International Journal of Heat and Mass Transfer 74 (2014) 448–459

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental analysis of heat transfer of supercritical fluids in plate heat exchangers

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ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 7 March 2014
Accepted 18 March 2014

Keywords:
Plate heat exchanger
Convection heat transfer
Properties
Buoyancy

ABSTRACT

Heat transfer of a supercritical refrigerant with highly variable properties close to pseudo-critical temperature was experimentally investigated in plate heat exchangers. Two different plate corrugation angles (30° and 60°) were examined while the Reynolds and the Prandtl number range from 800 to 4200 and 3.2 to 4.2, respectively. The results are found to be different from those obtained using classical Dittus–Boelter type correlations. Two possible effects were investigated: effect of wall-to-bulk property ratio and that of buoyancy. The former was found to be important and was accounted for in the correlation using the correction factor proposed by Jackson and Hall. The latter was found not to be significant for corrugation angle of 60°. For corrugation angle of 30°, however, buoyancy effects were found to have some influence, yet majority of the data points are found to be within 15% of those predicted using the correlation.

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1. Introduction

On account of their compactness and high heat transfer coefficients, plate-type heat exchangers (PTHEs) have been increasingly used in various industries in the past decades [1–3]. With improvements in manufacturing techniques and invention of novel designs, high pressure and temperature fluids can be pumped through PTHEs [3,4]. Queensland Geothermal Energy Centre of Excellence (QGECE) has been considering PTHE as a favorite candidate for being used in the development of binary geothermal power cycles. An area of major focus in QGECE is the study of power cycles with supercritical working fluids to bring about higher energy conversion efficiencies for geothermal energy resources.

The term 'supercritical fluid' is used in this paper to address a fluid with a pressure higher than its critical pressure. At any supercritical pressure, there is never two distinguishable liquid and vapor phases in equilibrium. What happens instead is a gradual transition from high-density liquid-like fluid to low-density gas-like fluid with an increase in the temperature. With temperature close to *pseudo-critical temperature* (T_{pc}), the rate of this decrease in density intensifies leading to very high thermal expansion coefficients untypical to most single phase fluids. Moreover, at a supercritical pressure, specific heat is considerably higher in the vicinity of T_{pc}. Pseudo-critical temperature itself depends on the pressure, and approaches *critical temperature* as the pressure tends to *critical pressure* [5].

Heat transfer of a supercritical fluid with rapid changes in density and specific heat, like what described above, can be different from that of normal fluids. It has been known since long time ago that heat transfer of supercritical fluids in straight tubes does not follow the prediction of conventional heat transfer correlations when fluid's temperature approaches the pseudo-critical temperature [6–9]. It is partly due to the fact that temperature-dependent thermophysical properties may be considerably different near the wall compared to those at bulk temperature. Obviously, new correlations were called for containing corrections for the unusually high wall-to-bulk ratios of density and specific heat. A number of such correlations have been suggested in the literature for turbulent heat transfer in circular pipes [6,8–12]. Although most of the correlations were derived based on experiments on a specific fluid – most commonly CO_2 or water – the correction factor expressions are very similar to each other. Jackson, therefore, proposed a semi-empirical correlation, according to which the Nusselt number of a variable-property fluid flow is equal to that of the same fluid flow with properties evaluated at the bulk temperature – using a constant property correlation – corrected by two correction factors representing variations of density and specific heat [9,13]:

$$Nu_{VP} = Nu_{CP} \cdot \left(\frac{\widetilde{C}_p}{C_{p,b}}\right)^{\alpha_1} \left(\frac{\rho_w}{\rho_b}\right)^{\alpha_2}, \tag{1}$$

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.052
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Nomenclature

Latin symbols

A	area [m^2]
C	correlation constant [–]
CP	effective wall-temperature correction factor [–]; Eq. (16)
C_p	specific heat [kJ/kg K]
d_h	hydraulic diameter [m]
G	mass velocity [kg/m^2 s]
g	gravity acceleration [m/s^2]
Gr	Grashof number$[-]; = \frac{\rho_b(\rho_b-\rho_w)\cdot g\cdot d_h^3}{\mu_b}$
h	enthalpy [kJ/kg]
HTC	convective heat transfer coefficient [kW/m^2 K]
i	data point index [–]
L	plate length [m]
m, n	correlation exponents [–]
$\dot{m}$	mass flow rate [kg/s]
N	total number of data points [–]
Nu	Nusselt number$[-]; = \frac{\mathrm{HTC} d_h}{\lambda_b}$
Pr	Prandtl number$[-]; = \frac{\mu C_P}{\lambda}$
Q	heat transfer power [kW]
Re	Reynolds number$[-]; = \frac{G\cdot d_h}{\mu_b}$
Ri	Richardson number$[-]; = \frac{Gr}{Re}$
S	standard deviation [–]
T	temperature [°C]
t	student's statistical factor [–];
TC	thermal capacity [kJ/s K]; $(= \dot{m} \cdot C_P)$
U	overall heat transfer coefficient [kW/m^2 K]
x	coordinate in flow direction [m]

Greek symbols

$\alpha_{1,2}$	correlation exponents [–]
β	corrugation angle [°]
γ	channel inclination angle [°]
ϵ	plate thickness [m]
λ	thermal conductivity [W/m K]
μ	viscosity [kg/m s]
ρ	density [kg/m^3]

Subscripts

b	bulk
CP	constant property
f, f'	fluid index
G	Ethylene Glycol
HT	heat transfer
i	data point index
in	inlet
$mean$	mean value
out	outlet
$plate$	plate
R	refrigerant
VP	variable property
w	wall

Superscripts

$(corr)$	correlation
(exp)	experimental

Abbreviations

HTC	heat transfer coefficient
LMTD	log mean temperature difference
NWC	not wall-temperature corrected
PTHE	plate type heat exchanger
QGECE	Queensland Geothermal Energy Centre of Excellence
THE	test heat exchanger
WC	wall-temperature corrected

where $\widetilde{C}_p = \left(\int_{T_w}^{T_b} C_p dT\right)/(T_b - T_w)$. Exponents α_1 and α_2 were suggested to be equal to the values used in correlation of Krasnoshchekov and Protopopov [10], which are variables themselves. In a simpler version of their correlation, Jackson and Hall [9] proposed constant values of 0.5 and 0.3 for α_1 and α_2, respectively.

A correlation of kind Eq. (1), however, may not be adequate to predict heat transfer to or from a supercritical fluid flow. In such a fluid flow, buoyancy force may affect the flow field in a range of Reynolds number where buoyancy is negligible in typical fluid flows. Most notable occurrence of this phenomenon is reported for turbulent heat transfer in vertical pipes. It has been observed that in such flows, with an increase in buoyancy forces, heat transfer is impaired, for upward flow direction, and is enhanced for downward flow direction [14–16]. For a laminar flow the converse is true. The reason is explained as the deformation of velocity profile due to the effect of buoyancy force leading to a reduction or enhancement of shear stress (depending on the flow direction) in a region of flow where turbulence production is concentrated. Such a change in the level of turbulence production is reflected by a change in the local heat transfer coefficient, which is highly sensitive to the amount of turbulence diffusivity. A detailed description of the underlying physics can be found in [17–20]. One would expect this phenomenon be geometry-dependent but as all above-mentioned references studied supercritical fluid flow through vertical pipes, it is hard to extend use of the existing experimental results for plate heat exchangers. Recently, Forooghi and Hooman, have reported numerical studies of this phenomenon for inclined pipes [21], and corrugated channels [22], which would be specifically useful in the study of plate heat exchangers. This issue will be discussed in Section 3.3.

A number of experimental researches on heat transfer of supercritical fluids in vertical and horizontal ducts have been published in the past decades. Watts and Chou [15] measured heat transfer coefficient of heated supercritical water flowing in vertical pipes, and developed an empirical correlation. Their correlation accounts for both physical effects discussed above (wall-to-bulk property variation and buoyancy). More recently, a similar correlation was developed by Bae and co-workers based on extensive experiments they carried out on heated supercritical CO$_2$ in vertical pipes and annuli [16,23,24]. As mentioned before, although the correlations are developed for different fluids, the suggested correction factors are fairly similar and indicate on generality of the analysis. Jiang et al. [25,26] and Kim and Kim [27] also performed experiments on supercritical heat transfer in vertical pipes under heating condition to provide further evidence on the effect of property variation on heat transfer coefficient. Liao and Zhao [28] studied a similar problem in horizontal tubes with diameters between 0.5 and 2.16 mm, and reported the influence of buoyancy in these tubes. A number of reports are available in the literature for heat transfer of supercritical fluids flowing in horizontal tubes or tube bundles being cooled by another fluid flowing outside tubes [12,29,30]. These reports mostly concerned about finding correction factors

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