Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Food Engineering 76 (2006) 433–439

JOURNAL OF FOOD ENGINEERING

www.elsevier.com/locate/jfoodeng

Thermal behaviour of stirred yoghurt during cooling in plate heat exchangers

Carla S. Fernandes [a,b], Ricardo P. Dias [b], J.M. Nóbrega [a], Isabel M. Afonso [c,d], Luis F. Melo [d], João M. Maia [a,*]

[a] *IPC—Institute for Polymers and Composites, Departamento de Engenharia de Polímeros, Universidade do Minho, 4800-058 Guimarães, Portugal*

[b] *Escola Superior de Tecnologia e de Gestão, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5301-854 Bragança, Portugal*

[c] *Escola Superior Agrária de Ponte de Lima, Instituto Politécnico de Viana do Castelo, Refóios, 4990-706 Ponte de Lima, Portugal*

[d] *Laboratório de Engenharia de Processos, Ambiente e Energia—LEPAE, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, s/n 4200-465 Porto, Portugal*

Received 18 December 2004; accepted 21 May 2005
Available online 26 July 2005

Abstract

In this study, CFD calculations were made in order to analyse the thermal behaviour of yoghurt in a plate heat exchanger, the yoghurt viscosity being described by a Herschel–Bulkley model.

The influence of Reynolds number on local Nusselt numbers was analysed as well as the influence of entry effects on average Nusselt number. Numerical runs considering and discarding the influence of temperature on the viscosity were performed and the impact on average Nusselt numbers was analysed. Transversal variations of viscosity were studied and thermal correlations including the ratio between bulk and wall viscosities are proposed.

The obtained thermal correlations were compared with the experimental ones (described in the literature) and a very good agreement was found, mainly when considering the effect of temperature on viscosity. Simulations with a non-Newtonian fluid having lower Prandtl numbers than yoghurt were performed in order to analyse the influence of this variation on the Reynolds number exponent of the thermal correlation.

© 2005 Published by Elsevier Ltd.

Keywords: Stirred yoghurt; Plate heat exchanger; Local Nusselt numbers; Computational rheology

1. Introduction

Plate heat exchangers (PHE's) are commonly used on food industry for tasks including the high-temperature short-time pasteurization of milk, beer and fruit juices (Gut & Pinto, 2003a) as well as the cooling of stirred yoghurt to stop lactic fermentation when a desired acidity is reached (Afonso, Hes, Maia, & Melo, 2003).

PHE's are extensively used in chemical, pharmaceutical, biochemical processing, food and dairy industries, to name but a few, due to the easy disassembly of the heat exchanger for cleaning and sterilization, low space requirement, low fouling tendency and high efficiency (Gut & Pinto, 2003a, 2003b; Kakaç & Liu, 2002; Reppich, 1999). Process fluid media generally have non-Newtonian characteristics and the shear thinning or thickening behaviour of these fluids greatly affects their thermal-hydraulic performance (Manglick & Ding, 1997).

Due to the broad range of application of this heat transfer equipment, several experimental and modelling works have been performed in order to study the thermal and hydraulic performance of different plate patterns, fouling tendency, corrosion mechanisms and

* Corresponding author. Fax: +351 53 510 339.
E-mail address: jmaia@dep.uminho.pt (J.M. Maia).

0260-8774/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.jfoodeng.2005.05.043

Nomenclature

a	constant (–)
b	distance between plates (m)
C_p	specific heat of fluids (J kg^{-1} K^{-1})
D_H	hydraulic diameter (m)
E	activation energy (J mol^{-1})
F	correction factor (–)
k	thermal conductivity (W m^{-1} °C^{-1})
K_1, K_2, K_c	consistency index (Pa s^n)
L	effective length (m)
m	constant (–)
M	mass flow rate per channel (kg s^{-1})
n	flow behaviour index (–)
Nu	Nusselt number (–)
q	heat flux (W m^{-2})
R	ideal gas constant (J mol^{-1} K^{-1})
Re	Reynolds number (–)
Pr	Prandtl number (–)
T	absolute temperature (K)
u	mean velocity (m s^{-1})
U	overall heat transfer coefficient (W m^{-2} K^{-1})
x, y, z	spatial coordinates (m)

Greek symbols

ϕ	area enlargement factor (–)
$\bar{\dot{\gamma}}$	mean shear rate (s^{-1})
$\dot{\gamma}_{max}$	maximum shear rate (s^{-1})
η	apparent viscosity (Pa s)
ρ	fluid density (kg m^{-3})
σ	shear stress (Pa)
σ_0	yield stress (Pa)

Subscripts

in	inlet
out	outlet
w	wall
wat	cooling water
yog	yoghurt

the optimization of different arrangements and configurations, when leading with Newtonian or non-Newtonian fluids (Afonso et al., 2003; Antonini, François, & Shuai, 1987; Bassiouny & Martin, 1984; Ciofalo, Stasiek, & Collins, 1996; Delplace & Leuliet, 1995; Gut & Pinto, 2003a, 2003b; Kho & Müller-Steinhagen, 1999; Leuliet, Maigonnat, & Lalande, 1987, 1988, 1990; Mehrabian & Poulter, 2000; Metwally & Manglick, 2004; Stasiek, Collins, Ciofalo, & Chew, 1996).

Heat transfer in a PHE is strongly dependent on geometrical properties of the chevron plates, namely on corrugation angle, area enlargement factor and channel aspect ratio. When dealing with a non-isothermal flow of a non-Newtonian fluid, the rheological behaviour of the fluid will enhance local variations of physical properties in the PHE, being computational fluid dynamics (CFD) calculations useful in order to understand the flows in the complex geometries of PHE's, more accurate described by implementing 3D channels (Kho & Müller-Steinhagen, 1999).

Nusselt numbers, Nu, are normally described by empirical correlations, the most common being the Dittus–Boetler type (René & Lalande, 1987):

$$Nu = aRe^{m}Pr^{0.3}, \tag{1}$$

where Re is the Reynolds number and Pr the Prandtl number. For Newtonian fluids, a and m are constants dependent on the flow regime and geometrical characteristics of the PHE plates (Kakaç & Liu, 2002). However, when the processed fluids exhibit a strong dependence of viscosity with temperature, the PHE induces changes in velocity fields and normally a Sider and Tate correction is introduced on Dittus–Boetler correlation to describe this effect (Antonini et al., 1987; René & Lalande, 1987):

$$Nu = aRe^{m}Pr^{0.3}\left(\frac{\eta}{\eta_w}\right)^{0.14}, \tag{2}$$

being η and η_w the apparent viscosity of fluid in the bulk and on the wall, respectively.

Stirred yoghurt is a non-Newtonian fluid and during the manufacture is submitted to a cooling process that is usually carried out in a PHE. Afonso et al. (2003) made an experimental thermo-rheological study of yoghurt during this process and found a Herschel–Bulkley behaviour type. Based on the results of that work, simulations were performed with a 3D channel in order to study, viscosity, shear rate and fanning friction factor (Fernandes et al., 2005).

The aim of the present work is to study numerically the thermal behaviour of yoghurt during cooling in a PHE.

2. Problem description

2.1. Mathematical formulation

Mathematically, the problem was described by a set of equations that comprises the governing and constitutive equations. The problem could be divided in two problems of heat conduction in the plates and one of laminar non-isothermal flow inside the channel, the governing equations being Fourier's law, to describe the heat conduction in the plates and the Navier–Stokes equations, that include the conservation equations for mass, linear momentum and energy, to describe the flow.

The constitutive model used to describe the rheological behaviour of stirred yoghurt under the conditions of the present study was that from Afonso et al. (2003):

$$\sigma = \sigma_0 + K_1\dot{\gamma} \quad \text{for } \sigma < 6.7 \text{ Pa}, \tag{3a}$$

$$\sigma = K_2\dot{\gamma}^n \quad \text{for } \sigma \geqslant 6.7 \text{ Pa}, \tag{3b}$$

σ_0 being the yield stress, K_1 and K_2 consistency indices and n the flow behaviour index.

Experimentally, we found in a previous work that the wall shear stress was always higher than 6.7 Pa for the considered operation conditions (Fernandes et al., 2005), which implies that the velocity profile is mostly parabolic, with the exception of the small region very near the centreline, where it is plug-like, which does not alter the data significantly (Fernandes et al., 2005). Thus, the constitutive equation used in the present work was based in Eq. (3b), the influence of temperature being introduced by a term of the Arrhenius type:

$$\eta(T) \propto e^{E/RT}, \tag{4}$$

where T is the absolute temperature, E the activation energy and R the ideal gas constant. Rheological parameters assume the values $K_2 = 3.65$ Pa s$^{0.42}$, $n = 0.42$ and $E = 94\,785$ J mol^{-1} (Afonso et al., 2003).

2.2. Numerical resolution

The problem was numerically solved using the finite element method package POLYFLOW and the simulations were performed using a Dell Workstation PWS530 with 1GB of RAM.

Simulations were performed for the Pacetti RS 22 PHE, the operation conditions being those referred in previous works (Afonso et al., 2003; Fernandes et al., 2005).

The geometrical domain, Fig. 1, represents half of a single 3D Pacetti RS 22 channel with 0.19 m length, 0.036 m width and a distance between plates, b, of 2.6 mm. This simplification was possible since the PHE had a parallel arrangement (Afonso et al., 2003). Uniform distribution of the total flow rate in the various channels was admitted, uniform flow was considered inside each channel and, due to the geometrical properties of the plates, a symmetry axis was established (Fernandes et al., 2005).

Boundary conditions and physical properties of yoghurt were established according to experimental data (Afonso et al., 2003). In particular a heat flux, q, was imposed in the plates as the thermal boundary condition, its value being determined by a linear form of the expression (Fernandes et al., 2005):

$$q(x) = UF\left(T_{\text{yog}_{\text{in}}} - T_{\text{wat}_{\text{out}}}\right) \times \exp\left[2ULF\phi x\left(\frac{1}{M_{\text{wat}}C_{p_{\text{wat}}}} - \frac{1}{M_{\text{yog}}C_{p_{\text{yog}}}}\right)\right], \tag{5}$$

where x is the dimension on the main flow direction, U is the overall heat transfer coefficient, F the correction factor M the mass flow rates per channel, C_p the specific heat and ϕ the area enlargement factor (Kakaç & Liu, 2002), which is given by:

$$\phi = \frac{\text{Effective area}}{\text{Projected area}}, \tag{6}$$

and, for the present PHE, assume the value 1.096.

In all the simulations slip at the wall and heat losses to the surroundings were neglected.

3. Results and discussion

Despite the complex flow developed in the present PHE and for the present yoghurt (Afonso & Maia, 1999; Afonso et al., 2003) and experimental operating conditions, the velocity profiles along the channel exhibit approximate Poiseuille flow characteristics, as in parallel plates, and this can be an explanation to the relation found by Fernandes et al. (2005):

$$\bar{\dot{\gamma}} = \frac{n}{n+1}\dot{\gamma}_{\max}. \tag{7}$$

Eq. (7) means that although the mean, $\bar{\dot{\gamma}}$, and maximum, $\dot{\gamma}_{\max}$, shear rates in the PHE where higher than those obtained in parallel plates, they were related by a typical expression for parallel plates in laminar flow. On Fig. 2, acquiring several profiles for different lines with $z =$ const., the obtained profiles have almost all a approximately parabolic-conical (Manglick & Ding, 1997) shape although the maximum velocity will change due to variations of cross section area offered to the fluid. This pattern is also observed for different planes with $x =$ const. along the channel.

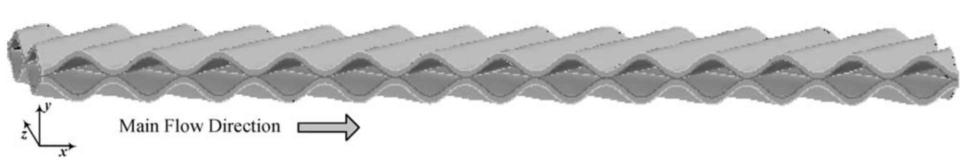

Fig. 1. Geometrical domain.

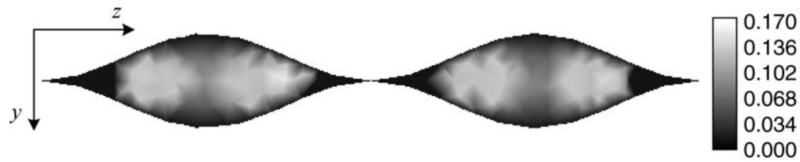

Fig. 2. Velocity local distribution in the plane $x = 0.05$ and for $Re = 0.31$.

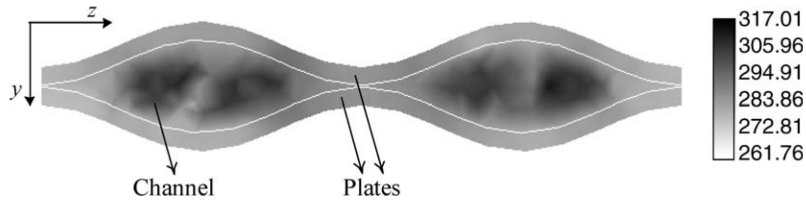

Fig. 3. Temperature local distribution in the plane $x = 0.05$ and for $Re = 0.31$.

The irregularity of temperature distribution in the planes of $x = \text{const.}$ can be observed in Fig. 3. Concerning temperature there's no typical profile in planes of $z = \text{const.}$ and that can be explained by the fact that although laminar flow occurs under the present operating conditions, elements of fluid with lower temperature coming from the walls mix with hot fluid in the bulk, and vice-versa, due to the 3D behaviour of the flow.

Local distribution of temperature allowed average values of yoghurt and plate temperatures along the channel on planes of equation $x = \text{const.}$ to be determined, as shown in Fig. 3. One example of the resulting temperature profiles along the channel is shown in Fig. 4.

These profiles, in conjunction with heat flux expression, were used in the calculation of local convective heat transfer coefficient, $h(x)$, that can be defined as:

$$h(x) = \frac{q(x)}{(T_{\text{yog}} - T_{\text{w}})(x)}, \tag{8}$$

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

Consequently, local Nusselt numbers were determined taking in account the following definition:

$$Nu(x) = \frac{h(x)D_{\text{H}}}{k}, \tag{9}$$

where k is the thermal conductivity and D_{H} is the hydraulic diameter, defined as:

$$D_{\text{H}} = 2b. \tag{10}$$

Fig. 5 represents the local Nusselt numbers for three different Reynolds numbers. Yoghurt assumes high Prandtl numbers in the present short length PHE (Afonso et al., 2003), resulting in important entry effects, mainly in higher Reynolds numbers (Ciofalo et al., 1996; Sourlier, Devienne, & Lebouché, 1987). Observing the evolution of Nusselt number for lengths higher than 0.05 m, it was possible to find a sinusoidal behaviour which, in turn, is consistent with the continuous x direction sinusoidal behaviour of viscosity, shear stress, temperature and velocity. These local variations were induced by the PHE corrugations (Fernandes et al., 2005).

Average values of Nusselt number were calculated for the simulations performed and for the studied

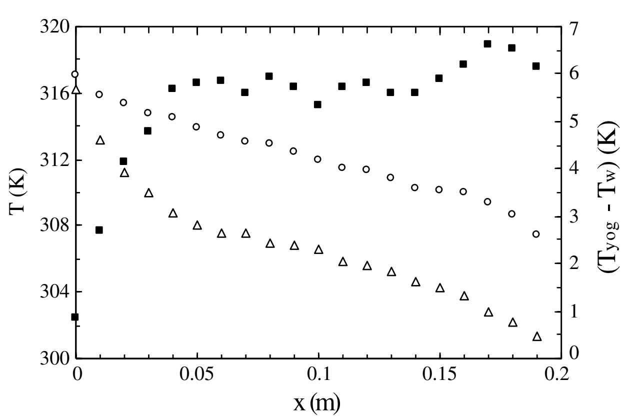

Fig. 4. Distribution of yoghurt temperature (○), plate temperature (△) and difference between yoghurt and plate temperatures (■) along the channel for $Re = 12.34$.

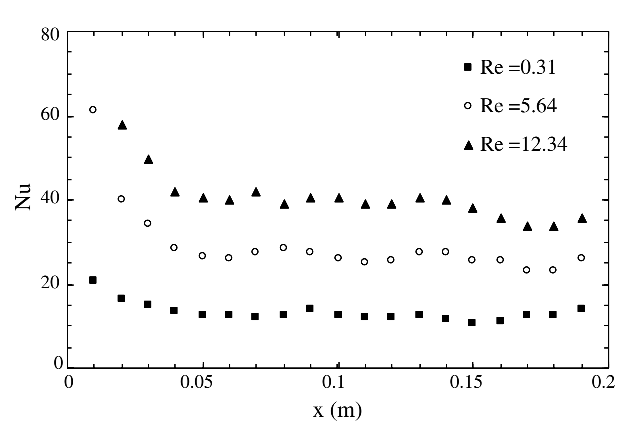

Fig. 5. Local Nusselt number for different Reynolds numbers.

PHE, yoghurt and present operation conditions, and a Dittus–Boetler correlation was determined:

$$Nu = 1.808Re^{0.449}Pr^{0.3}, \quad R^2 = 0.987, \tag{11}$$

the dimensionless numbers being given by:

$$Re = \frac{\rho u D_H}{\eta}, \tag{12}$$

$$Pr = \frac{C_p \eta}{k}, \tag{13}$$

where the apparent average viscosity was determined by POLYFLOW.

Additionally, simulations disregarding the temperature effect on viscosity ($E = 0$ J mol^{-1}) were performed, the following correlation being found:

$$Nu = 1.878Re^{0.463}Pr^{0.3}, \quad R^2 = 0.985. \tag{14}$$

The results above compare well with the experimental correlation presented by Afonso et al. (2003), as can be observed in Fig. 6:

$$Nu = 1.759Re^{0.455}Pr^{0.3}. \tag{15}$$

The best agreement with the latter correlation was achieved taking into account the effect of the temperature on viscosity (maximum deviation of 3.6%). However, the results without this effect are still quite satisfactory (maximum deviation of 8.9%), with the advantage that the required computational time was about 1/3 of that when the effect of temperature on viscosity was considered.

For laminar flows of Newtonian and non-Newtonian fluids, an m of about 1/3, i.e., lower than that obtained in the present study, can be found in the literature (Kakaç & Liu, 2002; Leuliet, Maigonnat, & Lalande, 1988). This fact could be related with the impact of the entry effects, Fig. 5, on the average Nusselt numbers determined on the present short length PHE. The PHE's

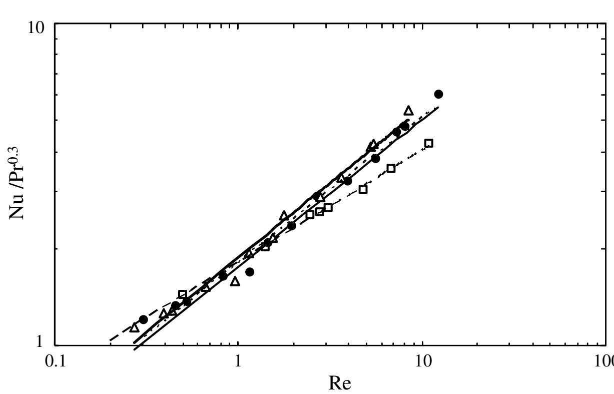

Fig. 6. Thermal correlations of convective heat transfer coefficient for stirred yoghurt with $E = 94\,785$ J mol^{-1} (- - -), $E = 0$ J mol^{-1} (—) and Afonso et al. (2003) (—). (●) are the numerical results for stirred yoghurt with $E = 94\,785$ J mol^{-1} and (△) numerical results for stirred yoghurt with $E = 0$ J mol^{-1}. (□) are the numerical results for cloudy apple juice and (– –) the thermal correlation for the juice.

used by Leuliet et al. (1988) had about 50 and 64 cm length, i.e., about three times longer that the used in this study. From Fig. 5 it seems reasonable to infer that expanding the geometry in the x direction, the average Nusselt number and m would decrease and that using only the lower Reynolds numbers to determine a correlation of the type of Eq. (1), will also decrease m. Considering only the six lowest Reynolds numbers, $E = 94\,785$ J mol^{-1} and $E = 0$ J mol^{-1}, it can be found that m assumes values of 0.334 and 0.335, respectively, witch are in much better agreement with the result of Leuliet et al. (1988) for non-Newtonian fluids and with the results presented by Kakaç and Liu (2002).

In order to further clarify the exponent m, additional simulations, Fig. 6, where performed considering the rheological parameters of a power-law fluid similar to a cloudy apple juice (Steffe, 1996): $K_c = 0.0499$ Pa s^n, $E/R = 3065$ K and $n = 0.5$. The obtained correlation was:

$$Nu = 1.809Re^{0.347}Pr^{0.3}, \quad R^2 = 0.993. \tag{16}$$

Since the present cloudy apple juice have a lower consistency index than yoghurt, the Prandtl numbers obtained (between 45 and 106) were lower than the obtained by Afonso et al. (2003) (between 581 and 1867) and in consequence the constant m decreased due to the lower entry effects. The order of magnitude of the constant a is confirmed since n are similar in the two cases. Constant a is higher than the typical values for Newtonian fluids and this is related by the shear thinning behaviour of the fluids. Manglick and Ding (1997) when studying Nusselt numbers of power-law fluids in a channel with $\beta = 90°$ concluded that Nusselt number decreases with the increase of n.

Since laminar flow was observed and yoghurt exhibits a viscosity dependency on temperature, a correction of Sieder and Tate (Antonini et al., 1987; René & Lalande, 1987) on the Dittus–Boetler correlation was included in the analysis.

For the case where the effect of temperature on viscosity is considered, (η/η_w) is given by:

$$\frac{\eta}{\eta_w} = \frac{K\bar{\dot{\gamma}}^{n-1}\exp\left(\frac{E}{RT_{yog}}\right)}{K\dot{\gamma}_w^{n-1}\exp\left(\frac{E}{RT_{yog_w}}\right)} = \left(\frac{n+1}{n}\right)^{1-n}\exp\left(\frac{E(T_{yog_w} - T_{yog})}{RT_{yog_w}T_{yog}}\right), \tag{17}$$

since, $\bar{\dot{\gamma}}$ and $\dot{\gamma}_{max}$ are related by Eq. (7) and $\dot{\gamma}_w = \dot{\gamma}_{max}$.

Neglecting the effect of temperature on yoghurt viscosity ($E = 0$ J mol^{-1}) implies that the viscosity variations are due to the shear thinning behaviour of yoghurt only, Eq. (17) being reduced to:

$$\frac{\eta}{\eta_w} = \left(\frac{n+1}{n}\right)^{1-n}. \tag{18}$$

Considering in Eq. (17) that the temperature of the yoghurt at the wall is equal to the wall temperature, (η/η_w) was analysed along the PHE, Fig. 7. The inlet temperature of yoghurt was similar in all simulations and is the typical yoghurt fermentation temperature (around 43 °C). After the zone were entry effects are evident, for the higher Reynolds numbers the ratio (η/η_w) had approximately a constant sinusoidal behaviour and remained in a value around 1.6–1.7. For lower Reynolds, where higher variations of yoghurt temperature occur and higher viscosities are obtained, this ratio had a similar sinusoidal behaviour but with a tendency to increase along the channel.

Resorting to the local values of (η/η_w), average values of the referred ratio were calculated for the different Reynolds numbers, Fig. 8. On the same figure it can be observed the good agreement between numerical calculations and Eq. (7) in the present case.

Tacking in account the average values of (η/η_w) for the different Reynolds numbers, for $E = 94\,785$ J mol^{-1} the following correlation was found:

$$Nu = 1.691 Re^{0.448} Pr^{0.3} \left(\frac{\eta}{\eta_w}\right)^{0.14}, \quad R^2 = 0.988. \tag{19}$$

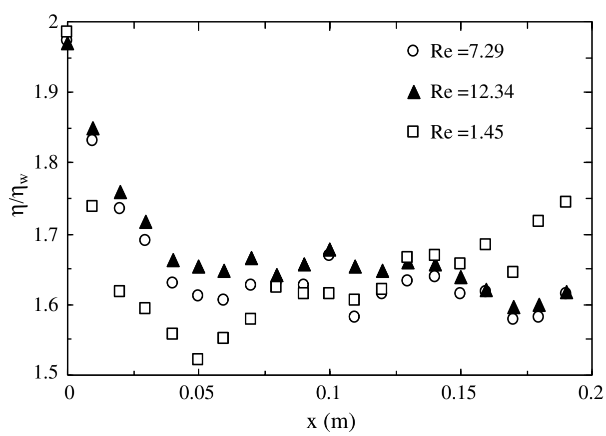

Fig. 7. Variation of (η/η_w) along the channel for different Reynolds numbers.

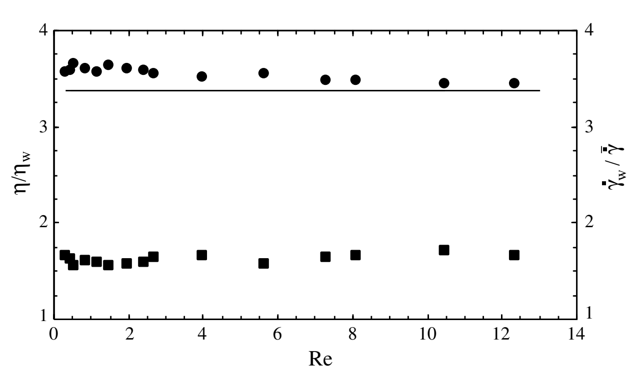

Fig. 8. Average values of ratio (η/η_w) (■) and ratio $(\dot{\gamma}_w/\bar{\dot{\gamma}})$ (●) for different Reynolds numbers and $E = 94\,785$ J mol^{-1}. (—) represents Eq. (7).

and for $E = 0$ J mol^{-1},

$$Nu = 1.701 Re^{0.462} Pr^{0.3} \left(\frac{\eta}{\eta_w}\right)^{0.14}, \quad R^2 = 0.985. \tag{20}$$

Comparing these correlations, with Eqs. (11) and (14) it can be observed that m is similar and that the constant a decreases, as expected.

For shear thinning fluids it's consensual that Nusselt numbers are higher than for Newtonian fluids. With the present PHE and fluids, that increase was translated in the thermal correlations by the increase of constant a, remaining constant m, tacking in account the results for the cloudy apple juice, on the typical range for Newtonian fluids with different corrugation angles (0.326–0.349) (Kakaç & Liu, 2002). Considering the processing of the present fluids on a PHE with a different corrugation angle than 30° it's reasonably to admit that wall and bulk shear rates will be different and necessarily different viscosities and ratios between bulk and wall viscosities will be obtained. Viscosity affects not only Prandtl numbers but also Reynolds numbers and for a PHE with a corrugation angle different than 30° the increase of Nusselt numbers in relation to Newtonian fluids can be translated by changes not only on the constant a from the thermal correlation but also by changes on the constant m.

4. Conclusions

The objective of this work was to study local and global thermal properties of yoghurt flow in a PHE.

Simulations have been performed considering the influence of temperature on viscosity and discarding this effect. It was observed that in the present case, i.e., yoghurt processing, the obtained results were similar and the CPU time was drastically reduced when the effect of temperature was neglected.

The local results of Nusselt number for the present short length PHE allowed a better understanding of the impact of entry effects on Reynolds number exponent of thermal correlation and simulations with a power-law fluid having lower Prandtl numbers than yoghurt conduced to a lower Reynolds number exponent. Higher Nusselt numbers than the typical for Newtonian fluids were obtained witch is explained by the shear thinning behaviour of the studied fluids.

Transversal variations of viscosity along the PHE and with Reynolds number were studied and thermal correlations tacking in account these variations where proposed for the present yoghurt, PHE and operating conditions.

References

Afonso, I. M., & Maia, J. M. (1999). Rheological monitoring of structure evolution and development in stirred yoghurt. *Journal of Food Engineering, 42*, 183–190.

Afonso, I. M., Hes, L., Maia, J. M., & Melo, L. F. (2003). Heat transfer and rheology of stirred yoghurt during cooling in plate heat exchangers. *Journal of Food Engineering, 57*, 179–187.

Antonini, G., François, O., & Shuai, X. S. (1987). Corrélations transfert/facteur de frottement por le chauffage/refroidissement d'un fluide visqueux à forte dépendance thermorhéologique en écoulement de conduite en régime laminaire. *Revue Générale de Thermique, 308–309*, 427–431.

Bassiouny, M. K., & Martin, H. (1984). Flow distribution and pressure drop in plate heat exchangers—I. *Chemical Engineering Science, 39*(4), 693–700.

Ciofalo, M., Stasiek, J., & Collins, M. W. (1996). Investigation of flow and heat transfer in corrugated passages—II. Numerical simulation. *International Journal of Heat and Mass Transfer, 39*, 165–192.

Delplace, F., & Leuliet, J. C. (1995). Generalized Reynolds number for the flow of power law fluids in cylindrical ducts of arbitrary cross-section. *The Chemical Engineering Journal, 56*, 33–37.

Fernandes, C. S., Dias, R., Nóbrega, J. M., Afonso, I. M., Melo, L. F., & Maia, J. M. (2005). Simulation of stirred yoghurt processing in plate heat exchangers. *Journal of Food Engineering, 69*, 281–290.

Gut, J. A. W., & Pinto, J. M. (2003a). Selecting optimal configurations for multisection plate heat exchangers in pasteurization processes. *Indian Journal of Engineering and Chemical Research, 42*, 6112–6124.

Gut, J. A. W., & Pinto, J. M. (2003b). Modeling of plate heat exchangers with generalized configurations. *International Journal of Heat and Mass Transfer, 46*, 2571–2585.

Kakaç, S., & Liu, H. (2002). *Heat exchangers selection, rating, and thermal design* (2nd ed.). Boca Raton: CRC Press, pp. 131–136, 373–412.

Kho, T., & Müller-Steinhagen (1999). An experimental and numerical investigation of plate heat transfer fouling and fluid flow in flat plate heat exchangers. *Transactions of IChemE, 77*(Part A), 124–130.

Leuliet, J. C., Maigonnat, J. F., & Lalande, M. (1987). Etude de la perte de charge dans de échangeurs de chaleur à plaques traitant des produits non-Newtonians. *Revue Générale de Thermique, 308–309*, 445–450.

Leuliet, J. C., Maigonnat, J. F., & Lalande, M. (1988). Thermal behaviour of plate heat exchangers with Newtonian and non-Newtonian fluids. In *Congrés Eurotherm 5 et 1erColloque TIFAN*. Compiègne, France.

Leuliet, J. C., Maigonnat, J. F., & Lalande, M. (1990). Écoulement et transferts de chaleur dans les échangeurs à plaques traitant des produits visqueux newtoniens et pseudoplastiques. *The Canadian Journal of Chemical Engineering, 68*, 220–229.

Manglick, R. M., & Ding, J. (1997). Laminar flow heat transfer to viscous power-law fluids in double-sine ducts. *International Journal of Heat and Mass Transfer, 40*(6), 1379–1390.

Mehrabian, M. A., & Poulter, R. (2000). Hydrodynamics and thermal characteristics of corrugated channels: Computational approach. *Applied Mathematical Modelling, 24*, 343–364.

Metwally, H. M., & Manglick, R. M. (2004). Enhanced heat transfer due to curvature-induced lateral vortices in laminar flows in sinusoidal corrugated-plate channels. *International Journal of Heat and Mass Transfer, 47*, 2283–2292.

René, F., & Lalande, M. (1987). Échangeur de chaleur à plaques et joints. Résolution numérique des équations d'échange thermique entre les différents canaux. *Revue Générale de Thermique, 311*, 577–583.

Reppich, M. (1999). Use of high performance plate heat exchangers in chemical and process industries. *International Journal of Thermal Science, 38*, 999–1008.

Sourlier, P., Devienne, R., & Lebouché, M. (1987). Ecoulement laminaire et transfert de chaleur por un fluide pseudoplastique entre deux plaques planes, parallels et horizontales. *Revue Générale de Thermique, 308–309*, 432–439.

Stasiek, J., Collins, M. W., Ciofalo, M., & Chew, P. E. (1996). Investigation of flow and heat transfer in corrugated passages—I. Experimental results. *International Journal of Heat and Mass Transfer, 39*, 149–164.

Steffe, J. F. (1996). *Rheological methods in food process engineering* (2nd ed.). East Lansing: Freeman Press, pp. 350–384.