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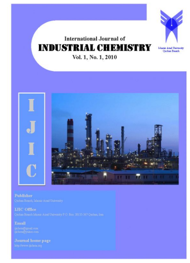

Modeling and Simulation of Hamburger Cooking Process Using Finite Difference and CFD Methods

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Abstract

Unsteady-state heat transfer in hamburger cooking process was modeled using one dimensional finite difference (FD) and three dimensional computational fluid dynamic (CFD) models. A double-sided cooking system was designed to study the effect of pressure and oven temperature on the cooking process. Three different oven temperatures (114, 152, 204°C) and three different pressures (20, 332, 570 pa) were selected and 9 experiments were performed. Applying pressure to hamburger increases the contact area of hamburger with heating plate and hence the heat transfer rate to the hamburger was increased and caused the weight loss due to water evaporation and decreasing cooking time, while increasing oven temperature led to increasing weight loss and decreasing cooking time. CFD predicted results were in good agreement with the experimental results than the finite difference (FD) ones. But considering the long time needed for CFD model to simulate the cooking process (about 1 hour), using the finite difference model would be more economic.

Keywords: CFD, Cooking process, FD, Oven temperature, Pressure effect , Weight loss

1. Introduction

The food material safety such as Hamburgers greatly depends on the presence or absence of bacteria E. Coli O157: H7. The presence of these bacteria is more likely in hamburgers that are not cooked enough. Therefore, thermal processes are important in determining the safety and quality of retail products [1]. However more researches should be done on this food material and its microbial safety. Studies show that applying pressure to hamburgers significantly increases the heat transfer in double-sided sandwich makers and leads to the faster heat transfer into the hamburgers while the cooking time is decreased. Most previous studies had been focused on the modeling and simulation of heat and mass (moisture and fat) transfer process during cooking of hamburger and the effect of these processes on the microbial safety of this food material. However, it seems study about the effect of pressure on the cooking process is still insufficient [2]. Chen et al. [2] used the finite element (FE) model to simulate transfer processes during convective cooking of chicken patties. They neglected the crust formation or shrinkage. Only water transfer was considered in mass transfer.

A model proposed to predict the temperature profiles during double-sided pan-frying of meat patties [3]. Enthalpy formulation was used to solve the heat transfer equation due to the phase change in the process.

Pan et al. proposed a model in contact-heating process of hamburger patty [4]. Enthalpy formulation was used to express the governing equation for the heat conduction. Capillary flow of water and liquid fat was used as the mechanism of mass transfer in the model. First order kinetic was used in the microbial destruction model to predict the microbial population.

USDA and FDA recommended that the cooking process of hamburger patties to a center temperature should be at least 71°C or 68.3°C and hold for 15 seconds [5]. Rate of heating to ground beef patties related to some properties such as retention of beef patty color, texture total crude lipid content, fatty acid, and cholesterol composition [6]. The heat transfer coefficient is an essential parameter in thermal processing of food materials. During air convection cooking of chicken patties, air humidity in the oven affects the heat transfer coefficient. Beside of the center temperature, soluble protein can be used as an indicator to determine the degree of cooking [7]. Pan and Singh studied ground beef and determined the rate of change in physical and thermal properties of it [8]. Temperature and holding time affected fat and water holding capacities, but the effect of temperature was more. The pressure applied on patties affected the cooking loss (i.e. exit of water and fat from hamburger) and was a function of cooking time and temperature in a linear manner. The high pressure of the top plate in double-sided cooking causes the thickness shrinkage of the cooked patty.

Far infrared radiation was used for cooking beef burger patties [9, 10]. Mass transfer mechanism is a combination of Fickian concentration driven molecular diffusion, capillary force, and bulk movement under gravity.

In double sided cooking of hamburger patties, there is a contact between patty and heating surface. The rate of heat transfer between them is described by the contact heat transfer coefficient. This parameter was studied in previous researches [2, 11]. The contact heat transfer coefficient is a function of heating temperature and time. Contact pressure, physical and thermal properties of heating surfaces, heating temperature and characteristics of medium at the interface may affect the heat transfer rate. When the hamburger was under pressure, a peak was observed in the heat flux profile between the patty and the heating surface and then disappeared immediately after the removal of pressure [2]. In addition to the contact heating method, far-infrared radiation was used to cooking beef patties, and a one-dimensional model was proposed. Heat transfer process that is predicted using this model is sensitive to fat content [10]. A mathematical model of double-sided cooking was developed to predict temperature profiles in meat patties [11]. In this mathematical model the approach of enthalpy formulation was used for heat transfer equation. In a study, some objective functions such as minimization of cooking losses were used to see their effects on plate temperature profiles in double-sided contact cooking [12]. Transfer processes in meat patties were studied in a double-sided pan fryer [13]. Oroszvari suggested that water and fat losses affects the heat transfer. It was shown that the frying time is a function of fat content and grill temperature; the longer processing time was achieved for beef burgers with higher fat content and lower grill temperature [14].

Studies show that Double-sided pan-frying of unfrozen/frozen hamburgers and developed a predictive model of heat and mass transfer and simulate the inactivation of E.coli O157:H7, Listeria innocua and salmonella serotypes within patties [15].

Oroszvari et al. studied the effect of cooking temperature of beef burgers on mass transfer and permeability. It was shown that the water loss is increased with the increase in average temperature [16].

Ou and Mittal developed a model of heat and mass transfer for the frying of frozen hamburger patties [17]. Moisture transfer was due to diffusion and capillary flow, but the contribution of diffusion was lower. The modified Darcy's law was used to describe the moisture transfer model. Moisture and fat transfer is commenced when the temperature in the patty is reached a certain level.

Santos el al. used a numerical model to establish time-temperature specification in order to inactive E.coli O157:H7 in black sausage [18].

Braeckman et al. studied the effect of various IR-grilling/hot air cooking condition on moisture and fat content and on some physical properties of meat patties [19]. The IR-grilling resulted in crust formation and reduced the fat and moisture content during subsequent convection cooking.

In this research, hamburgers were cooked in a double-sided scheme, at a static electrical oven with constant moisture and temperature. The effect of pressure and oven temperature on the cooking process was studied and compared with the prediction data by CFD and finite difference. A mathematical model of heat transfer was developed to study the change of temperature in the hamburgers. The 1-D modeling program was written in a simulation program (MATLAB R2008a) along the thickness. Also this process simulated in a simulation program (Fluent 6.3.26, 2006) for an accurate prediction of temperature change in the patties. The predicted data were compared to experimental ones to validate this modeling process. Hamburger geometry design with special mesh was created in gambit (Gambit 2.2.30).

2. Material and Methods

2. 1. Cooking procedure

Nine experiments were designed to study the effect of pressure and temperature on the cooking process. Three different oven (Binder, E240, Germany) temperatures, (114, 152, 204°C) and three different pressures, (20, 332, 570 Pa (pressure is equal to the mass of weights per surface area of plate)) were selected for these experiments. Hamburgers were placed between two copper sheets (Fig. 1). The dimensions of the copper sheets are as the same as the hamburger dimensions. In order to apply pressure on the surface of hamburger, different weights were used and these weights were placed on the copper sheet surface. Before cooking, copper plates were placed in the oven to reach the necessary temperature. Hamburger with copper sheets and thermocouples were placed in an oven with constant temperature and cooking was commenced. Cooking process finished when the hamburger center temperature reach about 71°C. An electrical oven was used to supply the required heat for cooking process (Fig. 1). Oven adjusted to a certain temperature, and then copper plates and weights were placed in it to reach the oven temperature. Two K-type thermocouples (-50°C to 700°C) were used to measure the surface and center temperature of the hamburgers. Temperature data were collected by a data acquisition system (Advantech, USB-4718, Taiwan). Top surface temperature of copper plate at predetermined time intervals was recorded using a radiational thermometer (IPT, DT-8811, Canada). Temperature inside the oven was also recorded at specified time steps and their average was used as oven temperature in models (CFD and finite difference. Thus, in this research statistical analysis was used to reduce the average of measurement errors for the variables. Experiment conditions applied for this study are presented in Table 1.

2. 2. Hamburger

Hamburgers were supplied from a local supermarket. Hamburgers were kept in isolated bags and were stored at -6°C temperature to prevent moisture loss. Thickness and diameter of hamburgers were 14mm and 117mm, respectively. The initial water content of hamburgers was about 60%. Properties of hamburger used in this research are given in Table 2.

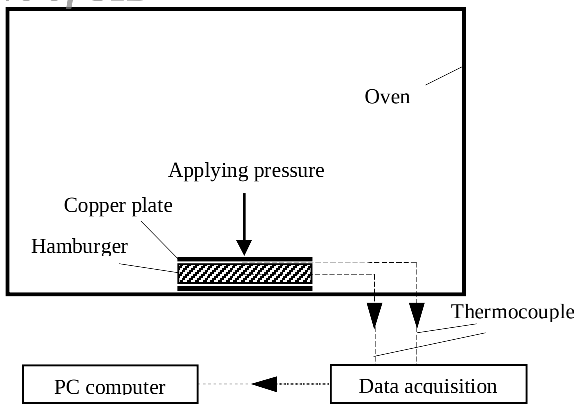


Fig. 1. Schematic of the test environment and its different components.

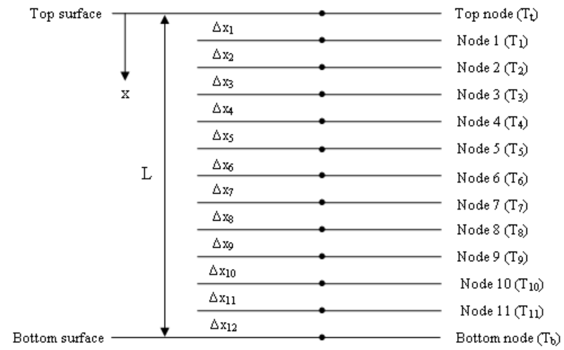


Fig. 2. Schematic of nodes considered in the axial direction for finite difference model.

2. 3. Models

Computational fluid dynamic was used for modeling of cooking process. This model is a numerical method to predict temperature, pressure, etc. A simple one dimensional method (finite difference) was created, in order to reduce computational time. Three dimensional CFD model was solved, and the results of these two models (CFD and finite difference) were compared with each other and with experimental ones to explore the validity of the models.

Table 1. Operational conditions of experiments in this study

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9
Initial temperature of hamburger (°C)	-3.12	-3.40	-4.54	-4.48	-4.86	-3.67	-4.00	-5.46	-3.67
Top surface temperature (°C)	100	100	90	130	130	130	189	190	190
Bottom surface temperature (°C)	117	117	117	152	154	165	208	209	200
Average oven temperature (°C)	114	114	114	152	152	152	204	204	204
Pressure (pa)	20	332	570	20	332	570	20	332	570
Cooking time (min)	30	30	28	23	22	20	18	15	15

Table 2. Properties of hamburger and coefficients used

Property	Symbol	Value	source
Thermal conductivity (W/m°C)	K	0.416	Ou and Mittal (2006)
Heat capacity (J/kg°C)	C_p	3268	Ou and Mittal (2006)
Density (kg/m^3)	ρ	5017	Calculated
Latent heat of fusion (MJ/m^3)	L_f	181.5	Ou and Mittal (2006)
Water conductivity of hamburger (1/s)	K_w	0.017	Pan and singh (2001)
Coefficient of water holding capacity (1/°C)	δ_{we}	0.0132	Pan and singh (2001)
Temperature of water transfer to begin (°C)	T_{w0}	30	Pan and singh (2001)
Patty diameter (mm)	D	117	In this study
Patty thickness (mm)	L	14	In this study

Table 3. Distances of nodes considered from top surface of hamburger for finite difference model

Nodes	Top node	1	2	3	4	5	6	7	8	9	10	11	Bottom node
Distance from top surface(mm)	0	0.635	1.905	3.175	4.445	5.715	6.985	8.255	9.525	10.79	12.06	13.33	14

2. 4. Finite difference model

The heat transfer model presented here is the same as indicated by Ou and Mittal [16]. The heat transfer process was divided into three parts, before melting, melting and after melting. Heat transfer equations of any part were written separately. 13 nodes (Fig. 2) were considered in attaining finite difference equations. The nodes distances from top surface of hamburger are given in Table 3. Conditions at the two ends of hamburger were different from each other, so heat balances were described for all nodes.

Hamburger was assumed with a given diameter and thickness. Since the hamburger diameter is eight times larger than its thickness, we assume that heat transfer is one-dimensional and only in the axial direction. Other assumptions considered for the heat transfer model consist of constant physical and thermal properties during cooking process, negligible chemical change during cooking, and hamburger as a uniform medium.

2. 4. 1. Heat transfer model

Heat flux was assumed from bottom plate to the top one, and energy balance for each element formulated as follows:

Energy in = Energy out + Accumulation of Energy

And it was assumed that hamburger surface is in contact with a convective medium with heat transfer coefficients h_b (bottom surface) and h_t (top surface). Therefore the equations for frozen and unfrozen states are as follows:

Top node: $$K\frac{dT_t}{dx_1} = h_t dT_{tp} + \rho C_p \frac{dT_t}{dt} \quad (1)$$

Node 1: $$K\frac{dT_1}{dx_2} = K\frac{dT_t}{dx_1} + \rho C_p \frac{dT_1}{dt} \quad (2)$$

Nodes 2-11: $$K\frac{dT_i}{dx_{i+1}} = K\frac{dT_{i-1}}{dx_i} + \rho C_p \frac{dT_i}{dt} \quad (3)$$

Bottom node: $$h_b dT_b = -K\frac{dT_{11}}{dx_{12}} + \rho C_p \frac{dT_b}{dt} \quad (4)$$

The initial condition for solving the above equations is:

$$T(x,0) = T_0 \quad (5)$$

In melting period it was assumed that all the heat enters a node used for melting, which melting was commenced at 0°C. The equations in this period are:

Nodes 1-11: $$K\frac{dT_i}{d\Delta x_{i+1}} = L_f \frac{d\Delta x_i}{dt} \quad (6)$$

Bottom node: $$h_b dT_b = L_f \frac{d\Delta x_{12}}{dt} \quad (7)$$

The finite difference form of mentioned equations is calculated in the following section.

2. 4. 1. 1. Period I (T_0 to 0°C)

The equations of finite differences for period I (T_0 to 0°C) are calculated as followed:

Top node:
$$K\frac{\left(T_1^j - T_t^j\right)}{\Delta x_1{}^j} = h_t\left(T_t{}^j - T_{tp}\right) + \rho C_p \frac{\left(T_t^{j+1} - T_t^j\right)}{\Delta t} \quad (8)$$

Node 1:
$$K\frac{\left(T_2^j - T_1^j\right)}{\Delta x_2{}^j} = K\frac{\left(T_1^j - T_t^j\right)}{\Delta x_1{}^j} + \rho C_p \frac{\left(T_1^{j+1} - T_1^j\right)}{\Delta t} \quad (9)$$

Nodes 2-11:
$$K\frac{\left(T_{i+1}^j - T_i^j\right)}{\Delta x_{i+1}{}^j} = K\frac{\left(T_i{}^j - T_{i-1}^j\right)}{\Delta x_i{}^j} + \rho C_p \frac{\left(T_i^{j+1} - T_i^j\right)}{\Delta t} \quad (10)$$

Bottom node:
$$h_b\left(T_{bp} - T_b^j\right) = K\frac{\left(T_b^j - T_{11}^j\right)}{\Delta x_{12}{}^j} + \rho C_p \frac{\left(T_b^{j+1} - T_b^j\right)}{\Delta t} \quad (11)$$

2. 4. 1. 2. Period II (melting period):

The equations of finite differences for period II (melting period) are calculated as followed:

Nodes 1-10:
$$K\frac{\left(T_{i+1}^j - T_i{}^j\right)}{\Delta x_{i+1}{}^j} = L_f \frac{\left(\Delta x_i{}^{j+1} - \Delta x_i{}^j\right)}{\Delta t} \quad (12)$$

Node 11:
$$K\frac{\left(T_b^j - T_{11}^j\right)}{\Delta x_{12}{}^j} = L_f \frac{\left(\Delta x_{11}^{j+1} - \Delta x_{11}^j\right)}{\Delta t} \quad (13)$$

Bottom node:
$$h_b\left(T_{bp}{}^j - T_b{}^j\right) = L_f \frac{\left(\Delta x_{12}^{j+1} - \Delta x_{12}^j\right)}{\Delta t} \quad (14)$$

The amounts of Δt and Δx were selected as followed:

$$Fo \le 0.5 \;\rightarrow\; \frac{\alpha.\Delta t}{(\Delta x)^2} \le 0.5 \quad (15)$$

Where Δt and Δx values for use in the models were determined 5 s and 1.27 mm, respectively.

2. 4. 1. 3. Period III (0°C to end of the process)

Equations of this period are similar to the equations of period I.

2. 4. 2. Mass transfer model

In the mass transfer model the fat transfer was ignored and only water transfer was considered. As indicated in the literature [8], the water transfer took place after reducing of patty temperature to certain level (T_{w0}). According to the Fick's law, mass transfer flux was calculated:

$$\text{Mass transfer flux} = \kappa A(C_s - C) \tag{16}$$

Where A is the cross-sectional area, C_s and C are the material concentration at a point within the meat and κ is the mass transfer coefficient.

The water transfer rate is determined using the following equation [8]:

$$\frac{dm}{dt} = -K_W\left(m^j - m_e^j\right) \tag{17}$$

The finite difference form of this equation is:

$$\frac{m^{j+1} - m^j}{\Delta t} = -K_W\left(m^j - m_e^j\right) \tag{18}$$

The equilibrium concentration of water is a function of temperature [8]:

$$m_e^j = m_0 \exp\left(-\delta_{we}\left(T^j - T_{w0}\right)\right) \tag{19}$$

The initial condition for solving the mass transfer equation is:

$$m(x,0) = m_0 \tag{20}$$

In this study, the weight loss of hamburgers is defined by the following equation:

$$WL = \frac{\text{mass of water evaporated}}{\text{initial mass of hamburger}} = \frac{M_0 - M_f}{M_0} \tag{21}$$

2. 5. CFD model

2. 5. 1. Designing geometry of hamburger in Gambit

For CFD simulation we first designed the geometry of hamburger in Gambit. This geometry was a cylinder with dimensions equal to the dimensions of a hamburger. Three surfaces (top, bottom and side) were defined with boundary condition of type wall. This cylinder was meshed as the total number of nodes and the number of nodes along the thickness of hamburger were 183915 and 15, respectively. Finally the output file was saved in ".msh" format to start the simulation in Fluent.

2. 5. 2. Modeling in Fluent

The output file from Gambit was read by Fluent and model parameters such as model type, definition of material, boundary conditions and the saving style of simulation results was set. In the experiments temperature changed with time, hence heat transfer was set as unsteady state. Hamburger was defined as a solid mass with given thermal properties. To define boundary conditions, it was assumed that hamburger was in convective medium with given heat transfer coefficients for top, bottom and side surfaces. By considering the amounts reported in literatures and temperature range of top, bottom and side surfaces the amounts of heat transfer coefficient were determined. Auto save was used for saving simulation results, and the results were recorded in defined time intervals. Finally, the initial condition of constant temperature type was applied throughout the hamburger and iteration was commenced. Pressure affects the heat transfer due to increase in contact area, therefore the effect of this parameter, pressure, cannot be considered directly in CFD (also in finite difference), and by selecting appropriate values of heat transfer coefficient we are able to observe the effect of this parameter on simulation results. A line along the thickness of hamburger was created in Fluent to export the simulation results so that the results are comparable with the results of finite difference. A point in the center of hamburger was choosen to plot the center temperature history.

3 Results and discussions

As previously mentioned, for solving finite difference equations and determination of boundary conditions in Fluent, heat transfer coefficient of top, bottom and side surfaces was needed. Corresponding values described in the references and temperature range of experiments that also used in this research, heat transfer coefficient values were selected and applied to the models. These values were 150-290, 80-140, and 5 $W/m^2.K$ for top, bottom and side surfaces, respectively.

Center temperature changes of hamburger were plotted versus time and the best fitted curves related to them are presented in Table 4.

Table 4. The best fitted curves by the curves of center temperature changes of hamburger versus time

Experimental No.	$T_C=f(t)$	R^2	RMSE
Exp. 1	$T_C=1\times10^{-6}t^6-1\times10^{-4}t^5+0.005t^4-0.1068t^3+1.152t^2-2.5796t-0.9907$	0.9997	0.4557
Exp. 2	$T_C=-1\times10^{-5}t^5+0.001t^4-0.0366t^3+0.6171t^2-1.4959t-1.832$	0.9998	0.3945
Exp. 3	$T_C=-3\times10^{-6}t^6+2\times10^{-4}t^5-0.0078t^4+0.1052t^3-0.4539t^2+1.7755t-5.1985$	0.9994	0.7033
Exp. 4	$T_C=2\times10^{-5}t^6-0.0018t^5+0.0547t^4-0.8311t^3+6.3017t^2-17.634t+11.047$	0.9992	0.9364
Exp. 5	$T_C=2\times10^{-5}t^6-0.0014t^5+0.0403t^4-0.584t^3+4.4035t^2-12.159t+6.3416$	0.9999	0.3642
Exp. 6	$T_C=9\times10^{-5}t^5-0.0047t^4+0.0844t^3-0.5205t^2+4.2144t-7.3949$	0.9996	0.5521
Exp. 7	$T_C=-2\times10^{-5}t^6+0.001t^5-0.0105t^4-0.0362t^3+1.3792t^2-3.609t-1.544$	0.9999	0.2941
Exp. 8	$T_C=-9\times10^{-4}t^5+0.0415t^4-0.6759t^3+5.0017t^2-10.359t+0.8929$	0.9995	0.643
Exp. 9	$T_C=-5\times10^{-4}t^5+0.0226t^4-0.3731t^3+3.0053t^2-6.1913t-0.1453$	0.9996	0.5947

The root mean square error (RMSE) and determination coefficient (R^2) are good. The performance of the model evaluated with the root mean square error (RMSE) and determination coefficient (R^2) between the modeled output and experimental data set that their relations are follow:

$$R^2 = 1 - \frac{\sum_P (x_{obs} - x_{est})^2}{\sum_P (x_{pred} - \bar{x}_{obs})^2} \tag{22}$$

$$RMSE = \sqrt{\frac{\sum_P (x_{obs} - x_{est})^2}{N}} \tag{23}$$

Where x_{obs} , x_{est} are experimental and estimated values, respectively, and N is the number of data. When the RMSE is at the minimum and R^2 is high, ≥ 0.8, a model can be judged as very good [20, 21].

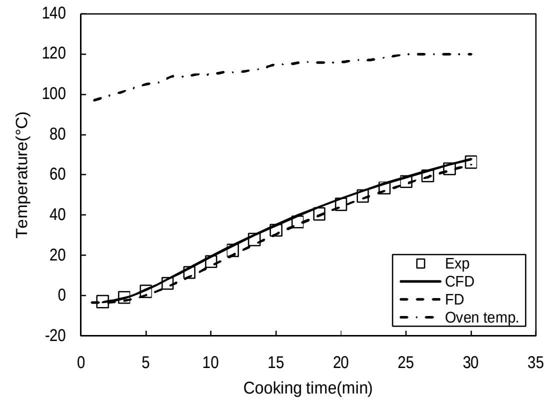
Fig. 3 shows temperature variation of oven and hamburger center versus time for 3 tests that has been compared with the results of CFD and finite difference.

As shown in Fig. 3, the slope of center temperature change of hamburger is low from the beginning until the melting (0°C), because the main heat transfer mechanism in this period is heat conduction in the solid phase (hamburger, ice and fat), the rate of heat transfer is not high due to the low thermal conductivity of ice in this period. As soon as ice the slope of the curve will increase, because the mechanism has changed and displacement of liquid inside the hamburger (water and fat) will be the main mechanism. This change in slope can be clearly observed in the three figures. Since melting takes place at a constant temperature it has been expected that this period appears as a horizontal line, but this is not obvious in the figures. In order to compare FD and CFD, the results of these two models versus experimental results were plotted. The extent of closeness of these lines to y=x line represents the prediction accuracy of the related model. Results of this comparison are presented in Table 5. As shown in this table, CFD has higher accuracy than FD in predicting of experimental data. However, the results of FD are also acceptable and with regard to the less time required for CFD simulation than FD, applying this model will be very economical, regardless of the prediction accuracy of both models.

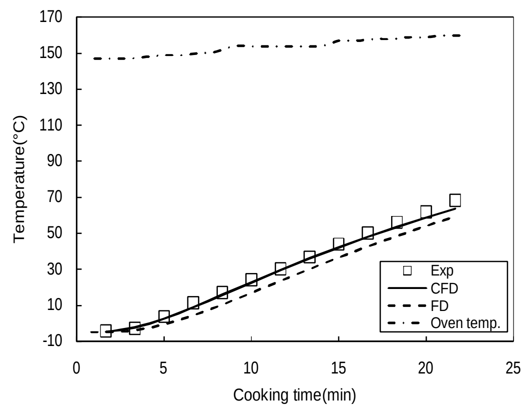
Effects of pressure on Hamburger and oven temperature on weight loss are presented in Fig. 4. The amount of weight loss, due to water evaporation, was decreased by increasing pressure on hamburger surface in a special oven temperature. This can be due to compression in hamburger and more contact of hamburger surface to the copper plate surface.

resulting in a limited space required for water evaporation, as a result space required of water vapor to out of the hamburger is more limited. In contrast with increasing oven temperature, as expected, rate of weight loss at a specified pressure increased, because the temperature gradient between the hamburger surface and oven environment increased, resulting increase in heat flux. It is expected that by increasing pressure on the surface of hamburger surface heat transfer coefficient increases, and thus hamburger will be cooked more quickly; Fig. 5 also refers to this fact. By increasing pressure or oven temperature, cooking time is reduced but increasing temperature will have more impact. Besides rising temperature is leading to increased weight loss. As a result an optimum temperature should be selected for oven. The best empirical equations obtained for Figs. 4 and 5 are presented in Table 6.

Fig. 6 shows temperature changes of hamburgers along their thickness at various times for test 5. These figures plotted regarding the predicted results of CFD. Hamburger surface temperature increases over time, hence the temperature gradient between the hamburger surfaces and heating plate is reduced leading decrease in slope of the temperature graphs. In central areas of hamburger the slope of graphs is low because of its low heat transfer rate from surface of hamburger to internal areas due to conduction mechanism in solid phase. But solid phase is melted over time and the rate of heat transfer increases because the heat transfer mechanism is changed to convection mode. Gradually approaching the end of process temperature distribution is more uniform inside the hamburger and therefore the slope of temperature graphs is again decreased.



(a)



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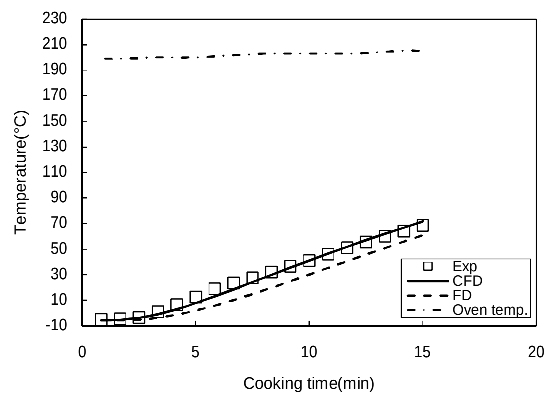


(c)

Fig. 3. Comparison of experimental results with CFD and finite difference results for three selected tests (Tests in pressure 332 pa); (a): Exp. 2, (b): Exp. 5, (c): Exp. 8

Table 5. Comparison of FD and CFD prediction with experimental results (y=Predicted values, x=Experimental values)

Experimental Numbers	Prediction method	y=f(x)	R^2	RMSE
2	CFD	y=0.9748x-1.1978	0.9987	0.8645
	FD	y=2.6034x-8.5555	0.9938	1.89
5	CFD	y=1.0411x+0.4667	0.9989	0.8685
	FD	y=3.7897x-13.624	0.9976	1.271
8	CFD	y=0.9343x+2.8706	0.9937	2.026
	FD	y=5.5712x-14.407	0.9953	1.758

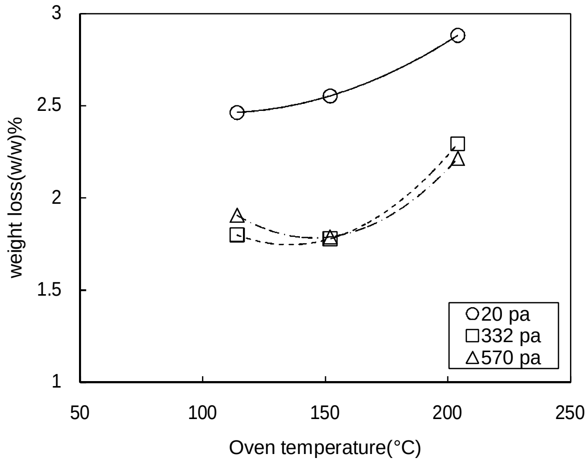


Fig. 4. Effect of pressure and oven temperature on weight loss

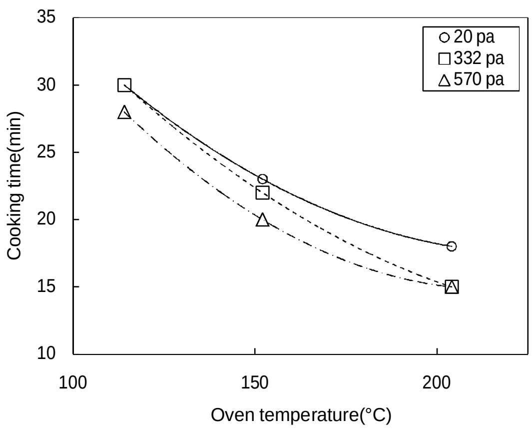


Fig. 5. Effect of pressure and oven temperature on cooking time

Table 6. Empirical equation for weight loss (WL) and cooking time (t) as a function of cooking temperature (T)

P (Pa)	WL=f(T) or t=f(T)	R^2	RMSE
20	$WL=0.0047T+1.89$	0.9484	0.0707
	$WL=55.847e^{-0.006T}$	0.9579	0.0639
	$t=-0.1311T+44.21$	0.966	1.572
	$t=57.54e^{-0.006T}$	0.9873	0.9507
332	$WL=0.0057T+1.057$	0.7945	0.1868
	$WL=1.212e^{-0.003T}$	0.8237	0.1731
	$t=-0.1648T+48.15$	0.9837	1.355
	$t=71.537e^{-0.008T}$	0.9992	0.3085
570	$WL=0.0037T+1.39$	0.5816	0.2008
	$WL=1.449e^{-0.0019T}$	0.6052	0.195
	$t=-0.1416T+43.18$	0.9515	2.042
	$t=59.467e^{-0.007T}$	0.982	1.209

Fig. 7 shows three-dimensional diagram of hamburger temperature which changes according to the thickness and process time. As shown in these figures, when oven temperature is less, sheets are wider at the end of process that represents a more uniform temperature distribution along the thickness of hamburger. While increasing the oven temperature at the end of the cooking process, the temperature distribution along the thickness of the hamburger is less uniform. This behavior could be due to the time required for the cooking process; it means that the more cooking time (in lower oven temperature) the more uniform temperature distribution inside the hamburger. This is especially important when the microbial distribution in hamburger is considered, indicates that if the temperature distribution inside the hamburgers is more uniform (in addition to improving cooking quality of hamburgers), and the possibility of microbial contamination of hamburger will be reduced. So in terms of microbial safety and also product quality it is recommended that the cooking process should preferably be conducted at lower temperatures so that the temperature distribution is more uniform inside the hamburger.

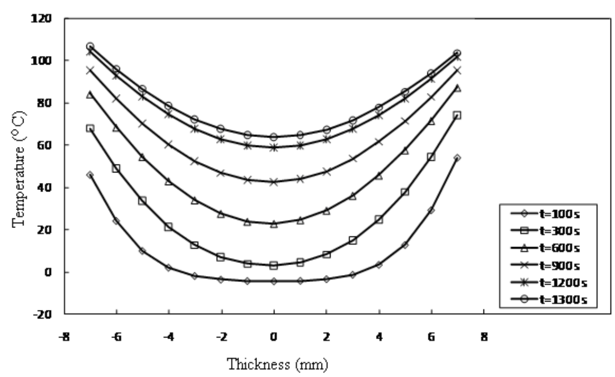
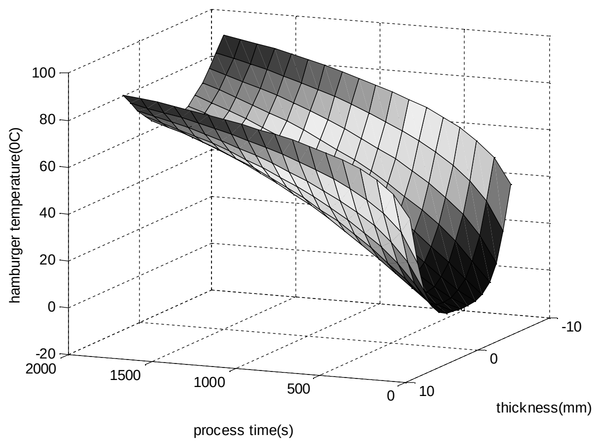
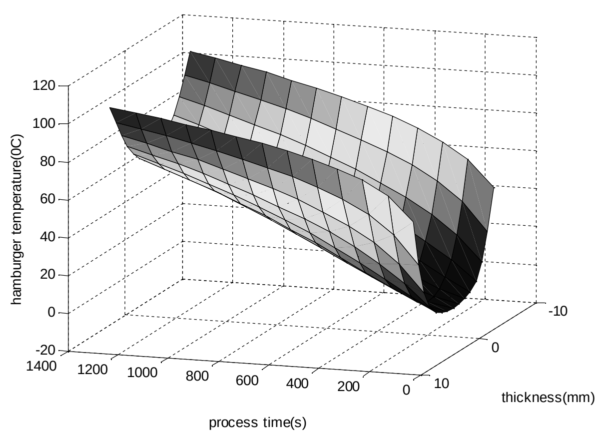


Fig. 6. Hamburger temperature changes along the thickness in different time for test 5 according to the CFD model

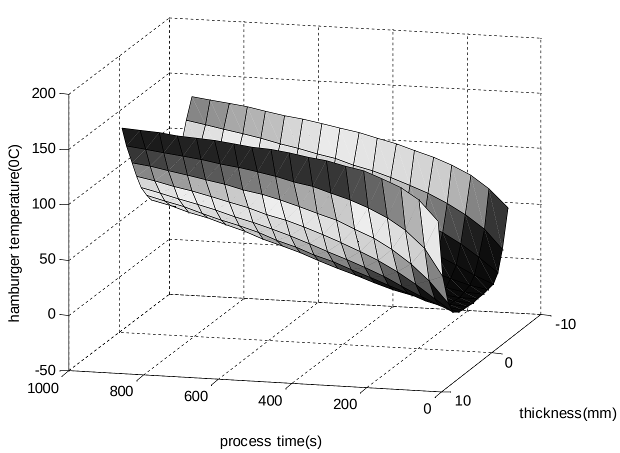
Fig. 8 shows temperature profile on the rectangular page assumed along the thickness of hamburger that its length and width equal to the diameter and thickness of hamburger, respectively. Since conditions on both sides of hamburger are almost non-similar, it is expected that the coldest heating point do not place at the center of the hamburger, visualized in Fig. 6. In general, since the bottom surface temperature of hamburger is more than its top temperature, due to direct contact of bottom copper plate with the oven floor, this point often is placed slightly above the center.



(a)

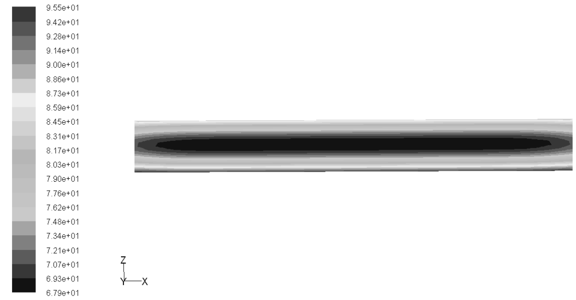


(b)

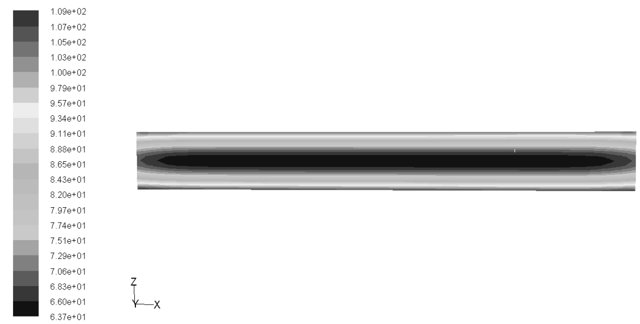


(c)

Fig. 7. Three-dimensional graphs of temperature changes according to process time and thickness in CFD; (a): Exp.2, (b): Exp.5, (c): Exp.8



(a)



(b)

(c)

Fig. 8. Temperature profiles obtained from CFD curves on the page assumed along the thickness of hamburger at the end of cooking process. (Tests in pressure 332 pa); (a): Exp.5, (b): Exp.3, (c): Exp.8

4. Conclusions

A double-sided cooking system was designed to study the effect of pressure and oven temperature on cooking process. Experimental data obtained were compared with the results of CFD and FD models. Predictions of both models were acceptable, but CFD model had better prediction of experimental results, while FD predicted experimental data less than their original values. However, considering the less time needed for the FD simulation than CFD method, FD method would be more economic. The results showed that applying pressure on the surface of hamburgers can reduce weight loss and cooking time. Also by increasing oven temperature weight loss was increased, while cooking time was decreased. Thus an optimum oven temperature in the range of 114°C to 204°C should be selected. Effect of oven temperature on weight loss is more than pressure. Three-dimensional graphs for hamburger temperature versus thickness and cooking times provided a good understanding of the uniformity of temperature distribution inside the hamburgers. Decreasing oven temperature and increasing cooking time can increase uniformity of temperature distribution in the hamburger and therefore, microbial safety will increase as well as product quality.

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Nomenclature

C_p specific heat (J/kg°C)
D hamburger diameter (mm)
h surface heat transfer coefficient (W/m°C)
K thermal conductivity (W/m°C)
K_w water conductivity of hamburger (1/s)
L hamburger thickness (mm)
L_f latent heat of fusion (MJ/m^3)
M hamburger mass (Kg)
m water content (wb)
T temperature (°C)
T_{w0} temperature of water transfer to beginning (°C)
t time (s)
Δt time step (s)
WL weight loss
x distance (m)
Δx node thickness (m)
ρ density of frozen hamburger (kg/m^3)
δ_{we} Coefficient of water holding capacity (1/°C)

Subscripts

0 initial
1,…,12 node numbers
b hamburger bottom
bp bottom plate
c center of hamburger
e equilibrium
f final
i node i
t hamburger top
tp top plate

Superscript

j time numerator

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