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INFLUENCE OF CORRUGATION ANGLE IN THE STIRRED YOGHURT PROCESSING IN PLATE HEAT EXCHANGERS

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Abstract

Research on heat transfer of non-Newtonian fluids during thermal processing is very useful for optimise heat exchanger design, as well as to define quality levels of the final product.

In the present study non-isothermal, non-Newtonian flow in plate heat exchangers were simulated numerically, in order to evaluate the influence of corrugation angles on the thermal and hydrodynamics characteristics of yoghurt cooling in a plate heat exchanger. Simulations were carried out using the commercial finite element method package POLYFLOW, being the geometrical domain the representation of a single 3D channel of the plate heat exchanger.

Two corrugation angles were considered, 30° and 60°, being the obtained numerical results for the first one compared with experimental data. A laminar flow was observed for the two cases and the decrease of the angle conducted to a decrease of pressure drop and maximum shear rate.

1. INTRODUCTION

Thermal processing is a usual operation in the food industry. During cooling or heating operations, fluids are submitted to several modifications of their physical properties, which could affect its structure and stability.

Stirred yoghurt is a typical non-Newtonian food fluid, being their rheological properties influenced by several factors related with its physical nature and processing conditions. These aspects have been subject of some previous studies in which the shear-thinning behaviour, partial thixotropic and viscoelastic properties were identified [1, 2, 3, 4, 5, 6].

Plate heat exchangers (PHEs) are commonly used on the processing of foodstuffs. Due to several advantages of this equipment, like their efficiency, ease of cleaning and maintenance, several modelling works have been performed in order to optimise their project and design namely, arrangements and configurations [7, 8, 9], pressure drop and fanning factors [10, 11, 12] and influence of corrugation angle on flow behaviour [13, 14, 15]. However, most of the above studies were performed for Newtonian fluids and, out of those that did not the majority restricted the analysis to isothermal flows. The aim of present work is to overcome some of the shortcomings above and study the influence of corrugation angle on the thermal and hydrodynamics characteristics of yoghurt processing in PHEs using a non-isothermal and non-Newtonian analysis.

2. PROBLEM DESCRIPTION

Cooling treatment of stirred yoghurt is usually carried out in PHEs since these equipments are suitable for liquid-liquid heat transfer duties that require uniform and rapid cooling or heating. In this operation, two mechanisms of heat transfer occur: conduction, in the plates, and convection inside the channels.
So, in order to simulate the non-isothermal flow of stirred yoghurt in a PHE three problems where solved simultaneously: one of non-isothermal flow inside the channel and two of heat conduction in the plates.
The set of equations that describe mathematically the problem were the Navier-Stokes equations, for incompressible and stationary flow, and Fourier's law for the conduction problems. Additionally, a constitutive model that describes the rheological properties of yoghurt under the cooling conditions has to be established in order to define totally the problem. The used model was proposed by Afonso *et al.* [6] and takes into account the influence of shear rate and temperature:

$$\mu_{app} = K\dot{\gamma}^{n} \exp\left(\frac{E}{RT}\right) \tag{1}$$

where μ_{app} is the apparent viscosity (Pa s), K the consistency index (Pa s^n), n the flow behaviour index (-), $\dot{\gamma}$ the shear rate (s^{-1}), E the activation energy (J mol^{-1}), T the absolute temperature (K) and R the universal gas constant (8.31451 J K^{-1} mol^{-1}). In above equation, rheological parameters assume the values n = 0.42, K = 3.65 Pa s$^{0.42}$ and E = 94785 J mol^{-1} [6].

3. NUMERICAL SIMULATION

The problem described above was simulated using the commercial finite element method package POLYFLOW. Numerical simulations were divided in three steps: construction of geometrical domain and mesh generation, establishment of boundary conditions and properties of the system and numerical resolution of the finite element problem.
Simulations were performed for PHEs with distinct corrugation angles: β= 30° and β= 60°. For the two exchangers, six flow rates of yoghurt are considered in the simulations, according to the operation conditions and fluids properties from Afonso *et al.* [6].

3.1 Geometrical domain and mesh generation

The studied PHE had a parallel arrangement [6] and admitting a uniform distribution of the total flow rate in the various channels, the flow simulations of yoghurt were carried out in a single channel. The plates were constructed considering an effective length, L, and width, w, represented in Fig. 1(a) [16], being the corrugations described by a sine curve [15]:

$$y(x) = \frac{b}{2}\sin\left(\frac{2\pi}{p_c}\left(x - \frac{p_c}{4}\right)\right) + \frac{b}{2} \tag{2}$$

where b is the distance between plates (m) and p_c the wavelength of corrugation (m) Fig. 1(b).

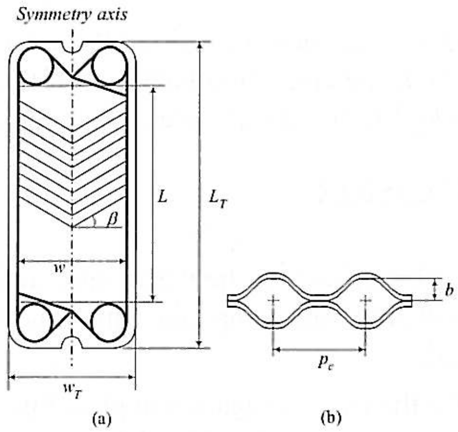


Fig. 1: (a) Schematic representation of a *chevron* plate; (b) Corrugations dimensions.

Additionally, uniform flow was considered inside each channel and, for this reason, a symmetry axis was established, Fig. 1(a), simplifying the geometrical domain to half of a channel, Fig. 2.

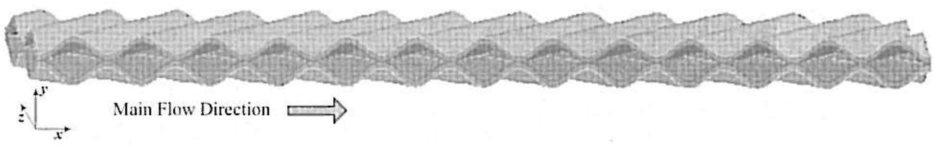


Fig. 2: Geometrical domain.

Although computational domain was highly complex due to the multiple contractions and expansions along the channel, it was found that a mesh constituted by tetrahedral, hexahedral, prismatic and pyramidal elements was adequate. The calculations on present work were made using a mesh with 1.2 mm of node distance, being this value the result of a previous grid independency test.

3.2 Boundary conditions

Boundary conditions were established based on experimental data [6] namely, flow rate and inlet temperature of yoghurt, taking into account that the PHE studied in this work operates with parallel arrangement and in counterflow.
In all the simulations slip at the wall and heat losses to the surroundings were assumed to be non-existent and a variable heat flux have been imposed in the plates. The heat flux for each x is given by the linear form of the expression:

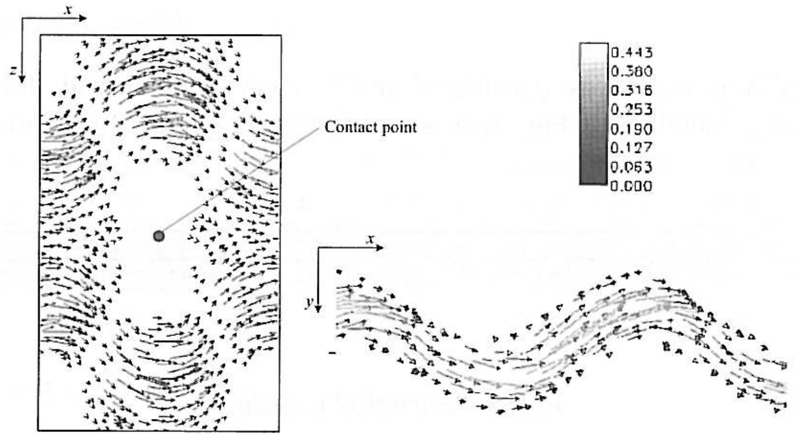
$$q(x) = UF\left(T_{yog_{in}} - T_{wat_{out}}\right)\exp\left[2ULF\phi x\left(\frac{1}{M_{wat}C_{p_{wat}}} - \frac{1}{M_{yog}C_{p_{yog}}}\right)\right] \quad (3)$$

where x is the dimension on the main flow direction ($0 \leq x \leq L$) (m), U is the overall heat transfer coefficient (W m^{-2} K^{-1}), F the correction factor(-), M the mass flow rates per channel (kg s^{-1}), C_p the specific heat (J kg^{-1} K^{-1}) and ϕ the area enlargement factor (-) [16].

4. RESULTS AND DISCUSSION

Numerical results concerning the difference between inlet and outlet yoghurt temperature obtained for the PHE with β = 30° were compared with experimental data [6] and a mean deviation of 6.9% was observed.

Analysing the velocity field for the two corrugation angles, Fig. 3, it was possible to observe the inexistence of recirculation zones, confirming this way a laminar flow in the present operation conditions.



(a) (b)

Fig. 3: Velocity vectors in the plane of contact points (a) and in plane z = 0.022 (b) for β= 30°.

Another way to evaluate the flow regime consists in the determination of fanning friction factor, f. The obtained relation between this factor and Reynolds number, Re, was a typical relation for laminar flows [16]:

$$f = a\,\mathrm{Re}^{-1} \quad (4)$$

where a is a constant and f and Re are given by

$$f = \frac{\Delta P D_e}{2L\rho u^2} \quad (5)$$

$$\mathrm{Re} = \frac{\rho u D_e}{\mu_{app}}. \quad (6)$$

In latest equations, ΔP is the pressure drop (Pa), u the average velocity of yoghurt (m s^{-1}) and D_e is the hydraulic diameter and is given by the quotient between $2b$ and ϕ.

For the studied PHEs and present operation conditions ($0.2 < Re < 1.3$) it was possible to observe in Fig. 4 the good agreement between the relation expressed by Eq. (4) and the computational fluid dynamic (CFD) calculations. It is also possible to observed the decrease of constant a with the corrugation angle, which is in agreement with the literature results [15, 16].

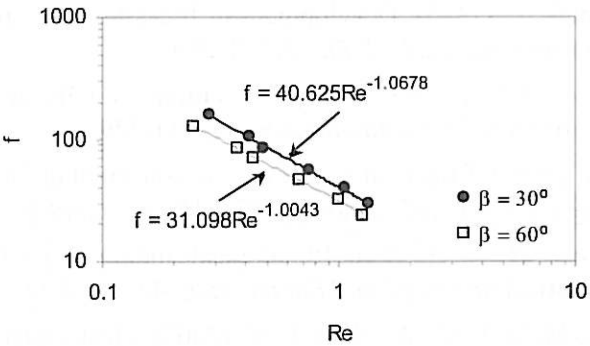


Fig. 4: Fanning friction factor for PHEs with $\beta = 30°$ and $\beta = 60°$.

The magnitude of the shear rate inside the heat exchanger is determinant on the consistency of packed yoghurt. In Fig.5 it's possible to observe that maximum shear rate, $\dot{\gamma}_{max}$, decrease when β increase from 30° to 60°. Infinite parallel plates, correspondent to $\beta = 90°$, is the lower limit for $\dot{\gamma}_{max}$.

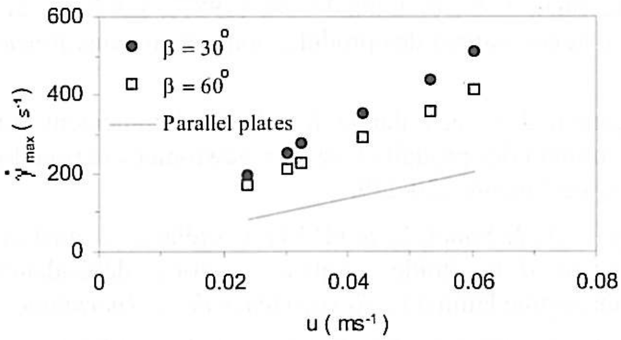


Fig. 5: Maximum shear rate for PHEs with $\beta = 30°$ and $\beta = 60°$ and infinite parallel plates.

The values of $\dot{\gamma}_{max}$ presented in Fig.5 for infinite parallel plates were calculated according the expression proposed by Delplace and Leuliet [17] for a generic duct.

5. CONCLUSIONS

In the present study, CFD calculations were made in order to study the influence of corrugation angle in the stirred yoghurt cooling in a PHE. Two corrugation angles were considered, 30° and 60°. It was observed a good agreement between numerical results, for $\beta = 30°$, and temperature experimental data.

Analysing velocity fields and fanning friction factors was concluded that flow is laminar for both PHEs in the present operation conditions. Higher flow rates of stirred yoghurt can be processed in a PHE with $\beta = 60°$, having in mind pressure losses and maximum shear rates.

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