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Boiling heat transfer and two-phase pressure drops within compact plate heat exchangers: Experiments and flow visualizations

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ABSTRACT

Infrared (IR) thermography was used to measure the local heat transfer coefficients within two plate heat exchanger geometries. The chevron patterns were machined into polycarbonate and IR transparent calcium fluoride plates, both of which were electrically heated using flexible film heaters at heat fluxes up to 0.8 W cm^{-2}. The test fluid was a refrigerant (HFE7100) at mass fluxes between 25 and 100 kg $\text{m}^{-2}\,\text{s}^{-1}$, and qualities from 0 to 0.9. The apparatus and data reduction technique were validated by comparing the single-phase heat transfer and pressure drop data against the prediction methods from the literature. Adiabatic flow visualizations were conducted to link the flow patterns with the observed heat transfer. The frictional pressure gradient and heat transfer coefficient were compared with available correlations. It was shown that the heat transfer coefficient and the frictional pressure gradient increased with mass flux and quality. The comparison indicated the need for new prediction methods for predicting the local thermal-hydraulic performance over a wide range of operating conditions.

1. Introduction and literature survey

Corrugated plate heat exchangers (PHEs) provide a very compact and efficient method to exchange heat between two fluids. They are low cost, relatively simple to manufacture, and can be disassembled, an advantage for applications where it is required to clean the heat exchanger frequently (e.g. gasketed PHE). PHEs can be optimized by varying geometric parameters to achieve the desired performance, such as length, width, corrugation geometry, number of plates, and flow arrangement. PHEs can be used in two-phase evaporation services where the shear stress between liquid and vapor can induce more turbulence and produce thinner boundary layers.

The geometry of the PHE corrugation pattern is typically characterized by the wavelength of the surface corrugation (λ), amplitude of the surface corrugation (a), and corrugation chevron angle (β). The nomenclature used in this paper to characterize the corrugation patterns is shown in Fig. 1. The wavelength and amplitude of the corrugation are indicated by L and A respectively. The chevron angle is indicated by the letter B and is followed by two numbers since PHEs can be arranged in a mixed configuration resulting in an overall angle which is the average of both plates, e.g., mixing a 60° and 30° plate would result in a 45° arrangement. As an example of the nomenclature, the PHE L3.7A0.5B65-65 would have a corrugation wavelength of 3.7 mm, an amplitude of 0.5 mm, and two plates both having chevron angles of 65°.

A summary of relevant single-phase correlations in PHEs was given by Ayub [1] along with a correlation for two-phase applications based on a vast collection of experimental data (including R22 and ammonia as working fluids). Manglik et al. [2] provided a knowledge base for designing single- and two-phase PHEs. Khan et al. [3] developed a set of correlations for two-phase evaporators with a focus on ammonia as a working fluid that included the effect of chevron angle on the thermal and hydraulic performance. Abu-Khader [4] provided a summary of the single- and two-phase PHE research in recent years.

Only a few groups have performed local measurements in order to obtain local heat transfer coefficients (HTC) within PHEs. Gaiser and Kottke [5] and Stasiek et al. [6] used ammonia absorption and liquid crystal thermography respectively to obtain the local heat transfer in a unit cell with a resolution of 0.2 mm^2. Freund and Kabelac [7] obtained a resolution of 0.5 mm^2 by using temperature oscillation IR thermography within two PHE plates (L12A1.6B63-63). All of these studies were limited to single-phase flow. Quasi local measurements for PHE evaporators were conducted by Djordjevic and Kabelac [8] who used an array of thermocouples in two PHEs (L12A1.6B63-63 and L12A1.6B27-27) to measure the

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Nomenclature

A	abbreviation for the plate corrugation
a	amplitude of the corrugation (m)
B	abbreviation for the chevron angle
b	corrugation pressing depth (m)
c_p	specific heat (J kg^{-1} K^{-1})
D_p	distance between two pressure taps (m)
d	diameter (m)
f	Fanning friction factor
g	gravitational constant, $g = 9.81$ (m s^{-2})
H	specific enthalpy (J kg^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	abbreviation for corrugation pitch
L_P	length of the CaF$_2$ plate (m)
Nu	Nusselt number, $Nu = hd_h/k$
MAE	mean absolute error
$\dot{m}$	mass rate (kg s^{-1})
n	number of data points
P	pressure (Pa)
$\dot{q}''$	heat flux [W/m^2]
$\dot{Q}$	power supplied to the preheater/PHE (W)
Re	Reynolds number, $\mathrm{Re} = G\, d_h/\mu$
s	path length along the corrugation (m)
T	temperature (K)
W_P	width of the CaF$_2$ plate (m)
x	quality
X, Y, Z	coordinates (m)

Greek

β	chevron angle (°)
γ	corrugation aspect ratio
ε	emissivity
φ	surface enlargement factor
λ	wavelength of the corrugation (m)
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
Υ	array of values for MAE

Subscript

a	acceleration
e	equivalent
exp	experimental
f	frictional
g	gravitational
h	hydraulic
i	inlet
l	liquid
lv	liquid to vapor
m	mean
$meas$	measured
o	outlet
pre	predicted
sat	saturation state
tot	total
v	vapor

Acronyms

HTC	heat transfer coefficient
CaF$_2$	calcium fluoride
PHE	plate heat exchanger
TC	thermocouple

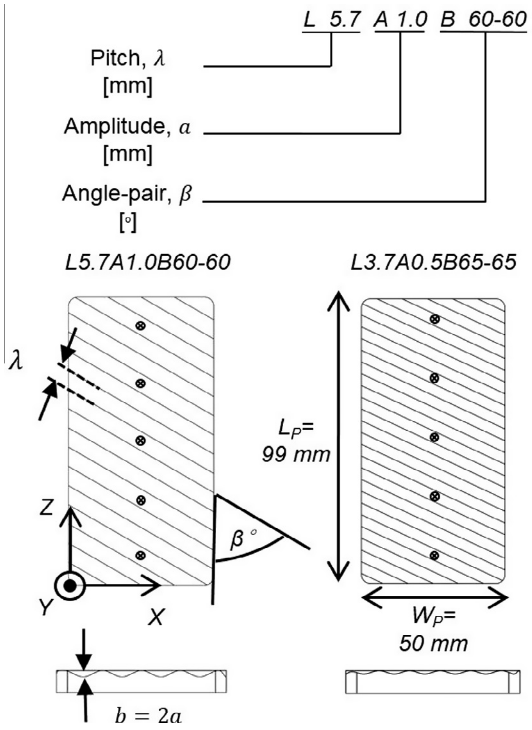

Fig. 1. Schematic of the two plate geometries tested in this study and the location of the thermocouples: (a) test section L5.7A1.0B60-60, (b) test section L3.7A0.5B65-65.

wall and liquid temperatures during boiling of R134a and ammonia. The overall length of the PHE was 0.8 m, meaning they could calculate the local quality and the associated local HTC. They observed, as have other groups, that HTC was independent of the heat flux, but depends heavily on the quality. They also concluded that the HTC increases with mass flux at a given quality, but can decrease with quality at lower mass fluxes when the quality exceeds 0.5. Finally, they compared their data to existing correlations and found that the modified Steiner and Taborek [9] and Danilova et al. [10] correlations best fit their experimental database.

Recently, Vakili-Farahani et al. [11,12] examined the local heat transfer and pressure drop within a PHE channel (L3.7A0.5B65-65, port-to-port length of 228 mm) created by two plates that were electrically heated. The fluid was R245fa. The plates were pressed together by two PVC plates to stabilize and insulate the test section. Six windows along the length of the PHE were machined into the PVC plates allowing the outer surface temperature (and thus the local HTC) to be measured with an IR-camera. Through adiabatic two-phase flow tests, the authors were able to measure the saturation temperature of the refrigerant and thereby calculate the quasi local pressure for each window. They concluded that the two-phase behavior in PHEs is similar to pipe flow, and the flow distributions at the PHE inlet and outlet have a significant effect on the overall thermal and hydraulic performance (this is also supported by Ayub [13]).

Amalfi et al. [14,15] provided a comprehensive literature survey of flow boiling heat transfer and two-phase frictional pressure drops mechanisms within chevron PHEs. In this study, the prediction methods available in the open literature from 1981 until 2014