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A mechanistic model for baking of leavened aerated food

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ABSTRACT

A mechanistic model for baking of leavened aerated food is proposed. The model accounts for heat conduction, moisture diffusion, diffusion of CO_2 that is produced by fermentation, and the resistance to bubble expansion by the viscoelasticity of the dough which is described by Oldroyd B constitutive equation. Unsteady state heat conduction and moisture diffusion equations are solved accounting for bubble expansion due to heating, evaporation of moisture as well as diffusion of CO_2 that is produced by fermentation to obtain the evolution of temperature, moisture and air volume fraction profiles as well as dough rise. The bubble expansion due to CO_2 diffusion is coupled to temperature and moisture profiles. The model predicts that the growth of bubble exhibits a lag time followed by an exponential growth phase consistent with experimental observations. Eventhough the surface region is more expanded initially, at longer times, it is found to be more dense. The calculated air volume fraction profiles at longer times indicated an expanded inner region of more or less uniform density and a denser surface crust region of decreasing air volume fraction (or increasing density). The thickness of the crust region is found to increase with baking time. The average air volume fraction is found to increase with time because of the combined effects of air expansion as well as CO_2 diffusion. The model predictions of dough rise as well as force exerted by the rising dough compare well with the experimental data (Singh and Bhattacharya, 2005; Romano et al., 2007).

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, and bread. 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 leavened foods, CO_2 is produced either due to fermentation or by chemical reaction during proofing followed by baking. In unleavened foods, only air is incorporated by mechanical means before baking.

Baking has been described by phenomenological models in which simultaneous heat and mass transfer during baking have been modeled by unsteady state heat conduction and diffusion (Fan et al., 1999; Zhang and Datta, 2006; Sakin et al., 2007; Feyissa et al., 2011) accounting for evaporation of moisture. A general phenomenological formulation (Lostie et al., 2002; Zhang and Datta, 2006) has been presented for the diffusion of liquid water and water vapor as well as pressure flow of air through a polyphasic material during baking. Bread is modeled to consist of a crumb and a crust region with a moving interface (Lostie et al., 2004; Purlis and Salvadori, 2009; Purlis and Salvadori, 2010) at which evaporation of moisture is assumed to occur. Salient features of various models that have been proposed can be found in comprehensive reviews on baking (Sablani et al., 1998; Mondal and Datta, 2008). In an earlier work (Narsimhan, 2013), a model for baking of unleavened food was developed. Unsteady state heat conduction and moisture diffusion equations were solved accounting for bubble expansion due to heating as well as evaporation of moisture to obtain the evolution of temperature, moisture and air volume fraction profiles as well as cake rise.

Growth of bubbles during proofing and baking occurs as a result of diffusion of the CO_2 that is generated by fermentation through the viscoelastic dough into the bubbles (Chiotellis and Campbell, 2003) and bubble expansion also occurs due to heating during baking. The resistance from the surrounding viscoelastic medium has to be overcome by the expanding bubble. Consequently, the bubble growth involves coupled momentum, heat and mass transfer leading to a highly non-linear moving boundary problem. Scriven (1959) was the first to describe the growth of bubbles in an infinite medium of Newtonian liquid. Two types of simplifications have been made in his analysis. In the first, mass transfer was replaced by the imposition of constant pressure difference across the bubble

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Nomenclature

A_{max}	preexponential factor for the fermentation reaction for the production of CO_2
$c_{p,eff}$	effective heat capacity of aerated food
D	diffusion coefficient of CO_2
D_{eff}	effective moisture diffusivity through dough
E	activation energy for the fermentation reaction for the production of CO_2
$h(t)$	height of sample at time t
H	Henry's law constant
k_{eff}	effective thermal conductivity of dough
K_s	constant in Monod equation for the rate of production of CO_2
N_{CO_2}	Number of moles of CO_2 in bubble
p_a	atmospheric pressure
p_{CO_2}	partial pressure of CO_2 inside the bubble
p_g	gas pressure inside the bubble
R	bubble radius
R_0	initial bubble radius
$\dot{R}$	rate of growth of bubble radius
R_g	gas constant
T	temperature
T_0	initial temperature of the food
T_b	oven temperature
x	distance from the bottom of the sample
x_2	mole fraction of solvent in the dough
y_2	mole fraction of moisture in the bubble
α_{eff}	effective thermal diffusivity
γ_2	activity coefficient of water in dough
ϕ	volume fraction of vapor in dough
ϕ_0	initial volume fraction of vapor in dough
ϕ^*	dimensionless vapor volume fraction
λ	relaxation time for viscoelastic dough
μ_{max}	maximum growth rate
μ_p	dough viscosity
μ	solvent viscosity
σ	surface tension
ρ_{eff}	bulk density of aerated food
τ_{rr}	radial normal stress
$\tau_{\theta\theta}$	normal stress along tangential direction on a radial plane
$Ca = \frac{\mu D}{\sigma R_0}$	Capillary number
$De = \frac{\lambda D}{R_0^2}$	Deborrah number
$\mathrm{Re} = \frac{\rho D}{\mu}$	Reynolds number
$\beta = \frac{\mu_s}{\mu}$	viscosity ratio
$c^* = cD/\mu_{max}R_0^2$	dimensionless CO_2 concentration
$k^* = kR_gT$	dimensionless Henry's law constant
$p^*_{CO_2} = R_0^2 p_{CO_2}/\mu D$	dimensionless partial pressure of CO_2
$r^* = r/R_0$	dimensionless radial coordinate
$R^* = R/R_0$	dimensionless bubble radius
$\dot{R}^* = (R_0\dot{R}/D)$	dimensionless rate of growth of bubble radius
$t^* = Dt/R_0^2$	dimensionless time
$\mu^*_{max} = \frac{\mu_{max}R_0^4 R_g T}{\mu D^2}$	dimensionless maximum growth rate
$\tau^*_{rr} = R_0^2\tau_{rr}/\mu D$	dimensionless radial normal stress
$\tau^*_{\theta\theta} = R_0^2\tau_{\theta\theta}/\mu D$	dimensionless normal stress along tangential direction on a radial plane

surface thus reducing the problem to that of momentum transfer in a viscoelastic medium (Scriven, 1959; street, 1968; Papanastasiou et al., 1984; Kim, 1994; Huang and Kokini, 1999). In the second, the growth of bubbles was assumed to be sufficiently slow so that the viscoelasticity of the medium could be neglected. Consequently, the resistance to the growth of bubbles was considered to be only due to surface tension (Shimiya and Yano, 1987, 1988; Shah et al., 1998). These coupled momentum and mass transfer equations were solved for an isolated bubble surrounded by a Newtonian fluid (Venerus and Yala, 1997) and for power law (Ramesh et al., 1991), viscoelastic (Venerus et al., 1998) and Oldroyd-B model (Feng and Bertelo, 2004) polymeric melts. The evolution of bubble size distribution during proofing of bread was predicted for a Newtonian liquid accounting for the production of CO_2 by yeast (Chiotellis and Campbell, 2003). Nucleation of bubbles was accounted for in the analysis of bubble growth in the foaming of Oldroyd-B polymeric melt (Feng and Bertelo, 2004) and in the extrusion of wheat dough described by the Lodge model (Hailemariam et al., 2007). In an earlier work (Narsimhan, 2012), we have developed a model for growth of bubbles during proofing in an infinite viscoelastic dough that is described by Oldroyd-B model. The production of CO_2 by yeast was described by a Monod model. This treatment was also extended to bubbles of finite volume fraction through a shell model.

In this manuscript, a mechanistic model for baking of leavened aerated food is proposed. The viscoelastic dough is described by Oldroyd-B model. The model predicts bubble expansion during baking in aerated food as a result of heating, moisture evaporation as well as diffusion of CO_2 produced by fermentation. The model is also able to predict the evolution of 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 rise are discussed in the subsequent section. This is followed by comparison of model predictions with experimental data.

2. Model formulation

Baking of leavened food (bread dough for example) 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 starch gelatinization and/or gelation of protein. (b) expansion of incorporated air bubbles, (c) evaporation of moisture from the batter into the bubbles as temperature increases, (d) production of CO_2 due to fermentation of leavened food, (e) diffusion of CO_2 from the medium into the air bubbles by diffusion and (f) loss of moisture from the dispersion due to evaporation from the surface. Let us consider a rectangular aerated food consisting of equal sized bubbles of radius R 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 air–liquid dispersion. 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. This liquid food of uniform initial temperature T_0 is exposed to an ambient