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Review

Modeling of starchy melts expansion by extrusion

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ABSTRACT

Background: Expansion phenomenon is a key-point of the development of extruded starchy foods. Despite the huge number of studies, the complexity of the phenomenon still challenges its modeling. Current available models based on continuum mechanics are still too complex to be coupled with any 1D extrusion model available, in order to predict the density and the cellular structure of the starchy foams.
Scope and approach: In this paper, the different modeling approaches for vapor expansion are reviewed. Then, a survey of the different mechanisms (bubbles nucleation, growth, coalescence, shrinkage and setting), using qualitative knowledge representation and reasoning, allows to improve the understanding of the effect of extrusion variables (temperature, moisture content, die geometry …) and material rheological properties on the expansion phenomenon. Based on experimental results reported in the literature, a phenomenological model of expansion can then be suggested.
Key findings and conclusions: The knowledge representation and reasoning leads to a concept map of the causal influences between input, physical mechanisms and output variables. The phenomenological model would allow to predict output variables characterizing foam macrostructure (bulk expansion indices and anisotropy factor) and cellular fineness based on X-ray tomography measurements. A scale down from macrostructure to cellular structure could be achieved by establishing a link between anisotropy factor and cellular fineness. Once validated, this model could be coupled with any 1D extrusion model in order to build a global model for the design of cereal-based extruded foods.

1. Introduction: expansion of starchy products by extrusion-cooking

Extrusion-cooking is extensively used for production of different categories of starch based foods, e.g. ready-to-eat breakfast cereals, expanded snacks, crisp breads, baby foods, pet foods and aqua feeds; these foods are characterized by a solid foam structure, which governs their texture. The texture of extruded foams, or at least their mechanical properties, can be approached by the model of cellular materials (Gibson & Ashby, 1997) provided that material properties and extrudate density are known. Several books provide relevant knowledge and information relative to extrusion technologies from the viewpoints of food science and engineering (Guy, 2001; Kokini, Ho, & Karwe, 1992), but the design of the required product texture is still a challenge. According to the state diagram of food biopolymers (Fig. 1a), the high temperature and pressure, and the intensive mechanical shearing and mixing conditions of moistened dough within the screw-barrel assembly, result in several transitions such as starch melting, polymer chains scission, formation of complexes between amylose and lipids, protein denaturation and destruction of anti-nutritional factors. Although these phenomena have been well documented in the literature, the changes occurring within the extruder are still studied nowadays.

Water acts both as a plasticizer for melting and as a blowing agent for expansion (Moraru & Kokini, 2003). After total or partial starch melting, the viscous material is forced through a calibrated orifice, the die. Expansion is produced primarily by two effects: (1) the extrudate swell due to the elastic recovery of deformation and (2) the bubble growth, due to moisture flash-off, which depends on the balance of thermal effects and rheological properties (Fan, Mitchell, & Blanshard, 1994; Wang, Ganjyal, Jones, Weller, & Hanna, 2005). The flash vaporization is predominant in foods at high temperatures and it is considered as the main factor affecting the structure of extruded foods (Guy, 2001; Kokini, Chang, & Lai, 1992).

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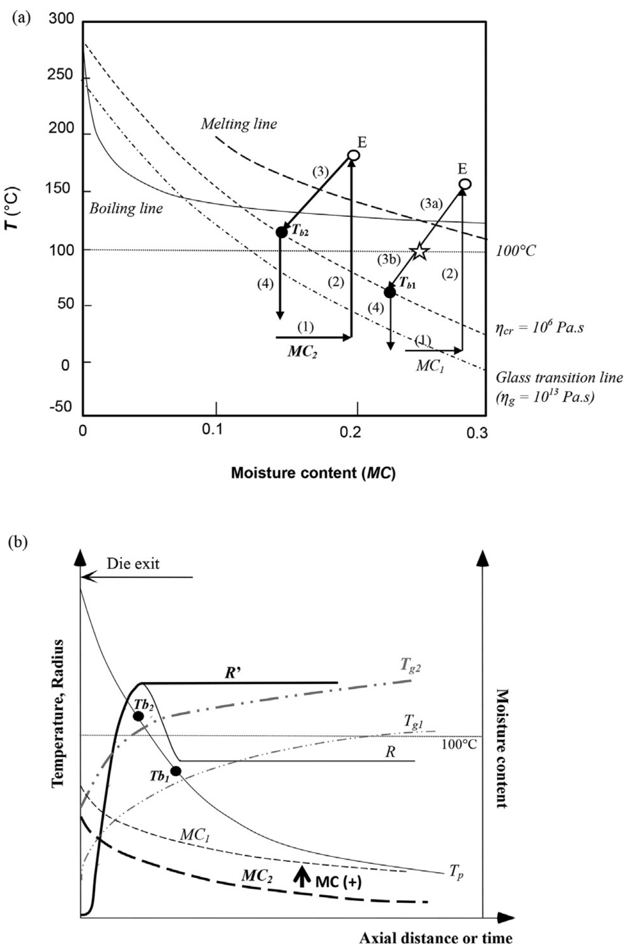

Fig. 1. Starchy product state diagram supplemented by material pathways during extrusion (a) and schematic view of extrudate expansion and shrinkage at the die exit (b). (a) Pathway of expanding starchy foods, presented in a supplemented state diagram (adapted from Della Valle et al., 1997, Moraru and Kokini (2003) and Sman and Broeze (2014a,b)). Full line (—): boiling point at $4\cdot10^5$ Pa, thick dashed line (— — —): melting temperature; thin dashed line (- - -): temperature for critical viscosity ($\eta_{cr} = 10^6$ Pa s), dashed dotted line (-.-.-): glass transition temperature ($\eta_g = 10^{13}$ Pa s). (b) Evolution of moisture content, melt and glass transition temperatures, bubble radius (R) of the extrudate for two different initial moisture contents (adapted from Fan et al. (1994) and Della Valle et al. (1997)). During extrusion, after wetting and mixing with water (stage 1, Fig. 1a), the starch is molten by both external heating and viscous dissipation (stage 2). When the melt leaves the die (point E), moisture flushes off and the expansion occurs instantaneously (stages 3, a, b). The rapid decline in product temperature and moisture content is accompanied by a rapid increase in glass transition temperature, as a bubble undergoes rapid expansion. During this period, very high rates of heat and mass transfer occur. A bubble expands to a melt temperature higher than 100 °C (MC_2 path, stage 3, Fig. 1a), and the evolution of its radius follows R' line (Fig. 1b). Depending on initial moisture conditions, the bubble can experience shrinkage as the cell temperature decreases below 100 °C (MC_1 path, stage 3b in Fig. 1a) due to vapor condensation. The state when the shrinkage starts is marked with a star symbol (MC_1 path, in Fig. 1a) and bubble radius variations are presented by the R line in Fig. 1b. A rapid decline in product temperature (T_p) and moisture content (MC) is accompanied by a rapid increase in glass transition temperature (T_{gi}). When the product temperature falls below $T_g + 30$ (T_{bi}), where a critical viscosity ($\eta_{cr} = 10^6$ Pa s) is reached, the expansion stops (marked with closed circle T_{bi}). During cooling (stage 4), the extrudate temperature becomes lower than T_g, and the structure sets to glassy state.

Expansion can be considered as a succession of various physical phenomena, occurring in a short time interval, less than 1 s: bubbles nucleation and growth, coalescence and finally setting, when the melt matrix becomes glassy, after an eventual collapse. The word “melt” does not imply that starch is totally amorphous, but rather that it has undergone sufficient order-disorder transition so that it can flow as a viscous fluid (Moraru & Kokini, 2003). Furthermore, it is assumed that, although other components (proteins, fats, sugars …) can have a significant influence on product final properties, starch has the most important contribution to the melt behavior, *i.e.* its thermal and rheological properties.

According to Fig. 1, when material flows through the die, its pressure decreases and may fall below the saturating vapor pressure of the melt. At this point, water begins to evaporate and generate vapor nuclei. At the die exit, a part of superheated water evaporates due to the sudden pressure drop and the nuclei, if they exceed a critical size (Kumagai, Kumagai, & Yano, 1993; Tuladhar & Mackley, 2004), give rise to bubbles which may then grow, leading to an expanded, porous structure. Based on the works of Della Valle, Vergnes, Colonna, and Patria (1997), Fan et al. (1994), Sman and Broeze (2014a,b), and Wang et al. (2005), a general scheme can be proposed for the concomitant evolutions of temperature, moisture content and bubbles radius during expansion (Fig. 1a and b). After leaving the die, the product cools down due to evaporation and convective heat transfer. Product temperature (T_p) and moisture content (MC) decrease simultaneously; due to moisture decrease, the glass transition temperature (T_g) increases. The bubble growth stops at a temperature (T_b) higher than the glass transition temperature. In their simulation, Fan et al. (1994) assumed that $T_b = T_g + 30$ °C, whereas experimentally, Horvat and Schuchmann (2013) obtained $T_b = T_g + 45$ °C. The difference between these values may result from the broad variations in the glass transition domain of starch. Based on modeling and experimental studies on indirect expansion of starch materials by frying, Sman and Broeze (2014a,b) proposed that the expansion stops if a critical viscosity ($\eta_{cr} = 10^6$ Pa s) is reached, hence at a temperature above the glass transition, where viscosity is around 10^{13} Pa s. According to Della Valle et al. (1997), two types of direct expansion mechanisms could be proposed, depending on moisture and amylose content in the case of starches. If the melt moisture content is high (MC_1), or the amylose content is low, T_b may be lower than 100 °C (denoted as T_{b1} in Fig. 1a and b). In this case, shrinkage may occur, because of vapor condensation; consequently, the evolution of bubble radius follows the R line of Fig. 1b. For low moisture content (MC_2) or high amylose content, T_b is higher than 100 °C (T_{b2} in Fig. 1a), the structure is then set before bubble may collapse, which results in higher expansion, as illustrated by the R' line of Fig. 1b. In both cases, expansion leads to a foam, a material having a cellular structure. Its main characteristic is its low density, inversely related to the volumetric expansion. Volumetric expansion results from radial and longitudinal expansions, each term being assessed by a specific index, defined in detail by Alvarez-Martinez, Kondury, and Harper (1988) and Launay and Lisch (1983). Longitudinal expansion characterizes the expansion in die flow direction, whereas radial expansion refers to the increase of cross section in the plane orthogonal to flow direction. The longitudinal expansion index (LEI) is defined as the ratio of the velocity of the extrudate after expansion to the average velocity of the melt in the die and is defined by:

$$LEI = S_d \cdot L_{se} \cdot \rho_m \frac{1 - MC_m}{1 - MC_e} \quad (1)$$

where ρ_m is the density of the melt, S_d the die cross section, L_{se} is the specific length of extrudate per unit mass, and MC_m and MC_e the moisture content of melt and extrudate, respectively. It can be shown that it is also, for a fixed volume of material, the ratio of the length of the sample after and before expansion. The radial expansion index (SEI) is defined as the ratio between the cross-sectional area of the extrudate (S_e) and that of the die (S_d):