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Computational Fluid Dynamics Simulation of Temperature Profiles during Batch Baking

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ABSTRACT

Baking is a process that plays an important role on product quality which is mainly influenced by temperature during a batch baking. Therefore, this project was aimed to develop a computational fluid dynamics (CFD) model to simulate temperature profiles during breadstick baking. By comparing the measured temperature at the different positions of oven with CFD model during baking, the model performance showed the correlation coefficient and mean square error of 0.9989-0.9992 and 35.78-71.50, respectively. Then the CFD model was used to determine temperature change due to variation of baking conditions. According to CFD simulation, baking by radiation and forced convective heat transfer tended to increase uniform temperature of product and reduce baking time, compared with baking by radiation and free convective heat transfer. The obtained information from the model could be used for the optimization of batch baking process in the future.

Key words: CFD, baking, oven, model, simulation

INTRODUCTION

Baking is one of the key processes for bread production. It is a step to change dough which is viscous material to bread crumb and crust, rigid materials. Moreover, the volume is expanded at the beginning of baking. The structural change can be explained by mechanisms of starch gelatinization and evaporation. In addition to the structural change, the color is developed during baking through Maillard reaction and caramelization (Zhou and Therdthai, 2006). These mechanisms can be impacted by temperature. Therefore, understanding how the temperature changes during baking is important to design an optimal baking process and thereby bread qualities. However an experimental trial-error to change baking condition and monitor of the consequent temperature profiles is expensive and time-consuming. Computational fluid dynamics (CFD) model may be an approach to overcome the trial-error problem. The CFD model is a numerical technique for discretising the flow equation into two or three-dimensional space. The solution domain is also divided into small volumes through grid generation step. For computation, the scalar values are determined at the volume centre whereas vector variables are determined on the volume faces (Mathioulakis *et al*., 1998).

CFD model has been used to deal with the complexity of baking oven, such as simulation of pressure inside the duct and oven for prevention of gas leakage inside a heating duct to the oven chamber (Fuhrmann *et al*., 1984), simulation of

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proportion of heat transfer modes (Carvalho and Mertins, 1991), simulation of homogeneity of velocity field affected by a perforated plate (De Vries *et al.*, 1995), Simulation of heat and mass transfer coefficient for improvement of uniformity of product surface during microwave baking (Verboven *et al.*, 2003), and the simulation of heat transfer for optimal design of baking process for a continuous baking oven (Therdthai *et al.*, 2004).

As above mention, CFD is a potential approach for simulating phenomena during baking. So, this project aimed to create CFD model for simulating temperature profiles under different baking conditions of breadstick. It can be used to further explain the obtained bread qualities.

MATERIALS AND METHODS

Material: breadstick dough composed of 33.9% rice flour, 6.3% potato flour, 5.8% cassava flour, 15.5% egg yolk, 4.3% palm oil, 1.8% xanthan gum, 1.7% yeast, 0.9% salt and 23.3% water was mixed for 11 minutes. After proving in an incubator (SIAM INCUBATOR, SIH288AEH) with controlled condition (47.5°C and 90%RH) for 10 minutes, the dough was delivered into a batch baking oven (King Machines).

Method: data logger (ACR SmartReader Plus 6) and type-K thermocouples were used to record temperature profiles within a 0.8m × 0.8m × 1.0m electrical baking oven as shown in Figure 1.The obtained information would be used for CFD model setting and validation.

For modeling, the commercial CFD code (Femlab v3.1) was used to solve a 2-dimensional problem with time dependent state. Boundary condition and initial condition were defined as following equations.

- Convective heat flux, q_a (W/m^2) from the duct wall in the back of oven

$$q_a = h_a\,(T_{duct} - T_{air\_inside\_oven}), \qquad (1)$$

where T_{a0} is the initial temperature of air, Initial condition, $T_{air\_inside\_oven} = T_{a0}$ at $t = 0$ and h_a is convective heat transfer coefficient.

- Radiant heat flux, q_b (W/m^2) from the oven wall and the metal sheet in oven

$$q_b = \sigma\varepsilon[(T_A+273)^4-(T_B+273)^4], \qquad (2)$$

where T_A is heat source temperature (°C), the initial condition, $T_B = T_{B0} = 30$°C at $t = 0$, T_B is heat sink temperature (°C) , ε is emissivity of product and

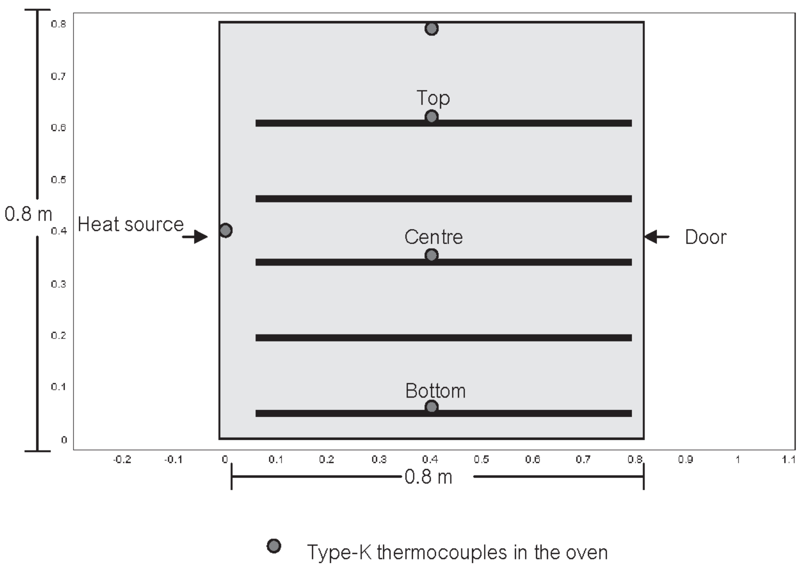

Figure 1 Positions of type-K thermocouples in the oven.

σ is Stefan-Boltzmann constant (5.6697×10^{-8} $W \cdot m^{-2} \cdot K^{-4}$)

- Conductive heat flux, q (W/m^2) through the product

$$q = -\frac{k}{x}\left(T_1 - T_2\right) \quad (3)$$

where k is the thermal conductivity of product (W/m· °C), x is the product thickness (m), and T_1 & T_2 are temperatures (°C) of the position (1) and (2) in the product.

For validation, product temperatures measured by type-K thermocouples at shelf No. 1, 3 and 5 were used to compare with CFD simulated temperature profiles. Difference between the values was defined as error. Mean square error (MSE) and correlation coefficient (r) between measured profiles and simulated profiles were used to evaluate the model performance.

RESULTS AND DISCUSSTION

1. Modeling and validation of temperature profiles during baking

Based on the heat transfer mechanisms including the convective heat transfer from oven wall in the back of the oven and the radiant heat transfer from oven walls and metal sheets in the oven, the boundary condition and initial condition (as shown in Eq.(1), (2) and (3)), a two-dimensional CFD model was developed. Simulation of temperature distribution within a baking oven was clearly presented (Figure 2).

To validate the simulation, air temperatures recorded by type-K thermocouples on shelf No. 1, 3 and 5 throughout the baking process were used to compare with the modeled temperatures, as shown in Figure 3. In addition, the correlation coefficient and MSE were presented in Table 1.

From Table 1, the correlation coefficients were higher than 0.9. It means that the prediction tends to be reasonably correct. However, MSEs of some locations were high. It can be due to under-prediction at the beginning of the process. For the whole baking processes, the two-dimensional CFD model presented reasonable performance, as shown in Figure 3. Therefore, the CFD model would be used for simulation of baking temperature profiles under different baking conditions.

2. Simulation of temperature profiles under different baking operations

The developed CFD model was used to simulate crumb temperature (core temperature) and crust temperature (surface temperature) under six operating conditions by varying temperature (200°C and 225°C) and air flow velocity (0, 1 and 3 m/s). The simulation of temperature profiles was carried out for 360 seconds to complete breadstick baking process (Figures 4 and 5).

In Figure 4b, the variation of crust temperature was significant when dough was baked on different oven shelves at 200°C. Without forced convection, crust temperatures at the top shelf were significant higher than others baked at oven centre and bottom shelf. This was possible due to the domination of radiation mechanism in

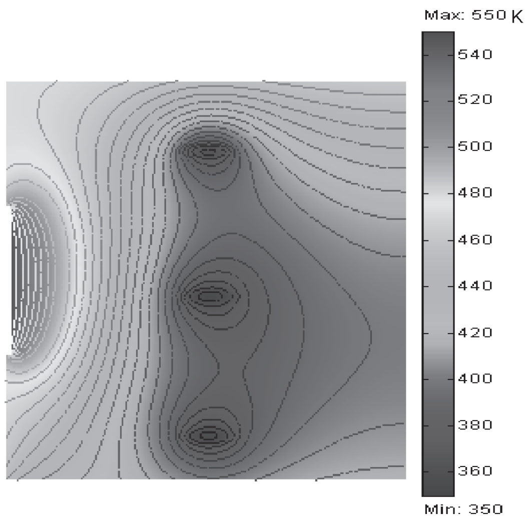

Figure 2 A two-dimensional CFD simulation of baking oven.

the oven. Therefore, top shelf, which was very close to the ceiling, obtained more heat than other shelves did. The amount of heat also presented the same effect on the crumb temperature profiles (Figure 4a). When forced convection was applied, variation of crust and crumb temperature profiles was reduced (Figures 4c-4f).

In addition to the increase uniform temperature of oven, rate of temperature change could be increased. However, the improvement was not significant when velocity was increased from 1 m/s to 3 m/s. By increasing velocity from 1 m/s to 3 m/s, heating rate was increased from 0.11°C/s to 0.12°C/s. The same phenomenon was also found during baking at 225°C (Figure 5).

As the crumb temperature was related to starch gelatinization, baking index could be estimated by the crumb temperature using a kinetic

Table 1 Model performance during oven heating up.

Locations of validation	Correlation coefficient	MSE
Centre of the top tray	0.9992	35.78
Centre of the bottom tray	0.9991	71.50
Centre of the middle tray	0.9989	62.80

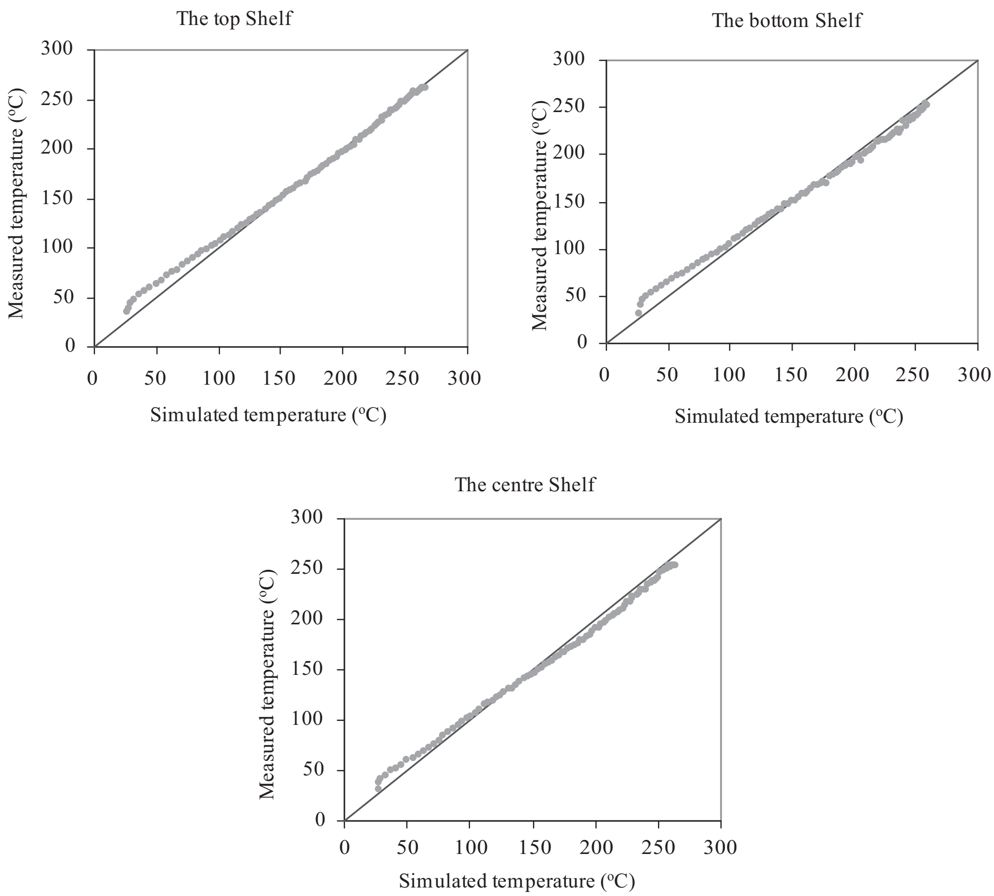

Figure 3 The comparison of simulated and measured temperature during baking at different locations in the oven.

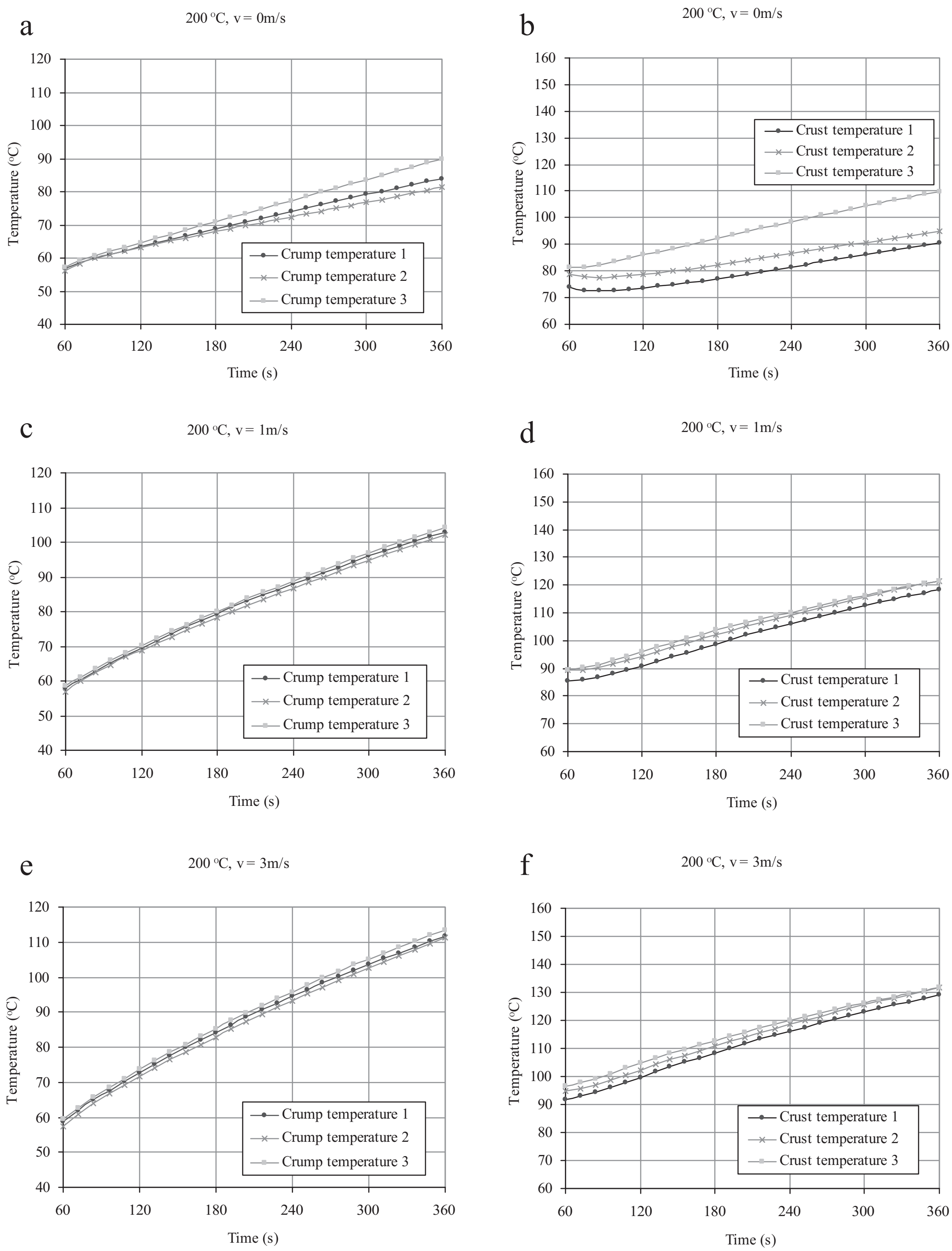

Figure 4 Simulation of crumb and crust temperatures of breadstick baked at 200°C with 0-3 m/s. Crumb temperature 1, 2 and 3 were simulated at bottom shelf, oven centre and top shelf. Crust temperature 1, 2 and 3 were simulated at bottom shelf, oven centre and top shelf.

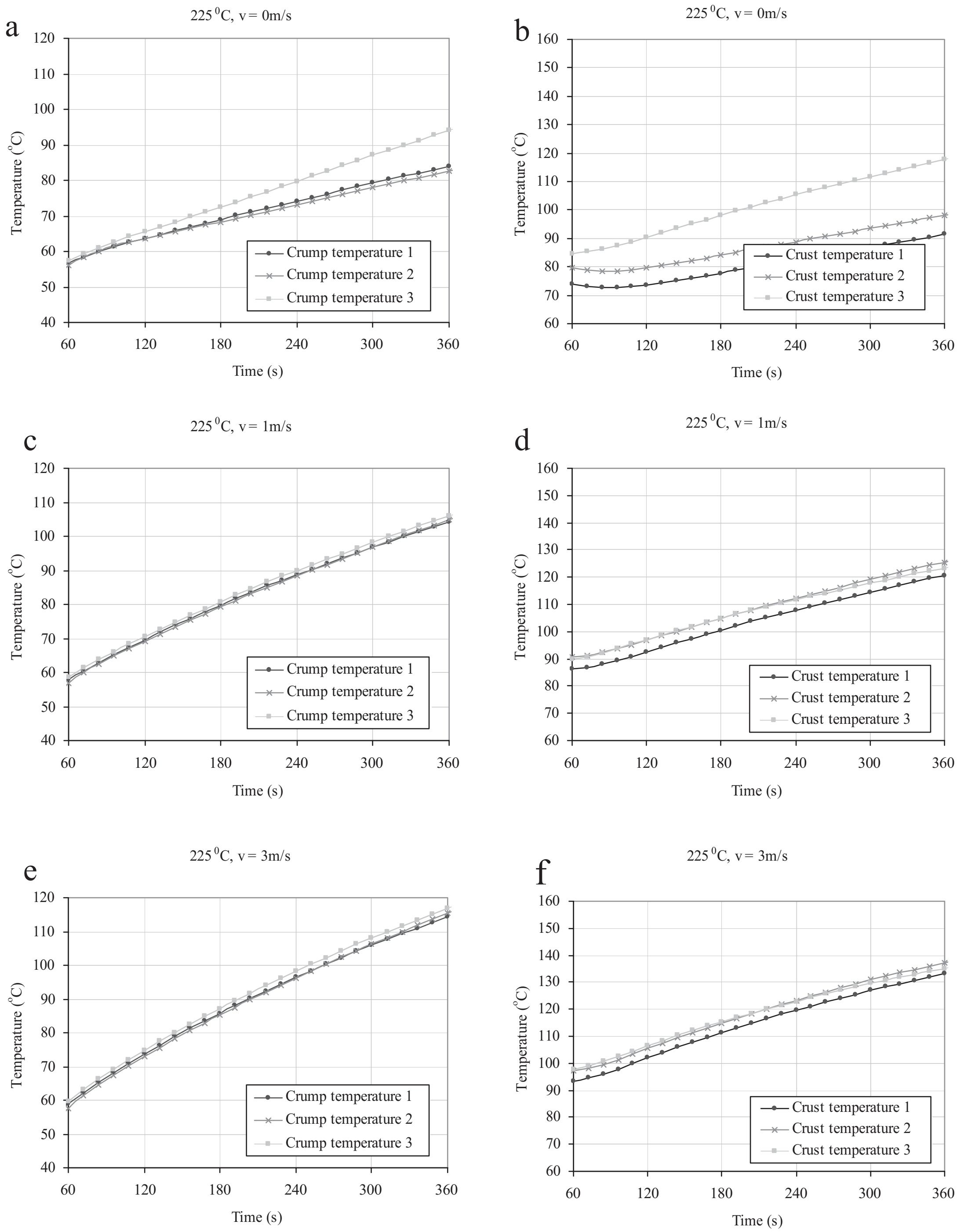

Figure 5 Simulation of crumb and crust temperatures of breadstick baked at 225°C with 0-3 m/s. Crumb temperature 1, 2 and 3 were simulated at bottom shelf, oven centre and top shelf. Crust temperature 1, 2 and 3 were simulated at bottom shelf, oven centre and top shelf.

model (Zanoni *et al*., 1995a). In addition, crust temperature could be used to predict crust color (Zanoni *et al*., 1995b). Therefore, the obtained simulation of the CFD model could be applied to further design the optimal baking operation for improving breadstick quality.

CONCLUSIONS

Two-dimensional CFD model with time dependent state was established to simulate temperature profiles during a batch baking of breadstick. From validation, simulated temperature profiles were reasonably good, compared with the measured temperature profiles. Therefore, the obtained CFD model could be used to simulate temperature profiles from various baking operations. Based on the CFD simulation, the combined mechanism of radiation and forced convection showed the potential to produce uniform temperature of product during baking. In addition, its heating rate was improved by comparing with the combined radiation and free convection.

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