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Friction factors of power-law fluids in chevron-type plate heat exchangers

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ABSTRACT

In the present work laminar flows of Newtonian and power-law fluids through cross-corrugated chevron-type plate heat exchangers (PHEs) are numerically studied in terms of the geometry of the channels. The plates area enlargement factor was a typical one (1.17), the corrugation angle, β, varied between 30° and 60° and the flow index behaviour, n, between 0.25 and 1. Single friction curves $fRe_g = K$ for both Newtonian and non-Newtonian fluids are proposed for each β by developing an adequate definition of the generalised Reynolds number, Re_g. The coefficient K compares well with experimental data, for all (seven) values of β, and depends on the tortuosity coefficient, τ. It was found that, for each β, τ decreases with the decrease of n. Food fluids are frequently processed in PHEs and usually behave as non-Newtonian fluids. This study can be useful in engineering applications as well as in the characterization of transport phenomena in PHEs.

1. Introduction

Food fluids are frequently processed in plate heat exchangers (PHEs) and usually behave as non-Newtonian fluids, this behaviour being scarcely considered for PHEs design purposes (Rene et al., 1991; Kim et al., 1999). Moreover, many food fluids (milk and milky desserts, fruit and vegetable juices, meat sauces, concentrates, etc.) processed in PHEs have a high viscosity and, therefore, data obtained in laminar flow regime is useful to practical applications (Rene et al., 1991; Metwally and Manglik, 2000, 2002; Leuliet et al., 1987, 1988).

The rheology of numerous food fluids (Steffe, 1996) can be described by a relation of the power-law type:

$$\eta = \eta_0 \dot{\gamma}^{n-1}, \tag{1}$$

$\dot{\gamma}$ representing the shear rate, η_0 the consistency index, n the flow index behaviour and η the apparent viscosity.

The heat exchange to stirred yogurt ($n = 0.42$) in a short length chevron-type plate heat exchanger was numerically studied by Fernandes et al. (2005, 2006). The PHE had an area enlargement factor, ϕ, close to 1.1, a corrugation angle, β, of 30° and an inter-plates distance (Fig. 1), b, of 2.6 mm. A good agreement was found between the numerical thermal data (Fernandes et al., 2005, 2006; Maia et al., 2007) and the experimental data from Afonso et al. (2003) for stirred yoghurt.

The thermal correlations – including important entry effects – developed by Fernandes et al. (2006) were based on apparent viscosity. The thermal or hydraulic correlations including apparent viscosity are of limited utility since this viscosity is difficult to predict, due to the geometrical complexity of the PHEs passages and, therefore, due to the complex behaviour of the shear rate.

One way of solving the referred limitation is to use a generalised viscosity. From the works of Metzner and Reed (1955) and Kozicki et al. (1966) it follows that the generalised viscosity, η_g, for the flow of power-law fluids in ducts of arbitrary cross-section can be defined as (Delplace and Leuliet, 1995; Gut and Pinto, 2003; Carezzato et al., 2007):

$$\eta_g = \eta_0 \left(\frac{K}{2}\right)^{n-1} \left(\frac{u}{D_H}\right)^{n-1} g^n(n), \tag{2}$$

where u is the mean velocity, D_H the hydraulic diameter, $g(n)$ a hyperbolic function of n and K a geometrical parameter given by the product of the Fanning friction factor, f, and the Reynolds number, Re_g, for a Newtonian fluid under laminar flow conditions (Metzner and Reed, 1955; Delplace and Leuliet, 1995):

$$fRe_g = K. \tag{3}$$

Re_g can be calculated by:

$$Re_g = \frac{\rho u D_H}{\eta_g}, \tag{4}$$

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Nomenclature

a	geometrical parameter (–)	x, y, z	cartesian coordinates (m)
c	geometrical parameter (–)	x^*	normalized length (–)
K	coefficient of fRe_g expression (–)		
K_0	shape factor (–)	*Greek symbols*	
B	inter-plates distance (m)	α	geometrical parameter (–)
D_H	hydraulic diameter (m)	β	corrugation angle (°)
f	Fanning friction factor (–)	ΔP	pressure drop (Pa)
$g(n)$	hyperbolic function of n (–)	ϕ	area enlargement factor (–)
L	plate length (m)	γ	channel aspect ratio on the main flow direction (–)
M_v	volumetric flow rate ($m^3\,s^{-1}$)	$\dot{\gamma}$	shear rate (s^{-1})
n	flow index behaviour (–)	η	apparent fluid viscosity (Pa s)
p_x	corrugation pitch on the main flow direction (m)	η_g	generalised fluid viscosity (Pa s)
Re_g	generalised Reynolds number (–)	η_0	consistency index (Pa s^n)
u	mean velocity ($m\,s^{-1}$)	ρ	fluid density ($kg\,m^{-3}$)
u_i	average interstitial velocity ($m\,s^{-1}$)	τ	tortuosity (–)
w	width of the channel (m)		

where ρ is the fluid density and D_H the hydraulic diameter:

$$D_H = \frac{4 \times \text{channel flow area}}{\text{wetted surface}} \cong \frac{2b}{\phi}. \quad (5)$$

The mean velocity, u, is given by:

$$u = \frac{M_v}{wb}, \quad (6)$$

where M_v is the volumetric flow rate and w the channel width.

The Fanning friction factor can be estimated by:

$$f = \frac{\Delta P D_H}{2L\rho u^2}, \quad (7)$$

with ΔP the pressure drop and L the length of the channel.

Kozicki et al. (1966) studied the flow of power-law fluids in straight ducts of arbitrary but uniform cross-section area along the flow direction and proposed the following relation for $g(n)$:

$$g(n) = a\frac{1}{n} + c, \quad (8)$$

a and c being geometrical parameters of the duct. For the same type of ducts, Delplace and Leuliet (1995) related a and c with K, reducing to one the number of geometrical parameters involved in Eq. (2).

PHE passages containing cross-corrugated chevron-type plates are much more complex than the ducts studied by Kozicki et al. (1966) due to the presence of a series of expansions and contractions (Edwards et al., 1974). As a result of this complexity, Edwards et al. (1974) and Charre et al. (2002) analysed the performance of chevron-type PHEs making use of the theory developed for granular beds (Broniarz-Press et al., 2007; Chhabra et al., 2001; Dias et al., 2006, 2007, 2008).

Delplace and Leuliet (1995) explored the applicability of Eq. (8) to the area of PHEs but suggested that due to the complexity of the passages of these equipments the best way of defining a hyperbolic function $g(n)$ is to measure the pressure drop and flow rates under laminar isothermal conditions with different shear-thinning fluids, i.e., different values of n, as it was performed in previous works (Rene et al., 1991). As a result of this empirical methodology, Rene et al. (1991) proposed the following expression for $g(n)$:

$$g(n) = \left(\frac{2}{3} + \frac{1/3}{n}\right)\left(\frac{1}{n}\right)^{\alpha/n}. \quad (9)$$

In Eq. (9) the geometrical parameter α assumed a value of 0.3 and 0.1 for PHEs containing chevron-type plates with $\beta = 30°$ and a washboard plates, respectively (Rene et al., 1991). Eq. (9) allowed establishing, for each PHE, a single friction curve equation (Eq. (3)) for both Newtonian and shear-thinning fluids (Delplace and Leuliet, 1995; Rene et al., 1991). It is important to note that this methodology, developed under isothermal conditions, can be used successfully in non-isothermal situations (Delplace and Leuliet, 1995; Leuliet et al., 1987, 1988).

Fernandes et al. (2007) studied the relation between the geometrical properties of the chevron-type PHEs plates and the coefficient K, for Newtonian flows under laminar regime and developed the relation:

$$K = \Bigg(\underbrace{1 + 0.5\sqrt{\left(\frac{1}{\sin(\beta)}\right)^{\gamma} - 1}}_{\tau}\Bigg)^2 \times \underbrace{16\left(\frac{90}{\beta}\right)^{0.6554-0.0929\gamma}}_{K_0}, \quad (10)$$

γ being the channel aspect ratio in the main flow direction:

$$\gamma = \frac{2b}{p_x}, \quad (11)$$

where p_x is the pitch in the main flow direction (Fig. 1). In Eq. (10), τ and K_0 represent the tortuosity coefficient and shape factor, respectively.

Wanniarachchi et al. (1995) proposed the following experimental correlation to predict coefficient K for laminar Newtonian flows in chevron-type PHEs:

$$K = 1774/\beta^{1.026}. \quad (12)$$

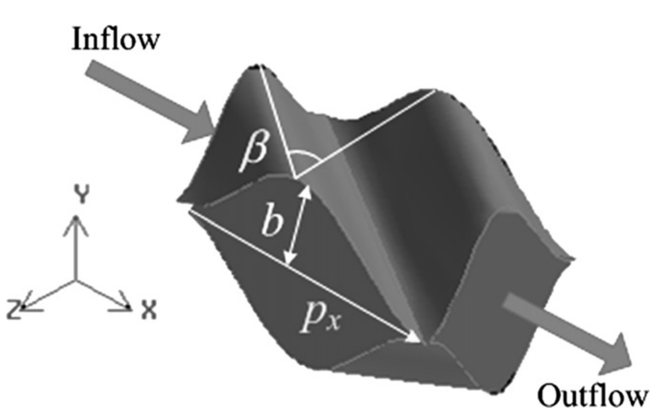

Fig. 1. Unitary cell for $\beta = 55°$.