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COUPLING FLUID FLOW, HEAT TRANSFER AND FOOD PRODUCT TRANSFORMATION: HEAT TREATMENT OF A STARCH SUSPENSION INSIDE A TUBULAR HEAT EXCHANGER

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Thermo-kinetic model, Thermal history of fluid particles,
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ABSTRACT

Many liquid food processes involve coupled phenomena of fluid flow, heat transfer and product transformation. A typical example is the heat treatment of a starch suspension inside a tubular heat exchanger. Fluid flow influences heat transfer which determines temperature evolution along fluid trajectories. Temperature locally influences the product transformation. The latter influences transport properties notably the viscosity which in turn influences the fluid flow behavior. In this study a numerical model was developed in order to account for these coupled phenomena in the case of a modified waxy maize starch suspension. Velocity and temperature fields were analyzed in view of the local state of the food product properties like the mean diameter of starch granules and the suspension viscosity.

INTRODUCTION

Numerical modeling of fluid flow and heat transfer inside liquid food process equipments has been largely developed (e.g., Norton and Sun 2006, Kumar and Dilber 2007). Transport phenomena properties, including the viscosity, are often assumed to be a function of the local temperature. Food transformation processes like starch gelatinization are more rarely taken into account.

Starch is the most widely employed thickener in the food industry. Most industrial processes for starch-thickened products involve temperatures which can be high enough for enabling starch phase transitions. The well-accepted concept of "gelatinization" refers to the destruction of the crystalline structure in starch granules, which is an irreversible process that includes, in a broad sense and in time sequence, granular swelling, native crystalline melting and molecular solubilization (Liu et al. 2009).

Liao et al. (2000) studied the continuous flow sterilization of a starch dispersion in which gelatinization is taken into account with the help of a thermo-rheological model. In such a model, the mixture viscosity depends on the local present temperature of the starch suspension, including two effects: with heating, the apparent viscosity increases due to the granule's swelling whereas the continuous phase viscosity decreases. Implicitly, that model assumes that the starch granules swelling state (for instance, evaluated in terms of the granules' mean diameter) is a function of the local present temperature only.

We argue that, rather than a straightforward relationship with the temperature, the food product viscosity can exhibit a non-negligible dependence on the thermal history of the fluid particle under consideration. Fluid particles running close to a heating wall evolve under thermal and kinetic conditions which are different from those associated with particles moving faster at greater distances from such wall. In the present work, the influences of the continuous phase viscosity and of the granule's volume fraction on the suspension viscosity are separated. The former depends instantaneously on temperature whereas the latter depends on the whole thermal history throughout the progressive swelling kinetic of the starch granules. Finite-element-based simulations are conducted, including a thermo-kinetic model based on the experimental work by Lagarrigue et al. (2008) about a modified waxy maize starch suspension.

MODELLING

The food product is an aqueous suspension of starch; because its high content of water, it is assumed to be a Newtonian liquid. Density and thermal properties are approximated by those of pure water. Conservation equations for the food product mass, momentum and energy can be written as:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot (-p \mathbf{I} + \eta (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)) \quad (2)$$

$$\rho C_p (\mathbf{u} \cdot \nabla) T = \nabla \cdot (k \nabla T) \quad (3)$$

The food product viscosity (η) can be obtained by multiplying the water viscosity (η_w) and the relative viscosity associated with the suspension of particles. A number of approximations have been proposed for estimating the latter (see a review by Cheng and Law, 2003). We adopted the model proposed by Thomas (1965) because it provides an increase of the product viscosity with temperature which is coherent with experimental results (see Fig. 7a of Lagarrigue et al. 2008). The product viscosity is hence expressed as a function of the volume fraction associated with starch granules (Φ):

$$\eta / \eta_w(T) = 1 + 2.5 \Phi + 10.05 \Phi^2 + 0.00273e^{16.6 \Phi} \quad (4)$$

The solid volume fraction can be estimated from the mean volume-weighted diameter associated with the granules' size distribution (D), employing also respective information characterizing the starch suspension before any heat treatment:

$$\Phi / \Phi_0 = (D / D_0)^3 \quad (5)$$

Following Lagarrigue et al. (2008), Rao and Tattiyakul (1999) and previous contributions, we define the degree of gelatinization X of the starch suspension at a given instant in terms of the values assumed by that mean diameter before (D_0), during (D), and after the heat treatment (D_M):

$$X = (D - D_0) / (D_M - D_0) \quad (6)$$

Starch granule swelling can be evaluated through a second-order kinetics:

$$(\mathbf{u} \cdot \nabla) X = V(1 - X)^2 \quad (7)$$

where the rate constant V can be suitably expressed in terms of the Arrhenius law:

$$V(T) = V_0 \exp(-E_A / (R T)) \quad (8)$$

Our attention is here focused on the 3.1 % w/w modified waxy maize starch dispersion studied by Lagarrigue et al. (2008); it corresponds to $D_0 = 15.5$ and $D_M = 39.6$ μm , $\Phi_0 = 0.03$, $V_0 = 2.9e+12$ s^{-1} , and $E_A = 84.8$ $\text{kJ} \cdot \text{mol}^{-1}$. Thermal and fluid properties of pure water are properly described as functions of the temperature.

The coupled phenomena are illustrated inside a tubular heat exchanger. Such a geometry represents typical industrial devices used, for example, in continuous flow sterilization (see a discussion by Liao et al. 2000). A two-dimension axial-symmetric domain was built, $L = 1$ m long and $R = 5$ mm wide. Conservation equations for the fluid mass, momentum and energy (eqs. 1-3), combined with the equation of convection and swelling of starch granules (eq. 7), were solved using the finite-element-based simulation package COMSOL Multi-physics (version 3.5a). The mesh contains identical rectangular elements only: suitable results

were obtained by adopting 2000 elements along the length by 40 elements along the tube radius.

A fully developed parabolic flow profile was assumed at the entrance of the tubular exchanger. The flow rate was fixed at 10 liters per hour (roughly 0.035 $\text{m} \cdot \text{s}^{-1}$). According to the Reynolds number (about 600), the flow regime is laminar. Boundary conditions are summarized in Table 1.

RESULTS AND DISCUSSION

Figure 1 overviews the temperature (left), the degree of gelatinization (center) and the viscosity (right) fields resulting from simulations described above. The viscosity field was deformed according to the velocity; inlet and outlet velocity profiles can be easily appreciated at domain extremes. Dark blue and red colors correspond to minimum and maximum values respectively. The volume fraction field was omitted, being a function of the degree of gelatinization (eqs. 5-6). The food product is heated from the wall (right of domain). Fluid particles move slower and reach higher temperatures when running near it. Starch granules swell after heating; their volume fraction increases as well as the food product viscosity. In comparison with the conditions prevailing near the inlet, the viscosity increases by a factor of about 7 near the wall at the outlet, slowing down the velocity in this region of the domain.

These results follow, in a partial extent, those obtained by Liao et al. (2000). They also observed in the heating section of their tubular exchanger an increase of viscosity near the heating wall due to gelatinization, leading to a velocity decrease near this wall and a velocity increase at the axis of symmetry. Nevertheless starch type and concentration were different (4 % of waxy rice starch), and heating conditions were stronger (145°C); hence a direct comparison seems difficult. Their maximum viscosity was much higher (about 6 Pa.s), which caused velocity profiles almost flat were the food product was very viscous; this was not observed in our case. Other geometries than tubular exchangers have been adopted in numerical models coupling fluid flow, heat transfer and starch gelatinization, like axially rotating cans (Tattiyakul et al. 2001). Any tentative of comparison with such results seems far to be straightforward.

The evolution of food product properties can also be studied with the help of hypothetical trajectories of fluid particles released at the domain inlet. We can imagine each fluid particle as a suspension droplet containing an ensemble of starch granules at similar thermodynamic and kinetic conditions. Figure 2 compares selected properties associated with fluid particles released at 0.5 and at 1.0 mm from the heating wall (see Figure 1). The residence time in the domain correspond to about 89 and 36 s, respectively, because the maximum velocity occurs at the symmetry axis. Figure 2 shows that the fluid particle moving closer to the wall is associated, at the outlet, with higher values of temperature (left), of mean diameter of starch granules (centre), and of viscosity (right). Other the granule starch swelling, the product viscosity depends also on the continuous phase (pure water) viscosity. The latter slowly decreases with heating,

and this fact explains why the product viscosity is slightly reduced during the first seconds after particle release.

Positions A and B in Figures 1 and 2 correspond to a same temperature value (about 67 °C) which is not experienced simultaneously in the time series of the two followed fluid particles. Position A represents the outlet for the fluid particle released at 1.0 mm from the heating wall; it reached this position after about 36 s from the inlet. Position B is far before the domain outlet; the fluid particle released at 0.5 mm from the wall moves slower and spent about 57 s to come there. Despite the same temperature, position B corresponds to a mean diameter of starch granules which is about 10 % greater, and to a product viscosity about 50 % greater, than respective values at position A. Such differences are explained by the fact that fluid particles running at different distances from the heating wall move with different velocities and hence experience different temperature time series (or histories). By analyzing these two trajectories it appears that the influence of temperature on viscosity is far to be instantaneous. The product viscosity depends on the continuous phase viscosity as well as on the starch granule volume fraction. The former depends on the present temperature and the latter depends on the whole thermal history of the respective fluid particle.

CONCLUSIONS

In this study our attention was focused on the main processes driving the starch gelatinization inside a tubular heat exchanger. Just one among the growing number of types of starch was taken into account. Starch research is a very active subject, and significant effort has been accomplished in characterizing native and modified starch, including different genotypes and various climates (e.g., Yeh and Li 1996, Patterson et al. 2001, Choi and Kerr 2004, Xie et al. 2009). The aim of this study was to demonstrate that coupling a gelatinization model (for a given starch type and concentration) with a fluid flow and heat transfer model can highlight what happens inside a tubular heat exchanger. The numerical model enables to follow selected food product properties along different fluid particle trajectories.

Food product properties, as simulated here, are the final result of a fully-coupled number of processes: fluid flow and heat transfer drive the temperature field; temperature influences the product transformation kinetics, which in turn modifies the product viscosity and hence the fluid flow behavior itself. Our results show that the local present temperature does not determine alone the present food product properties. The degree of transformation inside a fluid particle of food product depends on its whole thermal history. This means that the temperature evolution along the fluid particle trajectories is a major information which must

be properly assessed when, for instance, the product viscosity depends on the degree of transformation.

A relatively simple food product transformation was here considered (starch granules swelling). Further work will focus on coupling fluid flow and heat transfer with more complex transformation (like amylose solubilization, mechanical granules fragmentation, aggregation).

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Table 1: Boundary Conditions

	fluid flow	energy	gelatinization
inlet	$u_r = 0, u_z = u_{\max} (1 - (r/R)^2)$	$T = 20\text{ }^\circ\text{C}$	$X = 0$
outlet	$u_r = 0, p = p_o$	$\partial T / \partial z = 0$	$\partial X / \partial z = 0$
wall	$u_r = 0, u_z = 0$	$k \partial T / \partial r = 10\text{ kW}\cdot\text{m}^{-2}$	$\partial X / \partial r = 0$

Figure 1: Distribution of Selected Product Properties across the Domain

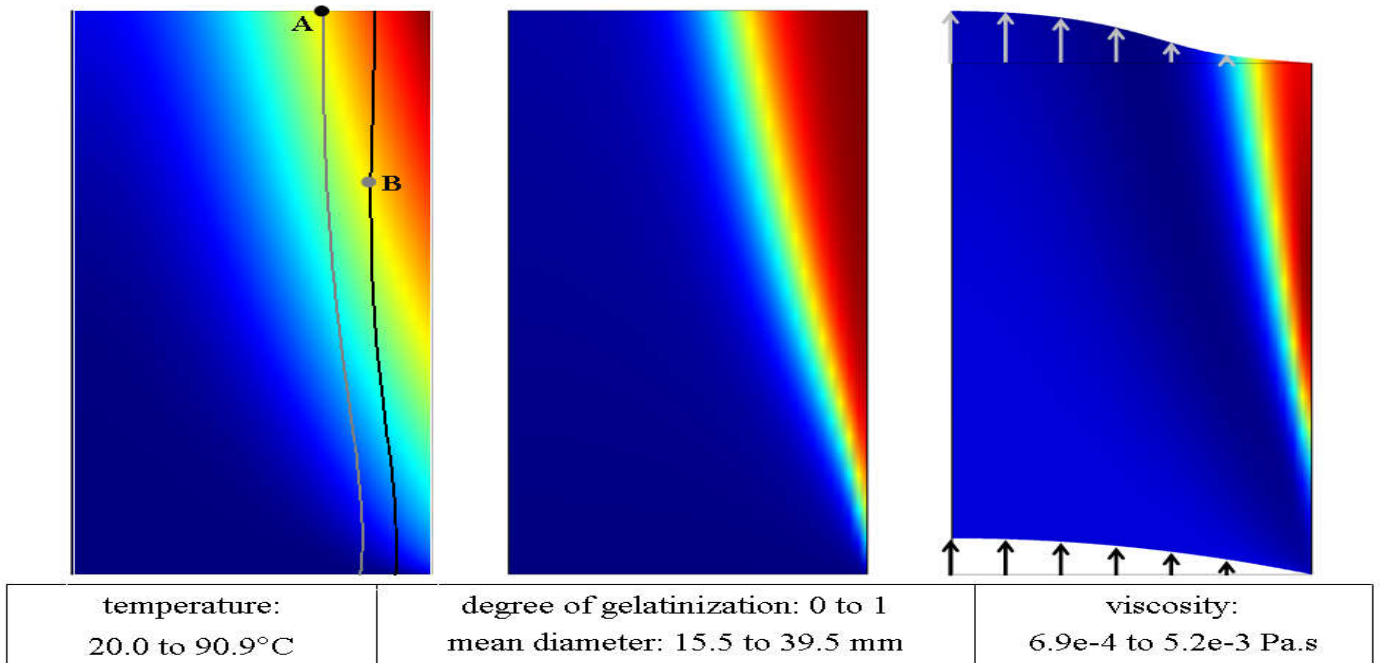


Figure 2: Time Series of Selected Product Properties corresponding to Two Hypothetical Particle Trajectories, released at 0.5 and 1.0 mm from the Heating Wall at the Inlet

