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Laminar flow in chevron-type plate heat exchangers: CFD analysis of tortuosity, shape factor and friction factor

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Abstract

Laminar or low Reynolds number flows are usually obtained when liquid foods with high viscosity are processed in plate heat exchangers (PHEs). The tortuosity coefficient is a key parameter used by PHEs manufacturers to estimate Fanning friction factors and convective heat transfer coefficients. Using the finite-element computational fluid dynamics program POLYFLOW®, fully developed laminar flows in double-sine chevron-type PHEs passages are analysed in this work. The corrugation angle and channel aspect ratio of the passages vary in a broad range, PHEs with common area enlargement factors and with high area density being studied. The tortuosity coefficient and the coefficient *K* (Kozeny's coefficient in granular beds) from the friction factor correlations increase with the increase of the channels aspect ratio and the decrease of the chevron angle. The shape factor from the PHEs passages also increases with the decrease of the chevron angle and is weakly influenced by the channel aspect ratio. In this paper, relations to predict the tortuosity coefficient and shape factor are proposed, the coefficient *K* being predicted resorting to the tortuosity coefficient and shape factor. The coefficient *K* compares well with literature data in the region of common chevron angles, channels aspect ratio and area enlargement factor.
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Keywords: Plate heat exchangers; Friction factor; Tortuosity; Shape factor

1. Introduction

1.1. Laminar flow in plate heat exchangers

Laminar flow in complex ducts geometries is of both fundamental and practical interest [1–6]. Of particular interest is the PHE which is extensively used in the chemical, pharmaceutical and food industries, among others [1,7,8]. Laminar or low Reynolds number flows are usually obtained when liquid foods are processed in PHEs, this low Reynolds number range being also observed in micro PHEs [7,9–12]. Besides the importance in pressure drops estimations, the development of Fanning friction factor correlations, determined for the isothermal laminar flow of Newtonian fluids in PHEs, can be useful in other areas. One of them is the prediction of port-to-channel flow maldistribution in these equipments [13,14], the referred correlations being also involved in the development of methodologies that allow the establishment of a single friction curve equation for both Newtonian and power law fluids, in different flow regimes [12,15].

In the referred methodologies, geometrical parameters of the ducts need to be estimated in order to define generalized Reynolds numbers. The geometrical parameters are estimated using Fanning friction factor expressions, determined for the laminar flow of Newtonian fluids in PHE passages [15] or other type of ducts [16].

Physical processing brings about irreversible textural and sensorial properties of nearly all the fluids in the food industry [17,18]. The above mentioned Fanning friction factor correlations can be helpful in the calculation of wall shear rates

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developed during the flow of Newtonian or power law fluids inside the PHE channels [11,12,15]. These wall shear rates can then be used to predict the viscosity breakdown of liquid foodstuffs during their processing [17].

Stirred yoghurt is very sensitive to physical processing, a low viscosity being a common manufacturing defect of this foodstuff [17]. During the flow through the cylindrical filling nozzles, the yoghurt is subjected to high wall shear rates (typical values are between 800 and 1250 s^{-1}) and this may lead to an irreversible breakdown of yoghurt viscosity [17].

PHEs are commonly used during the cooling of stirred yoghurt [7,19]. In the work from Fernandes et al. [19], it can be observed that in a commercial PHE and for a Reynolds number of 12.3 wall shear rate reaches 1800 s^{-1}, this value being substantially superior to the observed in the filling nozzles.

1.2. Corrugation geometry

Between the more than 60 different plate surface corrugation patterns, the most used PHEs consist of plates with chevron-type corrugations that have a sinusoidal shape [1] (Fig. 1). The thermal–hydraulic performance of PHEs is strongly dependent on the geometrical properties of the chevron plates [20–22], namely on the corrugation angle, β, area enlargement factor, ϕ, defined as the ratio between the effective plate area and projected plate area, and channel aspect ratio (Fig. 1).

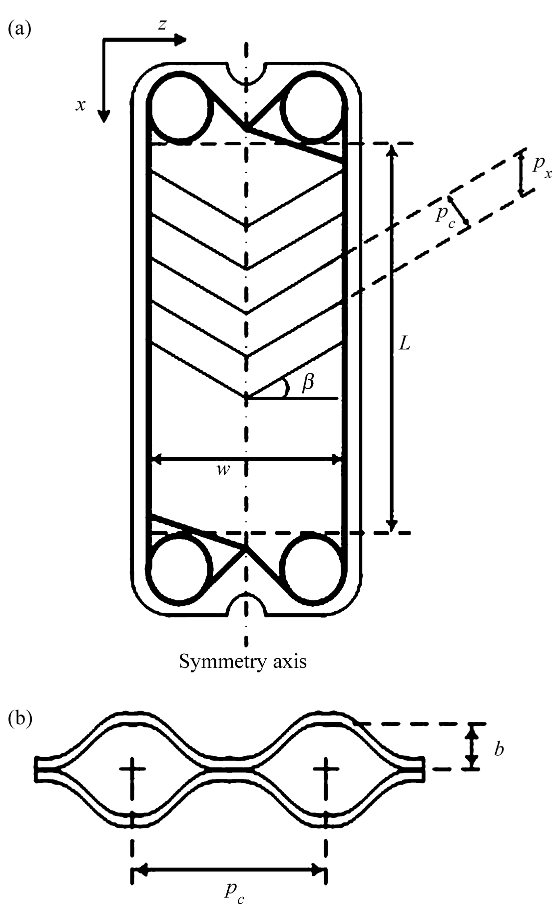

Fig. 1. (a) Schematic representation of a chevron plate; (b) corrugation dimensions.

The channel aspect ratio is usually defined by $2b/p_c$, p_c being the corrugation pitch and b the inter-plates distance (Fig. 1). In the present work, a different definition of channel aspect ratio, γ, will be used:

$$\gamma = \frac{2b}{p_x}, \tag{1}$$

p_x being the corrugation pitch in the main flow direction (Fig. 1). The reason for the use of a channel aspect ratio defined in the main flow direction is explained in Section 3.

Introducing Eq. (1) in the expression proposed by Martin [23] and resorting to the geometric relation between p_c and p_x (Fig. 1), the area enlargement factor can be estimated by:

$$\phi = \frac{1}{6}\left\{1 + \left[1 + \left(\frac{\pi}{2\cos(\beta)}\right)^2 \gamma^2\right]^{0.5} + 4\left[1 + \left(\frac{\pi}{2\sqrt{2}\cos(\beta)}\right)^2 \gamma^2\right]^{0.5}\right\}. \tag{2}$$

The area enlargement factor typically assumes values between 1.1 and 1.5 [22], b normally lies in the range 2–5 mm [21,24] and β is typically located in the range 22–65° [21,22].

1.3. Friction factor, shape factor and tortuosity coefficient

Fanning friction factors correlations, fRe, in the laminar regime take the form [21,22]:

$$f = K Re^{-1}, \tag{3}$$

where K is a coefficient dependent of the corrugation angle and channel aspect ratio and Re the Reynolds number:

$$Re = \frac{\rho u D_H}{\eta}, \tag{4}$$

ρ and η representing the fluid density and viscosity, respectively. In Eq. (4) the mean velocity, u, in the PHE channel and the hydraulic diameter, D_H, can be calculated by [21,22]:

$$u = \frac{M_v}{wb}, \tag{5}$$

and

$$D_H = \frac{4 \times \text{channel flow area}}{\text{wetted surface}} \cong \frac{2b}{\phi}, \tag{6}$$

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

The Fanning friction factor, f, can be estimated by:

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

where ΔP is the pressure drop and L the length of the channel.

In the experimental studies of Kumar [20] it was found that the critical Reynolds number (the Reynolds number where laminar flow ends) increased with the increase of the corrugation angle. Using plates with chevron angles of 30° and 65° the author

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