Chemical Engineering Science 139 (2016) 75–98

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Coupled multiphase transport, large deformation and phase transition during rice puffing

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HIGHLIGHTS

- A framework for transport and deformation is presented for puffing-type processes.
- Rubbery/glassy phase transition is a critical component for puffing-type processes.
- Large gas pressure generation and glass-to-rubber phase transition cause puffing.
- Salt-assisted and gun puffing of rice are explained in a fundamental way.

ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form
23 August 2015
Accepted 30 August 2015
Available online 18 September 2015

Keywords:
Rice
Salt-assisted puffing
Gun-puffing
Large deformation
Multiphase modeling
Porous media

ABSTRACT

Puffing of biomaterials involves mass, momentum and energy transport along with large volumetric expansion of the material. Development of fundamentals-based models that can describe heat and moisture transport, rapid evaporation and large deformations can help understand the factors affecting the puffing processes and optimize them. In this context, salt-assisted puffing of parboiled rice is described. A multiphase porous media model involving heat and mass transfer within the rice kernel undergoing large deformations is developed. The transport model involves different phases and multiple modes of transport. During puffing, intensive heating of rice leads to rapid evaporation of water to vapor resulting in large pressure development. Also, the rice starch undergoes Glass Transition from a rigid, glassy state to a soft, rubbery state. Development of large pressures within a soft matrix results in large volumetric expansion of the kernel causing it to puff. The developed model was validated against moisture changes and volumetric expansion of the rice kernel during the puffing process and good agreement was found. Gas porosity development in puffed rice was determined via 3D reconstruction of micro-CT images of rice puffed at different times which compared favorably well with model predictions. The expansion of the kernel began from the tip of the grain and the model could successfully capture this phenomenon. Expansion ratio, a key quality parameter associated with puffed products, was found to be sensitive to intrinsic permeability and bulk modulus of the solid matrix. The modeling framework for salt-assisted puffing was then extended to the process of gun-puffing (a completely different puffing process) without significant reformulations thus showing the applicability of the framework for a variety of puffing processes. The final expansion after gun-puffing was much higher compared with salt-assisted puffing and was found to be sensitive to the gun opening time.

1. Introduction

Cereal grains, e.g., corn, wheat, rice, oats, are widely processed for ready-to-eat-breakfast cereals, infant foods and snack foods (Maisont and Narkrugsa, 2010). One of the many ways in which grains are processed is by puffing. For example, corn has been widely used to make the popular puffed snack popcorn and breakfast cereal cornflakes (Hoseney et al., 1983). Rice has been consumed as a staple food for centuries. In many South-Asian countries, puffed rice is famously consumed as a light snack food in different forms like puffed rice balls and cakes (Simsrisakul, 1991). There is growing consumer interests towards puffed foods and snacks as they are healthy, low in fat, and bear quite a resemblance to the crispy texture of fried foods (Moraru and Kokini, 2006).

Puffing of cereals and starch based foods have been carried out using a variety of techniques, e.g. using hot oil (Villareal and Juliano, 1987), gun-puffing (Villareal and Juliano, 1987), sand or

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http://dx.doi.org/10.1016/j.ces.2015.08.057
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salt-assisted (Chinnaswamy and Bhattacharya, 1983; Hoke et al., 2007), hot-air (Guraya and Toledo, 1994; Varnalis et al., 2004; Nath et al., 2007; Norton et al., 2011), microwaves (Maisont and Narkrugsa, 2010; Rakesh and Datta, 2011; Joshi et al., 2014) and extrusion (Lue et al., 1991; Moraru and Kokini, 2006; Moscicki, 2011). In all these different processes, the material is subjected to very high temperatures resulting in “flash off” of liquid water to vapor. This sudden evaporation leads to pressure generation within the materials causing them to puff. The volumetric expansion ratio (i.e., the ratio of initial to final volume) of the puffed material could lie anywhere between 4 and 10 (Chandrashekhar and Chattopadhyay, 1991). From a quality standpoint, the higher the expansion ratio, the better is the quality of the puffed product. In order to obtain better quality products, a good understanding of the underlying mechanisms involved in the expansion process is needed through physics-based modeling and detailed experimentation. The present work aims toward developing a fundamentals-based model in order to understand puffing processes and apply the framework to study salt-assisted and gun-puffing of rice kernels. Although the model presented here is for rice puffing, the physics of the process is quite similar to other puffing processes and can be extended to understand and optimize those processes as well. Moreover, the manufacturing of foamed plastics, e.g., polystyrene, is quite similar during which a gas generating substance (i.e., blowing agent) is introduced into a molten polymer at elevated pressures. By suddenly reducing the surrounding temperature and pressure, expansion of the gas phase inside the polymer melt takes place, eventually causing them to puff (Arefmanesh et al., 1990; Elshereef et al., 2010). The framework developed here can be applied as well to foam forming processes that is of prime importance in the chemical process industry.

Rice puffing using different techniques has primarily been studied in the context of obtaining optimum processing conditions that would yield a product with a high expansion ratio (Hoke et al., 2005). Preprocessing of rice before puffing is a crucial step in order to obtain good quality puffed rice. Initial moisture content, puffing temperatures and degree of salt addition in the preprocessing steps are some of the most critical factors that favor large volumes of the puffed product. Studies have shown that an initial moisture content of rice kernels ranging between 10% and 15% (wet basis) and pre-gelatinization of rice starch have resulted in better quality puffed rice obtained using different intense heating processes (Chinnaswamy and Bhattacharya, 1983; Murugesan and Bhattacharya, 1991; Villareal and Juliano, 1987; Simsrisakul, 1991; Maisont and Narkrugsa, 2010). Starch is the prime component of rice and many other cereal grains. In its native crystalline form, starch does not allow for a large expansion of the kernel because when heated, starch reacts with water to undergo gelatinization (van der Sman and Broeze, 2013). This reduces the amount of water available for vapor generation during the puffing process. Rice is therefore pretreated before puffing by soaking it in water overnight followed by drying between 70–90 °C and 10–15% moisture content (wet basis) (Mohapatra et al., 2012). In the pretreatment process, starch and excess water undergo gelatinization during which starch molecules lose their crystallinity and become amorphous (Briffaz et al., 2012). Once starch loses its native form, it does not react with water during the puffing stage (van der Sman and Meinders, 2011). Therefore, with sufficient water available to generate vapors, a product with a high expansion ratio is achieved when compared with untreated rice (Chinnaswamy and Bhattacharya, 1983). Also, pre-gelatinized starch provides a crunchy texture to the puffed product (Willard, 1976).

After pre-treatment, rice kernels are subjected to intense heat for puffing. Initially, the starch in rice is in the glassy state, i.e., it is hard and rigid. During the heating step, two things happen: (1) moisture inside the rice grains starts to evaporate resulting in the formation of vapors, and (2) rice starch undergoes a phase transformation from the hard, glassy state to the soft, rubbery state. Due to intense vapor generation, large pressures are generated within the kernel in a soft and compliant matrix due to glassy–rubbery phase transformation. As a result, the matrix undergoes large expansion consequently releasing the gas pressure in this process. The end of rice puffing is marked by a distinct popping sound (Murugesan and Bhattacharya, 1991).

1.1. *Mathematical modeling of puffing-type processes*

Puffing of food materials involves mass, momentum and energy transport along with large volumetric expansion of a porous, thermoplastic material (Rakesh and Datta, 2011; Kong and Shanks, 2012). Mathematical models of puffing-type processes have primarily focused on understanding how a microscopic single vapor bubble grows in a pool of molten starch (bubble growth models). Some examples include modeling bubble growth during proving and baking of bread dough (Shah et al., 1998; Fan et al., 1999; Chiotellis and Campbell, 2003; Hailemariam et al., 2007; Deshlahra et al., 2009), vapor induced puffing of corn (Schwartzberg et al., 1995), extrusion cooking of starch (Kokini et al., 1992; Fan et al., 1994; Wang et al., 2005) and supercritical fluid extrusion (Alavi et al., 2003a,b). These models have ignored transport phenomena at the macroscale with one notable exception as shown by Alavi et al. (2003a,b). However, the model used effective diffusivity formulations and did not take into account the pressure driven flow and distributed evaporation that are critical to puffing type processes. Furthermore, in all of the above models, water vapor is assumed to be in equilibrium with liquid water which is not true for intense heating processes (discussed later).

Puffing involves a two-way coupling of transport phenomena and non-linear solid mechanics (Zhang et al., 2005; Rakesh and Datta, 2012; Nicolas et al., 2014) to be able to accurately describe the process. The transport phenomena involve multiple phases with multiple modes of transport and phase change inside a material that undergoes large inelastic deformations. Macroscopic models that include the detailed physics of the process can provide for an integrated understanding of how a material structure, e.g., porosity, develops as a whole that can ultimately be related to quality of the final puffed product. Models that account for transport and deformation have been developed for various other applications. Of them, most have assumed small deformations that are generally not true and are definitely not applicable to the process of rice puffing. Others have simplified transport models that do not take into account the different phases and modes of transport (Achanta, 1995; Shi et al., 1998; Yang et al., 2001; Mayor and Sereno, 2004; Katekawa and Silva, 2006; Ressing et al., 2007; Niamnuy et al., 2008; Perez et al., 2012). More recently, detailed models including transport with large deformations have been developed; however, the models assume constant mechanical properties and do not account for glassy–rubbery phase transformation that is important for puffing-type processes (Rakesh and Datta, 2011).

1.2. *Objectives and overview*

Therefore, the overarching goal of this study is to develop a general framework for puffing of biomaterials that can take into account a variety of features that are specific to puffing-type processes, using rice puffing as an example. The organization of the work is as follows: the coupled transport and large deformation model for puffing is described first. This is followed by experimental methodology undertaken to perform the puffing experiments on rice kernels and measurement of moisture