Computational fluid dynamics modeling of bun baking process under different oven load conditions

A. Tank · N. Chhanwal · D. Indrani ·
C. Anandharamakrishnan

Revised: 14 April 2012 / Accepted: 8 May 2012 / Published online: 22 May 2012
© Association of Food Scientists & Technologists (India) 2012

Abstract A computational fluid dynamics (CFD) model was developed to study the temperature profile of the bun during baking process. Evaporation-condensation mechanism and effect of the latent heat during phase change of water was incorporated in this model to represent actual bun baking process. Simulation results were validated with experimental measurements of bun temperature at two different positions. Baking process is completed within 20 min, after the temperature of crumb become stable at 98 °C. Further, this study was extended to investigate the effect of partially (two baking trays) loaded and fully loaded (eight baking trays) oven on temperature profile of bun. Velocity and temperature profile differs in partially loaded and fully loaded oven. Bun placed in top rack showed rapid baking while bun placed in bottom rack showed slower baking due to uneven temperature distribution in the oven. Hence, placement of bun inside the oven affects temperature of bun and consequently, the quality of the product.

Keywords CFD · Bun · Baking process · Evaporation-condensation mechanism

Introduction

Buns are much popular along with sliced bread, but there are variations in taste and sizes globally. Moreover, much popularly

buns are used as a base in burgers or in the form of sweet buns. Bread baking involves various physicochemical and biological transformations; such as evaporation of water, volume expansion, starch gelatinization, protein denaturation and browning reactions that occur simultaneously, which make bread baking a complex process to model (Purlis and Salvadori 2009; Chhanwal et al. 2012). A population balance model for aeration during mixing of dough was used by Martin et al. (2004). Mills et al. (2003) studied bubble formation and stabilization in bread dough during baking process. The structural change also occurs during the bread baking process which consists of solidification and expansion. The network like structure of bread crumb formation is mainly due to starch gelatinization and protein denaturation. Bread baking is considered as an irreversible process, which makes it economically critical; hence, producing consistent good quality bread has always been a great challenge for the bakery industry. Non-uniform heat distribution inside the oven causes variation in the moisture content and colour of bread. These variations in bread quality can be minimized by the proper design of the oven as well as maintaining proper processing conditions such as air temperature (uniform or non-uniform), heating power, baking time and bread size (Therdthai et al. 2003, 2004; Zhou and Therdthai 2007; Wong et al. 2006, 2007). However, many studies have been carried out which emphasize process parameters and oven design to be the major factors responsible for bread quality using simulation tool like computational fluid dynamics (CFD).

CFD is a numerical tool, which can predict fluid flow, heat and mass transfer, chemical reactions and other phenomena by solving set of governing mathematical equations (conservation of mass, momentum and energy) for discretized cells over a defined space and time domain using high computational power (Sun 2007; Kuriakose and Anandharamakrishnan 2010). In recent years, CFD has been applied more and more

A. Tank · N. Chhanwal · C. Anandharamakrishnan (✉)
Human Resource Development, CSIR – Central Food
Technological Research Institute,
Mysore 570 020, India
e-mail: anandharamakrishnan@cftri.res.in

D. Indrani
Flour Milling, Baking and Confectionery Technology,
CSIR – Central Food Technological Research Institute,
Mysore 570 020, India

to the design and development of baking ovens and also to investigate the baking process (Wong et al. 2006, 2007; Zhou and Therdthai 2007; Anishaparvin et al. 2010; Mondal and Datta 2010; Chhanwal et al. 2010, 2011, 2012). Chhanwal et al. (2010) developed a CFD model for the domestic scale electric heating oven to study the temperature profile of bread as well as oven during baking process. They also compared three radiation model i.e. discrete transfer radiation model (DTRM), surface to surface (S2S) and discrete ordinate (DO) and concluded that predictions by all these radiation models were alike. However, DO model has some advantages as it takes into account media participation (air) in addition to surface-to-surface radiation effect. It also allows the solution of radiation at semi-transparent walls. Further, Anishaparvin et al. (2010) studied temperature and air velocity profiles inside a pilot scale electric heating oven using CFD modeling. Discrepancy in an experimental and CFD simulated temperatures for bread center were observed in earlier studies (Wong et al. 2007; Chhanwal et al. 2010; Anishaparvin et al. 2010). Chhanwal et al. (2011) overcame this discrepancy by incorporating evaporation-condensation mechanism in CFD model for bread baking process and formation of two distinct zones i.e. crumb and crust, were well explained on the basis of bread temperature.

Most of the works published on bread baking process without evaporation-condensation mechanisms and only few works have been reported with evaporation-condensation mechanism. But, so far no work has been performed for bun baking process with evaporation-condensation mechanisms. Hence, the present work is aimed to develop a 3D CFD model for the bun baking process in a pilot-scale electrically heated oven using evaporation condensation mechanism within the bun. Further, this work was extended to study the effect of fully and partially loaded oven on bun temperature profile for industrial applications.

Experimental details

Doughs (6 numbers, each weighing 65 g at the time of moulding and placed over a tray) were prepared using a standard recipe consisting of wheat flour (100 %), water (60 %), compressed yeast (2 %), salt (1.5 %), sugar (20 %), and hydrogenated fat (10 %). The dough was prepared by mixing the ingredients in a mixer (Hobart, GmbH, Offenburg, Germany). Subjected to fermentation for 60 min in a chamber maintained at 30 °C and 75 % RH, remixing, dividing (65 g), rounding, proofing for 55 to 60 min at 30 °C, 85 % RH and baking in a pilot-scale electric baking oven (Rotel, APV Inc., Queensland, Australia) oven for 20 min at 200 ± 2 °C.

One of the chambers of a pilot-scale electric heating baking oven, having eight cylindrical chambers (each having radius 56 cm and height 42 cm) with total power of 52 kW was used for this simulation and experimental studies (Fig. 1). Each oven chamber has two racks in top and bottom and nine heating elements made up of sheathed stainless steel, positioned in three layers as shown in Fig. 1. The oven cavity was made up of stainless steel and heating of oven was controlled by a thermostat (located to the right side of the oven chamber), which keeps the heating element under On/Off according to the pre-determined set temperature (i.e. 200 ± 2 °C). Visual monitoring of baking process was possible through the thick glazed glass door. The air vent was at the bottom of the glass door. Temperature inside the oven and bun were measured using calibrated T-type thermocouples, which were connected to data logger (VR-18, Brainchild Electronics Co. Ltd. Taipei, Taiwan). One of the thermocouple was mounted inside the oven near to the bun-tray to measure the oven temperature. Two thermocouples were inserted to the bun dough moulded into a round shape at (i) point-1 i.e. 2.5 cm from top surface of bun dough (ii) point-2 i.e. inserted horizontally at the height of 3.1 cm from top surface and 3.5 cm from side of the bun dough mainly to monitor the temperature of crumb portion. Thermocouples were fixed soon after rounding of dough and before proofing step to avoid any structural collapse and leakage of gas. Experiments were carried out in triplicate and average of these value was used to compare the simulation predictions.

CFD modelling

Figure 1 shows the geometry of single tray loaded oven resembling the experimental conditions. While, Fig. 2 shows the geometry of the partially loaded (two baking tray placed diagonally) and fully loaded oven containing the

Fig. 1 Pilot scale electric heating oven (one chamber shown among eight) and meshed oven geometry

Fig. 2 Oven geometry of partially loaded and fully loaded (eight tray) oven

buns placed in baking trays. CFD simulations were carried out for all the cases (Fig. 2). The surface and the volume mesh were generated using GAMBIT and exported to the Ansys-12 (Fluent) for further processing. Mesh size of oven chamber were optimized and finalized for higher accuracy, and mesh size was dense near trays, buns and coils. Coarse mesh was given for the fully loaded oven in order to reduce the computing time. Coarse mesh normally used to reduce the computational time without compromising the accuracy. Mesh independency study was also carried out and it did not show any significant differences in predictions for the coarse mesh and normal mesh size simulations. The total numbers of cells for partially loaded two trays oven and fully loaded oven were 1.24 million and 1.15 million respectively.

Governing equations

The software Ansys Fluent 12 was used to solve the governing continuity, momentum and energy equations for the defined geometry and associated boundary conditions (Sun 2007). The generalized transport equations solved are

(a) Conservation of mass equation

The continuity equation describes the rate of change of density at a fixed point resulting from the divergence in the mass velocity vector $\rho\vec{v}$. Equation (1) is the unsteady, three-dimensional, mass conservation or continuity equation for the simplified case of a fluid flow.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

where, $\vec{v}$ is velocity vector (m/s), ρ is density (kg/m^3).

(b) Momentum equation

The principles of the conservation of momentum is an application of Newton's Second Law of Motion to an element of fluid and states that a small volume of element moving with the fluid is accelerated because of the force acting upon it.

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot [\mu(\nabla \vec{v} + (\nabla \vec{v})^+)] + S_m \quad (2)$$

where, p is pressure (Pa), μ is dynamic viscosity (kg/m.s) and S_m the body force term (ρg).

(c) Energy equation

The first law of thermodynamics states that the time rate of change of internal energy plus kinetic energy is equal to the rate of heat transfer less the rate of work done by system.

$$\frac{\partial}{\partial t}(\rho C_p T) + \nabla \cdot [\vec{v}(\rho C_p T)] = \nabla \cdot [k \nabla T] + S_T \quad (3)$$

where, k is thermal conductivity, C_p is the specific heat capacity, S_T is source term (W/m^3) represents volumetric heat sources defined for heating coils and T is the temperature (K).

DO radiation model

The DO radiation model solves the radiative transfer equation (RTE) for a finite number of discrete solid angles, each associated with a vector direction fixed in the global Cartesian system. The DO model has following equation

$$\nabla \cdot [I(\vec{r}, \vec{s}) \vec{s}] + (\alpha + \alpha_s) I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} \quad (4)$$

where, I is radiation intensity ($\text{kJ/m}^2 \text{ rad}$), α is gas absorption coefficient ($1/\text{m}$), α_s is absorption coefficient of surface, s is path length (m), σ is Stefan-Boltzmann constant ($\text{W/m}^2 \text{ K}^4$), $\vec{r}$ is position vector, $\vec{s}$ is direction vector, $\vec{s}'$ is scattering direction vector and n is refractive index (Chhanwal et al. 2010, 2012).

Evaporation-condensation mechanism

Simultaneous heat and mass transfer during bread baking is governed by evaporation-condensation mechanism, as shown in Fig. 3. Evaporation-condensation mechanism during bread baking process occurs as per the following steps; (i) water evaporates on the warmer side of the gas cell, absorbing latent heat of vaporization, (ii) migration of water vapor through the gas phase, due to vapor concentration gradient inside the cell, (iii) water vapor condenses on the colder side of the gas cell and becomes liquid, setting free its latent heat and (iv) heat and water were transported by conduction and diffusion respectively, through a dough membrane to the warmer region of the next gas cell, where the processes reiterate. When the gas phase becomes continuous, the fourth stage no longer exists. This evaporation-condensation mechanism takes place until temperature gradient remains and the temperature of the whole crumb reaches 100 °C (Thorvaldsson and Janestad 1999; Wagner et al. 2007; Purlis and Salvadori 2009, 2010; Chhanwal et al. 2012). Maximum moisture loss occurs at the surface of the bread, while moisture at the core region of bread remains unchanged due to evaporation-condensation of water. However, the completion of the baking results in two different zones with unique textures of crumb and crust in bread.

Boundary condition

Thermo-physical and radiative properties of air, steel, nickel and glass were shown in Tables 1 and 2 (Incropera 2006). Air density (change with respect to temperature) with natural convection was given by incompressible ideal gas law, where density depends only on the operating pressure and not on the local relative pressure field. Product (bun) was

Fig. 3 Simultaneous heat and mass transfer mechanism during bread baking process (Chhanwal et al. 2012)

Table 1 Thermo physical properties of the materials used in CFD model (Incropera 2006)

Material	Density [kg/m ³]	Specific heat capacity (C _p) [J/kg K]	Thermal conductivity (k) [W/m K]	Emissivity
Steel	8030	502.48	16.27	0.9
Glass	2225	835	1.4	0.93
Nickel	8900	460.6	91.74	0.85

considered as solid with constant density (245 kg/m³) (Hamdami et al. 2004) and enabled only heat transfer modes with conduction, convection and radiation. Thermo-physical properties of bread such as specific heat and thermal conductivity were incorporated in CFD model as a piecewise linear function of temperature (Chhanwal et al. 2011). Purlis and Salvadori (2009) proposed the specific heat of bread as a function of temperature including enthalpy jump at the phase change. In this study, the same approach of Purlis and Salvadori (2009) was used with specific heat of bread was taken (i.e. Eq. 5) from Zanoni et al. (1995) with constant moisture content ($X_w=0.39$) (Chhanwal et al. 2011):

$$C_p = (0.013T^2 - 0.217T + 4179)X_w + (5T + 1390) \times (1 - X_w) + \lambda(T - T_f, \nabla T) \quad (5)$$

where, T is temperature (°C) from Eq. 3, T_f is temperature of phase change (°C) and $T_f=100$ °C, ∇T is temperature difference in which phase change occurs (°C) and $\nabla T=0.5$ °C, X_w is water content (kg/kg) and λ is latent heat of phase change (J/m³).

Thermal conductivity i.e. k (W/m K) of bread was defined as a function of temperature, where thermal conductivity increases until bun reaches 100 °C and it was brought down to a constant (0.2 W/m K) when condensation starts. Hence, following Eq. (6) accounts for evaporation-condensation mechanism (Purlis and Salvadori 2009, 2010):

$$k(T) = \frac{0.9}{1 + \exp\{-0.1(T - 353.16)\}} + 0.2 \quad \text{if } T \leq 100^\circ\text{C} \\ k(T) = 0.2 \quad \text{if } T \geq 100^\circ\text{C} \quad (6)$$

Table 2 Thermo physical properties of air used in CFD model (Incropera 2006)

Temperature (K)	Specific heat capacity (C _p) [J/kg K]	Thermal conductivity (k) [W/m K]
250	1006	0.0223
300	1007	0.0263
350	1009	0.03
400	1014	0.0338
450	1021	0.0373
500	1030	0.0407

Buns (dimensions: height- 6.1 cm and width i.e. maximum diameter- 8.5 cm) were placed in baking trays equidistance from each other and simulated, with coupled convective heat transfer from hot air and the bun emissivity was considered as 0.9. The discrete ordinates (DO) radiation model was used in this simulation as it takes into account of media participation (air) in addition to surface-to-surface radiation. It also allows the solution of radiation at semi-transparent walls (Chhanwal et al. 2010). The heating coils have been modeled as volumetric heat source i.e. total power supplied is equally distributed among heating coils. A single coil volume and heat source used in the model was $1.5 \times 10^{-4} \text{ m}^3$ and $5.8 \times 10^3 \text{ kW/m}^3$, respectively. Combination of both convective and radiative heat transfer was considered for both glass door and oven walls. Dell workstation T5400 was used for running the CFD simulation. Baking process simulation was carried out for 20 min. Emulating baking process required pre-heating of oven, which was carried out by deactivating bread until air temperature reaches 200°C . The time step size of 1 s was used for the simulation. It took 105 h to compute a single bun baking process. Due to the limitation of the CFD software, volume expansion and moisture transport have been excluded in this study.

Results and discussion

Experimental validation

Figure 4a–b clearly indicates that the simulation results were in good agreement with the experimental measurement of temperature at both the points. Lag phase for first min followed by linear increase in temperature was observed for both the points (Fig. 4a–b). Initially, slow heating and steep rise in temperature followed by formation of plateau was noticed. Maximum temperature of crumb reaches in the

range of $98\text{--}99^\circ\text{C}$ and remains constant. A slight difference between experimental and simulated temperature was observed for point-1 i.e. top point (Fig. 4a). Experimental results for the temperature at point-1 crosses 100°C , which this model fails to replicate due to evaporation-condensation mechanism keeps bun temperature below 100°C (large value of latent heat added into specific heat). The slight variation in the results of the model and experiment may be due to combined effects of experimental and model assumptions as well as thermal properties of materials. All physical process such as evaporation and protein denaturation are maximized, once the crumb temperature reaches $98\text{--}99^\circ\text{C}$. Incorporation of evaporation-condensation mechanism and addition of latent heat during phase change in this model keeps bun crumb temperature below 100°C and similar results were also obtained by Chhanwal et al. (2011) for bread baking process. These predictions were different and more realistic from earlier CFD simulation studies (Therdthai et al. 2003, 2004; Zhou and Therdthai 2007; Wong et al. 2006; Anishaparin et al. 2010; Chhanwal et al. 2010), wherein crumb temperature crosses 100°C and it further increases with baking time.

Velocity and temperature profile of oven

Velocity and temperature profile of the oven was studied for the partially loaded (6 buns and 12 buns) and fully loaded oven conditions (48 buns) which were depicted in Figs. 5 and 6 respectively. Figure 5a–c shows that the non-uniform velocity and swirl flows were observed in case of partially loaded oven, whereas more uniform velocity was obtained for fully loaded oven. Temperature gradient creates natural convection which changes velocity of air flow and consecutively affects heat distribution inside the oven. The non-uniform velocity of air in fully loaded oven was due

Fig. 4 Validation of simulation predictions with experimental results of bun temperature profile during baking cycle at various locations: **a** point-1 (2.5 cm from top surface of the bun) and **b** point-2 (height of 3.1 cm from top and 3.5 cm from side of the bun)

Fig. 5 Comparison of velocity profile of oven: **a** partially (one tray) loaded and **b** partially (two tray) loaded and **c** fully loaded oven at 300 s of baking process

Fig. 6 Comparison of temperature profile of oven: **a** partially (one tray) loaded and **b** partially (two trays) loaded and **c** fully loaded oven at 300 s of baking process

to more number of trays placed. In partially loaded oven less velocity was observed near trays, heating source and buns whereas in case of fully loaded oven it was only observed near to trays and heating source.

Figure 6a shows temperature profile of partially loaded oven in which top portion of oven shows higher temperature as compared to the bottom due to the natural convection and presence of vent at the bottom, which in accordance to earlier observations by Anishaparin et al. (2010). Higher temperature noted at extreme left near to oven wall and right central portion compared to the remaining portion of the oven, which shows non-uniform heat distribution inside oven. This may be due to the arrangement of heating source (heating coils) covering uneven area within the oven cavity and location of vent. Temperature profile of partially (diagonally loaded bun tray) loaded oven was shown in Fig. 6b. It clearly shows different temperature profile than Fig. 6a due to diagonal placement of bun tray. Temperature difference was less between top and bottom portion of oven with diagonal placement of bun tray as compared to oven with single bun tray. Figure 6c shows lower temperature inside the fully loaded oven as compared to partially loaded oven (Fig. 6a–b). Thus, loading of more buns affects heat distribution inside the oven which eventually increases the baking time. Figure 7 depicts the air temperature of the oven (0.5 cm above the bun surface) at top and bottom portion of partially loaded (baking trays placed diagonally) oven. It indicates 25 to 30 °C difference was observed in top and bottom portion of oven.

Fig. 7 Comparison of partially loaded (bun trays placed diagonally) oven temperature during baking process in top and bottom portion of oven

Temperature profile of bun

Temperature profiles of bun at (a) 60 s (b) 240 s (c) 480 s (d) 720 s (e) 960 s and (f) 1,200 s were depicted in Fig. 8. Formation of different temperature layers inside the bun can be visualized during baking process. Bun temperature increased with time and temperature layers moves from bun surface towards the core region. Formation of two distinct zones i.e. crust and crumb, on the basis of temperature were observed. Crumb where temperature remains below 100 °C and where as in the crust it crosses 100 °C and reach to 160°C. Incorporation of evaporation-condensation mechanism and latent heat of phase change of water keeps bun crumb temperature below 100 °C. Temperature at the top surface was higher than the other sides of bun due to the dominance of radiative heat transfer. At 960 s bun center temperature reaches maximum of 98–99 °C and further remains constant whereas surface temperature increases continuously till the end of baking process. Therdthai et al. (2004), Wong et al. (2007) and Chhanwal et al. (2011) also reported higher temperature on top surface of the bread in their simulations of bread baking studies.

Figure 9 shows the surface temperature of buns placed diagonally in top and the bottom tray in oven during baking process. Buns placed in top tray shows higher temperature compared to buns placed in bottom tray. Moreover, the difference was much more noticeable near the end of baking cycle (900 s). Higher surface temperature for top baking tray buns lead to more browning of crust and in turn affect the final quality of bun. Thus, it

Fig. 8 Temperature profile of bun during baking process (partially loaded oven) at (a) 60 s (b) 240 s (c) 480 s (d) 720 s (e) 960 s and (f) 1,200 s

Fig. 9 Bun surface temperature during baking process in partially loaded (bun trays placed diagonally) oven

can be clearly concluded that placement of baking trays will also affect the final quality of buns.

Effect of placement of buns on bun temperature profile in fully loaded oven

Figure 10 shows the effect of bun placement on bun temperature (at centre point) in fully loaded oven. Initially, slow heating and steep rise in temperature

Fig. 10 Comparison of bun centre temperature during the baking cycle for fully loaded oven conditions

followed by formation of plateau was observed for all buns. Buns placed in baking tray-1 shows lowest centre temperature and tray-7 and tray-8 shows highest temperature during baking process. This might be due to the location of tray inside the oven as tray-1 placed in the bottom left of the oven and shows lowest temperature. However, tray-7 and tray-8 placed in top right of the oven shows highest temperature. Difference in centre temperature of bun directly affects baking time and consequently final quality of product. This result underlines the importance of placement of product inside the oven. Major cause for these differences in bun temperature was non-uniform heat distribution inside the oven. This can be minimised or rectified by using rotation of trays and it can be explored in future CFD studies.

Conclusion

A CFD model for the bun baking process was developed by incorporating evaporation-condensation mechanism with latent heat effect. The model predictions were validated with the experimental measurement of bun temperatures at different locations. Maximum temperature of crumb reaches in the range of 98–99 °C and further remains constant. The developed CFD model was extended to study the effect of fully and partially loaded oven for bun baking process. The temperature difference of 25–30 °C was observed in top and bottom zones of the oven cavity. This study clearly indicated that the lowest temperature zone requires almost 3 to 5 min more than the buns placed in the higher temperature zone. This model will help to optimize the final quality of bun by optimizing heat transfer during bun baking process as temperature is the most dominating parameter in affecting its quality. This model succeeded in defining bun crumb and crust temperature on the basis of heat transfer. Finally, it can be concluded that apart from temperature and time, placement of the bun also influences the final quality of product during the baking process in a pilot scale electric heating oven. This problem may be further rectified by rotating trays and thus uniform product quality may be achieved. With the advancement in CFD software, mass transport and volume expansion studies of bun can be studied in the future.

Acknowledgments We wish to acknowledge the Department of Science and Technology (DST), Government of India for the financial support for this work. Authors also acknowledge the CSIR for the financial support through Network project (NWP-02) for Ansys 12 software licensing.

References

- Anishaparvin A, Chhanwal N, Indrani D, Raghavarao KSMS, Anandharamakrishnan C (2010) An investigation of bread baking process in a pilot-scale electrical heating oven using computational fluid dynamics. *J Food Sci* 75:E605–E611
- Chhanwal N, Anishaparvin A, Indrani D, Raghavarao KSMS, Anandharamakrishnan C (2010) Computational fluid dynamics (CFD) modeling of an electrical heating oven for bread-baking process. *J Food Eng* 100:452–460
- Chhanwal N, Indrani D, Raghavarao KSMS, Anandharamakrishnan C (2011) Computational fluid dynamics modeling of bread baking process. *Food Res Int* 44:978–983
- Chhanwal N, Tank A, Raghavarao KSMS, Anandharamakrishnan C (2012) Computational fluid dynamics (CFD) modeling for bread baking process-A review. *Food Bioprocess Technol* 5:1157–1172
- Hamdami N, Monteau JY, Le Bail A (2004) Heat and mass transfer in par-baked bread during freezing. *Food Res Int* 37:477–488
- Incropera (2006) Fundamentals of heat and mass transfer, 6th edn. Wiley, New York
- Kuriakose R, Anandharamakrishnan C (2010) Computational fluid dynamics (CFD) applications in spray drying of food products. *Trends Food Sci Technol* 21:383–398
- Martin PJ, Chin NL, Campbell GM (2004) Aeration during bread dough mixing ii. A population balance model of aeration. *Food Bioprod Process* 82:268–281
- Mills ENC, Wilde PJ, Salt LJ, Skeggs P (2003) Bubble formation and stabilization in bread dough. *Trans IChemE Part C Food Bioprod Process* 81:189–193
- Mondal A, Datta AK (2010) Two-dimensional CFD modeling and simulation of crustless bread baking process. *J Food Eng* 99:166–174
- Purlis E, Salvadori VO (2009) Bread baking as a moving boundary problem. Part 2: model validation and numerical simulation. *J Food Eng* 91:434–442
- Purlis E, Salvadori VO (2010) A moving boundary problem in a food material undergoing volume change – simulation of bread baking. *Food Res Int* 43:949–958
- Sun DW (2007) Computational fluid dynamics in food processing. CRC Press, Boca Raton
- Therdthai N, Zhou W, Adamczak T (2003) Two dimensional CFD modeling and simulation of an industrial continuous bread baking oven. *J Food Eng* 60:211–217
- Therdthai N, Zhou W, Adamczak T (2004) Three-dimensional CFD modeling and simulation of the temperature profiles and airflow patterns during a continuous industrial baking process. *J Food Eng* 65:599–608
- Thorvaldsson K, Janestad H (1999) A model for simultaneous heat, water and vapour diffusion. *J Food Eng* 40:167–172
- Wagner MJ, Lucas T, Le Ray D, Trystram G (2007) Water transport in bread during baking. *J Food Eng* 78:1167–1173
- Wong SY, Zhou W, Hua J (2006) Robustness analysis of CFD model to the uncertainties in its physical properties for a bread baking process. *J Food Eng* 77:784–791
- Wong SY, Zhou W, Hua J (2007) CFD modeling of an industrial continuous bread-baking process involving U-movement. *J Food Eng* 78:888–896
- Zanoni B, Peri C, Gianotti R (1995) Determination of the thermal diffusivity of bread as a function of porosity. *J Food Eng* 26:497–510
- Zhou W, Therdthai N (2007) Three-dimensional modeling of a continuous industrial baking process. In: Sun DW (ed) Computational fluid dynamics in food processing. CRC Press, Boca Raton, pp 287–312