International Journal of Heat and Mass Transfer 90 (2015) 878–893

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Local vs global heat transfer and flow analysis of hydrocarbon complete condensation in plate heat exchanger based on infrared thermography

K. Sarraf*, S. Launay, G. El Achkar, L. Tadrist

Aix-Marseille Université, CNRS, IUSTI UMR 7343, Technopôle de Château-Gombert, 5 rue Enrico Fermi, 13453 Marseille cedex 13, France

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 30 June 2015
Accepted 7 July 2015

Keywords:
Two-phase flow
Condensation
Pressure drop
Heat transfer
Complex geometry
Brazed plates heat exchanger
n-Pentane
Experiment
Infrared thermography
Flow zones

ABSTRACT

Plate heat exchangers (PHE), compact and energy-efficient, are used as condensers in various industrial applications to recover and recycle heat energy. The condenser optimization still represents a challenge. Due to complex thermo-hydraulic couplings inside three-dimensional PHE geometry, most of the literature studies are correlatives based on hypothesis as uniform heat flux or heat transfer coefficient along the condenser. In this article, some new information on the analysis of condensation heat transfer along the PHE is highlighted. The experimental study focuses on complete condensation of saturated pentane inside a PHE of 4.4 mm hydraulic diameter placed vertically with a descending flow of the refrigerant. The global and local thermo-hydraulic characteristics, as the vapor quality, the heat flux density and the heat transfer coefficient, were identified along the PHE based on the infrared thermography, and the effect of mass flux, between 9 and 30 kg m^{-2} s^{-1}, on these characteristics is analysed. The results show a significant variation, of the heat transfer coefficient and the heat flux density, between the inlet and the outlet of the condensation region for most of the mass fluxes. In our operating range, the heat flux rate decreases till 400% between the PHE inlet and outlet, while the condensation heat transfer coefficient decreases by 5–10 times. The PHE mean heat transfer coefficients, calculated from the local values are then 10–20% higher than the ones calculated from the literature assumption of uniform heat fluxes or the assumption of constant heat transfer coefficient. Moreover, the variation of the mean heat transfer coefficient with pentane mass flux allowed the identification of two condensation regimes, from gravity mode to a mix gravity/convection mode, with a transition limit around 15 kg m^{-2} s^{-1}. Condensation flow analysis was conducted based on pressure drop measurements and calculations. Hence the global pressure drop measured experimentally and the local profile deduced from infrared images, are compared to the results obtained by models from the literature. The comparison shows that the homogeneous model and the Lockhart–Martinelli (1949)'s model predict with good agreement the experimental results.

1. Introduction

The brazed plate heat exchangers (BPHE) consist of a set of plates with corrugated surface stacked the one on the other. Thus, each two adjacent plates form a channel of complex three-dimensional fluidic structure. Initially used for heat transfers in single-phase flows, this type of heat exchanger has subsequently been implemented for applications with phase change without any real modification in its geometry. One reason is the difficulty to approach the thermo-hydraulic behavior analysis inside such a complex geometry [1]. Two main categories of studies conducted on the convective condensation inside PHE are available in the literature: 1/ the studies pre-conditioning the vapor quality at the heat exchanger inlet and the exchanged heat flux density allowing the control of the vapor quality variation of 0.1 or 0.2 in the heat exchanger; and 2/ the studies carried out on the partial or complete condensation inside the heat exchanger and leading to predictive correlations. In both categories of studies, the effects of the exchanged heat flux density, the mass velocity and the saturation temperature of the working fluid were highlighted. Nevertheless, the studies implementing specific metrologies for the determination of the vapor quality variation along the heat exchanger are few so far.

We present hereafter some significant observations on condensation characteristics inside PHE deduced from the various approaches of the literature. Based on the first category of studies, Yan et al. [2] studied the convective condensation of the fluid R134a inside a BPHE, of corrugation amplitude 3.3 mm, corrugation pitch 10 mm and chevron inclination angle 60°. The vapor

---

* Corresponding author.
E-mail address: kifah.sarraf@hotmail.com (K. Sarraf).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.036
0017-9310/

Nomenclature

A	heat transfer area, m^2
b	channel spacing or corrugation amplitude, m
Cp	specific heat capacity, ($J\,kg^{-1}\,K^{-1}$)
D_h	hydraulic diameter, m
e	plate thickness, m
Fc	correction factor
f	friction coefficient
g	acceleration of gravity, ($m\,s^{-2}$)
G	mass flux or Mass velocity, $kg\,m^{-2}\,s^{-1}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
L	length, m
L_v	latent heat of vaporization, ($J\,kg^{-1}$)
LMTD	logarithmic mean temperature difference, °C
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
Nu	Nusselt number, $Nu = h.D_h/\lambda$
p	pressure, (Pa)
P_c	chevron pitch, m
Pr	Prandtl number, $Pr = \mu.Cp.\lambda^{-1}$
$\dot{Q}$	heat power, (W)
q	heat flux density, ($kW\,m^{-2}$)
Re	Reynolds number, $Re = G.Dh.\mu^{-1}$
S	flow cross section, m^2
T	temperature, (°C)
U	global heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
W	width of the plate, m
x	vapour quality
y	horizontal position in the BHPE, (m)
z	vertical position in the BHPE, (m)
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, °

Subscripts

BPHE	brazed plate heat exchanger
cond	condensation
desup	desuperheating
eq	equivalent
f	friction
i	inlet
IR	infrared
l	liquid
m	mean value
o	outlet
p	plate
r	refrigerant
sat	saturation
sub	subcooling
tot	total value
tp	two-phase parameter
tr	local heat transfer area
v	vapor
w	water

quality at the BPHE inlet was accurately controlled using a pre-evaporator. By varying the vapor quality at the inlet with fixed vapor quality variation of 0.1 between the BPHE inlet and outlet, the authors finally proposed a condensation heat transfer correlation of Dittus–Boelter type. Kuo et al. [3] carried out a study on an identical characteristic BPHE using the R410A as the working fluid. For the same ranges of mass velocity and heat flux density, the results show an enhancement of the thermo-hydraulic performances with respect to the R134a. These results have conducted to a new heat transfer correlation.

The effect of the chevron inclination angle on the BPHE performances was studied by Han et al. [4] using the fluid R410A. Three different geometries were tested having the same corrugation amplitude of 2.55 mm, with chevron inclination angles of 45°, 55° and 70°, and corrugation pitches of 4.9, 5.2 and 7 mm, respectively. The results show an increase of the mean internal heat transfer coefficient and the pressure drop with the increase of the chevron inclination angle and the mass flux. With a maximum relative deviation of 30%, the correlation developed by Yan et al. [2] predicts well the experimental data of Han et al. [4] for the BPHE of chevron inclination angles of 55° and 70°, while the correlation widely over-estimates the experimental data for the BPHE of chevron inclination angle of 45°.

The results of Yan et al. [2], Kuo et al. [3] and Han et al. [4] show quite similar trend with an almost linear increase of the heat transfer coefficient $h(x_m)$ versus mean vapor quality x_m (for $x_m > 0.2$). In the operating range, $h(x_m)$ increases with the mass flux and the heat flux density regardless of x_m, and the maximum heat transfer coefficient ratio between the high and low vapor qualities is between 1.2 and 1.7. Otherwise, the results show relatively insensitive effect of the saturation pressure on the heat exchanger performances (except [4]).

In addition to the studies conducted on the convective condensation with limited vapor quality variation, many authors studied the whole phenomenon in the heat exchanger. Djordjevic et al. [5] studied the complete condensation of the fluid R134a inside a BPHE of corrugation amplitude 3.2 mm, corrugation pitch 12 mm and chevron inclination angle 63.26°. They measured the wall and coolant temperatures in order to deduce some local parameters, as the liquid and vapor phase distribution and the vapor quality. The authors show a quite linear increase of the condensation heat transfer coefficient with the mean vapor quality and the increase of the mass flow rate and the heat flux induces a better condensation heat transfer. Shi et al. [6] conducted a similar study to that of [5], but for different boundary conditions, allowing thus to extend the experimental database. The result trends are almost similar at the exception of the heat transfer coefficient for the highest vapor quality. They have established a heat transfer correlation basing on the Shah's [7] correlation, which was adapted to their experimental data. Note that in both studies, [5,6], the experiments were achieved with a vapor superheating at the BPHE inlet of 25 K and a liquid sub-cooling at the BPHE outlet of 4 K, and this point is not discussed in the papers.

Jokar et al. [8] and [9] studied the complete condensation of the fluid R134a inside three plate heat exchangers consisted of 30, 40 and 54 plates, and having a corrugation amplitude of 2 mm and a chevron inclination angle of 60°. The authors proposed a correlation for heat transfers, involving the difference between the saturation and the wall temperatures, based on the correlation developed by Wang et al. [10]. According to the authors, the mean heat transfer coefficient increases significantly with the decrease of the temperature difference (low heat flux densities), for temperature differences lower than 2 K, indicating thus a gravitational condensation regime, whereas for great temperature differences