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A mechanistic model for baking of unleavened aerated food

Ganesan Narsimhan*

Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, United States

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ABSTRACT

A mechanistic model for baking of unleavened aerated food is proposed. The aerated food was assumed to consist initially of uniformly distributed same sized bubbles. The liquid medium was assumed to be Newtonian. Bubble coalescence, nucleation of bubbles and formation of interconnected channels were neglected. Unsteady state heat conduction and moisture diffusion equations were solved to obtain the evolution of temperature, moisture and air volume fraction profiles as well as cake rise. Consistent with experimental observations reported in the literature, the height of aerated food was found to increase with time, reach a maximum and decreased at longer times. The cake rise was found to be faster and larger at higher oven temperatures and for aerated food of higher initial air fraction and larger sugar content. The model predictions of cake rise agreed fairly well with the experimental data of Pernell, Luck, Foegeding, & Daubert, 2002 for fitted initial air volume fractions with the agreement being better at longer times for decreasing air volume fractions. The calculated air volume fraction profiles indicated an expanded inner region of more or less uniform density and a denser surface crust region whose thickness increased with baking time.

1. Introduction

Baking is a common operation that is employed to make a variety of food products. Examples of some baked foods include cakes, muffins, bread etc. The common feature of these baked goods is that air or carbon dioxide (or a mixture of the two) are incorporated in the food matrix either by mechanical or other means before the dispersion is subjected to baking in an oven. These products can be subdivided into unleavened and leavened baked foods. In unleavened foods, only air is incorporated by mechanical means before baking. In the following we limit our discussion to unleavened baked products. The composition of the matrix into which air is incorporated will depend on the type of food and particular food formulation and usually contains sugar, starch, protein and water.

Phenomenological models for baking have been developed in which simultaneous heat and mass transfer during baking are described by unsteady state heat conduction and diffusion (Fan, Mitchell, & Blanshard, 1999; Feyissa, Gernaey, Ashokkumar, & Adler-Nissen, 2011; Sakin, Kaymak-Ertekin, & Ilicali, 2007; Zhang & Datta, 2006) accounting for evaporation of moisture. Some of these models (Lostie, Peczalski, Andrieu, & Laurent, 2002b; Zhang & Datta, 2006) give a general phenomenological formulation that accounts for the diffusion of liquid water and water vapor as well as pressure flow of air through a polyphasic material during baking. The actual heterogeneous and polyphasic material was assumed to be a continuous medium characterized by equivalent transport properties. Zhang and Datta (2006) also considered the viscoelastic nature of the medium in their analysis. Some other models (Lostie, Peczalski, & Andrieu, 2004; Purlis & Salvadori, 2009, 2010) assumed bread to consist of a crumb and a crust region with a moving interface at which evaporation of moisture is assumed to occur. Heat and mass transfer equations were then solved for this system with a moving boundary. Comprehensive reviews on baking (Mondal & Datta, 2008; Sablani, Marcotte, Baik, & Castagne, 1998) give salient features of various models that have been proposed.

Lostie, Peczalski, Andrieu, and Laurent (2002a) measured the temperature and moisture profile as well as cake rise for sponge cake made by baking in a natural convection oven and found that the cake height increases with time reaches a maximum followed by shrinkage. Similar observation was also reported by Pernell et al. (2002) for angel food cake stabilized by whey or egg white proteins. Cakes containing whey protein isolate produced higher volumes than those containing egg white protein though the latter retained cake volume better. The rheological properties of these formulations as a function of G' and G'' vs temperature reported by Pernell et al. (2002) show that G' and G'' decrease with temperature until one reaches the protein denaturation temperature above which they start increasing as a result of gelation. The temperature profile

* Tel.: +1 765 430 8136.
E-mail address: narsimha@purdue.edu.

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within the cake as measured by Lostie et al. (2002a) at 1500 s is steep with the interior of the cake close to room temperature. At longer times, however, the interior temperature increases and the profile becomes more uniform. Even at 15,000 s, the temperature within the cake does not exceed 100 °C for most of the region because of relatively poor heat transfer from the oven. Video images of batter during baking (Lostie et al., 2002a) indicate clearly the surface crust region and an interior crum region. The crust region is dense with less voids and the crum region is fluffier with more voids. Confocal microscopy images of batter foam (Berry, Yang, & Foegeding, 2009) during baking indicated that bubbles become polyhedral separated by thin aqueous films when heated to 45 °C and above in case of egg white protein stabilized foam. On the other hand, bubble expansion was found to lead to coalescence of polyhedral foams at higher temperature in case of whey protein isolate stabilized batter. Interestingly, system consisting of a mixture of egg white and whey protein isolate was found to behave similar to whey protein isolate system irrespective of the composition.

In this manuscript, a mechanistic model for baking of unleavened aerated food is proposed. The proposed model does not have any adjustable parameters. The model accounts for the changes in rheological properties of the batter as a function of temperature and predicts bubble expansion in aerated food as a result of heating as well as moisture evaporation as well as moisture loss due to evaporation from the surface. The model is also able to predict the evolution of cake rise as well as density profile. The formulation of the model is given in the next section. The effects of different variables on the evolution of moisture and density profile as well as cake rise are discussed in the subsequent section.

2. Model formulation

Baking will lead to an increase in the temperature of the dispersion due to heat transfer (either by natural or forced convection, depending on the type of oven) from the oven. This, in turn, lead to (a) increase in the viscosity of the matrix due to gelation of protein such as whey, egg white and gluten that may be included in the formulation and/or starch gelatinization. (b) expansion of incorporated air bubbles (c) evaporation of moisture from the batter into the bubbles as temperature increases and (d) loss of moisture from the dispersion due to evaporation from the surface. Therefore, baking involves simultaneous heat and mass transfer in the food dispersion. Since the food dispersion is not mixed during baking, heat and mass transfer are usually by conduction and diffusion respectively. As a result, temperature and moisture profiles will be setup within the food (see schematic in Fig. 1).

Let us consider a rectangular aerated food consisting of equal sized bubbles of radius a and volume fraction φ. It is assumed that the bubbles are distributed uniformly. If the volume fraction of the bubbles is less than 0.74, the liquid food can be considered as

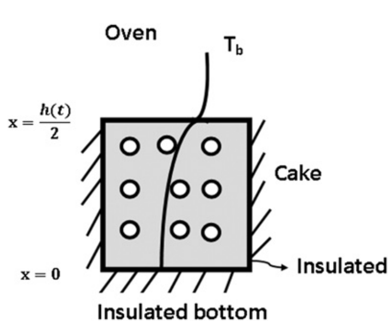

Fig. 1. Schematic of one dimensional heat transfer in aerated food.

air–liquid dispersion consisting of uniform size spherical bubbles. On the other hand, if the volume fraction of air in the aerated food is greater than 0.74 so that the air bubbles are deformed into polyhedra, the liquid food is a foam. As will be seen later, even if the liquid food is a dispersion to begin with, in the course of baking, the air volume fraction increases because of (i) bubble expansion due to increase in temperature and (ii) loss of liquid during baking. As a result, the liquid dispersion may become foam during baking.

This liquid food of uniform initial temperature T_0 is exposed to an ambient temperature T_b in an oven during baking. The length, width and thickness of the sample are L, W and h_0 respectively (Fig. 1). It is assumed that $h_0 << W$ and $h_0 << L$ so that heat transfer can be considered one dimensional along x direction. $x = 0$ refers to the axis of symmetry with $x = h_0/2$ referring to the surface. This will also be applicable to situation in which the second surface is insulated (instead of surface of symmetry).

Following assumptions are made in the model:

1. The aerated food is unleavened and initially consists of air bubbles of the same size that are uniformly distributed.
2. The liquid medium is Newtonian. The experimental data of complex viscosity of the *viscoelastic* medium at different temperatures is employed to describe its *equivalent* Newtonian behavior.
3. The gas phase consisting of air and water vapor is always dispersed consisting of spherical bubbles, i.e. bubble coalescence is neglected. Consequently, the formation of interconnected channels and the resulting transport of air and water vapor through these channels to the atmosphere are neglected.
4. The water vapor in the gas phase (bubbles) is assumed to be in equilibrium with the liquid phase. In the present analysis, the partial pressure (water activity) of water in the vapor phase is given by Raoults law for binary liquid solution consisting of water and sugar. This can be generalized by assuming appropriate moisture adsorption equilibrium.
5. The moisture diffusion coefficient through the liquid medium is inversely proportional to its viscosity.
6. The nucleation of water vapor bubbles in the liquid medium is neglected. This assumption is reasonable so long as the temperature of aerated food during baking does not approach the boiling point of water, i.e. the oven temperature is not very high.

Unsteady state heat conduction equation through the sample is described by,

$$\frac{\partial}{\partial t}\left[T + \left(\frac{\Delta H \gamma_2 x_2 P^{sat}(T)\varphi}{\rho_{eff} c_{p,eff}\left(P + 2\gamma/R_{bub}\right)}\right)\right] = \alpha_{eff}\frac{\partial^2 T}{\partial x^2} \quad (1)$$

where T is the sample temperature at any location x at time t, k_{eff} is the effective thermal conductivity of the sample, $c_{p,eff}$ is the effective heat capacity of the sample and α_{eff} is the thermal diffusivity of the sample. The first term within the parenthesis on the left hand side is the sensible heat and the second term is the latent heat corresponding to the evaporation of moisture from the liquid phase into the air bubbles. Here, ΔH is the latent heat of evaporation per mole of moisture and the pressure inside an air bubble of radius R_{bub} is $(P + 2\gamma/R_{bub})$ where P is the pressure and γ is the surface tension, the second term representing the capillary pressure. For bubble sizes of the order of 0.1–1 mm or larger that is encountered in baked food, the capillary pressure is usually negligible. One can assume that the vapor is an ideal gas in equilibrium with the solution so that the partial pressure of solvent (water) in the vapor $p_2(T)$ at temperature $T$is given by,