Applied Thermal Engineering xxx (2014) 1–8

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Generalised semi-empirical correlation for heat transfer in channels of plate heat exchanger

Olga P. Arsenyeva [b,*], Leonid L. Tovazhnyanskyy [b], Petro O. Kapustenko [a], Oleksiy V. Demirskiy [a]

[a] AO SPIVDRUZHNIST-T LLC, 2 Krasnoznamenny Per., 61002 Kharkiv, Ukraine
[b] Department of Integrated Technologies and Processes and Apparatuses, National Technical University "Kharkiv Polytechnic Institute", 21 Frunze Str., 61002 Kharkiv, Ukraine

HIGHLIGHTS

- The analysis of turbulent flow in channels of PHEs.
- The analysis of the Prandtl number influence on heat transfer in PHE is performed.
- The semi-empirical model of turbulent heat transfer inside PHEs channels is proposed.
- The proposed model enables to design the PHEs for different duties.

ARTICLE INFO

Article history:
Received 18 February 2014
Received in revised form
13 April 2014
Accepted 15 April 2014
Available online xxx

Keywords:
Plate heat exchanger
Heat transfer
Heat and momentum transfer
Friction factor
Prandtl number
Reynolds number

ABSTRACT

The analogy of heat and momentum transfer in turbulent flow modified for channels of Plate Heat Exchanger (PHE) is proposed. The effects of channel geometry, flow velocity and fluid properties on heat transfer are accounted in the resulting equation, which permits the calculation of film heat transfer coefficients using the generalized correlation for friction factor at the main corrugated field of the inter-plate channel. The results of calculations are compared with data from experimental study. The good accuracy of film heat transfer coefficients prediction is shown. In the case when the corrugations direction is parallel to the flow direction, the calculations results are quite close to the predicted by the Equation published in the literature for straight pipes. The Prandtl number influence on heat transfer is discussed and semi-empirical Equation for its evaluation is proposed. The comparison with experimental data available in the literature confirmed the accuracy of the heat transfer prediction. The proposed Equation is recommended to be used for optimization of PHEs channels geometry for different conditions in the process industries. It can be employed also for optimizing PHEs heat exchange networks and also to determine PHEs heat transfer area targets when process integration methodology is employed.

1. Introduction

Plate Heat Exchangers (PHEs) with intensified heat transfer are one of the most efficient types of modern heat transfer equipment. Their application in process industries, and especially in utilization of low grade heat, renewables and waste and biomass to energy technologies, as shown by Kilkovsky et al. [1], save space and construction material, enhance reliability and operability as compare to traditional shell and tube heat exchangers. The principles of operation of PHE and its design are well described in literature, as e.g. Ref. [2] and in Russian language [3]. PHE channels of intricate geometry are formed by plates produced by stamping from thin metal sheets. It induces high levels of turbulence leading to enhancement of heat transfer. The heat and hydraulic performance of the PHE is strongly influenced by the form of plate corrugations. PHE design must account for this factor [4]. The researches on heat transfer and pressure drop in PHE channels, published in literature, are presenting results in form of empirical correlations. The influence of flow velocity and fluid properties is usually accounted in such correlations by functions of Reynolds and Prandtl numbers. Such functions are of different forms, which are specific for studied channels, their geometries and the range of tested conditions.

* Corresponding author. Tel./fax: +380 57 7202278.
E-mail addresses: o.p.arsenyeva@gmail.com, olga.p.arsenyeva@gmail.com (O. P. Arsenyeva).

http://dx.doi.org/10.1016/j.applthermaleng.2014.04.038
1359-4311/

Nomenclature

b	height of corrugation, m
c	the fluid heat capacity, J/(kg K)
C^*	empirical coefficient
D_e	equivalent diameter of the channel, m
F_x	the surface area enlargement factor
I	Integral in Eq. (4)
R	the distance from the tube centre, m
S	pitch of the corrugation, m
w	the local velocity, m/s
W	the average velocity, m/s

Numbers

$Nu = h \cdot D_e/\lambda$ the Nusselt number
$Pr = c \cdot \rho \cdot \nu/\lambda$ the Prandtl number
$Re = w \cdot D_e \cdot \rho/\mu$ the Reynolds number

Greek letters

β	the angle of corrugations inclination to flow direction, degrees;
β_M	the proportionality coefficient;
χ	constant for turbulent flow in pipes;
ε	the eddy diffusivities ratio for heat and momentum;
$\gamma = 2 \cdot b/S$	the ratio of corrugation doubled height to its pitch;
η	the dimensionless distance from the channel wall;
λ	the heat conductivity, W/(m K);
μ	the dynamic viscosity, cP;
ν	the kinematic viscosity, m^2/s;
ν_T	the turbulent viscosity (momentum eddy diffusivity), m^2/s;
ρ	the fluid density, kg/m^3;
τ_W	shear stress at the wall, Pa;
ω	the relative velocity;
ξ	the relative distance from the tube centre;
ψ	share of friction pressure losses in total loss of pressure at the channel main corrugated field;
ζ_S	the friction factor accounting for total pressure losses in channel;
ζ_τ	the friction factor for friction pressure losses

Superscripts:

$'$	buffer layer

Subscripts:

T	core of turbulent flow;
B	buffer sub-layer;
L	viscous sub-layer;
W	the wall surface

The heat transfer and hydraulic performance of inter-plate channels affects the selection of the plate corrugation optimal geometry for PHE. The semi-empirical model of the link between heat and momentum transfer for turbulent flows in straight round pipes was firstly developed by Reynolds in 1874 and later modified by Prandtl in 1928 and Von Karman in 1939. Then it was utilized and developed by many researchers and has been proved useful in obtaining more accurate representation and physical background for turbulent heat transfer. In a number of practical cases it enabled to correlate experimental data and to extrapolate correlations for a wider range of their application. E.g. the correlation for heat transfer in straight pipes and channels presented by Gnielinski [5], based on the Prandtl analogy, has been proved accurate for turbulent and also for transitional flow regimes in a wide range of Prandtl numbers and is recommended by the authors of Perry's Chemical Engineers Handbook [6] for the use in practical applications.

To predict the heat transfer based on the data of friction factor in PHE channels Martin [7] have utilised the equation of the Leveque analogy, proposed initially for laminar flows. The same approach was employed later by Dović et al. [8] and it gave some reasonable accuracy in predicting data on heat transfer for a number of experimental data presented by different authors. The modification of Reynolds analogy for PHE channels was proposed by Tovazhnyansky and Kapustenko [9]. It showed a good agreement with data of their experimental study carried on the models of PHE channel's main corrugated field. Similar modification of the Reynolds analogy is proposed by Arsenyeva et al. [10] and is proved fairly accurate when comparing with the experimental data obtained from different studies of heat transfer inside the PHE channels. All these generalisation attempts use the fixed power at the Prandtl number in the correlating equation (0.33 in the Leveque equation and 0.4 fixed in the modified Reynolds analogy). According to the empirical correlations for different PHE channels published by different authors the power at the Prandtl number varies in fairly wide range, mostly from 0.3 up to 0.5. The attempt to use the Gnielinski Equation [5] for the PHE channels gives discrepancies with experimental results up to 300%. The modification of the Von Karman analogy for PHE channels is proposed in paper [11], where the simplified assumption was made for turbulent viscosity distribution in buffer sub layer. The complicated resulting equation is rather cumbersome for the practical application of multi variant calculations in optimization problems.

In present paper more rigorous approach is presented. The results of the solution are approximated with the use of heat and momentum transfer Reynolds analogy and the equation which account the influence of the Prandtl number on heat transfer. The obtained equation enables to predict the film heat transfer coefficients for turbulent flows inside PHE channels in a wide range of the Reynolds and Prandtl numbers using the data for friction factor at the main corrugated field of the channel.

2. The theoretical analysis

Lyon [12] proposed one of the modifications of the Von Karman analogy inside pipes. The following Equation is derived there:

$$\mathrm{Nu}^{-1} = 2 \cdot \int_0^1 \frac{\left(\int_0^{\xi} \omega \cdot \xi \cdot \mathrm{d}\xi\right)^2}{(1 + \varepsilon \cdot \mathrm{Pr} \cdot \nu_T/\nu) \cdot \xi} \mathrm{d}\xi \tag{1}$$

where $\xi = R/R_0$ is the relative distance from the centre of the pipe;

$\omega = w/W$ is the relative velocity and w is the local velocity, m/s;
$\varepsilon = \lambda_T/(c\rho)/\nu_T$ is the ratio of eddy diffusivities for the heat and momentum;

Eq. (1) can be used for any flow regime, with the correct estimation of the velocity, ν_T and ε profiles, as it was shown by Lyon [12]. Kukuteladze [13] proposed the method to use Eq. (1) for the