Innovative Food Science and Emerging Technologies 25 (2014) 40–52

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

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

Modeling of baking behavior of semi-sweet short dough biscuits

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ARTICLE INFO

Article history:
Received 19 June 2013
Accepted 28 December 2013
Available online 9 January 2014

Editor Proof Received Date 29 January 2014

Keywords:
Baking process
Foam
Dough
Biscuit
Bubble expansion
Rheology

ABSTRACT

Dough materials are interesting systems widely used in biscuit production. Baking is one of the most important steps, because the raw dough is transformed into the final biscuit during cooking time, resulting in a specific texture. A mathematical program describing the transport phenomena and the physical changes inside the oven is presented in this study in order to predict biscuit temperature, water content, height, porosity and other baking attributes. The evolution of the heterogeneous structure is taken into account by the expansion of the internal bubbles in the viscoelastic medium. The system was considered pseudo-homogenous, with the aim of modeling both the baking process and the gas cell growth in the matrix. This approach was used to analyze the evolution of the biscuit properties, considering “effective” properties. The model was solved by a finite difference method and numerical results were in good agreement with industrial experimental data.

Industrial relevance: This paper describes the mathematical modeling of biscuit baking that can be used as a tool to improve the baking conditions and the final biscuit texture. Food is very complex both in composition and structure; therefore, generic realistic models are required that can mimic this complexity. This model can facilitate the evaluation of the impact of changing composition or processing conditions. This research can help the optimization of processing and formulations (reverse engineering), because the baking program takes into account the ingredients and the rheological food properties and than can be used as a tool for design and control of new biscuits.

1. Introduction

Short-dough biscuit is a very popular product in many countries where it is presented with different commercial names. Short dough is a simple system consisting of three main ingredients (flour, sugar and fat) distinguished from other biscuits in that it is not coherent under tension and breaks easily (Baltsavias, Jurgens, & van Vliet, 1997) and, generally, it contains a low amount of water (<20% w.b.). The evolution of the biscuit during baking is very complex and expansion is a crucial factor for texture formation (Chevallier, Della Valle, Colonna, Broyart, & Trystram, 2002).

Short-dough biscuit can be considered as a foam, since air bubbles incorporated during mixing are separated and surrounded by a continuous phase. In fact, a biscuit may be described as a matrix in which gas bubbles of various size and shape are embedded (Baltsavias, Jurgens, & van Vliet, 1999). It is generally accepted that the rheological properties of the dough are extremely important for the final quality of every baked product and that it is very important to control this latter from the mixing stage onwards (Baltsavias et al., 1997; Chevallier et al., 2002). In fact, the biscuits baking unit is a critical phase in process. During baking dough, pieces of biscuits undergo changes in structure (onset of a micro- and a macro-porous structure), taste, color, size and moisture content (Broyart & Trystram, 2003). During the baking period, heat energy is mainly transferred to the product surface by radiation from the oven walls and by convection from hot air flowing inside the oven, and by conduction from the surface to the core of the product (Mirade, Daudin, Ducept, Trystram, & Clément, 2004). The baking causes marked physical and biochemical changes, including water evaporation, volume increase, porous structure and crust formation, browning, protein denaturation and starch gelatinization (Mirade et al., 2004).

Industrial-scale biscuit baking is done in continuous or tunnel ovens of variable length (15–100 m) and width (0.8–1.2 m). The dough pieces are carried through the baking chamber by a steel conveyor band. Heat is generated by gas burners or electrical heating elements placed above and below the band. The baking oven is usually divided into several zones ((3–5) baking zones) and the gas conditions (air temperature, humidity, velocity and gas concentrations) can be different according to the cooking requirements, meaning high flexibility in the process (Mirade et al., 2004). In every case, it is always rather difficult to control this type of oven due to the relatively short baking time used for biscuit production (less than 5 min) (Broyart & Trystram, 2003). Heat flux, humidity and other oven conditions change also in relation to biscuit type. Biscuit baking ovens are often empirically controlled (generally developed by trial and error methods) and, if not well optimized for

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http://dx.doi.org/10.1016/j.ifset.2013.12.022

recipe, they may strongly affect the biochemical and physicochemical reactions in biscuit dough during baking (Chevallier et al., 2002). The rheological properties of the dough are very important for the final texture, because they can limit the expansion and then the eating quality of the baked product. Even if the biscuit is an inherently heterogeneous system, most of the proposed approaches (Lostie, Peczalski, Andrieu, & Laurent, 2002; Sablani, Marcotte, Baik, & Castaigne, 1998) stand on a so called pseudo-homogeneous system, capable to translate the physical aspects into a mathematical model allowing final biscuit characteristics prediction. This means that all the phenomena are referred to an equivalent homogeneous system, the properties of which are somehow modified to account for the presence of bubbles. Thus effective material properties are properly defined. However, such approaches have an evident, undoubtedly mathematical advantage when numerically solving the obtained equations, and can be transferred to industrial conditions, being essentially based on some adjustable parameters introduced by the heat and mass transport models, nevertheless in such a way the heterogeneous feature is missed. This implies that properties appearing to be mainly responsible for the product structure and texture, as for instance the rheological behavior of dense cereal paste, its surface tension, and the interface thermodynamic equilibrium, cannot be taken properly into account. The only two scale approach taking into account the evolution of the bubbles in a continuous matrix during baking or foam formation was developed during the last two decades by de Cindio and coworkers (de Cindio & Correra, 1995; Gabriele, Baldino, Migliori, de Cindio, & Tricarico, 2012) and in a different approach by Bikard, Coupez, Della Valle, and Vergnes (2008, 2012). These studies deal with modeling of aerated systems described at two scale levels: at the microscopic scale the single bubble growths in a surrounding medium that is assumed either as viscoelastic (de Cindio & Correra, 1995; Gabriele et al., 2012) or as viscous (Bikard et al., 2008, 2012); on a macroscopic level the information obtained by the single bubble expansion is used to describe the global structure evolution. The obtained models allow in relating the macroscopic technological parameters with rheological properties of paste and formulations.

In the present work the gas bubble evolution in the dough medium during baking process was modeled priorly at microscale level where equilibrium conditions apply. The information obtained by radius bubble evolution at the microlevel, were then transferred to the bulk, at the macrolevel, where changes are governed by transport phenomena. The solution of the balance equations is obtained through a proper numerical solution giving the transient values of temperature, humidity, component concentrations and height of the biscuit at any time. In such a way the pseudo-homogeneous computational advantages are maintained without missing the heterogeneous character.

2. Mathematical modeling

In a typical two-stage mixing for short-dough biscuits all the ingredients, except the flour, are placed in the mixer to dissolve, gently mixing, as much of the sugar as possible in the available water and emulsify the whole with fats, obtaining a semi-stiff white "cream". On adding the flour at gently rate it is possible to obtain a uniform dispersion of the "cream" over the flour. Thanks to the large quantity of fat, a very little water is needed to achieve a soft consistency (Maache-Rezzoug, Bouvier, Allaf, & Patras, 1998), This two stages give a coherent homogeneous-appearing dough inside which are entrapped gas bubbles and which can be now sheet an molded (Manley, 2000).

The system to be modeled is a digestive biscuit assumed to be cylindrically shaped (about 0.004 m of height and 0.067 m of diameter with an initial void fraction of 5.7%), made up of wheat flour, sugar, fat, as major ingredients, and water (<10% w.b.), salt, soda and ammonium carbonate (1.2–1.5% ca.) as minor ingredients.

From a macroscopic point of view, the dough is a quasi-homogeneous continuous medium showing a solid–liquid rheological behavior. At a microscopic scale the behavior of the material is determined by the interactions between the ingredients and the raising agents, responsible of the growth of gas bubbles during baking, which are supposed to be perfectly mixed within the dough. It was assumed that the bubbles inserted at the beginning during mixing into the dense cereal paste, grow as a consequence of the combined actions due to raising agent decomposition, water evaporation, and temperature increase and no new bubble germination is considered during expansion (Bikard et al., 2008).

All these factors directly and indirectly influence gas cell composition and consequently their volume. Owing to their initial dimensions, at the start the bubbles may be considered as single submerged objects in an infinite medium of paste and therefore the considered system is inherently heterogeneous. The modified pseudo-homogenous approach for biphasic systems, proposed by de Cindio and Correra (1995), is based on the splitting of the mathematical model into a micro- and macrosystem. The microsystem is heterogeneous and describes the physical behavior of a single bubble and its surrounding medium. The macrosystem couples together all the single microsystems by balance equations written for an equivalent homogenous-like medium where the physical properties are obtained by the local microsystems; therefore it can be considered homogenous.

As a consequence, a microsystem can be used to describe bubble evolution during baking time; from the analysis of this microsystem, macroscopic properties, such as height, are computed and used to describe the macroscopic dough expansion. According to the previous description, the proposed model aims to deal only with the baking phase, while mixing and rest period are roughly considered as an initial condition for the baking. In addition no biscuit spreading, under its own weight, was considered and therefore forming on the belt was neglected resulting in a cylindrically shaped sample.

It is worth noticing that height to diameter ratio is much lower than unity, therefore the lateral surface is very small with respect to the upper biscuit surface where the main mass and heat fluxes are present. As a consequence flat radial profiles, for temperature and concentration of each component, can be assumed and a 1D model can be considered sufficient to describe, in a simplified way, the main physical phenomena during baking. Moreover, owing to the considered height to diameter ratio, the potential change in diameter biscuit caused by the isotropic bubble expansion, is very small when compared to the height change and, therefore, in the model, it was neglected assuming a constant value for it, equal to the initial one.

For this reason, the gas cells grow due to gas formation due to raising agent (R.A.) decomposition and water evaporation and the thermodynamic and mechanical variables (pressure and temperature) are computed by the so-called microsystem operating in equilibrium condition. Then the equilibrium information obtained at the microlevel, essentially being the bubble radius, and the split of the components between gas and dough phases, are transferred to the macrosystem that deals with the transport phenomena, operating essentially with effective properties. By integrating heat and mass balance equations, with reference to a discretized 1-D spatial grid and for any given initial and boundary conditions, the new values of the thermodynamic and mechanical variables are obtained and sent again to the microsystem. This procedure is iterated at any grid point and at any time. By collecting the data coming from this computing procedure at any instant, the transient height, temperature and water content of a biscuit are obtained.

2.1. Bubble growth: single microsystem

The modeled system is defined as a single bubble surrounded by a fixed amount of dough that can be determined by the mass balance if the bubble concentration is known (number of bubbles per unit of volume). The production of carbon dioxide and other products of fermentation reactions that diffuse into the gas cells during baking drives single cell growth, but this is limited by the bulk properties of the viscoelastic medium (Gabriele et al., 2012).