilibrium in an element length channel

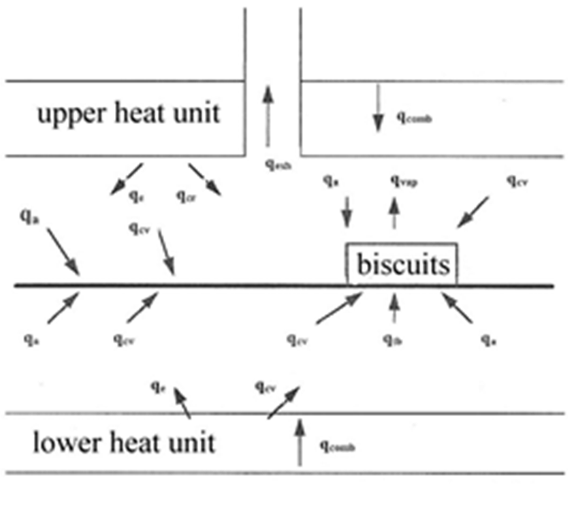

Figure 4. heat transfer fluxes in baking chamber [6]

$$\left[k_w e_w A_w \frac{\partial^2 T_w}{\partial x^2}\right] = h_i A_w (T_{a,i} - T_w) - A_w h_o (T_o - T_w) - A_w F_b \sigma \left(T_W{}^4 - T_b{}^4\right) - A_w F_t \sigma \left(T_W{}^4 - T_t{}^4\right) \tag{9}$$

In this relation q_e is radiation heat transfer, q_{cv} is convection heat transfer, q_i is the entered heat transfer to heat unit, e_w wall thickness, K is thermal conductivity

3.5. Heat equilibrium on baking chamber air

$$V_o e_o \rho_o cp_o A_w \frac{\partial T_o}{\partial x} = q_{cv} + q_{vap} - q_{cv.b} - q_{cv.t} \tag{10}$$

$$V_o e_o \rho_o cp_o A_w \frac{\partial T_o}{\partial x} = A_w h_o (T_w - T_o) + A_b m_{vap} cp_{vap} (T_o - T_b) - A_b h_o (T_o - T_b) - A_t h_o (T_o - T_t) \tag{11}$$

Where q_{vap} is Heat flux due to the drying of the biscuit, V_o is the air velocity inside the baking chamber, m_{vap} is mass transfer rate.

Considering the air enters to baking chamber from both sides, and generated vapor exhausts from baking chamber by some fans along oven, q_{ext} should be added to the final equation in points associated to vapor exhausting chimney. Where:

$$q_{exh} = -da_i .cp(T_o - T_{in}) \tag{12}$$

T_{in} is temperature of air entered to baking chamber, da_i is exhausted rate of vapors in valve.

3.6. Heat equilibrium on the band conveyor

$$V_t e_t \rho_t Cp_t A_t \frac{\partial T_b}{\partial x} = q_{cv} + q_a - q_{tb} \tag{13}$$

$$V_t e_t \rho_t Cp_t A_t \frac{\partial T_b}{\partial x} = h_o A_t (T_o - T_t) + A_t F_t \sigma \left(T_W{}^4 - T_t^4\right) - A_{tb} k_{tb} (T_t - T_b) \tag{14}$$

q_a is the absorbed heat by radiation, q_{tb} is conduction heat between biscuit and the band conveyer.

3.7. Heat equilibrium on biscuit

$$V_t e_b \rho_b Cp_b A_b \frac{\partial T_b}{\partial x} = q_{cv} + q_e + q_{tb} - q_{vap} \tag{15}$$

$$V_t e_b \rho_b Cp_b A_b \frac{\partial T_b}{\partial x} = A_b h_o (T_o - T_b) + A_w F_b \sigma \left(T_W{}^4 - T_b{}^4\right) + A_{tb} k_{tb} (T_t - T_b) - A_b m_{vap} \Delta H_{vap} \tag{16}$$

The heat required to evaporate existing moisture on biscuits in the oven can be obtained as follow**:**

$$q_{vap} = A_b m_{vap} \Delta H_{vap} \tag{17}$$

Where q_{vap} is heat transfer rate and ΔH_{vap} is latent heat of vaporization in biscuit and m_{vap} is mass transfer rate $\left(\frac{kg}{m^2 s}\right)$ [11].

Biscuit cooking procedure includes drying, biochemical changes, and expansion, though due to procedure complexity in this model we have just explained drying method and it is supposed in the modeling that biscuits have steady temperature and moisture.

3.8. Humidity equilibrium on biscuits

We assume that the biscuit is homogenized with moisture, and the temperature and pressure over the biscuit surface in the baking chamber are in ambient conditions. So, moisture equilibrium on biscuit can be written as follows [6]:

$$V_t e_b \rho_b (\frac{\partial X_b}{\partial x}) = -m_{vap} \tag{18}$$

Where X_b is moisture content of biscuit, e_b is biscuit thickness and m_{vap} is mass transfer rate $\left(\frac{kg}{m^2 s}\right)$

4. Heat transfer coefficient and Thermo-physical properties

4.1. Heat transfer coefficient in baking chamber

Heat transfer coefficient is calculated by the properties of the air. By Considering one of effective materials in dryers is airflow inside them and this the air circulation is free and forced convection in the tunnel oven, which generates different air velocity profiles, a distinction between free and forced convection is made. For convection, Barreteau and Mureau correlations are used for a tunnel oven based on a hydraulic diameter approach. This hydraulic diameter is calculated regarding geometrical characteristics of the oven [6].

For laminar flow:

$$\mathrm{Re} \langle 40 \qquad NU = 4.5\ \mathrm{Re}^{0.27} \tag{19}$$

For turbulent flow:

$$\mathrm{Re} \rangle 40 \qquad NU = 0.7\ \mathrm{Re}^{0.61} \tag{20}$$

Re is Reynold’s number, Nu is Nusselt’s number, and u is average air velocity inside the chamber whose efficient rate, is 1 meter per second experimentally [4]. Vapors generated by biscuit drying are exhausted by fans installed on the steam valves in the oven. Mass flow rate of the Fans is changeable. Fans, or in fact the exhaust valves of the vapors, have been installed in a way that obtained vapors are accompanied with air inlet from both sides (the beginning and end) to baking chamber. Where dai is the air flow rate at section i and i+1. If we suppose that the middle vapor valve in which the direction of the airflow is changed from the parallel movement of transporter belt to opposite state inside the baking chamber is IF, then we will have:

$$i \langle if \ : \quad d_{a(i+1)} = d_{ai} - d_{exh(i)} \tag{21}$$

Where d_{exh} is the flow rate of dry air extracted from the chimney i.

$$i \langle if \ : \quad d_{a(i-1)} = d_{ai} - d_{exh(i)} \tag{22}$$

We established an overall mass balance. Then, we assumed that half of the total dry air rate entered on each side.

4.2. Humidity equilibrium of baking chamber air

If Y_a is moisture of the baking chamber air, so amount of vapor exhausted from biscuit is equal to moisture amount which is absorbed by baking chamber air, hence we have:

$$da_i \times \frac{dY_a}{dx} = \pm m_{vap} \tag{23}$$

Where + is used for compatible and – is used for the stream which is opposite to band conveyor movement [2].

4.3. Mass transfer coefficient

For mass transfer coefficients no correlation that can be applied to tunnel ovens could be found in the literature, except for mass transfer between biscuit and the oven air. A correlation resulting from the Colburn analogy is used [8, 10]:

$$h_m = \frac{h_q}{64.7 \Delta H_{vap}(T_b)} \tag{24}$$

Where h_m is mass transfer coefficient, and h_q is heat transfer coefficient.

4.4. Thermo-physical features

The values of the physical properties were obtained from the literature. Heat transfer coefficient between band conveyor and biscuits was taken to be $35\left(\frac{w}{m^2k}\right)$ [7]. The densities of biscuit was taken to be $946\left(\frac{kg}{s}\right)$ and specific heat of biscuit was taken to be $2100\left(\frac{j}{kg.k}\right)$ [3, 14]. Metals and biscuits are supposed to behave as gray bodies and their emissivity is taken as 0.9 [9, 13].

5. Solutions method

Numerical solution is in steady-state mode. The method for numerical solutions is that we first provide the related equations, then they are discretized with finite difference method (FDM), and finally, after encoding and writing a program for the computer, we run it. For discretizing the first derivative, "Back ward" method and for the second one, "Central" method is used from which the numerical results of their solving are obtained after exercising initial and boundry condition.

One of the solution methods for nonlinear equation is the simple iteration method. In this way, first we select an estimated initial value for each nodal on which the equations turn to be linear. Now, the equation can be solved using iteration method. If we assume the coefficient matrix is K, and the passive matrix is T, and the constant value and nonlinear sentences matrix is F, so the equation system can be the following:

$$[K][T] = [F] \tag{25}$$

Algorithm of the computer program:

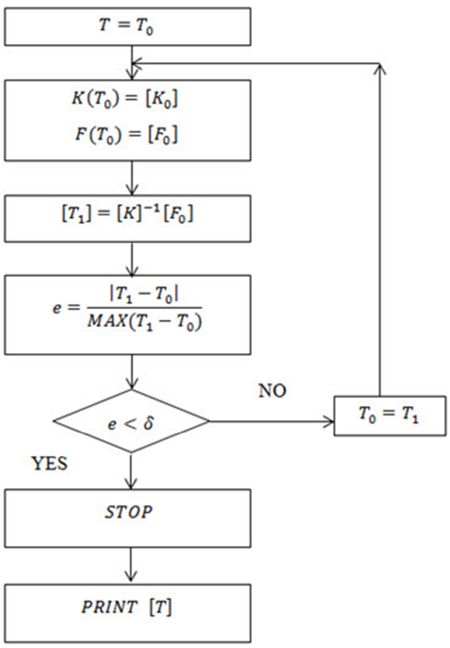

Figure 5. the Algorithm of the computer program

6. Results and discussion

In spite of diversity in biscuit cooking ovens, the results obtained from them may not be completely similar due to specific conditions and the type of design implemented by oven makers and designers, except for conditions where all are similar and oven conditions do not influence it. In this section we try to compare and investigate results obtained from scientific and experimental studies of numerical solutions and experimental results.

In this simulation, 24 points were used along the x-axis. For studying the independency of simulation network, it was repeated in 48 points, but there were no significant differences in aspect of network results. Horizontal dimension, i, e, axis x is related to the length of the oven which is 24 meter. In diagram 6, the values of biscuit moisture are obtained in each meter.

The moisture of Biscuit dough was about 20%, and after baking, the standard moisture of Biscuit is 4%. The time required to reach this rate of moisture is considered to be the time of baking.

As seen in fig 6, since dough has not reached balance conditions, mass transfer rate is low and moisture starts to be evaporated gradually from biscuit surface in relatively constant rate. The simulated data are in good agreement with the results of the experimental measurements, and small deviations in numerical solution may be due to changes in baking temperature and air velocity through the baking chamber.

Fig 7 shows the variation of temperature in the cooking chamber. How to change the cooking chamber temperature has a great effect on baking quality. The gradual increase and reduction in baking chamber temperature has appropriate effect on cooking quality. It is so that gradual increase in baking chamber temperature gives sufficient time for the biochemical and physical changes of the dough. Because surface moisture of biscuit decreases near the bottom of the oven, the relative reduction of the temperature provides needed coordination between water infiltration to biscuit surface and evaporation rate to prevent the drying of biscuit surface, making cracks on it, and finally poor quality cooking. The variations of diagram are related to the location of valves for out let moisture from the baking chamber. As energy exits a decrease in temperature is observed in the diagram.

The considered design for air velocity throughout the oven is in such a way that entering air velocity with lower temperature at the beginning and end of the oven is high and it causes a fall in temperature of the baking chamber till a good condition is created for cooking. Results obtained from numerical solutions are in good

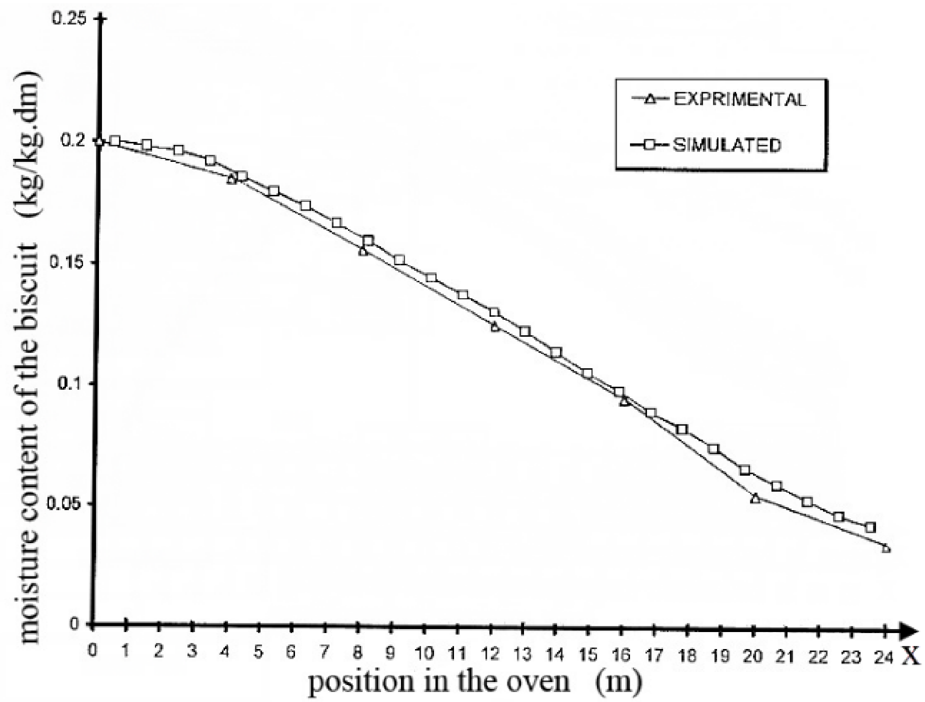

Figure 6. Biscuit moisture changes in oven and comparing it with experimental results

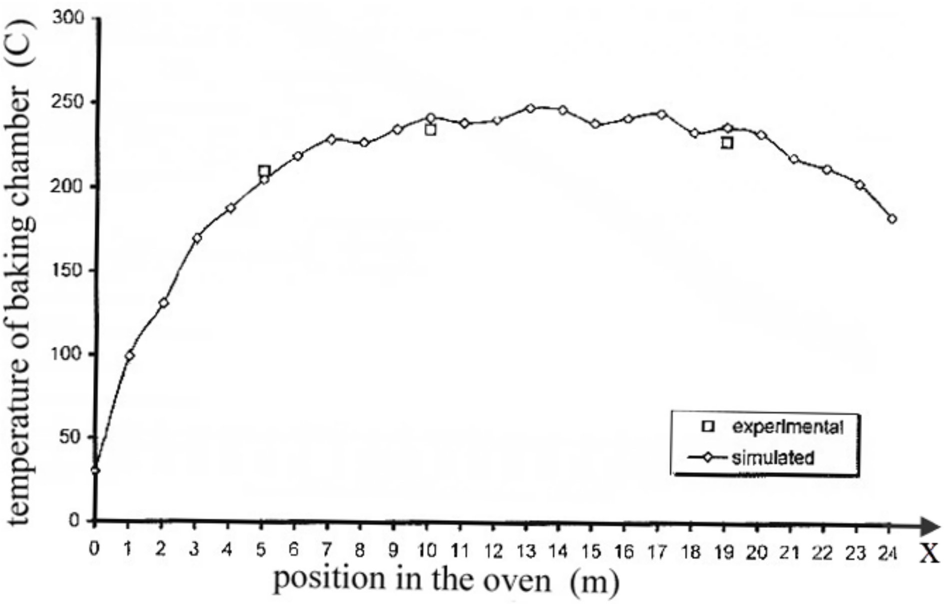

Figure 7. Changes of the temperature of baking chamber in oven

agreement with the results measured at three points. Regarding the fact that outflow of vapour with along the thermal energy output through chimneys is done via baking chamber, thus in these points, the decrease in temperature resulting from decrease in energy can be observed in diagram.

As seen in fig. 8, using the result of numerical solution, biscuit temperature increases gradually due to a gradual increase in baking chamber temperature and receiving heat through radiation, convection and conduction. And biscuit temperature also falls at the end of the oven, because baking chamber temperature is quite reduced.

Fig. 9 shows the changes in baking chamber air moisture. When the fan absorbs the air from inside the baking chamber, the replacing air tries to be provided through the shortest path. So the air stream moves in parallel with conveyor belt up to the half of the oven and it moves in opposite direction of the conveyor belt from the half of belt to the end; and air enters from both sides inside the baking chamber. The closer we get to the half of the oven, the less air velocity flows to the baking chamber due to reduction in mas flow rate of the fans. Therefore, as air velocity gets lower, the moisture resulting from the evaporation of dough moisture on biscuit becomes higher till it reaches its maximum amount at the half of the oven.

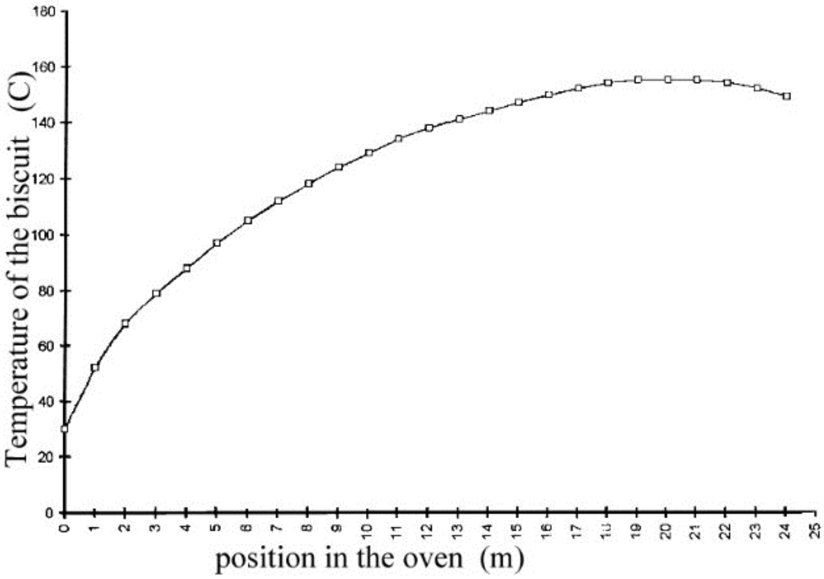

Figure 8. Biscuit temperature in the oven

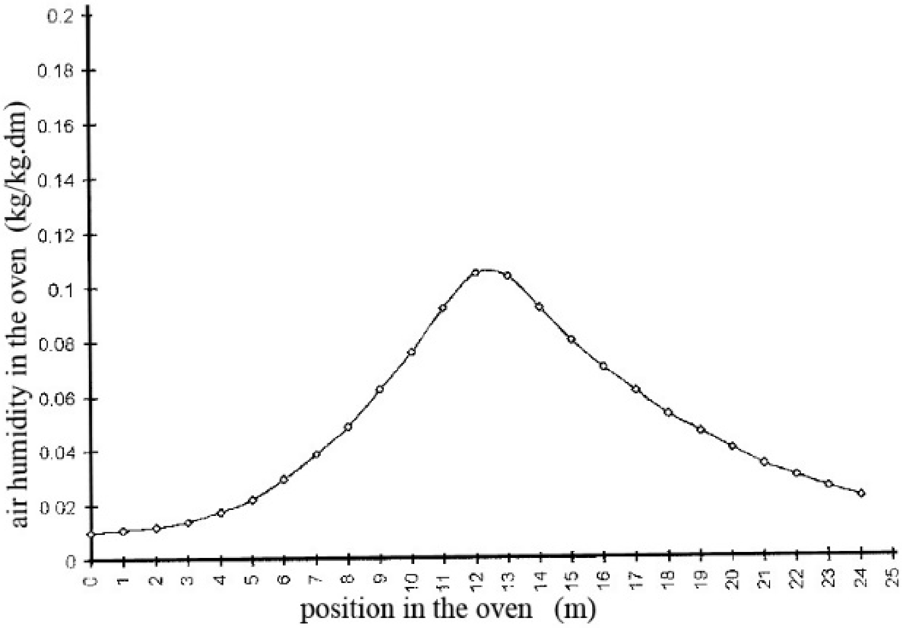

Figure 9. Simulated changes in air humidity inside the oven

Fig. 10 shows the absorbed heat of biscuits in three forms of radiation, convection and conduction. As seen, the absorbed heat by the biscuit is highly due to radiation. The biscuit absorbs lower of heat from conveyor belt by conduction up to the middle point of the oven because it takes some times for conveyor belt to reach at the required temperature for conveying heat to biscuit. The other reason for this is that contact area between grid conveyor belt and biscuit is too low, almost less than 5% of the absorbed heat by biscuit is carried out through conduction. The percentage value of conduction depends on type of conveyor belt.

Heat absorbed by biscuit by convection depends on the air velocity of baking chamber and consequently heat transfer coefficient. So, if we increase the air velocity of baking chamber up to permitted amount, the heat transfer through convection will increase and consequently its percentage increases compared to total heat transfer.

Percentages of absorbed heat for the biscuits by three modes of heat transfer are about 69% by radiation, 28% by convection and 3% by conduction where conduction value depends on the type of the conveyor belt. Fig. 11.

It is implied From Fig. 10 that the moisture rate is decreased by increasing temperature of the baking chamber. Baking chamber temperature OF 200 ^{0} C and 7 minutes is needed to reach moisture of 4%. And for moisture of 4% in 250^0 C we need 5.7 minute time duration.

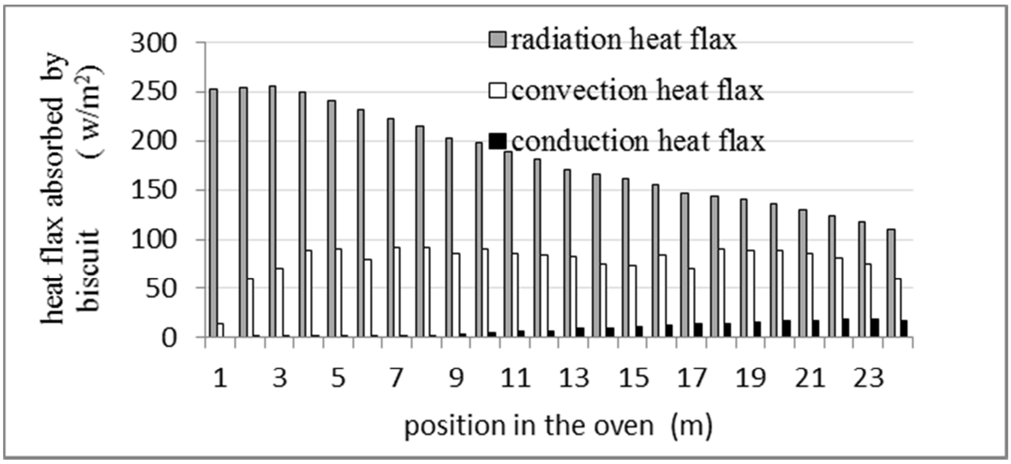

Figure 10. Heat flax absorbed by biscuit (w/m^2)

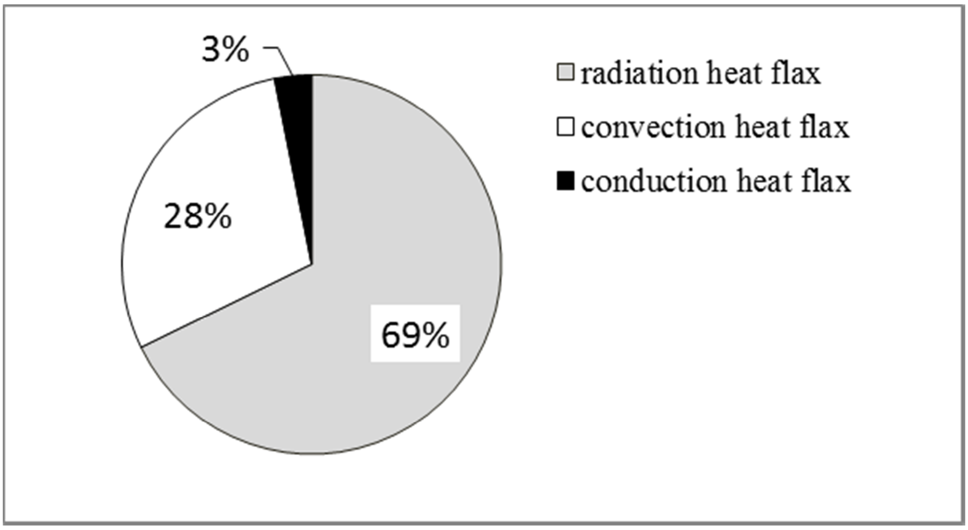

Figure 11. Percentages of absorbed heat flax by biscuit %

7. Conclusion

As a consequent, the most absorbed heat by biscuits was through radiation. With an increase in conveyor belt speed and channel wall temperature, baking time would reduce and there was a balance between heat and mass transfer rate. The results could be used to control baking time and create appropriate quality for biscuits.

In an oven made with an industrial scale, computational results are in good agreement with measured experimental results of real device. This indicates the importance of experimental and computational data for similar industrial application. The maximum error between experimental and numerical data is about 10 percent. The effects of using heat exchangers on energy consumption can be studied in the future.

Nomenclature:

A	surface (m^2)
Cp	the specific heat at constant pressure $\left(\frac{j}{kg.k}\right)$
da_i	exhausted rate of vapors in valve (kg/s)
e	thickness (m)
F	The radiation shape factor, dimensionless.
h	Heat transfer coefficient, $\left(\frac{w}{m^2.k}\right)$
K	thermal conductivity $\left(\frac{w}{m.k}\right)$
m_{vap}	mass transfer rate $\left(\frac{kg}{m^2 s}\right)$
Nu	Nuselt's number
q	Heat transfer (w)
q_e	radiation heat transfer (w)
q_{cv}	convection heat transfer (w)
q_i	the entered heat transfer to heat unit (w)
q_a	absorbed heat by radiation (w)
q_{tb}	conduction heat between biscuit and the band conveyer (w)
q_{vap}	Heat flux due to the drying of the biscuit (w)
Re	Reynold's number
T	temperature (K or C)
V, u	velocity ($^m/_s$)
X_b	moisture content of biscuit, $\left(\frac{kg}{kg}\right)$
Y_a	moisture of the baking chamber air $\left(\frac{kg}{kg}\right)$
ε	Emissivity of surfaces.

ΔH_{vap}	latent heat of vaporization in biscuit $\left(\frac{j}{kg}\right)$
ρ	Density $\left(\frac{kg}{m^3}\right)$

Subscript

a	internal air of heat units
b	biscuit
cv	convection
e	radiation
in	air entered to baking chamber
o	baking chamber air
t	conveyor belt
tb	conveyor belt and biscuit
vap	vapor
wall	wall

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