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Modelling the heat treatment of a starch suspension inside a tubular exchanger: the influence of food product transformation on residence time distributions

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ABSTRACT

An experimentally based thermo-kinetic model of starch granule swelling is coupled with a fluid flow / heat transfer numerical model, allowing a tool for studying the evolution of a starch suspension in laminar flow inside a tubular heat exchanger. Both granule swelling and suspension viscosity are the highest near the heating wall, where fluid particles move slower and reach higher temperatures. Fluid particles running at the exchanger's axis have the highest velocity; when heat transfer and food product transformation are both considered, the fastest particles spend only 43 % of the mean residence time for leaving the domain. Such a value is significantly lower than for an isothermal flow without transformation where the lowest residence time is 50 % of the mean value. This result indicates that the two-way coupling of fluid flow, heat transfer and transformation has to be considered in this case. The evolution of food product properties is also studied with the help of two hypothetical trajectories of fluid particles released at the inlet, the first at 1.0 mm and the second at 0.5 mm from the heating wall. When both fluid particles reach the temperature 66°C (i.e. when the first reaches the domain outlet), the mean diameter of starch granules for the second fluid particle was about 10 % greater, and the suspension viscosity was about 45 % greater, than the respective values for the first one. Hence the temperature evolution along the fluid particle trajectories must be properly assessed when the food product viscosity depends on the degree of transformation.

Keywords: Fluid flow; heat transfer; starch granule swelling; heat exchanger; residence time distribution

INTRODUCTION

Many liquid food processes involve coupled phenomena of fluid flow, heat transfer and product transformation. Fluid flow and heat transfer determine the temperature field, which can influence the product transformation. Transformation can in turn modify the rheological and thermal properties associated with the product. This two-way dependence has been taken into account in modelling of coupled processes; nevertheless, few attention has been devoted to the fact that the fluid particles move slower near heating walls and therefore experience thermal and / or kinetic histories in the process unit that are different from those associated with particles running far from walls.

The present study considers a relatively well-known product transformation in the food industry, namely the thickening of a starch suspension after a thermo-mechanical treatment in excess water. Our aim is three-fold: a) to demonstrate that coupling a thermo-kinetic model of granule swelling with a fluid flow / heat transfer model can highlight what happens for a waxy modified starch suspension inside a tubular heat exchanger, b) to evaluate the influence of the thermal history on local values of the suspension viscosity, and c) to assess, on the residence time distribution, the impact of neglecting or not the suspension viscosity increase induced by the food product transformation.

METHODS

Conservation equations for the food product mass, momentum and energy can be written as:

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

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

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

The liquid food product is an aqueous suspension of starch granules: because its high content of water, it is assumed to be a Newtonian liquid. Its density and thermal properties are approximated by those associated with pure water. The mixture viscosity η is obtained by multiplying the continuous phase (pure water)

viscosity η_w and the relative viscosity φ , which is a function of the state of the transformation S . Such a state (varying from 0 to 1) is evaluated through a second-order kinetics equation, $dS/dt = V(1-S)^2$; V is the rate constant which is estimated through the Arrhenius law, $V(T) = V_0 \exp(-E_a/(RT))$. Under steady-state conditions and after including a diffusion term for starch granules in the suspension, this kinetics equation can be written as a convection-diffusion equation:

$$\mathbf{u} \cdot \nabla S = V (1 - S)^2 + \nabla \cdot (D_s \nabla S) \quad (4)$$

Following Lagarrigue *et al.* [1], the state of the transformation is expressed in terms of the swelling degree defined by $S = (D - D_0) / (D_m - D_0)$, where D is the mean volume-weighted diameter of starch granules, and D_0 and D_m are its values before thermal treatment (native starch) and after complete treatment, respectively. The availability of mean diameter estimates enables to evaluate the solid volume fraction that is occupied by the particles, $\Phi = \Phi_0 (D / D_0)^3$, where Φ_0 and D_0 values characterize the starch suspension before any treatment. Such a solid volume fraction is the key parameter for assessing the relative viscosity increase, for instance through the model proposed by Thomas [2]:

$$\varphi = (1 + 2.5 \Phi + 10.05 \Phi^2 + 0.00273 \exp(16.6 \Phi)) \quad (5)$$

Significant effort has been accomplished in characterizing native and modified starch, including different genotypes and various climates [3-7]. We focused the attention on a 3.1 % w/w modified waxy maize starch dispersion experimentally that has been studied by Lagarrigue *et al.* [1]: it corresponds to $D_0 = 15.5$ and $D_m = 39.6 \mu\text{m}$, $\Phi_0 = 0.03$, $V_0 = 2.9 \cdot 10^{12} \text{ s}^{-1}$ and $E_a = 84.8 \text{ kJ} \cdot \text{mol}^{-1}$.

Coupled phenomena under laminar flow are illustrated inside a tubular heat exchanger with length 1 m and radius 5 mm, represented through a two-dimension axial-symmetric domain. Equations (1-4) were solved under steady-state conditions with the finite-element method (simulation package COMSOL Multi-physics, version 3.5a). A uniform flux of $10 \text{ kW} \cdot \text{m}^{-2}$ was applied on the heating wall, and the temperature of the starch dispersion was assumed to be $20 \text{ }^\circ\text{C}$ at the inlet. These conditions enable a maximum temperature near the wall at the exchanger outlet of about $91 \text{ }^\circ\text{C}$, which corresponds to a relevant degree of starch granule swelling (see Table 2 of Lagarrigue *et al.* [1]). A fully developed flow profile was assumed at the inlet, and the flow rate was fixed at 10 litres per hour (mean velocity of $0.035 \text{ m} \cdot \text{s}^{-2}$). According to the Reynolds number (below 600), the flow regime is laminar.

The numerical representation of coupled processes is difficult at the heating wall because the high magnitude of thermal and velocity gradients that prevail there. Both granule swelling and suspension viscosity are expected to increase sharply near the corner of the domain inlet with the heating wall. Results discussed below were obtained with a mesh constituted of 80 rectangular cells along the domain's radius and 3200 along the domain's length; it represents the finest regular mesh allowing model convergence with our present capabilities (a 64-bits calculator disposing of 24 Gb of RAM).

RESULTS & DISCUSSION

Figure 1 shows the temperature, mean diameter and suspension viscosity fields resulting from the simulations. The suspension viscosity field was deformed according to the inlet and outlet velocity profiles. The food product is heated from the wall (bottom of domain). Fluid particles move slower and reach higher temperatures when running near it. After heating, starch granules swell; their mean diameter increases, then their volume fraction and finally the suspension viscosity. In comparison with the conditions prevailing at the inlet, the suspension viscosity increases by a factor of about 7 near the corner of the outlet with the wall, slowing down the velocity in this region.

These results follow, in a partial extent, those obtained by Liao *et al.* [8]. Those authors also observed in the heating section of their tubular exchanger an increase of viscosity near the heating wall due to granule swelling, 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 ($145 \text{ }^\circ\text{C}$) than those considered in our study; therefore a direct comparison of results seems difficult. Their maximum suspension 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, for instance axially rotating cans [9]. Any comparison with such results seems far to be straightforward.

The evolution of food product properties can also be studied with the help of forward Lagrangian trajectories associated with fluid particles released at the domain inlet. Each fluid particle can be imagined as a suspension droplet containing an ensemble of starch granules at similar thermodynamic and kinetic conditions. In its right section, Figure 1 displays selected properties associated with fluid particles released at 1 and at 0.5 mm from the heating wall; they spent about 36 and 86 s respectively for reaching the outlet. Fluid particles released the nearest to the wall are associated with higher values of temperature and suspension viscosity. The suspension viscosity also depends on the continuous phase (water) viscosity, which weakly decreases with heating; this fact explains why the suspension viscosity is slightly reduced during the first seconds after particle release. Positions A and B correspond to a same temperature value (about 66 °C), where A represents the outlet for fluid particles released at 1 mm. Fluid particles released at 0.5 mm move slower and spent about 55 s to come at position B. Despite the same temperature, position B corresponds to a mean diameter and a suspension viscosity values which are about 10 and 45 % greater than the respective values at the position A. Such a difference shows clearly that fluid particles running at different distances from the heating wall move with different velocities, and therefore experience different thermodynamic and kinetic histories.

More generally, each fluid particle of a liquid food product takes a different route and spends a different time to flow through the processing unit. The distribution of these times at the outlet characterizes the residence time distribution of the process. Since Danckwerts [10], the analysis of residence time distributions has been usefully applied to study the flow pattern, to determine the degree of mixing and to diagnose flow problems such as recirculation, channelling, short-circuiting or stagnation [11].

In this study the residence time distribution is estimated from velocity numerical simulations, with the help of backward Lagrangian trajectories starting at the domain outlet. Such a procedure was implemented for three scenarios of interest.

Figure 2 compares the cumulative residence time distributions obtained after a) fully coupling the fluid flow, heat transfer and food product transformation processes as described above, b) discarding the occurrence of starch granule swelling, and c) discarding the occurrence of transformation and of heat transfer, i.e. assuming constant viscosity. The latter condition corresponds to a fully developed flow; hence first fluid particles leaving the domain spent 50 % of the mean residence time. After taking into account the influence of heat transfer alone, water viscosity decreases in the vicinity of the heating wall, enabling higher velocity there than for constant viscosity. On the contrary, velocity is lower near the axis; therefore the lowest residence time is higher than for constant viscosity: fastest fluid particles leave the domain after about 55% of the mean residence time. Finally, after taking into account the influence of both heat transfer and starch swelling, the suspension viscosity increases in the vicinity of the heating wall, slowing down fluid particles moving there. As a consequence, fluid particles running at the tubular exchanger's axis are relatively accelerated: the fastest particles spent about 43 % of the mean residence time for leaving the domain. Therefore the suspension viscosity increase induced by starch granule swelling cannot be neglected.

CONCLUSIONS

A number of issues related to the coupled modelling of fluid flow, heat transfer and food product transformation were illustrated above in studying the evolution of a starch suspension under continuous thermal treatment. Previous experimental work provided key parameters for the thermo-kinetic swelling model, and also guided us in the selection of the approximation describing the suspension viscosity increase induced by the starch granule swelling. It is recommendable to separate the influence of temperature on the continuous phase viscosity from the influence of transformation on the overall suspension viscosity; their effects can be opposite and, more importantly, they can be associated with different time scales. The former depends on the present local temperature whereas the latter depends on the whole thermal history of fluid particles. Finally, residence time distributions can be assessed from numerical model simulations, and the implementation of such an approach can contribute to the reactor performance evaluation.

A simple food product transformation was here considered (starch granules swelling), and a just one among the growing number of types of starch was taken into account. Future efforts will be focused on coupling fluid flow and heat transfer with more complex food product transformation processes, like particles aggregation, mechanical granules fragmentation, and amylose solubilization.

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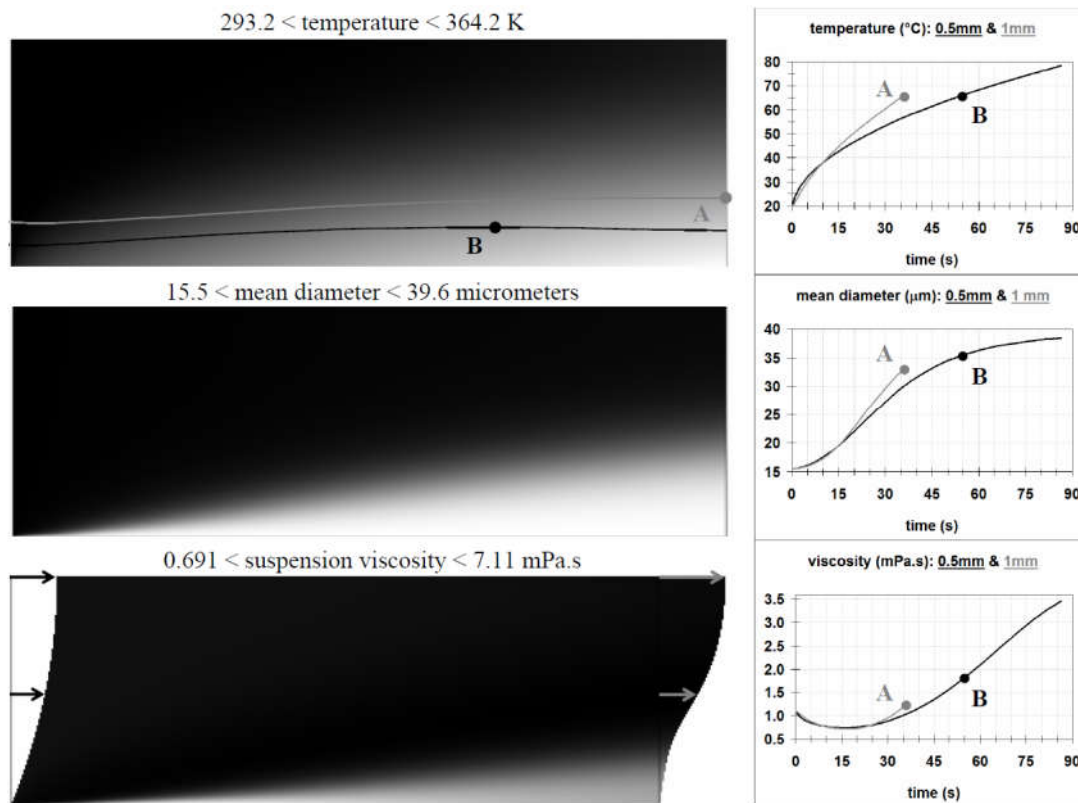


Figure 1. Left: temperature (top), mean diameter (center), and suspension viscosity (bottom) fields, where the heating wall is on the bottom; dark and clear picture elements correspond to the minimum and maximum values respectively. Right: time series corresponding to two trajectories followed by hypothetical fluid particles released at the inlet at 0.5 and 1 mm from the heating wall.

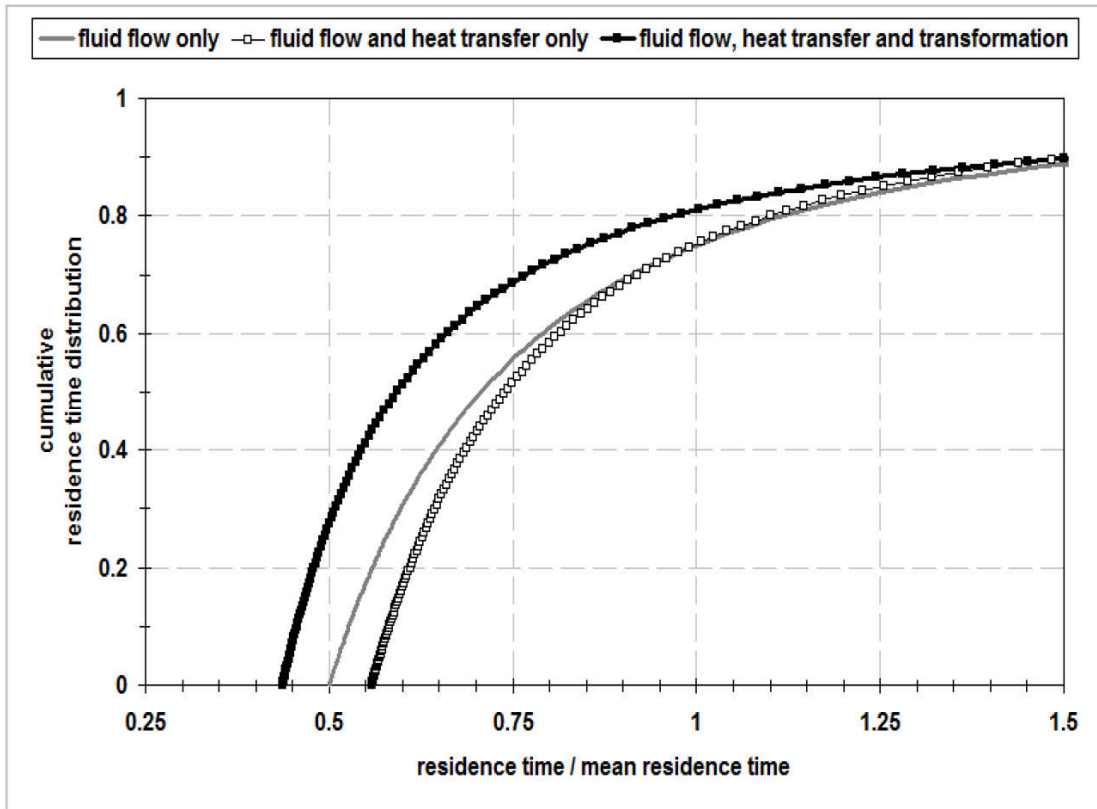


Figure 2. Cumulative residence time distributions resulting from the coupled numerical model (black squares), and from successively simpler versions that discard starch swelling (white squares) and discard both heat transfer and starch swelling (grey line).