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Bread baking and its color kinetics modeled by the spatial reaction engineering approach (S-REA)

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ABSTRACT

Baking is a relatively complex process involving simultaneous heat and mass transfer coupled with reactions and structural changes. An accurate and physically-meaningful model of baking is useful to assist process design and product quality improvement. The reaction engineering approach (REA), which has been proven to accurately model the drying rate of porous foods, is implemented here to describe the local evaporation/condensation rate during bread baking for the first time. The REA is coupled with a set of equations of conservation of heat and mass transfer to yield the spatial reaction engineering approach (S-REA). The results of modeling match well with the experimental data. The S-REA can also model the browning kinetics during bread baking accurately. The S-REA is readily implemented for process design by implementing it in computational fluid dynamics (CFD)-environment. The S-REA can also be used for optimization to determine baking trajectories to achieve the desired product properties.

1. Introduction

Baking is one of the most common unit operations in food processing involving simultaneous heat, mass transfer and reactions. Prediction of baking performance is relatively difficult since the mechanisms of baking process, particularly the chemical reactions, are still not fully understood (Mondal & Datta, 2008). The baking process is complicated because the engineering description on the relationships between volume change, temperature and distribution of moisture content is still not clear (Zhang & Datta, 2006). The local evaporation rate during baking may be affected by crumb and crust formation, volume expansion, shrinkage, starch gelatinization and protein denaturation (Altamirano-Fortoul, Le-Bail, Chevallier, & Rosell, 2012; Lostie, Peczalski, Andrieu, & Laurent, 2002a,b). Rheological parameters, including viscosity and elasticity, play an important role in determining dough structure. Starch gelatinization tends to solidify the walls of air bubbles which affect the extensibility of dough and increase pressure in closed cells (Mondal & Datta, 2008).

De Vries, Sluimer, and Bloksma (1989) explained that the mechanisms of baking process include water evaporation on the warmer side of bubble cells, vapor migration across the cells, water vapor condensation on the cooler side of the bubble cells and diffusion of liquid water to the warmer adjacent gas cells. The process mentioned above occurs as far as there is a temperature gradient inside the sample (De Vries et al., 1989). It is further explained that conduction may not be the only heat transport mechanism inside the sample; the evaporation/condensation transport should be involved in the heat transport considering the time-scale of heat transport of the baking process (De Vries et al., 1989). Savoye, Trystram, Duquenoy, Brunet, and Marchin (1992) proposed other mechanisms of baking process which involve condensation, drying and boiling. The surface temperature of the product increases as a result of conduction, convection and radiation. The moisture content inside the product will instantly approach the surface moisture content (Savoye et al., 1992). However, this may only be applied for the case when internal resistance can be neglected (Zanoni, Pierucci, & Peri, 1994).

Study of baking is important to assist in maintaining product quality during baking. Consumer preference of bread is often deduced by texture and aroma closely related to change in surface color of bread. For example, the acceptable average of *L* value of crust color of bread is between 54 and 62 (Therdthai, Zhou, & Adamczak, 2002). The color change, usually as a result of Maillard reactions and caramelization, is more severe at high temperature (Zanoni, Peri, & Gianotti, 1995). The rate of color change is relatively complex since it is affected by water activity, heat transfer mode, temperature and air velocity (Mundt & Wedzicha, 2007; Wahlby & Skjoldebrand, 2002). The Maillard reactions and caramelization, resulted from degradation of sugar, are affected by temperature, pH, reagents and water activity (Zanoni et al., 1995).

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Several mathematical models have been proposed and implemented to describe baking processes (De Cindio & Correra, 1995; Lucas et al., 2015; Purlis & Salvadori, 2007, 2009; Thorvaldsson & Skjoldebrand, 1998; Zanoni et al., 1994; Zhang & Datta, 2006; Zhang, Datta, & Mukherjee, 2005). The liquid diffusion model coupled energy conservation was used to describe the baking process and a good agreement towards the experimental data was shown (Zanoni et al., 1994; De Cindio & Correra, 1995; Thorvaldsson & Skjoldebrand, 1998). Purlis and Salvadori (2009, 2010) employed a classical diffusion equation which assumes liquid diffusion governs the transport from the core to the evaporation front and vapor diffusion controls the transport from the front to the bread surface. A detailed mechanistic modeling based on liquid diffusion, vapor diffusion, capillary flow and evaporation/condensation was implemented by Zhang et al. (2005) and Zhang and Datta (2006). Although evaporation/condensation was incorporated in the modeling, the local equilibrium between moisture content in the matrix and concentration of water vapor inside a void space was assumed in the modeling. Therefore, no explicit expression of local evaporation/condensation rate was presented and the local concentration of water vapor during baking was not shown (Zhang & Datta, 2006; Zhang et al., 2005). Similarly, Lucas et al. (2015) conducted comprehensive mathematical modeling of baking using diffusion–evaporation–condensation by incorporating the effects of open and closed pores inside the samples but the local equilibrium was also assumed.

The use of non-equilibrium multiphase heat and mass transfer model is useful since it is more general than the equilibrium one and can be used to assess the applicability of the equilibrium modeling. However, the model requires explicit expression of the local evaporation rate (Chen, 2007; Putranto & Chen, 2015; Zhang & Datta, 2004). Recently, Putranto and Chen (2015) indicated that the non-equilibrium multiphase model was more suitable to describe several challenging drying process. The parameters of local evaporation/condensation rate should be easy to be predicted and derived from simple experiments (Papasidero, Manenti, & Pierucci, 2015). Due to its accuracy to describe the global evaporation rate of several challenging heat and mass transfer processes (Chen & Putranto, 2013), the REA (reaction engineering approach) may be an appropriate expression to describe the local evaporation/condensation rate of bread baking. The REA parameters describing the local rates i.e. the relative activation energy are easy to be established since the relative activation energy can be generated from one accurate run (Chen & Putranto, 2013). The combination of the reaction engineering approach (REA) and a set of heat and mass conservation equations yields the spatial reaction engineering approach (S-REA) which has been shown to model convective and intermittent drying accurately (Putranto & Chen, 2013a,b,c). Nevertheless, the REA may have a challenge to model the local evaporation/condensation rate during baking since it may be affected by crumb and crust formation, volume expansion, shrinkage, starch gelatinization and protein denaturation (Altamirano-Fortoul et al., 2012). In addition, the transport of liquid and vapor inside the pore structure may be complex since water may evaporate in one end of pore and condense in another end of pore (Luyten, Plijter, & van Vliet, 2004).

For describing the surface color change during baking, several models have been proposed (Han & Floros, 1998; Mundt & Wedzicha, 2007; Tan & Zhou, 2003, 2008). Empirical polynomial model relating color change with heating temperature and time was implemented by Han and Floros (1998). First order reaction kinetic was commonly used to describe the browning kinetics during baking of bread (Broyart, Trystram, & Duquenoy, 1998; Tan & Zhou, 2003, 2008; Zanoni et al., 1995). Zanoni et al. (1995) proposed a model relating the browning kinetics with surface temperature while Broyart et al. (1998) developed a model relating the lightness with moisture content and/or temperature. Similarly, Tan and Zhou (2003, 2008) employed first order kinetics model in which the reaction constants were made to be dependent on the surface temperature and/or moisture content. Nevertheless, to the best of our knowledge, there has been no model which employs directly surface moisture content and/or temperature predicted by mechanistic modeling of heat and mass transfer to estimate the browning kinetics during bread baking.

In this study, the S-REA is attempted to model the bread baking and quality changes of bread by implementing the REA to describe local evaporation/condensation rate. This study is aimed to evaluate the applicability of the REA to model local evaporation/condensation rate during baking, assess the accuracy of the S-REA to describe the bread baking and employ the results of modeling to estimate the browning kinetics. The predictions of surface moisture content and temperature from the S-REA are used to estimate the browning kinetics during baking. The outline of the paper is as follows: the experimental details are reviewed briefly, followed up by mathematical modeling. The S-REA is then implemented for bread baking process and its quality changes during baking. A relevant discussion is provided subsequently. A brief review of the REA is provided in Appendix A.

2. Review of experimental details

The accuracy of the S-REA is validated against the experimental data of Banooni et al. (2008a,b);,Banooni, Hosseinalipour, Mujumdar, Taheran, and Mashaiekhi (2008b)) and Banooni et al. (2008b). For better understanding of the modeling implemented, the experimental details of Banooni et al. (2008a,b) are reviewed briefly here. Baking experiments were carried out in a laboratory oven with active length and width of belt of 1 and 0.72 m respectively. The oven was equipped with an electrical heater and a temperature control. The dough was mixed, divided into pieces of 250 g and kept for 15 min then shaped and punched to produce flat bread with initial thickness of 0.2 cm (Banooni et al., 2008a). The samples of bread were put in the belt of an oven in which high velocity of heated air impinged into the surface of the samples. The air was propelled by a centrifugal fan and directed into the samples through 'fingers' with the jet holes of 1.2 cm. The velocity of air was 1–10 $m \cdot s^{-1}$. During the bread baking, the online system monitored the weight of the samples and Pt-100 probes were used to measure the top and bottom surface temperatures of the samples (Banooni et al., 2008a,b).

In order to monitor volume changes during baking, a digital camera was placed horizontally and photos were taken every 30 s for 25 min. Bread surface color was measured every 30 s by a digital camera and processed using an image processing technique. From photos taken by a digital camera, Matlab® in RGB system was used to calculate the surface color. The color space was then converted from RGB to XYZ. The calculation of conversion was provided in published literature (Dogan, 2000). Subsequently, the color space was converted to $L^*a^*b^*$ using the correlations (Banooni et al., 2008b). L^* indicates the lightness (range of 0–100, black to white), a^* is in the range of −120 and 120 (green to red) and b^* is in the range of −120 to 120 (blue to yellow). The total color change was then calculated subsequently with initial values of L^*, a^* and b^* being 92, −2 and 31 respectively (Banooni et al., 2008b).

3. Mathematical modeling of bread baking using the spatial reaction engineering approach (S-REA)

The details of the reaction engineering approach (REA) have been published previously (Chen & Putranto, 2013) and summarized in Appendix A. In this section, the adaptation of REA to spatially-distributed cases i.e. S-REA (spatial reaction engineering approach) for modeling the bread baking is explained. Based on the experiments of Banooni et al. (2008a,b) summarized above, the S-REA is set up. It consists of a set of equations of conservation of mass and heat transfer using the REA to describe the local evaporation/condensation rate.