Journal of Food Engineering 99 (2010) 166–174

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Two-dimensional CFD modeling and simulation of crustless bread baking process

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ARTICLE INFO

Article history:
Received 26 June 2009
Received in revised form 14 December 2009
Accepted 14 February 2010
Available online 23 February 2010

Keywords:
Bread
Baking
Crustless
CFD
Modeling
Simulation
Heat transfer
Mass transfer

ABSTRACT

A special type of baking oven was developed where crustless bread was made by gently baking the dough at controlled temperature by spraying water at prefixed intervals on the surface of the dough. In this study, a two-dimensional (2D) CFD model for crustless bread during baking has been developed to facilitate a better understanding of the baking process. Simultaneous heat and mass transfer from the bread during baking was successfully simulated. It was found that core temperature of the bread reached at 95 °C at the end of baking where as moisture of the bread satisfies the normal bread quality. The model can be successively applied to study the unsteady heat and mass transfer from the crustless bread during baking.

1. Introduction

During baking crust develops at the upper surface of the dough as maximum evaporation takes place from that surface (Therdthai et al., 2002). Crustless bread making process is a new technology where bread was made by spraying water gently upon the surface of the dough intermittently at controlled temperature so that surface of the dough does not get hot and no crust forms (Mondal and Datta, in press). Crust formation was avoided as it is proved that bread crust contains acrylamide which is a probable human carcinogen (Ahrne et al., 2007; Brathen and Knutsen, 2005; Granda and Moreira, 2005; http://www.fda.gov). The application of crustless bread in the industry is likely to be far reaching once the technology of crustless bread making process is properly documented. British Food Group RHM launched crustless bread baked by proper baking process. Crustless bread is also available in countries including USA, Italy, and Spain but that is created by cutting the crusts off after baking. Another important consumer research carried out by Sara Lee Bakery Group of USA (http://www.ironkids.com) revealed that 35% of mothers remove the crusts from their children's sandwiches. This wastes up to 45% of the actual loaf. So, crustless bread could lead to significantly lower wastage of loaves as well as better financial return for the bakers. Any attempt to modify or alter the baking process requires an understanding of the physico-chemical changes involved in the process. Experimental and mathematical modeling approaches are often used for this purpose.

Computational fluid dynamics is a simulation tool which uses numerical methods and algorithms to solve and analyze problems that involve fluid flow. However, it is only in the recent decade that CFD has been applied to agri-food based industries. Scott and Richardson (1997), Xia and Sun (2002) and later Norton and Sun (2006) reviewed the general applications of CFD to the food processing industry. From 1990, technical transfer of the CFD approaches to the food industry yields many benefits, e.g. it can reliably predict the likely performance of fluid handling equipment at the design stage. CFD application in the food industry is expanding day by day. Baking is a process of simultaneous transportation of heat, liquid water, and water vapor within the product as well as within the environment inside the baking chamber (Therdthai and Zhou, 2003). During baking, dough experiences changes in physical structure, composition, and thermo-physical properties. Wong et al. (2006) investigated the robustness of a CFD model to changes of physical property of bread. Therdthai et al. (2004) developed three-dimensional CFD model with the first-order kinetic model of starch gelatinization, in order to simulate the gelatinization profiles at different positions within loaves during a continuous baking process. The lack of a good understanding of the baking process in a continuous oven retards the design and implementation of advanced control systems for the oven. Wong et al.

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doi:10.1016/j.jfoodeng.2010.02.015

Nomenclature

A	height of sphere part of bread, m
c	moisture concentration of domain at any time, kg/m^3
c_b	air moisture concentration, kg/m^3
C_m	specific moisture capacity, dimensionless
C_p	specific heat capacity, J/(kg K)
D	diffusion coefficient, m^2/s; height of cylindrical part of bread, m
h	surface heat transfer coefficient, W/(m^2 K)
h_m	mass transfer coefficient (mass units), kg/(m^2 s)
k	conductivity parameters, W/(m K)
k_c	mass transfer coefficient, m/s
k_m	moisture conductivity, kg/(m s)
lda	latent heat of vaporization, J/kg
L	diameter of cylindrical part of bread, m
n	normal vector of the boundary
N	mass flux vector, kg/(m^2 s)
N_0	inward mass flux in normal to the boundary, kg/(m^2 s)
q	heat flux vector, W/m^2
q_0	inward heat flux, W/m^2
R	radius of sphere part of bread, m
t	time, s
T	temperature, K
T_{inf}	external temperature, K
V	volume of bread, m^3

Greek symbols

∇T	temperature gradient inside the bread in K/m
∇c	concentration gradient inside the bread near to the surface in kg/m^3/m
ρ	apparent density, kg/m^3

(2007a) applied a two-dimensional Computational fluid dynamics (CFD) model to the process control design for an industrial continuous bread baking oven. Many researchers used CFD to determine the temperature and air flow pattern in the oven. Therdthai et al. (2003) developed a 2D CFD steady state model to simulate the temperature profile and airflow pattern under different operating conditions including different energy supply and fan volume. Their work was then extended to a three-dimensional (3D) dynamic model with moving grid (Therdthai et al., 2004). The 3D model could describe the different temperature profiles for different moving trays. However, due to the limitation of the software used, the oven configuration had to be simplified, particularly to ignore the U-turn movement of baking tray in the oven. To eliminate some of the existing simplifications and assumptions due to the limitation of computational capacity Wong et al. (2007b) successfully simulated the U-turn movement of bread by dividing the solution domain into two parts, then flipping and aligning them along the traveling tracks. All the above mentioned works are related to design of oven. There are few paper related to direct determination of temperature and moisture profile of bread during baking. Zhang and Datta (2006) developed a model considering multiphase heat and moisture transfer including dough deformation. Based on the hypothesis made by Zanoni et al. (1993) the same author later (Zanoni et al., 1994) developed a mathematical model which describes heat and mass transport phenomena during baking of a cylindrical bread sample. Purlis and Salvadori (2009b) predicted temperature and water content in the bread during baking using finite element method based on a mathematical model considering moving evaporation front, evaporation–condensation mechanism, crust development during baking (Purlis and Salvadori, 2009a). Further information about the state of the art is available in Mondal and Datta, 2008.

Owing to the limitations of FLUENT in modeling simultaneous heat and mass transfer phenomenon as applied to baking, a time-dependent model of the convection baking process of crustless bread was developed using more efficient software COMSOL. COMSOL Multiphysics is a finite element based software with enhanced capabilities and features and is able to model complex food processes such as frying, microwave heating, etc., involving simultaneous heat and mass transfer in which food is considered as a porous medium efficiently. Most CFD based software solves Navier–Stokes equation to calculate velocity and pressure but COMSOL allows incorporation of Darcy's law. Navier–Stokes equation is difficult to solve and since, Darcy flow is valid in case of food (porous media), there is no need to solve the complex Navier–Stokes equation.

Crustless bread was different from the normal bread in terms of making procedure. Water (2 ml/8.6 min interval) was sprayed by specially designed sprayer upon the surface of the dough kept in a special baking oven at controlled temperature (168 °C) to prevent crust formation (Mondal and Datta, in press). Because of spraying water, thermo-physical properties were different from the normal bread, so that heat and mass transfer from the crustless bread during baking is also different from normal bread baking. In this study, a 2D CFD model of bread during baking was developed to simulate the simultaneous heat and mass transfer from the bread during baking. As baking oven was isothermal and air inside the oven was moving at a constant rate (1.5 m/s), simulation was done only for crustless bread. It determines the temperature rise over time in the bread as well as the moisture concentration in the bread, which is defined as the mass of water per volume of bread. Results from this model help to determine the actual baking time of bread as central temperature and moisture of the bread can be determined from this model.

2. Materials and methods

2.1. Experimental method

In this experiment cylindrical moisture boxes made of aluminum were used as baking cups. Each box contained 30 g dough. After full proofing, the boxes were placed below the water nozzles in the crustless bread baking oven, which was preheated to 168 °C. Baking was done for 7, 14, 21, 25, and 30 min respectively. In the mean time 2 ml water was sprayed on the dough at 8.60 min interval. Three thermocouples were placed at the top, centre, and bottom of the dough. The temperature corresponding to respective time of each thermocouple was noted by a temperature indicator. After 7 min, one loaf was removed from the oven for moisture concentration analysis and the oven door was immediately closed. The box was covered immediately to avoid moisture loss. Moisture content of crustless bread was determined by a digital infrared moisture analyzer (Mettler LJ16). Approximately 1 g of bread sample from central portion of bread was dispersed uniformly on the plate and evaporation of moisture was carried out by setting the temperature of the infrared drying chamber of the instrument at 105 °C. Moisture content of the bread was displayed as percentage moisture in wet basis.

Volume and total weight of the crustless bread were also measured at 0, 7, 14, 21, 25, and 30 min of baking time. These properties were measured immediately after removing the bread from

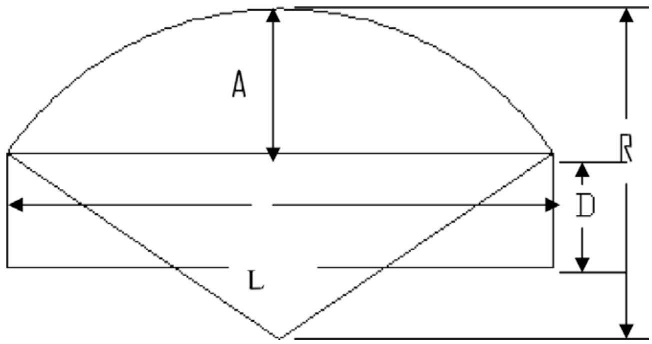

Fig. 1. Schematic diagram of crustless bread.

the oven at predetermined time interval. Apparent density was measured by the well-known formula as follows:

$$\rho = (\text{Totalweight}/\text{Volume}) \tag{1}$$

Volume of the bread was measured by according to bread dimension shown in Fig. 1. Volume of the bread was measured by the following equation:

$$V = \pi R A^2 \left(1 - \frac{A}{3R}\right) + \pi (L/2)^2 D \tag{2}$$

Moisture concentration was determined by multiplying the apparent density value with the moisture content of crumb in wet basis at different baking time.

This procedure was repeated for the remaining three loaves, heated for 14, 21, 25, and 30 min respectively. Three replications were performed at each stages of baking for reducing experimental error.

2.2. Development of model

In any modeling procedure the very first step is to describe the underlying physics of the modeling system. A physical model represents the scientific features of a system being modeled.

As bread baking is a complex phenomena where heat and mass transfer occurs simultaneously, so to simulate the bread baking process a 2D axial symmetry space dimension was selected for developing the model. In the present study a 2D cross section of the dough was considered, instead of 3D since it is axi-symmetric. The reason for selecting such geometry is attributed to the fact that the temperature and moisture variation obtained across this cross section would be the same at points with similar distance from the centre, considered along any section of the bread in the entire area. During bread baking heat transfer occurs by conduction and outside the bread it is by convection. Similarly for mass transfer during baking mass transfers occurs from the bread by only diffusion process. Convective heat transfer due to water migration is neglected and water migration due to Darcian flow (relative to total pressure gradient) is not taken into account.

2.3. Model geometry

Second step of the CFD analysis of bread baking is the design of the system geometry and its discretization into a computational grid of finite elements. For this model, hypothetical bread geometry of size roughly 3.5 cm by 2.5 cm with shoulder height of 1 cm was taken. Bread was considered as a domain and central axis, bottom wall, side wall, and top wall of the bread were considered as boundary 1, boundary 2, boundary 3, and boundary 4 respectively as shown in Fig. 2.

2.4. Mesh generation

The mesh/grid quality plays a significant role in the accuracy and stability of a CFD numerical computation. For a 2D geometry the mesh generator partitions the sub-domains into triangular or quadrilateral mesh elements which contain nodes. If the boundary is curved, these elements represent only an approximation of the original geometry. Each of the element nodes has specific thermal properties of apparent density, thermal conductivity, specific heat capacity, etc. A dense unstructured mesh with triangular elements of appropriate size was generated in COMSOL Multiphysics 3.3a. The mesh is finer near the top surface than elsewhere as maximum heat and mass transfer takes place there. It was done by prescribing maximum local mesh element size by free mesh parameters option. Maximum mesh element size at the boundary 4 was 10^{-3} m. In this problem the meshed domain contains 751 triangular elements. There were no quadrilateral elements. Number of degrees of freedom, mesh points, boundary elements, vertex elements were 3152, 413, 73, and 4 respectively. Minimum meshed element quality is 0.7541 whereas element area ratio is 0.069. As meshed element quality is >0.3, mesh quality will not affect solution quality. The meshed dough has been shown in Fig. 2.

2.5. Thermal properties

Apparent density, specific heat, thermal conductivity of crustless bread made by spraying water measured independently following well established methods. Density was measured using Eq. (1) and specific heat and thermal conductivity of crustless bread was measured by heater insertion method and line heat source method respectively (Mondal, 2009). From the experimental data polynomial relationship between apparent density, specific heat capacity and thermal conductivity with time was established as follows:

$$\rho = 2.388 \times c - 0.1677 \times t + 2.253 \times 10^{-4} \times t^2 - 7.533 \times 10^{-8} \times t^3 \tag{3}$$

$$C_P = 14.25 \times c - 0.2788 \times t + 7.048 \times 10^{-4} \times t^2 - 3.176 \times 10^{-7} \times t^3 \tag{4}$$

$$k = 1.092 \times 10^{-3} \times c - 2.424 \times 10^{-4} \times t + 3.415 \times 10^{-7} \times t^2 - 1.175 \times 10^{-10} \times t^3 \tag{5}$$

The values assigned for the various other model parameters required for the simulation are listed in Table 1, while some of these were derived from experimental data and formulations given in Geankoplis (1993) and Sebaibi et al. (2003). Other (e.g. latent heat) were taken from the literature.

2.6. Description of the theoretical model

The mathematical description of the transport processes in the bread during baking outlined above led to a system of partial differential equations. However, to simplify the solution process, some assumptions were made which are described in the following sections.

2.6.1. Hypotheses

The following valid simplified assumptions were made to develop the model for geometry shown in Fig. 2:

(i) Effect of spraying water on the dough was neglected due to limitation of computational capacity of used software.

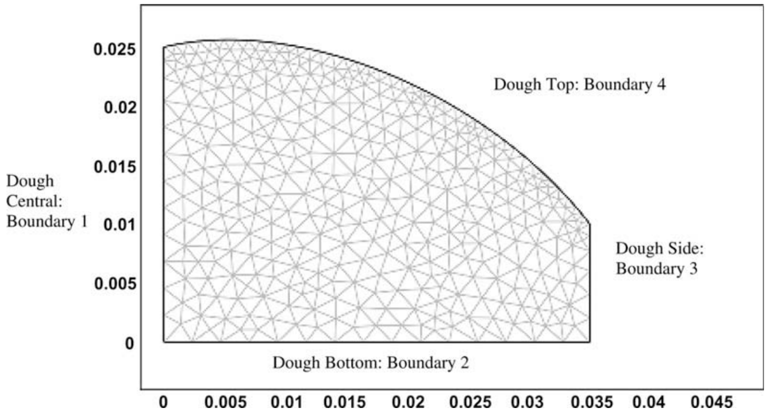

Fig. 2. 2D Geometry of the dough developed in COMSOL Multiphysics.

Table 1
Various constants and process variables assigned to the baking model in COMSOL.

Description	Value
Oven air temperature	168 (°C) at boundary 4
Bottom temperature	165 (°C) at boundary 2
Side Temperature	145 (°C) at boundary 3
Initial temperature of dough	30 (°C)
Heat transfer coefficient	5.5 [W/(m^2 K)] at boundary 2,3 15 [W/ (m^2 K)] at boundary 4
Initial moisture concentration	218.26 (kg/m^3)
Initial air moisture concentration	0.034 (kg/m^3)
Specific moisture capacity (C_m)	0.7323
Inward flux	0.0002 (kg/m^2 s)
Moisture conductivity (k_m)	1.53×10^{-6} [kg/(m s)]
Mass transfer coefficient in mass unit (h_m)	5.09×10^{-4} [kg/(m^2·s)]
Mass transfer coefficient	$h_m/(\rho \times C_m)$
Surface moisture diffusivity	5×10^{-10} (m^2/s)
Latent heat of vaporization	2.3×10^6 (J/kg)

(ii) Heat transfer in the bread was governed by both conduction and convection mechanism, neglecting the radiation effect in the bread as the added heat transfer due to radiation was assumed to have been nullified by intermittent spraying of water.
(iii) Mass transfer from side and bottom surface of the bread was neglected. It occurs only from the top surface.
(iv) The effects of CO_2 transport and water vapor transport leading to volume expansion during the baking process was neglected.

2.6.2. Governing equations

The following set of equations that governed the heat and mass transfer in the developed model was solved in the COMSOL Multiphysics 3.3a (COMSOL Multiphysics: user's guide). The mathematical model for heat transfer by conduction in the bread domain is the following version of simple heat balance equation:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = 0 \quad (6)$$

Mass transfer is a diffusion process, so the generic diffusion equation has the same structure as the heat equation. Diffusion is governed by the following equation:

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D\nabla c) = 0 \quad (7)$$

2.6.3. Boundary conditions

The relevant boundary conditions with respect to oven condition in the model were supplied depending upon the required output of the model. To simulate the heat and mass transfer under constant condition of oven air, the surrounding air outside the domain was maintained at constant temperature. Also air moisture concentration outside the domain also the same throughout baking time. For boundary 1 which is axial symmetry, there is no heat and mass transfer. Heat transfer occurs simultaneously from boundaries 2, 3, and 4 respectively. So heat flux was applied for above mentioned boundaries with the following general formulation:

$$-n \cdot q = q_0 + h(T_{\inf} - T) \quad (8)$$

q is defined by the following equation:

$$q = -k\nabla T \quad (9)$$

It is already assumed that mass transfer occurs only from top surface, so for boundaries 2 and 3 q_0 is zero but for boundary 4 where mass transfer also occurs q_0 is defined by the following equation:

$$q_0 = -k\_c \times lda \times (c - c_b) \quad (10)$$

The term $h(T_{\inf} - T)$ models convective heat transfer with the surrounding environment. The value of h depends on the geometry and the ambient flow conditions.

For diffusion process the following general formula for boundary 4 was used:

$$D\nabla c \cdot n = N_0 - k_c(c - c_b) \quad (11)$$

Bottom and side surface of the bread was insulated.

2.7. Solver setting

The computation was performed on Pentium-IV personal computer (PC) having 1 GB random access memory (RAM) with the help of commercially available software COMSOL Multiphysics 3.3a. A time step of 5 s for second order element and fully implicit scheme was used for solving the model. The process was simulated for a total baking time of 1800 s (30 min). The direct UMFPACK solver of COMSOL Multiphysics has been used to compute the solution. The solver takes 5.89 s to simulate the process.

3. Results and discussion

3.1. Temperature at different location of the bread during baking

The most interesting result from this simulation is the time required to heat the dough from room temperature (30 °C) to at least 90 °C throughout the entire dough. It is important because it is well known fact that baking completes when centre of the dough reaches 90–95 °C temperature (Cauvain, 2003). The middle section of the dough takes the highest time to reach this temperature. The model shows that at oven air temperature of 168 °C, baking time of 1650 s was required to reach a centre temperature of 90 °C. Fig. 3 shows how the temperature increases over time at the geometrical centre of the bread. Centre temperature of the dough slowly increases from 30 to 90 °C almost in a linear way throughout the baking period as heat covers the longest way to reach centre of the dough from all sides of the dough. At the end of baking centre temperature reaches to 94 °C. The top surface (top position of boundary 1) of the bread reaches 90 °C when baking time is around 1140 s. Fig. 4 shows how the temperature increases over time at the top surface of the bread. It shows that temperature of the top surface of the dough increases almost in an exponential way to 104 °C at the end of baking. It is important to see that top surface temperature does not go above 110 °C during baking so that no crust forms (Wahlby and Skjoldebrand, 2002). From this simulation it is observed that surface temperature remains below 110 °C at the end of baking. So there is no development of crust. Bottom surface of the bread reaches 90 °C when baking time is around 1400 s. It can be seen that temperature at the bottom surface reaches 102 °C at the end of baking. Fig. 5 shows how the temperature increases over time at the bottom surface of the bread. As temperature remains below 110 °C, there is no development of crust at this surface also.

3.2. Temperature profile across crustless bread at different time of baking

The nodal solution for the temperature variation across the vertical section of crustless bread at different time viz., 7, 14, 21, and 30 min of baking are represented in Fig. 6–9 respectively in surface diagrams in this section. From Figs. 6–9, it can be seen that temperatures increase slowly towards central portion of bread. Fig. 6 shows that when top surface of the bread reaches 75 °C the central temperature of bread is around 41 °C. Fig. 7 and 8 show how temperature increases towards central portion of the bread as time progress. Fig. 8 shows that after 21 min of baking when top surface reaches around 94–104 °C then, central temperature of the bread is around 76 °C. Baking completes when the temperature in the interior of the bread reaches around 90 °C. At the end of baking i.e. at around 30 min of baking (shown in Fig. 9) when top and side surface temperature remains around 105 to115 °C, at that time temperature of central portion reaches 94 °C. It is found that overall top surface temperature remains around or below 112 °C, so there is no development of crust. It can be observed that the model well

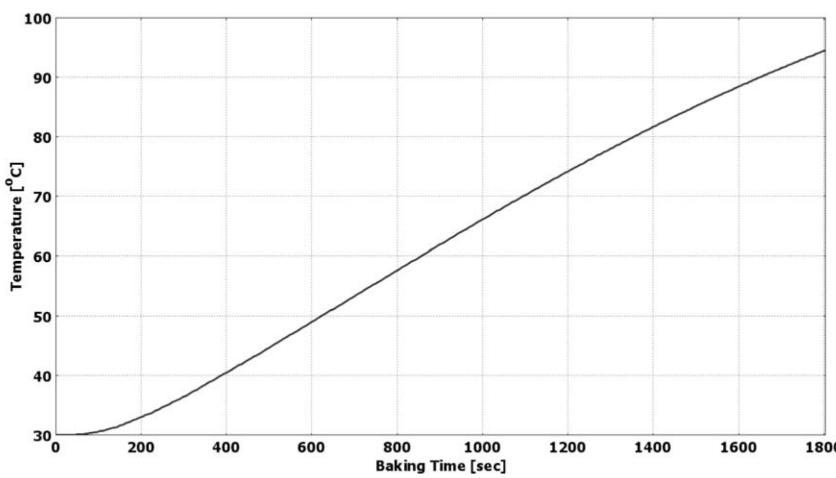

Fig. 3. Temperature increase over time in the centre of the dough at an air temperature of 168 °C.

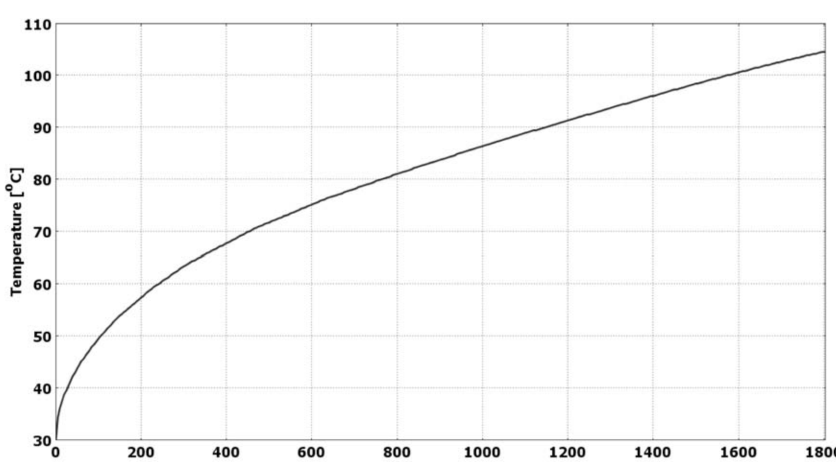

Fig. 4. Temperature increase over time at the top surface of the dough at an air temperature of 168 °C.

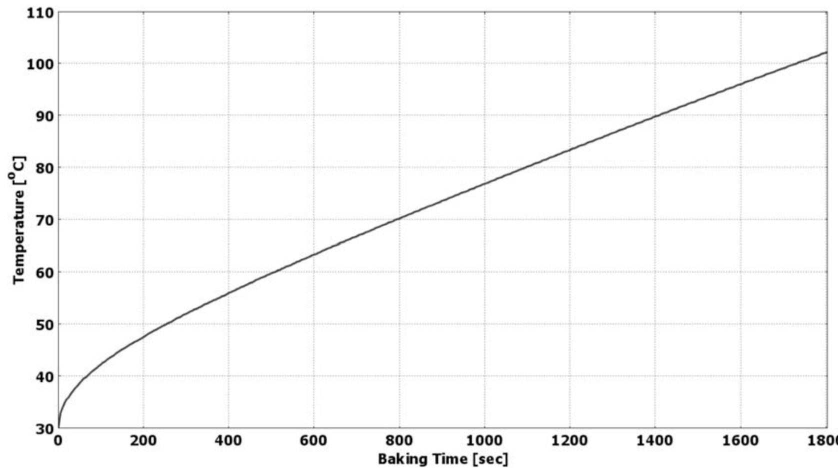

Fig. 5. Temperature increase over time at the bottom of the dough at an air temperature of 168 °C.

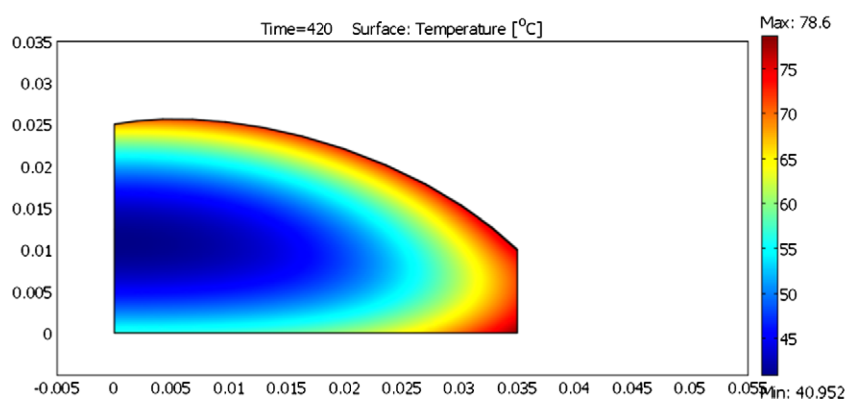

Fig. 6. Simulated temperature profile of bread at 7 min baking.

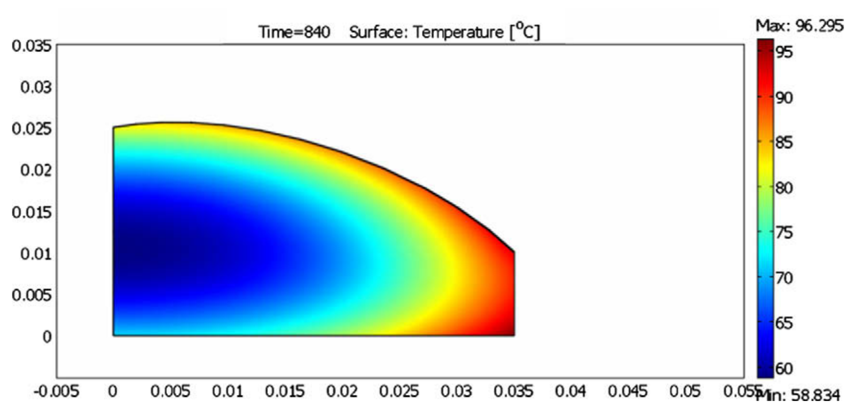

Fig. 7. Simulated temperature profile of bread at 14 min baking.

portrays the temperature profile of actual bread baking conditions and it fulfills the aim behind crustless bread baking modeling.

3.3. Moisture profile across crustless bread at different time of baking

The nodal solution for the moisture variation across the vertical section of crustless bread at different time viz., 7, 14, 21, and 30 min of baking are represented in Fig. 10–13 respectively in surface diagrams in this section. It was well established that water content in the centre of the bread is the same as dough after baking as heat transfer in the bread occurs according to Watt principle. The water vapor evaporates at the hot end of pore and condenses at the cold end, closer to the centre of bread. As expected all the figures show that convective loss of moisture in combination with high temperature at the surface boundary results in a lower moisture concentration compared to its inner parts. As surface temperature is higher than the other surfaces at this place partial water vapor pressure is far from saturation. Water vapor from this surface diffuses into the air and the surface starts to dry out. Under the surface where there is still liquid water, water probably evap-

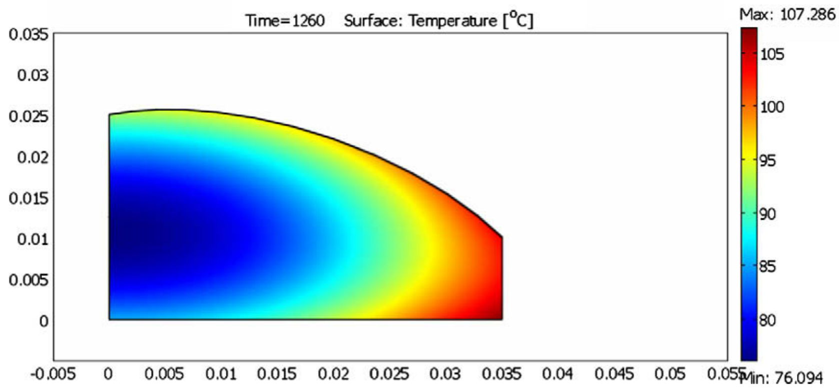

Fig. 8. Simulated temperature profile of bread at 21 min baking.

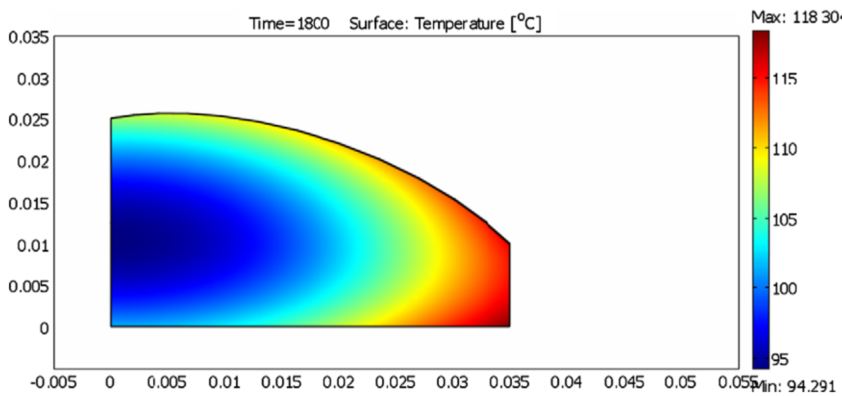

Fig. 9. Simulated temperature profile of bread at 30 min baking.

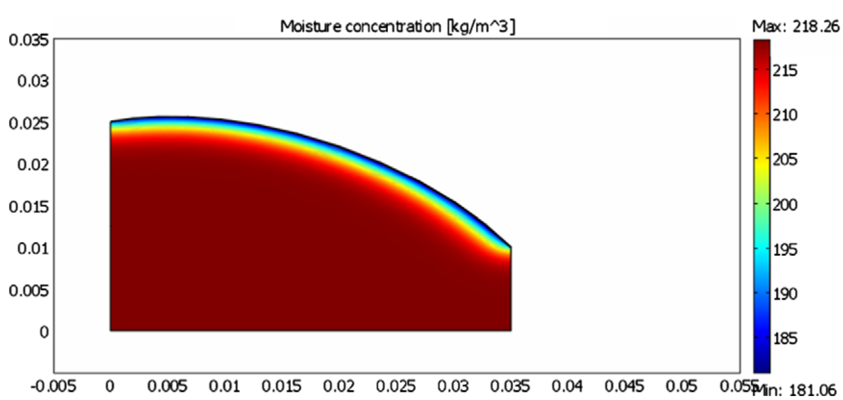

Fig. 10. Simulated moisture profile of bread at 7 min baking.

orates to saturate the partial water vapor pressure. The water vapor diffuses away towards the surface, or towards the centre, and more water evaporates until there is no liquid water left. A drying zone is developed, which slowly increases in size (shown in Figs. 10–13). Fig. 10 shows that surface moisture concentration decreased from 218.26 to 181.06 kg/m^3 after 7 min of baking. As time progresses surface moisture decreases and drying zone increases as explained. After 14 and 21 min of baking surface moisture decreases to 165.07 and 156.05 kg/m^3 (shown in Fig. 11 and 12). At the end of baking surface moisture remains at 146.64 kg/m^3 (shown in Fig. 13).

It was also interesting to see that moisture removal rate is higher during first 7 min of baking when surface temperature increases sharply so that moisture removal rate is also high. As time progresses, moisture removal rate becomes lower with decrease in surface temperature deviation and also for moisture replacement at the surface from time to time to prevent the surface from crust development. It was also found that there is no difference between the water content of crumb with dough at the end of baking which agrees with the result found by Zanoni et al. (1993).

3.4. Validation of the model with experimental results

It was found during experimental measurements for temperature during bread baking that at the end of baking the centre temperature increases to around 95 °C, while that of top and bottom

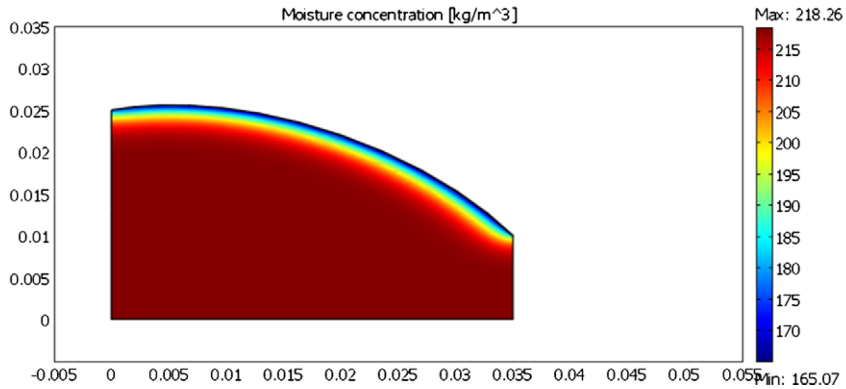

Fig. 11. Simulated moisture profile of bread at 14 min baking.

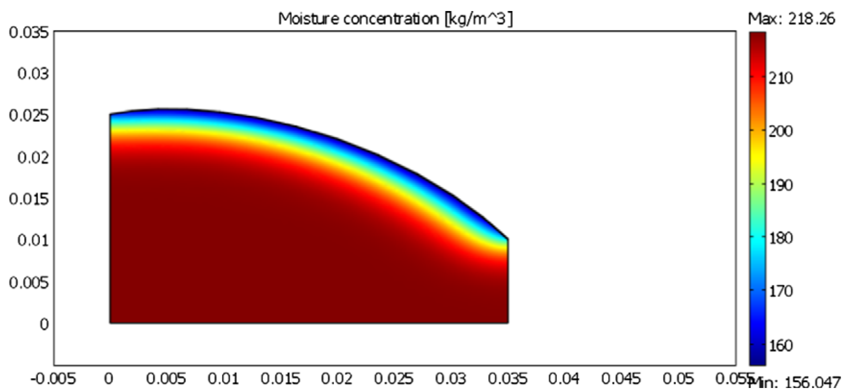

Fig. 12. Simulated moisture profile of bread at 21 min baking.

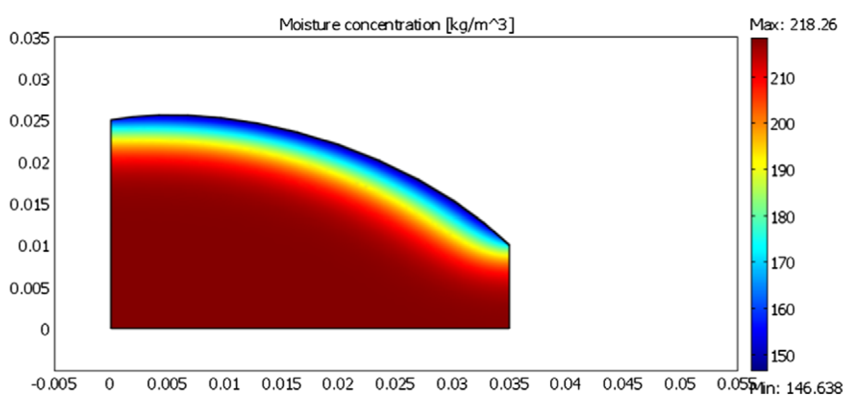

Fig. 13. Simulated moisture profile of bread at 30 min baking.

surfaces increases to a temperature of the order of 112 and 102 °C. This is closely similar to the results predicted by the model solution obtained from COMSOL simulation. Experimentally average moisture concentration of the crustless bread decreases from 218.26 kg/m^3 to around 204.73 kg/m^3 at the end of 30 min baking, while simulated moisture profile shows it decrease from 218.26 to 210.27 kg/m^3. The results for temperature and moisture profile as predicted by the simulation are in close conjunction with the experimental data. So it can be concluded that simulated model is in good agreement with the experimental results and is able to predict very well the pattern of temperature and moisture profile during bread baking process. Hence the model can be successfully applied to baking or for the design of baking process, optimization of baking oven conditions, etc., to obtain a better quality product and more efficient process.

4. Conclusions

A 2D CFD model for crustless bread has been developed. The direct UMFPACK solver of COMSOL Multiphysics has been used to compute the general heat and mass transfer from the crustless bread during baking. It was found that simulated model was able to predict very well the pattern of temperature and moisture profile during bread baking process. In general the model can be successfully applied to baking or for the design of baking process, optimization of baking oven conditions, etc., to obtain a better quality product and more efficient process.

References

Ahrne, L., Andersson, C., Floberg, P., Rosen, J., Lingnert, H., 2007. Effect of crust temperature and water content on acrylamide formation during baking of white bread: Steam and falling temperature baking. LWT – Food Science and Technology 40 (10), 1708–1715.

Brathen, E., Knutsen, S.H., 2005. Effect of temperature and time on the formation of acrylamide in starch based and cereal model system, flat breads and bread. Food Chemistry 92 (4), 693–700.

Cauvain, S.P., 2003. Bread Making–Improving Quality. CRC Press, New York.

COMSOL Multiphysics 3.3a. COMSOL User's Guide. COMSOL Inc., Los Angeles, CA, USA.

Geankoplis, C.J., 1993. Transport Processes and Unit Operations. Prentice Hall-Gale, New Jersey, USA.

Granda, C., Moreira, R.G., 2005. Kinetics of acrylamide formation during traditional and vacuum frying of potato chips. Journal of Food Process Engineering 28, 478–493.

Mondal, A., 2009. Development of Process Technology for Baking of Crustless Bread. Unpublished Ph.D. Thesis (submitted to Indian Institute of Technology Kharagpur, India).

Mondal, A., Datta, A.K., 2008. Bread baking – a review. Journal of Food Engineering 86, 465–474.

Mondal, A., Datta, A.K. (in press). Investigation of the effects of process parameters using response surface methodology on the quality of crustless bread baked in a water spraying oven. Journal of Food Process Engineering.

Norton, T., Sun, Da-W., 2006. Computational fluid dynamics (CFD) – an effective and efficient design and analysis tool for the food industry: a review. Trends in Food Science and Technology 17 (11), 600–620.

Purlis, E., Salvadori, V., 2009a. Bread baking as a moving boundary problem. Part 1: mathematical modeling. Journal of Food Engineering 91 (3), 428–433.

Purlis, E., Salvadori, V., 2009b. Bread baking as a moving boundary problem. Part 2: model validation and numerical simulation. Journal of Food Engineering 91 (3), 434–442.

Scott, G., Richardson, P., 1997. The application of computational fluid dynamics in the food industry. Trends in Food Science and Technology 8 (4), 119–124.

Sebaibi, Y., Dheilly, R.M., Queneudec, M., 2003. Study of water-retention capacity of a lime–sand mortar: influence of the physicochemical characteristics of the lime. Cement and Concrete Research 33 (5), 689–696.

Therdthai, N., Zhou, W., 2003. Recent advances in the studies of bread baking process and their impact on the bread baking technology. Food Science and Technology Research 9 (3), 219–226.

Therdthai, N., Zhou, W., Adamczak, T., 2002. Optimisation of the temperature profile in bread baking. Journal of Food Engineering 55 (1), 41–48.

Therdthai, N., Zhou, W., Adamczak, T., 2003. Two-dimensional CFD modelling and simulation of an industrial continuous bread baking oven. Journal of Food Engineering 60 (2), 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. Journal of Food Engineering 65 (4), 599–608.

Wahlby, U., Skjoldebrand, C., 2002. Reheating characteristics of crust formed on buns, and crust formation. Journal of Food Engineering 53 (2), 177–184.

Wong, Shin-Yee, Zhou, Weibiao, Hua, Jinsong, 2006. Robustness analysis of CFD model to the uncertainties in its physical properties for a bread baking process. Journal of Food Engineering 77 (4), 784–791.

Wong, Shin-Yee, Zhou, Weibiao, Hua, Jinsong, 2007a. Designing process controller for a continuous bread baking process based on CFD modeling. Journal of Food Engineering 81 (3), 523–534.

Wong, Shin-Yee, Zhou, Weibiao, Hua, Jinsong, 2007b. CFD modeling of an industrial continuous bread-baking process involving U-movement. Journal of Food Engineering 78 (3), 888–896.

Xia, B., Sun, D.W., 2002. Applications of computational fluid dynamics (CFD) in the food industry: a review. Computers and Electronics in Agriculture 34, 5–24.

Zanoni, B., Peri, C., Pierucci, S., 1993. A study of the bread-baking process. I: A phenomenological model. Journal of Food Engineering 19 (4), 389–398.

Zanoni, B., Pierucci, S., Peri, C., 1994. Study of bread baking process – II. Mathematical modeling. Journal of Food Engineering 23 (3), 321–336.

Zhang, J., Datta, A.K., 2006. Mathematical modeling of bread baking process. Journal of Food Engineering 75 (1), 78–89.