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Complex 3D-flow analysis and corrugation angle effect in plate heat exchangers

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ABSTRACT

This article presents a detailed analysis of the thermo-hydraulic transfers for single-phase flow in brazed plate heat exchangers (BPHE) using numerical simulations. The comparison of the simulation and experimental results show similar trends on the variations of the global thermo-hydraulic quantities, as the friction and convective heat transfer coefficients, with respect to Reynolds number. Whether for simulations or experiments, there is a significant change in the hydraulic behavior for $Re \approx 200$, which may suppose a change of the flow structure into the BPHE. The influence of the chevron angle (β) on the flow structure and on the pressure drops for Reynolds numbers ranging from 1 to 2500 has been conducted on a representative flow fields. Based on the analogy that complex 3D-flow may be regarded as two 1D-flows of sinusoidal cross-section in flow interaction, it was defined a flow characteristic observable, which quantifies the mass transfer rate from one groove to the other. The analysis shows that flow structures are not only sensitive to chevron angle but also to the mass flow rate. It is pointed out that the variation of the friction coefficient versus the Reynolds number is correlated to the flow structure classes, of type "helical" and "cross-flows". Based on these results and for the full range of Reynolds number, the study reveals two categories of PHE hydraulic behavior depending on the chevron angle with a limit around 60° for the change of the PHE behavior.

1. Introduction

Brazed plate heat exchangers (BPHE) are widely used in industrial processes, food industry, engine oil cooling, heat pumps, etc. They are selected as heat exchanger in main energy recovery systems for their high efficiency and compactness [1]. In general, they are used for convective single-phase or phase-change heat transfer phenomena, between two streams in co—or counter-current configurations. Considering single-phase flows in BPHE, several approaches characterizing the global coefficients of friction or heat transfer are presented in the literature. Most of these studies have established predictive correlations of the global heat transfer coefficient for their specific BPHE design (patterns, inclination angle, corrugation amplitude …) valid under certain operating conditions (mass flow rate, temperature range …) [2–6]. More rarely, the established correlations are presented with a generalized form [7,8].

Understanding the flow patterns inside this type of heat exchanger should allow apprehending the thermo-hydraulics' transfer physics, in the aim of optimizing the channel geometry. Two main types of flow pattern have been experimentally identified by Focke et al. [9], and recently validated by Dović et al. [8]: 1/the "cross-flows" pattern, for which the flow mainly follows the corrugations; and 2/the "helical" pattern, also named in the literature by "zig-zag" pattern, for which the flow changes corrugations in the longitudinal direction of the heat exchanger. The results show a strong dependency of the flow structures on plate geometry characteristics. The limit between the two flow patterns was defined for a corrugation inclination angle of $\beta = 45°$ (relative to vertical direction): $\beta < 45°$ promotes the "cross-flows" pattern, while $\beta > 45°$ conducts to the "helical" one. The observations of Dović et al. [8] and Focke et al. [9] are confirmed by the numerical study of Zhang et al. [10], whose objective was to examine the effect of the inclination angle on the flow patterns. The tests of Dović et al. [8] and Focke et al. [9] have been conducted at low Reynolds numbers (<100) and the mass flux effect on flow patterns was not clearly identified.

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Nomenclature

A	heat transfer area, m^2
b	channel spacing or corrugation amplitude, m
D_h	hydraulic diameter, m
e	plate thickness, m
f	friction coefficient
G	mass flux or Mass velocity, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
L	length between channel inlet and outlet, m
w	width of the plate, m
$LMTD$	logarithmic mean temperature difference, °C
$\dot{m}$	mass flow rate, kg s^{-1}
P	length of the interaction plane edge, m
P_c	chevron pitch, m
Pr	prandtl number, $Pr = \mu\ Cp\ \lambda^{-1}$
Q	heat transfer rate, W
Re	Reynolds number, $Re = G\ Dh\ \mu^{-1}$
S	flow cross section, m^2
U	global heat transfer coefficient, W m^{-2} K^{-1}
z^*	normalized vertical position, $z^* = z\ L^{-1}$
ΔP	pressure drop, Pa

Greek letters

λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
Cp	specific heat capacity, j kg^{-1} K^{-1}
μ	dynamic viscosity, Pa s
β	chevron or corrugation angle, °
τ	mass transfer rate, %

Subscripts

$BPHE$	brazed plate heat exchanger
c	cold
f	friction
h	hot
i	Inlet
$i\|o$	relative to inlet/outlet
IR	infrared
m	mean value
o	outlet
t	total value
w	water

In addition to the experimental and analytical studies, numerical simulations have been recently used to investigate the thermo-hydraulic transfers in BPHE [4,10–14]. The numerical approaches may be classified into two types: 1/Studies on a representative cell (periodic region) of the heat exchanger allowing the characterization of the heat transfer and friction coefficients; 2/Studies on the whole heat exchanger in order to apprehend the fluid distribution, whether between channels, or within a channel. Tsai et al. [4] and Liu et al. [13] have conducted numerical simulations of water flow inside a BPHE composed of 2 channels ($\beta = 65°$ and $b = 2$ mm). In the studied range of the Reynolds number ($Re < 430$), the results of Tsai et al. [4] indicate an underestimation of 20% of the pressure losses while comparing with experimental results. Concerning the study of Liu et al. [13], pressure losses are underestimated using k-ε model of FLUENT, while they are in good agreement with the experimental results for the laminar range using the laminar model. According to the flow streamline representation, the observed flow pattern is of "helical" type. Kanaris et al. [11] have performed thermo-hydraulic simulations for the whole geometry of a BPHE using the software CFX (ANSYS) with *K-ω* and *SST* models. The good agreement between the temperature profiles obtained by simulations and the ones measured by an infrared camera confirms the capability of CFD codes to predict the flow characteristics and the heat transfers in complex three-dimensional structures. Gherasim et al. [15] have conducted a numerical study of thermo-hydraulic transfers of water flow inside PHE with trapezoidal corrugation profile ($b = 2.5$ mm, $P_c = 9$ mm, $\beta = 60°$). The comparisons between experimental and simulations results, for the Nusselt number and the friction coefficient, show a good agreement for $Re < 400$, for which a laminar model is applied in the simulations. For $Re > 400$, five combinations of two-equation turbulent models with different wall functions have been compared and the "*Realizable k-ε*" model with Non-Equilibrium Wall Function (NEWF) gives the closest results to the experience.

In the literature review on PHE, one can note the maturity of numerical simulations in predicting the hydraulic behavior of flows inside PHE. Consequently, numerical simulations are an interesting and effective way to access information on flow structures within a BPHE that are particularly difficult to obtain experimentally. However the simulation results of the literature on the thermo-hydraulic flow behavior are not extensively exploited, in order to establish a relation between the flow structures and the coefficients of friction and heat transfer.

In this article we attempt to highlight the relation between flow structures and friction coefficients by analyzing the numerical simulation results. Previously to the flow analysis, the validation of the numerical simulations, by comparing them to the results obtained during the experimental characterization of the heat exchanger, is first presented.

2. Characteristics of the study

2.1. Experimental parameters

The study is conducted for single-phase flow of water inside the BPHE in a counter-current heat transfer configuration. The BPHE characteristics are presented in Fig. 1, The BPHE prototype is composed of three brazed plates, thus forming two channels with a hydraulic diameter $D_h = 2.b = 4.4$ mm, where b is the corrugation amplitude. In this configuration, the BPHE prototype has the advantage of allowing infrared visualization of both hot and cold flows by the external plates. The central plate has an inversed orientation of the corrugations relative to outer plates, which gives a three-dimensional structure of the flow within the channels. The plate corrugation has an inclination angle of 55° relative to the longitudinal axis of the BPHE. The BPHE is tested in vertical position. The experimental setup and the infrared metrology that have been used are detailed in Sarraf et al. [16]. Measurements of flow rates, temperatures and differentials pressure are carried out for each water flow.

2.2. Simulation parameters

The CFD software STARCCM+® was used to perform the numerical simulations. The plate geometry was drawn using the CAO software Pro/ENGINEER® by the industrial partner CIAT. It consists