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Analysis of enhanced vapor desuperheating during condensation inside a plate heat exchanger

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ABSTRACT

The presence of superheated vapor in condenser heat exchanger is common in many applications, as heat pump or organic Rankine cycle. Rarely taken into consideration in the literature of plate heat exchangers, the present article focuses on the influence of the superheated vapor on the condensation characteristics of an organic fluid (pentane) in a brazed plate heat exchanger (BPHE). A specific experimental approach has been developed for this objective. The tested BPHE prototype consists of 2 channels with chevron angle of 55°, and a hydraulic diameter equal to 4.4 mm. The effect of the pentane mass flux, 9–30 kg m^{-2} s^{-1}, and the vapor superheat, 5–25 K, at a mean constant saturation temperature of 36.5 °C (1.029 bars), on the global and local thermo-hydraulic characteristics has been identified. An infrared (IR) metrology is used to distinguish the different fluid state distributions, which are representative of various heat transfers along the BPHE. The IR thermography shows a significant impact of the vapor superheat, on the fluid distribution at the channel inlet depending on the mass flux.

Comparing the results with vapor superheat going from 5 to 25 K, we note: 1/an increase of the heat transfer coefficient reaching 70% for the lowest mass flux; 2/an increase of the pressure drop, whose rate (18%) is equivalent to the increase of the heat transfer coefficient for the larger mass fluxes. Superheated vapor is therefore very favorable to heat transfer for condensation in the gravity mode compared to the convective one. Based on experimental measurements and observations, various vapor desuperheating scenarios are tested. The analysis justifies that the suitable desuperheating scenario involves condensation from superheated vapor directly from the channel inlet with liquid vaporization from the condensate film.

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.

BPHE consists of a set of plates with corrugated surface stacked the one on the other. Thus, each two adjacent plates form a corrugated 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]. For heat pump or ORC (Organic Rankine Cycle) applications, the vapor at the heat exchanger inlet is generally superheated. In certain cases, high levels of superheating that can reach 30 K are applied. Thus, it seems essential and of great interest to investigate the condensation phenomenon with superheated vapor at the condenser inlet. Nevertheless, the effect of the superheated vapor on the thermo-hydraulic behavior of the BPHE in condenser mode is rarely taken into consideration and is little presented in the literature.

Jokar et al. (2004, 2006) [2], and [3], and Djordjevic et al. [4] did not study specifically the effect of the vapor superheat on condensation heat transfer, but the experimental conditions of their studies present vapor superheats higher than 25 K at the condenser inlet. Djordjevic et al. [4] studied the complete condensation of the fluid R134a inside a BPHE of 3.2 mm

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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_c	Correction factor
f	Friction coefficient
g	Acceleration of gravity, m s^{-2}
G	Mass flux or Mass velocity, kg m^{-2} s^{-1}
h, HTC	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}
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, $Re = G.D_h.\mu^{-1}$
T	Temperature, °C
U	Global heat transfer coefficient, W m^{-2} K^{-1}
W	Width of the plate, m
x	Vapor mass fraction
y	Horizontal position in the BHPE, m
z	Vertical position in the BHPE, m
ΔP	Pressure drop, Pa
ΔT	Temperature difference, K

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

a	ambient air
$BPHE$	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
sup	superheated vapor
$static$	Relative to static pressure drop
tot	total value
tp	two-phase parameter
tr	heat transfer area
v	vapor
w	water
z	relative to local position along vertical z axis

corrugation amplitude, 12 mm corrugation pitch, and 63° chevron inclination angle. Some local parameters, as the fluid temperature distribution and the vapor mass fraction, are deduced from the wall and coolant temperature measurements. Based on the presented results, it looks like that 20% of the plate surface is used to desuperheat the vapor by 25 K, while a simple calculation of the ratio between the sensible heat to the total heat (sensible plus latent) gives 14%. In consequence, the vapor desuperheating phenomena seems to degrade the global heat transfer in PHE. Jokar et al. (2004, 2006) [2,3], studied the complete condensation of the fluid R134a superheated vapor inside three plate heat exchangers consisting of 30, 40 and 54 plates. The tested BPHEs have corrugation amplitude of 2 mm and chevron inclination angle of 60°. In order to study the mean heat transfer coefficient and the pressure drop in the two-phase (condensation) zone, Jokar et al. (2006) [3] divided the BPHE surface into three zones of heat transfer: 1/the vapor desuperheating zone, 2/the condensation zone and 3/the liquid subcooling zone. By this approach, the authors have considered the vapor desuperheating based on single-phase convective heat transfer before condensing.

Longo (2008, 2009 and 2011) [5–7], and Mancin et al. (2012, 2013) [8,9], have specifically investigated the influence of the superheated vapor on the BPHE global heat transfer.

Longo (2008, 2009 and 2011) [5–7], studied the complete condensation phenomenon of the R134a, the R410A, the R236fa, and three pure fluids, isobutane (HC-600a), propane (HC-290) and propylene (HC-1270) with and without vapor superheating. The studies were conducted with BPHE, of 2 mm corrugation amplitude, 8 mm corrugation pitch, and 65° chevron inclination angle, at mass velocities lower than 41 kg m^{-2} s^{-1}. The mean heat transfer coefficient with superheated vapor (10 K) showed an increase between 8 and 10% compared to that one with the saturated vapor. According to the author, the condensation occurs even if the vapor is superheated as far as the wall temperature is lower than the saturation temperature. Hence, the desuperheating changes the condensation kinetics and reduces the film thickness, which increases the heat transfer coefficient. For mass fluxes higher than 18–20 kg m^{-2} s^{-1}, the experimental results of the mean condensation heat transfer coefficient with superheated vapor were compared to the results of Webb's model [10]. Webb's model overestimates the heat transfer coefficient by 10–20%. It could be noted that Webb's [10] model is developed for condensation with annular flow configuration without liquid entrainment in the vapor phase while the vapor desuperheating is ensured by forced convection of the vapor phase with the liquid film at the wall. The study of Longo (2011) [7] presents no effect of the vapor desuperheating on the pressure drop.

Mancin et al. (2012, 2013) [8,9], studied the partial condensation of R-407c R-410A and R-32 in BPHE (65° of corrugation inclination angle) with vapor mass fraction at the heat exchanger outlet varying between 0 and 0.65. The vapor at the condenser inlet is superheated between 5 and 25 K and the mass flux varied between 15 and 40 kg m^{-2} s^{-1}. The results indicate that the mean heat transfer coefficient increases with the vapor superheating for all the mass fluxes. At a given vapor superheating level, the increase in the heat transfer coefficient is less significant for larger mass fluxes. The increase in the heat transfer coefficient can reach up to 18% for low mass fluxes and for high superheating. In the developed modeling,