

PROGRESS IN RHEOLOGY OF BIOLOGICAL AND SYNTHETIC POLYMER SYSTEMS

Edited by
**A. C. Diogo, N. B. Alvarenga,
J. Canada, S. Ferro Palma
and J. Dias**



GER



SPR

A COMPARISON BETWEEN HEAT TRANSFER CORRELATIONS OBTAINED FROM EXPERIMENTAL DATA AND NUMERICAL SIMULATION OF THE FLOW OF STIRRED YOGHURT DURING COOLING IN PLATE HEAT EXCHANGERS

I. M. Afonso ^{(a)(b)}, C. S. Fernandes ^{(c)(d)}, J. M. Maia ^{(c)*} and L. F. Melo ^(a)

(a) LEPAE, Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, s/n 4200-465 Porto, Portugal. Fax: +351-225081449; Phone: +351-225081588

(b) Escola Superior Agrária de Ponte de Lima, Instituto Politécnico de Viana do Castelo, Refóios, 4990-706 Ponte de Lima, Portugal. Fax: +351-258909779; Phone: +351-258909740

(c) IPC - Institute for Polymers and Composites, Department of Polymer Engineering, University of Minho, 4800-058 Guimarães, Portugal. Fax: +351-253510339; Phone: +351-253510320

(d) Escola Superior de Tecnologia e de Gestão, Instituto Politécnico de Bragança, Campus de Santa Apolónia, Apartado 1038, 5301-854 Bragança, Portugal. Fax: +351-273325405; Phone: +351-273303127

iafonso@fe.up.pt, cveiga@ipb.pt, jmaia@dep.uminho.pt, lmelo@fe.up.pt

Keywords: Stirred Yoghurt, Plate Heat Exchanger, Heat Transfer, Computational Fluid Dynamics

Abstract

Thermal processing is widely used in the food industry mainly to improve quality and safety of food products. The investigation of heat transfer problems of non-Newtonian fluids during heating and cooling in heat exchangers is of major interest since the main factor limiting heat transfer is the viscous behaviour of these fluids. Therefore, the knowledge of the interface heat transfer coefficients is important in the design of food processes and processing equipment.

In the present work, simulations of stirred yoghurt cooling in a plate heat exchanger were performed using computational fluid dynamics (CFD) calculations and the obtained results were compared with experimental data. 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 with a 30° corrugation angle.

The correlation obtained numerically was compared to the one obtained from previous experimental work and they were found to be very similar to the experimental one. The constitutive model, under the assumptions used, was found to be a very good approximation for predicting the convective coefficients of stirred yoghurt during cooling in a plate heat exchanger.

1. Introduction

Heating and cooling are common thermal processes in the food industry. These thermal processing techniques are widely used to improve quality and safety of food products, and to extend shelf life of the products.

Most of the fluid foodstuffs exhibit a complex rheological behaviour such as non-linear shear stress-shear rate dependency, time-dependency effects and viscoelasticity, due to their structure complexity, composition and processing conditions [1, 2].

Stirred yoghurt is a typical non-Newtonian fluid resulting from the addition of lactic acid bacteria *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus salivarius* subsp. *thermophilus* to milk producing lactic acid from milk sugar lactose [3].

Yoghurt production is a biological process and cooling is one of the popular methods used to control the metabolic activity of the starter culture and its enzymes. Cooling the coagulum

commences directly after the product reaches the desired acidity, around pH 4.6 or 0.9% lactic acid depending on the type of yoghurt produced, the method of cooling used and/or the efficiency of heat transfer [4].

The rheological properties of stirred yoghurt have been evaluated and modelled by several authors [1, 5, 6, 7, 8, 9].

The industrial development of plate heat exchangers was considerable in recent years. Although thermal performance data still remains commercially confidential, some studies have been published focusing on plate heat transfer performance [10, 11, 12, 13] and modelling [14, 15, 16, 17].

Plate heat exchangers (PHEs) are used extensively in the food processing industries, but very little basic information has been published on their flow and heat transfer characteristics [18, 19].

The food industry benefits from numerical modelling in analysing the processes for better understanding of the complex physical mechanisms, underlying the processes, designing and optimising food processes and systems with aid of the predictive models [20, 21].

The aim of present work is to compare convective heat transfer correlations obtained from numerical approaches to the one obtained from previous experimental work, in the case of stirred yoghurt cooling in a plate heat exchanger.

2. Experimental description

An experimental investigation was conducted in order to obtain a correlation for the determination of convective heat transfer coefficients of stirred yoghurt in a plate heat exchanger [19]. A rheological characterisation was carried out in order to characterise the stirred yoghurt flow behaviour, evaluating its dependency both on shear rate and temperature. The rheological model that better described the stirred yoghurt can be mathematically expressed as:

$$\tau = \tau_0 + K_1 \dot{\gamma}, \quad \text{for } \tau < 6.7 \text{ Pa} \quad (1)$$

$$\tau = K_2 \dot{\gamma}^n, \quad \text{for } \tau > 6.7 \text{ Pa} \quad (2)$$

where τ_0 is the yield stress, K_1 and K_2 consistency indexes and n is the flow behaviour index. At shear stresses lower than 6.7 Pa, the stirred yoghurt exhibited a Bingham viscoplastic features with a yield stress τ_0 , of approximately 0.54 Pa and a consistency index K_1 of 1.45 Pa s. At shear stresses higher than 6.7 Pa, the stirred yoghurt exhibited a strong shear-thinning character described by a power-law model with a consistency index K_2 of 3.65 Pa s and a flow behaviour index n , of 0.42. Temperature effects were included in the rheological model by means of an Arrhenius type term [19].

Heat transfer experiments were carried out in the laboratory-scale plate heat exchanger with generalised Reynolds numbers (which take into account the rheological effects) of yoghurt varying from 0.51 to 14.47.

A correlation for the convective heat transfer coefficient was obtained revealing significant thermal entrance effects due to the high Prandtl numbers (between 581 and 1867) and to the short length of the plates used in the experimental work. The experimental dimensionless convective heat transfer coefficient of stirred yoghurt number was written as a function of the generalised Reynolds, and the corresponding correlation is (a correction factor, named as area enlargement factor (ϕ) of 1.096, related to the ratio of the developed length to the projected length [22] of was introduced):

$$\text{Nu}_m = 1.67 \cdot \text{Re}_g^{0.455} \cdot \text{Pr}_g^{0.3} \quad (3)$$

where Nu_m is the average Nusselt number. The generalised Reynolds (Re_g) and Prandtl (Pr_g) numbers were calculated considering that the apparent viscosity of stirred yoghurt assumed the power-law form presented in equation (2) taking into account the influence of shear rate and temperature, expressed as follows:

$$\mu_{app} = K \dot{\gamma}^n \exp\left(\frac{E}{RT}\right) \quad (4)$$

In above equation, E is the activation energy ($J \text{ mol}^{-1}$), T the absolute temperature (K) and R the universal gas constant ($8.31451 \text{ J K}^{-1} \text{ mol}^{-1}$). The activation energy assume the value of 94785 J mol^{-1} [19].

3. Numerical Simulation

3.1. Problem description

During cooling treatment, 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 plate heat exchanger three problems were 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 was established in order to define totally the problem, represented by equation (4).

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 fifteen flow rates of yoghurt, correspondent to the operating conditions and fluid properties from Afonso *et al.* [19].

The studied PHE had a parallel arrangement [19] 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 construction of geometrical domain and mesh generation steps are described in a previous work carried out by Fernandes *et al.* [23].

3.2. Boundary condition

Since experimental data was available [19], boundary conditions were determined based on this data, taking into account that the plate heat exchanger 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:

$$q(x) = UF(T_{yog_{in}} - T_{wat_{out}}) \exp\left[2ULF\phi x \left(\frac{1}{M_{wat}C_{p_{wat}}} - \frac{1}{M_{yog}C_{p_{yog}}}\right)\right] \quad (5)$$

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

4. Results and Discussion

Numerical results concerning the difference between inlet and outlet yoghurt temperature were compared with experimental data and a mean deviation of 6.9% was observed.

The velocity profiles obtained numerically confirmed that a laminar flow prevailed in the present conditions, by the inexistence of recirculation zones. The results obtained are in agreement with the experimental data that revealed that the flow was fully developed from the momentum viewpoint but not from the thermal viewpoint (very high Prandtl numbers) [19].

The local distribution of temperature data obtained by numerical simulation allowed to determine average values of yoghurt and plate temperatures along the channel on planes of equation $x = const$. One example of the resulting temperature profiles along the channel is presented on Figure 1.

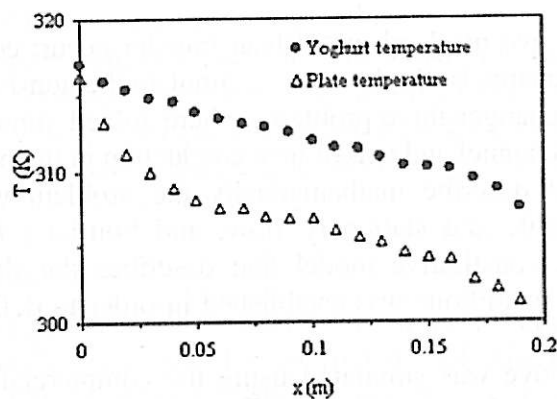


Figure 1 - Distribution of yoghurt and plate temperature along the channel for a given Reynolds number ($Re_g = 12.3$).

Temperature profiles in conjunction with heat flux data were used in the calculation of local convective heat transfer coefficient, defined as:

$$h(x) = \frac{q(x)}{(T_{yog} - T_w)(x)} \quad (6)$$

where $q(x)$ was calculated by Eq. (5) and $(T_{yog} - T_w)(x)$ was given by POLYFLOW.

Consequently, the dimensionless heat transfer coefficient (Nusselt number) can be determined by means of the definition equation:

$$Nu(x) = \frac{h(x)D_H}{k} \quad (7)$$

where k is the thermal conductivity and D_H is the hydraulic diameter ($D_H = 2b/\phi$), b is the plate spacing distance.

Figure 2 shows the local Nusselt number variation along the PHE channel length, for three different Reynolds numbers.

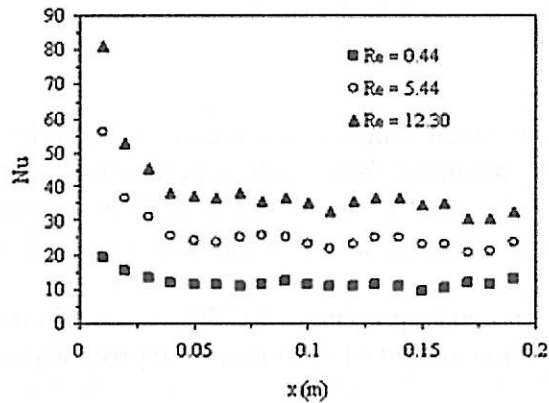


Figure 2 – Local Nusselt number variation along the plate heat exchanger channel length for different Reynolds number.

In Figure 2 it is possible to observe that the decrease tendency of the dimensionless heat transfer coefficient along the PHE channel length. As the Reynolds number values increase more pronounced is the decrease tendency of the local Nusselt number values. Stirred yoghurt assumes high Prandtl numbers [19] in the present short length PHE, resulting in thermal developing laminar flows for in the whole range of Reynolds number values.

Since the thermal correlation for the convective heat transfer coefficient of the stirred yoghurt obtained from the experimental work is based on the average Nusselt number, the average values of Nusselt number obtained by numerical simulation were determined for the fifteen simulations performed.

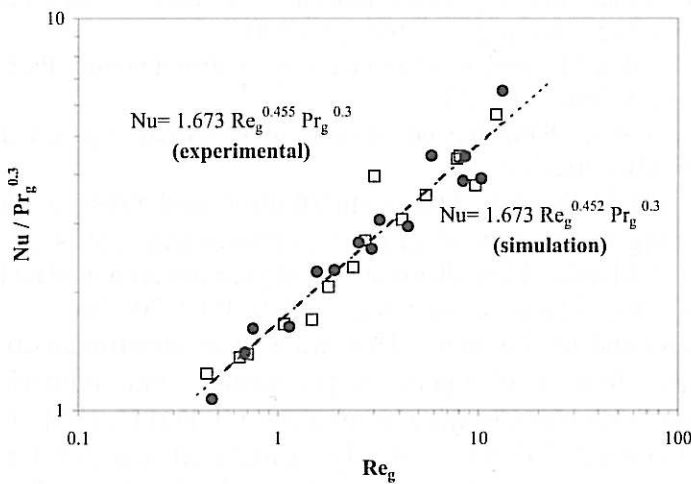


Figure 3 - Experimental heat transfer correlation and numerical correlation computed for constant wall temperature boundary condition. ● experimental, □ simulation,

Figure 3 compares the experimental correlation to the one obtained by numerical simulation. The correlation obtained from numerical simulation for the dimensionless convective heat transfer coefficient of stirred yoghurt was:

$$Nu_m = 1.673 \cdot Re_g^{0.452} \cdot Pr_g^{0.3} \quad (8)$$

Comparing the correlations obtained from experimental data (eq. 3) and the simulated one (eq. 8) one can observe their similarity, only a small difference is observed in the Reynolds

number exponent. The good similarity may be due to the introduction of geometric factors, such as the area enlargement factor, on both correlations.

5. Conclusion

Correlations for the convective heat transfer coefficients of stirred yoghurt during cooling in plate heat exchangers were obtained from both experimental data and from a numerical simulation study. A good agreement between the two types of results was obtained when some geometric factors, like channel aspect ratio and effective to projected area, were included in the simulation.

The present work emphasizes the importance of CFD as a predicting tool for the design of food processing equipment achievement of optimum food process parameters

References

- [1] T. Benezech and J. F. Maingonnat, "Characterization of the rheological properties of yoghurt – a review", *J. of Food Engineering*, 21, 1994, 447-472
- [2] B. Hallström, C. Skjöldebrand, and C. Trägårdh, in *Heat Transfer and Food Products*, Elsevier Applied Science Publishers, Essex, 1988
- [3] A. Y. Tamime, R. K. Robinson, Fermented milks and their future trends. Part II. Technical aspects (review), *J. of Dairy Research*, 55, 1988, 281-307
- [4] A. Y. Tamime, R. K. Robinson, in *Yogurt- Science and Technology*, second ed., CRC Press LLC, Boca Raton, 1999.
- [5] T. Benezech and J. F. Maingonnat, "Flow properties of stirred yoghurt: structural parameter approach in describing time dependency", *J. of Textures Studies*, 24, 1993, 455-473.
- [6] H. Rohm and A. Kovac, "Effects of starter cultures on small deformation rheology of stirred yoghurt", *Lebensm.-Wiss. U.-Technol.*, 28, 1995, 319-322
- [7] I. M. Afonso and J. M. Maia, "Rheological monitoring of structure evolution and development in stirred yoghurt", *J. of Food Engineering*, 42, 1999, 183-190
- [8] H. J. O'Donnell and F. Butler, "Time-dependent viscosity of stirred yogurt. Part I: couette flow", *J. of Food Engineering*, 51(3), 2002, 249-254
- [9] H. J. O'Donnell and F. Butler, "Time-dependent viscosity of stirred yogurt. Part II: tube flow", *J. of Food Engineering*, 51(3), 2002, 255-261
- [10] M. K. Bassiouny and H. Martin, "Flow distribution and pressure drop in plate heat exchangers-I. U-type arrangement", *Chemical Engineering Science*, 39(4), 1984, 693-700
- [11] M. K. Bassiouny and H. Martin, "Flow distribution and pressure drop in plate heat exchangers-II. Z-type arrangement", *Chemical Engineering Science*, 39(4), 1984, 701-704
- [12] F. Rene, J. C. Leuliet and M. Lalande, "Heat transfer to Newtonian and non-Newtonian food fluids in plate heat exchangers: experimental and numerical approaches", *Transactions of the Institution of Chemical Engineers*, 69, Part C, 1991, 115-126
- [13] A. Muley, R. M. Manglik and H. M. Metwally, "Enhanced heat transfer characteristics of viscous liquid flows in a chevron plate heat exchanger", *J. of Heat Transfer*, 121, 1999, 1011-1017
- [14] F. Rene and M. Lalande, "Échangeur de chaleur à plaques et joints. Résolution numérique des équations d'échange thermique entre les différents canaux", *Revue Générale Thermique Fr.*, 311, 1987, 577-583
- [15] T. Kho and H. Müller-Steinhagen, "An experimental and numerical investigation of heat transfer fouling and fluid flow in flat plate heat exchangers", *Transactions of the Institution of Chemical Engineers*, 77, Part A, 1999, 124-130
- [16] H. U. Zettler and H. Müller-Steinhagen, "The use of CFD for the interpretation of fouling data in PHEs", in *Heat Exchangers Fouling- Fundamental Approaches & Technical Solutions*, Davos, Switzerland: UEF- United Engineering Foundation, Inc., 2001

- [17] J. A. W. Gut and J. M. Pinto, "Modelling of plate heat exchangers with generalized configurations", *International Journal of Heat and Mass Transfer*, 46, 2003, 2571-2585
- [18] H. B. Kim, C. C. Tadini and R. K. Singh, "Heat transfer in a plate exchanger during pasteurization of orange juice", *J. of Food Engineering*, 42, 1999, 79-84
- [19] I. M. Afonso, L. Hes, J. M. Maia and L. F. Melo, "Heat transfer and rheology of stirred yoghurt during cooling in plate heat exchangers", *J. of Food Engineering*, 57, 2003, 179-187
- [20] L. Wang and D.-W. Sun, "Recent developments in numerical modelling of heating and cooling processes in the food industry – a review", *Trends Food Science & Technology*, 14, 2003, 408-423
- [21] B. Xian and D.-W. Sun, "Applications of computational fluid dynamics (CFD) in the food industry: a review", *Computers and Electronics in Agriculture*, 34, 2002, 5-24
- [22] S. Kakaç and H. Liu, in *Heat exchangers- selection, rating and thermal design*, second ed., CRC Press LLC, Boca Raton, 373-396, 2002
- [23] C. S. Fernandes, R. Dias, I. M. Afonso, L. F. Melo and J. M. Maia, "Simulation of stirred yoghurt processing in plate heat exchangers", *J. of Food Engineering* (submitted).