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Milk Heat Treatments: Temperature Effect on Fouling

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The purpose of this work is to examine the effect of heating temperature on milk fouling by comparing the evolution of deposits for three different heat treatments, respectively, pasteurization, sterilization and Ultra-High Temperature treatment. A numerical approach was used to resolve the governing equations of fluid flow, heat transfer and fouling model in a plane two-dimensional channel, which represents the first channel of the plate heat exchanger. Fouling model is based on the chemical alterations of β-lactoglobulin protein. Different simulations were conducted according to the type of heat treatment. The results show that the evolution of deposits over time differs from one treatment to another and that the amount of deposit increases with the increase of the heating temperature. A correlation was determined to evaluate heat losses due to deposits according to heating temperature. This work will allow the dairy industry to better plan cleaning steps of equipment, which generate losses in terms of capital, energy and product quality.

1. Introduction

Heat treatment is a very important operation in dairy industry. It is necessary to ensure microbial safety and increase the shelf life of milk. For this purpose, several treatments have been developed with different operating conditions. Plate heat exchangers are widely used in the dairy industry because of their compactness, ease of maintenance and high thermal performance. However, they are particularly prone to fouling.

Studies show that milk fouling formation is due to β-lactoglobulin protein. This protein become thermally unstable at high temperatures and undergoing irreversible chemical alteration causing formation of undesirable deposits on heating surface. These deposits reduce thermal performances of equipment and increase pressure drop.

Many factors can affect the evolution and amount of deposits. It is shown that the increase in turbulence implies a decrease in deposits (Belmar-Beiny et al., 1993; Santos et al., 2003). Also, a seasonal variation of milk composition affects formation of deposits (Burton, 1967; De Jong, 1997). Temperature is the most important factor that affects milk fouling (Bansal, 2006). It is clear from the studies that the increase in temperature increases the rate and amount of deposits. Fouling nature changes at about 110 °C from type A to type B (Burton, 1968). It should also be mentioned that the absolute temperature and the average temperature (or the difference in temperature) are important in the measurement of fouling. A study on the effect of the average temperature and the heat exchange surface area of three milk varieties on fouling showed that the temperature at the heat exchange surface is the most important factor (Chen et al., 1998). The use of preheating causes the denaturation and aggregation of the proteins before the heat treatment, thus inducing a greater amount of fouling in the heat exchanger (Mottar, 1988).

Modeling and simulation of transfer phenomena, as for various domains (Balocco and Petrone, 2018; Reddy and Ramesh, 2018; Jing, 2017), were used to study fouling mechanism. Georgiadis and Macchietto (2000) presented a two-dimensional dynamic model to determine the amount of fouling in a plate heat exchanger. (Mahdi et al., 2009) proposed a two-dimensional dynamic fouling model for milk fouling in a plate heat exchanger, which takes into account fouling caused by both β-lactoglobulin protein and calcium phosphate. Recently, (Bouvier et al., 2014) used a CFD model to simulate β-lactoglobulin heat-induced denaturation and aggregation in a plate heat exchanger. (Aouanouk et al., 2018) determined a mathematical relationship

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between the wall temperature and deposit thickness in the first channel of plate heat exchanger by the use of a calculation code developed to study the evolution of fouling during milk pasteurization.
This work aims to study the effect of the temperature of the heat exchange surface on the formation and evolution of the deposits. Three different treatments were studied, pasteurization, sterilization and UHT treatment. For this purpose, a numerical study was carried out based on a model of fouling by chemical reactions of the protein.

2. Mathematical formulation

2.1 Fluid flow and heat transfer

In this paper, milk flow is investigated in a vertical channel, which is considered as the first channel of plate heat exchanger, between two parallel plates of L = 75 cm length and W = 20 cm width, separated by a distance of e = 4 mm. The schematic of the system is represented in Figure 1.

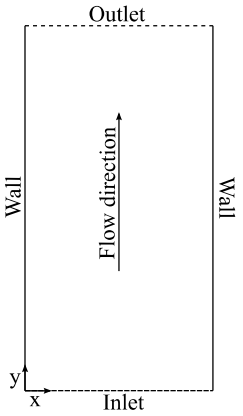

Figure 1: Schematic of geometry.

Assuming that flow of Newtonian fluid is laminar and neglecting gravitational force, Eqs. (1 – 3) represent governing equations for, respectively, continuity, momentum and energy.

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho \partial \vec{V} / \partial t + \rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \mu \nabla^2 \vec{V} \tag{2}$$

$$\partial T / \partial t + (\vec{V} \cdot \nabla)T = \alpha \nabla^2 T \tag{3}$$

where V is velocity, P pressure and T temperature. μ represent viscosity of milk, ρ its density and α its thermal diffusivity.

2.2 Fouling model

Milk fouling model used in this study, is a dynamical two-dimensional model considering that formation of deposits is due to β-lactoglobulin protein. From 65 °C, β-lactoglobulin in its native form undergoes a chemical alteration of order 1.5 producing another form of the protein containing a sulfhydryl group (-SH). The denatured protein polymerizes irreversibly giving an aggregate. The chemical reactions are both in bulk fluid and thermal boundary layer and mass transfer between bulk of fluid and the thermal boundary layer takes place. Only the aggregated protein in the thermal boundary layer adheres to the heat exchange surface. This model is mathematically represented by mass balance of both protein forms Eqs (4-6) where C_N, C_U and C_A represent the concentration of native, denatured and aggregated protein, respectively.

$$\partial C_N / \partial t + (\vec{V} \cdot \nabla)C_N = D_N \nabla^2 C_N - R_N \tag{4}$$

$$\partial C_U / \partial t + (\vec{V} \cdot \nabla)C_U = D_U \nabla^2 C_U + R_N - R_U \tag{5}$$

$$\partial C_A / \partial t + (\vec{V} \cdot \nabla)C_A = D_A \nabla^2 C_A + R_U \tag{6}$$

D_N, D_U and D_A denote diffusion coefficients of each protein. R_N and R_U are, respectively, the rates of denaturation and aggregation reactions. Details of reactions kinetic parameters can be found in (Aouanouk et al., 2017)
The Biot number allows coupling between heat and mass transfer at the wall. By definition, it is the ratio of resistance to heat transfer by convection and conduction in a solid (deposit). It is calculated by Eq (7) where β is an experimentally determined coefficient, β = 129 $m^2.kg^{-1}$ (Georgiadis and Macchietto, 1998) and $k_w = 10^{-7}$ $m.s^{-1}$ the mass transfer coefficient of the aggregated protein to the wall.

$$\partial Bi(y)/\partial t = \beta k_w C_A(0,y) \tag{7}$$

The mass of the deposit per unit area on each wall is determined by (8) where U_0 represents the overall heat transfer coefficient of the channel under clean conditions, ρ_d = 1030 $kg.m^{-3}$ and λ_d = 0.5 $W.m^{-1}.K^{-1}$ are, respectively, density and thermal conductivity of the deposit. Equation (9) gives the average mass of deposit on each wall.

$$M(y) = \rho_d Bi(y) \lambda_d / U_0 \tag{8}$$

$$\overline{M} = W \int_0^L M(y)\,dy \tag{9}$$

2.3 Boundary conditions

Milk enters the channel with uniform velocity corresponding to Reynolds number of Re = 1700, inlet temperature denoted T_{in} = 293 K and native β-lactoglobulin concentration of 5 $kg.m^{-3}$. At the outlet, established flow is imposed for all variables.
Non-slip and non-penetration conditions are imposed at walls for velocity components. Temperature of the walls is initially imposed at T_0 and in order to link heat transfer to the amount of deposit (10) is used.

$$T_w(y) = T_0 /(1 + Bi(y)) \tag{10}$$

The concentration of native and denatured proteins is zero at the walls according to the fouling model, which states that only the aggregated protein adheres to the wall. The adhesion of aggregated protein on the wall is modelled by Eq (11) where $k_w = 10^{-7}$ $m.s^{-1}$ and δ_T the thermal boundary layer.

$$\partial C_A / \partial x = -k_w C_A / \delta_T \tag{11}$$

2.4 Numerical procedure

The equations presented in this model are a set of partial differential equations. In order to solve it, a computer program was developed in Fortran 90 language. It uses the finite volume method for spatial discretization with power law scheme. Establishment of pressure / velocity linkage is done with SIMPLE algorithm proposed by Patankar (1980). The implicit scheme was used for temporal discretization. The plate heat exchanger channel is assumed as a rectangular domain that consists of 80 x 160 nodes in staggered grid. The obtained systems of algebraic equations are solved by a Semi Implicit Procedure (SIP) method. The run of simulation has taken about 7 hours of computing time on a Xeon server (2.53 GHz CPU, 6 Go RAM).

3. Results

This work aims to evaluate the effect of the different thermal treatment of milk on the deterioration of the thermal performance of a heat exchanger. For this purpose, three simulations were conducted by imposing different values of initial wall temperatures T_0. These values are 373, 393 and 413 corresponding to pasteurization, sterilization and ultra-high temperature treatments, respectively.

3.1 Milk outlet temperature

The evolution of mean temperature at the channel outlet, for each treatment, is shown in Figure 2. The shape of curves is the same for all heat treatments. Firstly, outlet temperature increases during the first seconds of heat treatment where the temperature increases considerably and remains constant. There is no fouling formation in this time laps. Then, the outlet temperature decreases until the end of operation. However, it is seen that temperature drop varies according to the initial wall temperature imposed. The denaturation rate, which increase for higher temperature in the channel, allows an increase in deposits on the wall. Also, it's seen that outlet temperature tends to the same value at the end of heating operations.

Thermal performances of the heat exchanger are more deteriorated by fouling for higher wall temperature initially imposed.

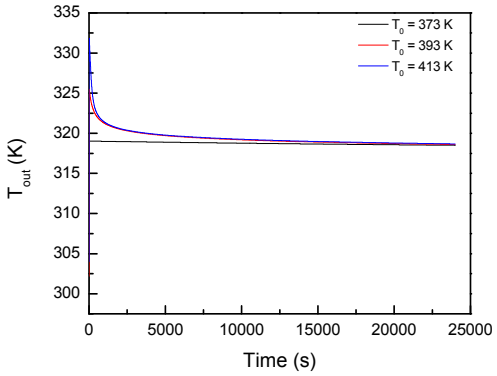

Figure 2: Channel outlet temperature evolution

3.2 Deposits amounts

In this section, evolution of the average mass of deposit, for different initial wall temperatures imposed, is discussed. Figure 3 represents the results obtained by simulations. The amount of deposits increases quickly, for sterilization (T_0 = 393 K) and UHT (T_0 = 413 K) treatments, then the rate of deposition decreases to reach an asymptotic value of fouling amounts. As for pasteurization (T_0 = 373 K), the rate of deposition is less important and the evolution of the mass deposits is almost linear. It is clear that the heat treatment type affects the mass of fouling. The amount of deposit reaches 141.56 grams for UHT and 72.67 grams for the sterilization. As for pasteurization, it is about 4.72 grams.

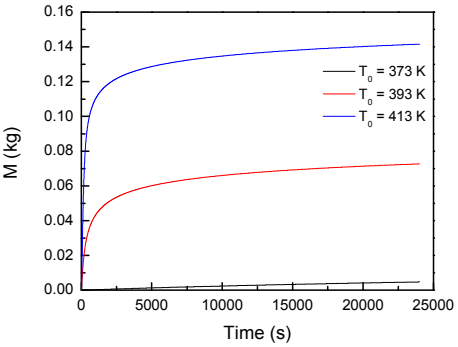

Figure 3: Average mass of deposit evolution

3.3 Proteins distribution

In order to observe the heat treatment type effect on denaturation and aggregation reactions, distributions of both proteins concentrations in the channel are presented in Figure 4.
It is seen that native protein is concentrated in the bulk of channel. It is also noticed that, neighboring walls, native β-lactoglobulin concentration decrease with increasing initial wall temperature imposed.
As for aggregated protein, it is principally concentrated near the walls. The maximal value of its concentration decreases with increasing wall temperature. This is due to transformation of the aggregate into solid deposits.
The denatured protein distribution is more complex; it is a product of the denaturation reaction and reactant of the aggregation reaction at the same time. This protein is mainly concentrated at the interface of the thermal boundary layer. This is due to mass transfer that takes place between bulk of the fluid and thermal boundary layer thickness. It is observed that this protein concentration is higher at the output than at inlet channel. This is explained by the fact that temperature is higher at the outlet of the channel and thus the protein is denatured in great quantities in this zone of the channel.

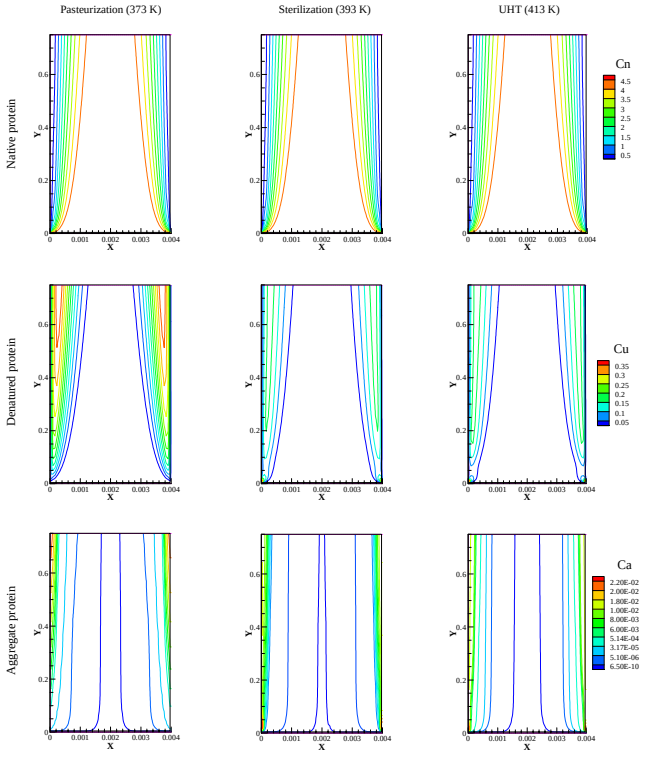

Figure 4: Proteins concentration distributions in the channel (kg.m^{-3})

3.4 Energy losses

For an optimal cleaning operations schedule of installations, it is necessary to evaluate thermal performances deterioration of the heat exchangers. For that, an attempt to model the heat losses due to fouling was studied by calculating the difference of heat exchanged, between the walls and the product, at the end of heat treatment in the cases of clean and fouled walls conditions. The amount of heat exchanged is calculated from Eq (12) where m is the mass flow rate of the fluid, Tout the outlet temperature and T_{in} the inlet temperature.

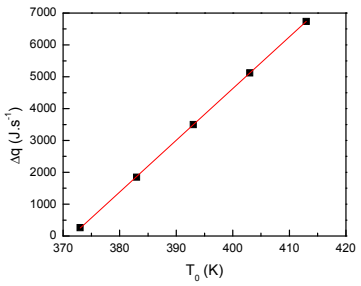

Figure 5: Heat losses vs. initial wall temperature

$$q = mC_P\left(T_{out} - T_{in}\right) \tag{12}$$

The results are illustrated in Figure 6. It is clear that there is an increase of energy losses with increasing initial wall temperature. By performing a fitting of points obtained in Figure 6, a linear expression was determined, Eq. 13, giving the heat losses, during a day of heat exchanger operation (24000 seconds), due to fouling according to heat treatment temperature. This adjustment gives a widely acceptable coefficient of determination whose value is $R^2 = 0.99$.

$$\Delta q = 162.13T_0 - 60224.18 \tag{13}$$

4. Conclusions

Milk fouling is strongly affected by temperature. In this work, a computational code developed in Fortran 90 language is used to evaluate the amount of fouling due to chemical reactions of β-lactoglobulin for three different heat treatments. The results obtained show that accumulated deposits evolve slowly and linearly for pasteurization treatment. As for sterilization and Ultra-High temperature treatments, average mass of deposits is more important and progresses in exponential shape with an asymptotic value. It is shown that the outlet temperature decreases along heating operation and reach a value of about 318 K for both treatments. Proteins concentration distributions in the channel indicate that denatured and aggregated protein concentrations decrease with the increase of the temperature treatment. This is due to the instantaneous transformation of the denatured protein into aggregated protein and the transformation of the latter into a solid deposit which adheres to the wall. The heat losses due to deposits were determined as function of heating temperature and their evolution is linear.

However, it is demonstrated that with the increase of heating temperature salts, like calcium, present in milk affect the deposits. It is interesting to study this interaction between chemical reactions of proteins and salts precipitation for a better approximation of deposits amounts.

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