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Effect of the perforation design on the fluid flow and heat transfer characteristics of a plate fin heat exchanger

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ABSTRACT

Three dimensional numerical simulations are carried out to explore the performance of vortex generators in a plate fin heat exchanger. Rectangular and perforated wings are used as vortex generators to enhance the heat transfer rates. A comparison is made between the performances of a plate fin with and without baffles. When the heat exchanger is equipped with baffles, the efficiency of two configurations was compared: a baffle with and without perforation. Also, the effects of the perforation shape were studied. It concerns three cases: rectangular, triangular and circular. Validation of our numerical results with the available experimental data has revealed a satisfactory agreement. The obtained results show that the baffled cases perform better than the unbaffled one. The performance factor is found to be higher in the perforated baffle than the baffle without perforation. Compared to the unbaffled case, the maximum thermal performance factor (TPF) of 2.14 was obtained with the circular perforated baffle, followed by the rectangular perforated baffle (TPF = 1.57), triangular baffle (TPF = 1.46) and finally the baffle without perforation (TPF = 1.41). At the end of paper, new correlations for the prediction of friction factor and Nusselt number depending on Reynolds number and the shape of perforation in baffles are developed.

1. Introduction

Plate fin heat exchangers (PFHEs) are widely encountered in several industrial processes such as in refrigeration, heating, air conditioning, radiator of vehicles and other areas. Therefore, some criteria are desired during the production of such heat exchangers, as the small size, low weight, low cost and high performance. From the different kinds of PFHEs available in industries, the vortex-generator (VG) channel is the most promising technique to meet these criteria [1,2]. Different shapes of plate are used in channels as vortex generators, such as plain, perforated, wavy, louvered, pin and offset strip. This technique allows a swirling and disturbed fluid flows and consequently a great exchange between fluid particles in the whole channel volume [3].

From the different types of fins cited previously, the plain plate is the widely used for its durability, simplicity, versatility in applications and lower pressure drop. However, the wavy or corrugated fins ensure higher thermal performance than the plain plate since they increase the length of the flow path and enhance the mixing, but with higher pressure drop [4].

According to the direction of rotating axes, i.e. when the main flow direction is lied parallel or perpendicular to the VG, the VG is named as longitudinal or transversal, respectively. The longitudinal vortex generators (LVGs) are found to be very efficient to enhance the heat transfer in fin-tube and plate-fin heat exchangers [5–7]. Biswas et al. [8] reported in their study that the heat transfer may be enhanced by about 240% in the zone behind the cylinder with the presence of a winglet LVG.

Others researchers investigated the hydraulic and thermal characteristics of VGs in various heat exchangers, such as plate-fin heat exchanger [9–12], plate-fin and tube heat exchanger [13–15], fin and flat tube heat exchanger [16], shell and tube heat exchanger under different baffle arrangements [17], ducts with various cross-sectional shapes [18–22], and electronic chips [23–27].

Khoshvaght-Aliabadi et al. [1] assessed experiments on the thermo-hydraulic performance of copper–water nanofluid flow through various plate-fin channels, including: pin, vortex generator, offset strip, wavy, louvered, plain and perforated. Their results showed an enhancement in heat transfer coefficients and pressure drop with the rise of nanoparticles weight fraction. They reported also that the vortex generator channels have given the appropriate thermal–hydraulic performance. In

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another paper [2] for water fluid, these authors obtained the optimal performance with wavy channels at low Reynolds numbers. And compared to the typical wavy plate-fins (WPFs), Khoshvaght-Aliabadi et al. [28] obtained a thermal performance of 1.26 with the winged WPF at the highest waviness aspect ratio and at low Reynolds number.

Khoshvaght-Aliabadi et al. [29] studied the effect of delta-winglets under different arrangements. For the plain tube and at the transitional flow, they observed a good prediction of Nusselt number by the Notter-Rouse equation than the Gnielinski equation. Compared to the plain tube, they found a maximum PEC (performance evaluation criterion) of 1.41 with this VG at $Re = 8715$.

For water and cu-water fluids flowing at Reynolds number varying between 5200 and 12,200, Khoshvaght-Aliabadi et al. [30] studied the effect of pitch, length and width of delta-winglet VGs on the performance of a tubular heat exchanger. Compared to the smooth tube, they found a maximum PEC of 1.83 with the Cu-water nanofluid at the winglets-width ratio of 0.6 for the maximum Reynolds number, accompanied by an increase in pressure drop and heat transfer coefficient by about 2.03 times and 1.24 times, respectively. In another paper [31], they explored the influence of longitudinal spacing among delta-winglets in VG channels with water and Al_2O_3/water nanofluid (NF). They found an enhancement in heat transfer rates by about 10% to 50% for water and by 8.5% to 17.6% in NF.

The recirculation flow formed in the downstream zone of VGs creates hot points in this area. This great issue may be solved by using perforated baffles [32–34]. With experiments, Chamoli [35] showed the great heat transfer enhancement for a rectangular channel equipped with V-down perforated baffles. The number of holes influences highly on the flow fields and heat transfer rates, and two perforated baffles perform better that one baffle, as reported by Ary et al. [36]. The study achieved by Sheikholeslami et al. [37] for air to water heat exchangers by using perforated circular rings reveals an increase in the thermal efficiency with increased numbers of holes, but increased Reynolds number and pitch ratio yields a decrease in heat transfer rates. A reduced pressure drop may be also obtained with baffles equipped with perforations [38–41]. Sahel et al. [42] investigated the performance of a perforated baffle having a row of four holes placed at three different locations (the so called pores axis ratio, PAR), namely PAR = 0.190, 0.425 and 0.660. The obtained results revealed that the case with PAR = 0.190 performs better than the other ones. Using the combination between inclined and perforated baffles participates to the reduction of lower heat transfer areas, as reported by several authors [43–46].

Our search in the literature suggests that the effect of the shape of perforation in PFHEs have not yet been studied, especially for viscous complex and non-Newtonian fluids. Therefore, the present paper discusses the thermal and pressure drop performance in PFHEs under various operating conditions. With a shear thinning fluid, effects of the shape of perforation in baffles are investigated.

2. Definition of the problem

A hot shear thinning fluid (CMC solution) is flowing through a rectangular channel with an inlet temperature T_{in} = 52 °C (Fig. 1). The

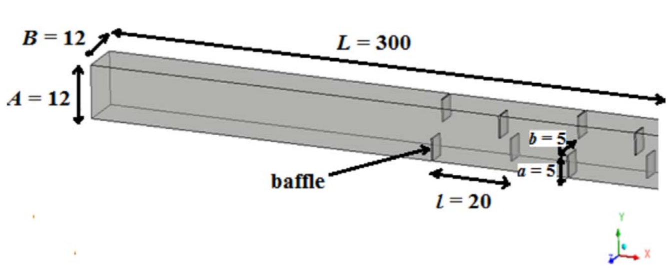

Fig. 1. Geometry simulated.

Table 1
All cases studied.

Case 1	Case 2	Case 3	Case 4	Case 5
A channel without baffles	A channel equipped with rectangular baffles without perforation	With rectangular perforation	With triangular perforation	With circular perforation

wall temperature is fixed at $T_w = -6.5$ °C. The length L of channel is 300 mm and its width is $A = B = 12$ mm. The length and width of each baffle is $a = b = 5$ mm and the thickness of each one is 1 mm. Six ranges of baffles are inserted and the distance l between two consecutives ranges is 20 mm. As shown in Fig. 1, the flow is described in a coordinate system (x, y, z) in which the spanwise direction is z-direction, the normal direction is y-direction, and the flow direction (streamwise direction) is x-direction.

The effect of baffles with/without perforations is investigated. As summarized in Table 1, five cases are studied (Fig. 2). The flow is laminar and Reynolds number is ranging from 0.1 to 150. Extended regions were added at the inlet and the outlet sections of the tube to ensure the fully developed flow at the inlet, and to avoid the appearance of reversed flows at the outlet [47].

3. Governing equations

All investigations were performed via numerical simulations. The working fluid has a shear thinning behavior (the flow behavior index $n = 0.69$ and the density is $\rho = 997$ kg/m^3), modeled by the Otwald law (power law) as follows:

$$\tau = \mu_a \dot{\gamma}^n \tag{1}$$

where μ_a is the apparent viscosity and $\dot{\gamma}$ is the shear rate.

$$\mu_a = k\dot{\gamma}^{n-1} \tag{2}$$

where k is the consistency index. All cases simulated are considered continuous and steady state. The viscous dissipation is negligible.

In this paper, we interested to the cooling of complex non-Newtonian fluids. Usually, these fluids are encountered in industrial applications under laminar flow conditions, as reported by Azevedo et al. [48]. So, the convective heat transfer is studied for low Reynolds numbers.

The boundary conditions of the computational domain are defined as follows:

- At the inlet of channel (Inlet condition):

$$u_y = u_z = 0;\ u_x = u_{in} = \text{cste};\ T = T_{in} = 52^\circ\text{C} \tag{3}$$

where u is the velocity and T is the temperature of fluid.

- Lower and upper surfaces (wall condition):

$$u_x = u_y = u_z = 0;\ \ T = T_{wall} = -6.5^\circ C;\ \ \frac{\partial T}{\partial z} = 0 \tag{4}$$

- Right and left sides (symmetry condition):

$$u_x = u_y = u_z = 0;\ \ \frac{\partial T}{\partial x} = 0 \tag{5}$$

- Exit of channel (outlet condition):

$$\frac{\partial u_x}{\partial x} = \frac{\partial u_y}{\partial x} = \frac{\partial u_z}{\partial x} = 0;\ \ \frac{\partial T}{\partial x} = 0 \tag{6}$$

- Baffles: adiabatic walls.