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A deterministic approach for predicting the transformation of starch suspensions in tubular heat exchangers

A. Plana-Fattori [a, b, *], D. Flick [a, b], F. Ducept [a, b], C. Doursat [a, b], C. Michon [a, b], S. Mezdour [a, b]

[a] AgroParisTech, UMR1145 Ingénierie Procédés Aliments, F-75231 Paris, France
[b] INRA, UMR1145 Ingénierie Procédés Aliments, F-91300 Massy, France

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ABSTRACT

Numerical modeling of fluid flow, heat transfer and transformation is conducted for an aqueous suspension of starch granules running throughout a four-heating-section tubular exchanger. The numerical model considers the transformation kinetics and the rheological behavior of the starch suspension as determined from laboratory work; further, the model includes the geometrical characteristics of the heat exchanger, as well as the operating conditions which were considered in running it. Model predictions are compared with results from experimental work, after sampling the starch suspension under thermal processing and later characterizing it using laboratory techniques. The numerical model predicts the bulk swelling state of the starch suspension at a level of agreement (−41% in volume mean diameter increase) which is better than the one reached after assuming plug-flow and radially-independent temperature (−66%). The inclusion of two-way coupling between the relevant phenomena constitutes therefore a positive improvement.

1. Introduction

Manufacturing food products in a reproducible manner requires understanding the mechanisms which drive the transformation of the ingredients along the processing pathway. For instance, in dairy desserts the milk is mixed with starch, to which carrageenan is added as a gelling agent (Doublier and Durand, 2008). Experimental work at laboratory scale has been conducted in order to study the influence of thermal treatment on the structure of whey proteins (Tolkach and Kulozik, 2007; Nicolai et al., 2011), of starch granules (Ratnayake and Jackson, 2008; Liu et al., 2009; Schirmer et al., 2013) and of carrageenan chains (Piculell, 2006; Nunez-Santiago et al., 2011). The interactions occurring between these ingredients have been studied and, for a variety of blends, the rheological behavior was analyzed along the batch thermal history (Verbeken et al., 2006; Doublier and Durand, 2008; Noisuwan et al., 2009; Huc et al., 2014; Matignon et al., 2014a, 2014b, 2015). The preparation of dairy desserts at industrial scale includes, among other steps, thermal processing under continuous flow. The phenomena of fluid flow, heat transfer and product transformation are strongly coupled within heat exchangers: transformation affects the characteristics of the product (e.g., particle sizes), with consequences on its rheological behavior and hence on the velocity field inside the processing unit. In turn, fluid flow influences heat transfer while the temperature level drives the transformation rate. As a consequence, the final structure of the liquid product can depend not only on the interactions between the ingredients but also on the geometry and on the thermal and dynamical operating conditions associated with the heat exchanger.

To predict the transformation of a liquid food product along its thermo-dynamical history is a challenging task. Physics-based and observation-based modeling approaches constitute complementary tools for food product, processes, and equipment designers. Physics-based models especially can provide a level of insight that is often not possible experimentally (Datta, 2008). The phenomena of fluid flow, heat transfer, and product transformation need to be considered in the case of the thermal processing of liquid food products under continuous flow. The rheological behavior of liquid food products is typically non-Newtonian and temperature-dependent; therefore, it is difficult to derive analytical solutions for the conservation equations of mass, momentum and energy.

Computational Fluid Dynamics (CFD) has been employed to study a number of problems in food engineering and related disciplines (Norton and Sun, 2006; Galeazzo et al., 2006; Lemus-

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* Corresponding author. Artemio Plana-Fattori, AgroParisTech, 16 rue Claude Bernard, 75231 Paris, France.
E-mail address: artemio.planafattori@agroparistech.fr (A. Plana-Fattori).

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Mondaca et al., 2011; Khatir et al., 2013; Norton et al., 2013; Rocha et al., 2013; Defraeye, 2014). However, limited efforts were devoted to coupled problems involving liquid food products whose rheological behavior evolves as the transformation progresses along the processing pathway. Bouvier et al. (2014) studied the thermal denaturation–aggregation of whey proteins flowing under turbulent flow in a plate heat exchanger; those authors obtained promising agreement between model predictions and observations of the transformation state reached by the liquid product, after assuming a simple rheological behavior for the whey protein solutions under consideration (Newtonian, temperature-dependent). Liao et al. (2000) considered a more complex rheological behavior and developed a numerical model coupling fluid flow, heat transfer and gelatinization of waxy rice starch paste; the apparent viscosity of the product was described through a power law, and both the consistency coefficient and the behavior index were assumed to be temperature-dependent. We can argue that describing the rheological behavior as a function of the local temperature is not a robust strategy. It can be shown that the characteristics of the liquid product, and hence its rheological behavior at a given position in the heat exchanger, depend not only on the local conditions but also on the thermal (and eventually dynamical) histories associated with the fluid parcels running at this position (Chantoiseau et al., 2012; Plana-Fattori et al., 2013). The two-way coupling between product transformation, fluid flow and heat transfer phenomena via the rheological behavior constitutes a robust strategy for predicting the transformation of a liquid product along its thermodynamical history.

In the logical continuation of previous efforts (Plana-Fattori et al., 2013), this study presents a numerical model for predicting the transformation of a starch suspension running throughout an existing four-heating-section tubular exchanger. We focus on a given starch suspension (type and concentration), and the parameters relevant to the numerical model are estimated through our own experimental protocol at laboratory scale. Both the swelling kinetics and the rheological behavior are represented more realistically than in that previous study; on the one hand, a threshold temperature is assumed for the swelling kinetics rate (rather than an Arrhenius-like approximation); on the other hand, the progressive shear-thinning behavior of the starch suspension is described. Later, we compare model predictions of the swelling state reached by the suspension, with observations obtained at pilot scale by running the tubular heat exchanger whose geometry and operating conditions are considered in the numerical model. The objective of this study was double: firstly to implement the coupled model for thermal processing at pilot scale by applying key model parameters obtained from experimental work at laboratory scale, and secondly to assess the improvement that this coupled model represents relatively to a simpler approach, based on the assumption of plug-flow and radially-independent temperatures. Results constitute a meaningful step towards the implementation of numerical models able to represent the variety of dynamical and thermal conditions experienced by realistic food fluid parcels during their pathway in the processing unit. They will be useful for the design of starch suspension thermo-mechanical treatments.

2. Coupled physical problem

We are interested in the phenomena of fluid flow, heat transfer and liquid product transformation occurring within a tubular heat exchanger which is running under stationary conditions. Conservation equations for mass, momentum and energy can be expressed as:

$$\vec{\nabla}\cdot(\rho\vec{u}) = 0 \tag{1}$$

$$\rho(\vec{u}\cdot\vec{\nabla})\vec{u} = \vec{\nabla}\cdot\left(-p\vec{I} + \eta\left(\vec{\nabla}\vec{u} + (\vec{\nabla}\vec{u})^{T}\right) - \frac{2}{3}\eta(\vec{\nabla}\cdot\vec{u})\vec{I}\right) \tag{2}$$

$$\rho C_P(\vec{u}\cdot\vec{\nabla})T = \vec{\nabla}\cdot(\lambda\vec{\nabla}T) \tag{3}$$

where $\vec{u}$ is the velocity (magnitude in m/s), p is the pressure (Pa), T is the temperature (K); ρ is the product's density (kg m^{-3}), η its apparent viscosity (Pa s), C_P its specific heat capacity (J kg^{-1} K^{-1}), and λ its thermal conductivity (W m^{-1} K^{-1}).

In this exploratory study focus is on the transformation of an aqueous suspension of chemically-modified waxy maize starch. Under heating, this liquid product undergoes a quite simple transformation: starch granules swell without either rupture of swollen granules or release of soluble species in water (Matignon et al., 2015). Hence, the volume occupied by the granules can indicate the transformation state regarding its influence on the apparent viscosity of the starch suspension. At a given time in the thermal history of a suspension droplet, the solid volume fraction Φ can be estimated as:

$$\Phi = \Phi_0(D/D_0)^3 \tag{4}$$

where D (μm) is the volume mean diameter of starch granules; valuesD_0 and Φ_0 correspond to the condition of untreated starch, before any thermal treatment. The transformation state associated with the starch suspension can also be indicated by the dimensionless value of the volume mean diameter (also known as swelling degree, S):

$$S = (D - D_0)/(D_{MAX} - D_0) \tag{5}$$

where D_{MAX} is the volume mean diameter after the maximum thermal treatment here considered. In the case of a modified waxy starch suspension in water, the variation in the swelling degree over time can be described using a second-order kinetics equation (Lagarrigue et al., 2008):

$$\frac{dS}{dt} = V\{T\}(1-S)^2 \tag{6}$$

where V is the temperature-dependent swelling kinetics rate (s^{-1}). Equations (4)–(6) summarize the product swelling for a travelling droplet in the starch suspension. The following conservation equation puts in evidence the inherent coupling which occurs between starch swelling, fluid flow and heat transfer at every position of the processing unit:

$$\vec{u}\cdot\vec{\nabla}S = V\{T\}(1-S)^2 + \vec{\nabla}\cdot(d_S\vec{\nabla}S) \tag{7}$$

where d_S is a diffusion coefficient (m^2 s^{-1}). Equation (7) states that the swelling state results from a) convective transport, b) temperature-dependent swelling of starch granules, and c) diffusion around the position under consideration. The coefficient d_S considered in this equation expresses the Brownian (random) diffusion affecting the starch granules in the suspension as well as some diffusion between parallel pathways along the exchanger.

Governing Equations (1)–(3), (7) are solved in this study with the help of numerical modeling tools throughout a sequence of computational domains, as summarized in Section 4. The first step of our modeling approach is the description of the transformation