



# Modeling of bread baking with a new, multi-scale formulation of evaporation–condensation–diffusion and evidence of compression in the outskirts of the crumb



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## ABSTRACT

Porous media approaches to bread baking involving energy, mass transport and continuous mechanics have now been widely explored and can be implemented with commercial software. The challenges now are thorough experimental verification, and understanding of the physicochemical phenomena both on the small scale and the way they are taken into account in continuous macroscopic models. A new evaporation–condensation–diffusion formulation that idealizes the distribution of bubbles in dough as periodic cubes is presented here. The effects it elicited on water flux, total water loss and variations in local water content were investigated. Additionally, a continuous approach involving four components (dough, CO<sub>2</sub>, air and water), mass, energy transport and dough deformation was developed. Experimental validation was performed both on usual variables such as temperature, total height and water loss, and on CO<sub>2</sub> release, and profiles of local gas fraction and water content. The mechanisms of expansion and compression in the expanding dough during baking are discussed for the first time, with the help of both a non-invasive technique (MRI) and numerical simulations. Only two parameters related to the mechanical properties of dough (viscosity and rupture leading to the opening of pores) were tuned; both CO<sub>2</sub> release (onset), and local gas fractions (position of the squeezed region) were revealed to be highly sensitive to these parameters. A single set of physically-consistent values was found to reproduce satisfactorily the experimental findings related to the transport and expansion of the gaseous phase.

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## 1. Introduction

Many studies have modeled bread baking, varying in their sets of assumptions and/or their levels of experimental verification (Table 1), and generally there has been a wide gap between the scales of description of the governing mechanisms in the baking models and those of observations. Experimental studies have often been performed at the loaf level, thus resulting in findings from the combination of several mechanisms taking place on a smaller scale. The relevance of addressing some specific physical/chemical aspects of baking in a given baking model while omitting others is therefore difficult to evaluate. In accordance with the aims of the

present study, the literature analyzed below focused only on the gaseous phase in bread during baking, production and transport. More details about heat transport and deformation for instance can be found in Zhang et al. (2005).

Only water vapor and air were considered when modeling the baking of cakes and in leavened dough, water and often CO<sub>2</sub> were considered but air was ignored (Table 1). The omission of air in bread dough is not physically consistent. Indeed, solubilized CO<sub>2</sub> and water rapidly escape from the outer layers of dough to the oven, because of their low concentrations in the oven air. Since mass transport from the inner to the outer layers of the dough proceeds at a low rate (low liquid diffusivity and closed pores at the beginning of baking) and since there is no mass transfer from the oven atmosphere to the outer layers of the dough in models omitting air entry, gas pressure in the outer layers is likely to decrease below the atmospheric pressure, a feature which has not been demonstrated experimentally to date e.g. Grenier et al. (2010).

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**Table 1**

Main models of baking proposed in the literature with their major mechanisms and their levels of experimental verification. “–” indicates that the associated mechanism/validation was not dealt with in the reference. In the studies marked by “\*”, the total volume obtained experimentally was used as an entry parameter of their model, assuming a uniform distribution.

References	Product	Model assumptions relative to the mechanics and gaseous phase				Comparison with experimental data (with TIME-course changes)			
		Bubble scale taken into account	Mechanics	Number and type of gases	Closed to open pores	Temperature at 2–4 locations	Total height/volume	Water content	
							Total loss	At different locations in dough during baking	
De Vries et al. (1989)	Bread dough	–	–	Carbon dioxide water vapor	–	–	–	–	✓ (profile in water content at the end of baking)
Zanoni et al. (1994)	–	–	–	Water vapor	–	✓	*	✓	–
De Cindio and Correr (1995)	✓	–	Linear visco-elasticity	Carbon dioxide water vapor	–	–	–	–	–
Fan et al. (1999)	✓	–	Power law viscosity	Carbon dioxide water vapor	–	–	✓	–	–
Zhang and Datta (2006), Zhang et al. (2005)	–	–	Non-linear visco-elasticity	Carbon dioxide water vapor	Permeability function of water saturation	✓	Qualitative comparison of shapes	✓	–
Purlis (2011) Purlis and Salvadori (2009)	–	–	–	Water vapor	–	✓	*	✓	✓ (progress in the crust thickness)
Bikard et al. (2008, 2012)	✓	–	Viscosity	Carbon dioxide water vapor	–	–	–	–	–
Thorvaldsson and Janestad (1999)	Crumb (after baking)	–	–	Water vapor	–	✓	–	–	✓ (3 locations)
Lostie et al. (2002a,b)	Sponge cake	–	Power law viscosity	Water vapor air	Permeability function of gas fraction	✓	✓	–	✓ (2 locations, core and surface)

Species can move by both diffusion through the liquid phase and by convection through pores once connected. In most baking models, the porous structure has been considered closed throughout the baking process (Table 1), and at best convection transport was included in an effective diffusivity coefficient. In some studies (Lostie et al., 2002a; Zhang et al., 2005), the water vapor flow is the sum of a convection term due to gradients in total pressure and a diffusion term governed by gradients of molar fractions. In Darcy's law permeability is related to local gas fraction (Lostie et al., 2002a) or to liquid saturation (Zhang et al., 2005). The model developed by Zhang et al. (2005) therefore considered the opening of pores occurring only in the outer layers of dough.

The temperature gradient inside bread induces a partial water vapor pressure gradient via the saturation water vapor pressure. Beneath the drying region, water vapor migrates along this gradient, towards the thermal core of the bread. The “evaporation–condensation–diffusion” phenomenon is well known in bread baking because it increases the water content (WC) at the core of the loaf up to 3% above the initial value (De Vries et al., 1989) and speeds up heat transport to the core (Zhang et al., 2005). The set of equations used by Lostie et al. (2002a) and Zhang et al. (2005) is able to reproduce this kind of water transport. However, when bubbles are still closed (very low permeability) and contain only water vapor, these equations provide a quasi-nil flow whereas the evaporation–condensation–diffusion is expected to be maximal because there is no opposite convection flow.

Zhang et al. (2005) considered production of CO<sub>2</sub> to be temperature-dependent, but with zero concentration of CO<sub>2</sub> in the liquid phase throughout the baking process. Although this was consistent with the conditions of their experimental verification (using soda), this is unusual in the bread-making process where high concentrations of CO<sub>2</sub> solubilized in the liquid water are expected at the very

beginning of baking due to previous fermentation steps (Hibbert and Parker, 1976). Moreover, significant production of CO<sub>2</sub> during baking is very unlikely since yeasts die early, as soon as the temperature exceeds 50 °C. In such a case, bread expansion is mostly caused by desolubilization of the CO<sub>2</sub>, and to a lesser extent the formation of water vapor, with the increase in temperature (Bloksma, 1990).

A coupled deformation and multiphase heat and mass transfer model was therefore developed in the present study.

It took into account only one dimension to avoid adding geometrical complexity to the diversity of the coupled phenomena and thus to simplify interpretations when comparing experimental to simulated data. A specific experimental device involving one-directional heat transfer and dough displacement was developed for this purpose.

Water, CO<sub>2</sub> and air were taken into consideration. In the initial state, dough contained liquid water, CO<sub>2</sub> solubilized in water and dry matter, and the gaseous phase contained water vapor and CO<sub>2</sub>. Air could migrate once pores were open. Particular attention was paid to describing the different mechanisms of water transport. Along with diffusion in the liquid phase and convection in the gaseous phase, a new formulation of evaporation–condensation–diffusion, valid for closed and open pores, was proposed. In contrast to most previous studies, pores were considered to be closed at the beginning of baking and to open in the course of baking at any place in the bread. This assumption provided greater respect for the main dough-to-crumb transitions taking place during baking. In addition, the opening of pores was disconnected from water saturation and from the gas fraction and linked to temperature. This is consistent with the relationship established in the literature (Daniels and Fisher, 1976; He and Hosney, 1991) between rupture of dough walls and the onset temperature of

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