Applied Thermal Engineering 51 (2013) 347–363

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Numerical and experimental investigation of buoyancy effects in a plate heat exchanger

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HIGHLIGHTS

► Heat transfer of a chevron-type PHE under mixed convection was studied.
► Aiding and opposing buoyancy experiments performed for $Re = 100–400$.
► Heat transfer is improved under aiding mixed convection conditions.
► Aiding buoyancy forces cause higher pressure losses.
► Opposing buoyancy deteriorates the flow symmetry inside channels.

ARTICLE INFO

Article history:
Received 11 May 2012
Accepted 6 September 2012
Available online 18 September 2012

Keywords:
Plate heat exchanger
Natural convection
Mixed convection
Buoyancy
Nusselt number
Pressure losses
Temperature distribution
Experimental study
Numerical study
CFD

ABSTRACT

This paper presents an experimental and numerical investigation of the hydrodynamic and thermal fields in a two-channel chevron-type plate heat exchanger (PHE) under mixed convection conditions. Eight pairs of experiments were performed, with water on both sides, with Reynolds number varying between approximately 100 and 400. Each pair consisted of two experiments: one with aiding mixed convection and the other with opposing mixed convection conditions. The temperature distributions on the end-plates, the outlet temperatures, the heat flux and the Nusselt number obtained in the two positions of the PHE were compared. A validation of the numerical model in this flow regime has been made in order to analyze numerically the pressure losses and the flow structure. Comparisons of the experimental data obtained for the fluid outlet temperatures, heat transfer rate and Nusselt number showed that the heat transfer is improved under aiding mixed convection conditions. The numerical data analysis shows that opposing mixed convection deteriorates the symmetry of the flow distribution inside the PHE's channels and that aiding buoyancy forces cause higher pressure losses.

1. Introduction

Plate heat exchangers (PHEs) are widely used in many applications (food, oil, chemical and paper industries, HVAC, heat recovery, refrigeration, etc.) because of their small size and weight, the ease of cleaning as well as their superior thermal performance compared to other types of heat exchangers (for a synthesis of the applications of PHEs see, for example [1]). Therefore several experimental and numerical studies have been conducted in order to determine operating characteristics of PHEs such as flow and temperature distributions, Nusselt numbers, friction losses, etc.; many of the latter use simplifying assumptions.

Thus, Lozano et al. [2] analyzed numerically and experimentally the flow distribution inside one channel of a PHE without considering heat transfer. They concluded that the flow was non-uniform and preferentially moved along the lateral extreme edges of the plates. Kanaris et al. [3] studied experimentally and numerically the flow and heat transfer in a two-channel PHE. They observed a good agreement between the numerical results and the experimental data and concluded that CFD was an effective and reliable tool to predict flow characteristics, pressure losses and heat transfer in this type of equipment. Tsai et al. [4] investigated experimentally and numerically the hydrodynamic characteristics and distribution of the flow inside a two-channel PHE. Heat

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1359-4311/$ – see front matter
http://dx.doi.org/10.1016/j.applthermaleng.2012.09.009

Nomenclature

A	heat transfer area of the plate, m^2
b	gap between two consecutive plates, m
C_p	specific heat, J kg^{-1} K^{-1}
D_h	channel hydraulic diameter, m
f	Darcy friction factor, Eq. (2)
g	gravitational acceleration, m s^{-2}
Gr	Grashof number, Eq. (4)
h_m	average heat transfer coefficient, W m^{-2} K^{-1}, Eqs. (6a) and (6b)
k	thermal conductivity, W m^{-1} K^{-1}
L	effective length of the plates, m
Nu	average channel Nusselt number, Eq. (3)
p	pressure, Pa
ΔP	pressure loss between inlet and outlet of a channel, Pa
Pr	Prandtl number, $Pr = C_p\mu/k$
ΔQ	heat transfer rate, W
Ra	Rayleigh number, Eq. (5)
Re	channel flow Reynolds number, Eq. (1)
Ri	Richardson number, $Ri = Gr/Re^2$
T	temperature, K
u_i	i-axis velocity component, m s^{-1}
u_m	mean velocity of the fluid in a channel, m s^{-1}
$\dot{v}$	volume flowrate in the channel, m^3 s^{-1}
x_i	i-axis
X, Y, Z	coordinates

Greek letters

β	volumetric expansion coefficient, 1/K
δ	plate thickness, m
μ	dynamic viscosity, Pa s
ρ	fluid density, kg m^{-3}
φ	chevron angle with respect to the length of the plate, deg

Subscripts

b	refers to the bulk temperature of the fluid, i.e. the average between the inlet and outlet temperatures in the channel
c, h	refer, respectively, to the cold and the hot fluids
i, o	refer, respectively, to the inlet and outlet
m	evaluated at channel average temperature
w	refers to the wall

transfer was not considered in this study. The numerical model illustrated the same zigzag and rotational fluid flow structure previously observed by Kanaris et al. [3]. The numerically obtained pressure loss underestimated by about 20% the corresponding experimental value. Galeazzo et al. [5] studied experimentally and numerically the heat transfer in an industrial PHE with four channels. However, this PHE was a non-chevron-type, the five plates being smooth. The authors investigated parallel and series flow arrangements and compared two numerical approaches: one- and three-dimensional. The predictions of the 3D model were always in better agreement with the experimental data. In our previous experimental [6] and numerical [7] studies we analyzed the three-dimensional hydrodynamic and thermal fields in a two-channel chevron-type PHE for forced convection. The CFD model was validated by comparing the numerical and experimental results for the temperature distributions on the exterior plates of the PHE, the friction factor and Nusselt numbers for each channel, as well as the outlet temperature of the two streams. This model was used in a further study [8] to analyze the flow distribution in the case of two fluids, water and engine oil, and to assess comparatively the performances of the side-flow and diagonal-flow configurations.

None of the above studies considered the effect of buoyancy on the performance of PHEs even though, given the multitude of applications, it is possible that they may operate, temporarily or permanently, in the low flowrate regime for which mixed convection can develop. In fact, to the best of our knowledge, the only work that considered buoyancy effects in a PHE is the experimental study by Okada et al. [9] who compared the temperature distributions on the first and last plates of a two-channel PHE for upwards and downwards flow of the cold and hot fluids. The PHE used was of the non-chevron-type (the plates had rectangular furrows parallel to one of their edges). Their analysis showed a deterioration of heat transfer and a severe increase in the non-uniformity of temperature in the direction of the width of the plates in the cases of upward flow of hot fluid and downward flow of cold fluid. The lack of information on the behavior of chevron-type PHEs under mixed convection operating conditions is surprising since it is well established that, for Richardson numbers of the order of one, the mixed convection influences considerably the flow and heat transfer characteristics in individual ducts [10] and double-pipe heat exchangers [11].

Considering this situation, the present experimental and numerical work was undertaken in order to enrich the literature with information on the behavior of chevron-type PHEs under mixed convection operating conditions. In the present paper the flow and heat transfer characteristics in a two-channel chevron-type industrial PHE are presented for aiding and opposing buoyancy. Specifically the effects on the temperature of the end-plates, the outlet temperatures of the two fluids, the heat flux, the Nusselt number, the pressure losses and the mass flowrate distribution obtained by reversing the flow direction of the two fluids are analyzed and compared. Compared to the study by Okada et al. [9] the present one uses a different, more realistic, type of PHE (chevron versus non-chevron); it includes an analysis of the hydrodynamic field and presents results for a wider range of operating parameters.

2. Experimental setup and procedures

2.1. Description of the experimental setup, uncertainties and procedure

The PHE used for this study is an industrial one. It contains three plates i.e. two channels, which have a herringbone pattern with trapezoidal shape corrugations, the gap between the plate being $b = 2.5$ mm. The main dimensions of the plates are indicated in Fig. 1. Other characteristics of the PHE were given in our previous papers [6,7] and are not repeated here for the sake of space. The flow in the PHE is countercurrent. The coordinate system presented in Fig. 1 was chosen so that the length, width and height of the channels are aligned with the X, Z and Y axes, respectively. The inlet and exit ports for each fluid are located on the same side (side-flow PHE) with the two inlets on opposite sides, at the extremities of one of the plate's diagonals, as presented in Fig. 1. At the longitudinal sides of the plates (Z_{min} and Z_{max}) there are areas free of corrugations, which form two small vertical straight smooth passages that run over the entire length of the channel. As observed in our previous paper [7] and also by Lozano et al. [2] in a PHE with similar