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Flow boiling in horizontal flattened tubes: Part I – Two-phase frictional pressure drop results and model

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ABSTRACT

Experiments of diabatic two-phase pressure drops in flow boiling were conducted in four horizontal flattened smooth copper tubes with two different heights of 2 and 3 mm. The equivalent diameters of the flat tubes are 8.6, 7.17, 6.25, and 5.3 mm. The working fluids are R22 and R410A, respectively. The test conditions are: mass velocities from 150 to 500 kg/m^2 s, heat fluxes from 6 to 40 kW/m^2 and saturation temperature of 5 °C (reduced pressures p_r are 0.12 for R22 and 0.19 for R410A). The experimental results of two-phase pressure drops are presented and analyzed. Furthermore, the predicted two-phase frictional pressure drops by the flow pattern based two-phase pressure drop model of Moreno Quibén and Thome [J. Moreno Quibén, J.R. Thome, Flow pattern based two-phase frictional pressure drop model for horizontal tubes, Part I: Diabatic and adiabatic experimental study, Int. J. Heat Fluid Flow 28 (2007) 1049–1059; J. Moreno Quibén, J.R. Thome, Flow pattern based two-phase frictional pressure drop model for horizontal tubes, Part II: New phenomenological model, Int. J. Heat Fluid Flow 28 (2007) 1060–1072] using the equivalent diameters were compared to the experimental data. The model, however, underpredicts the flattened tube two-phase frictional pressure drop data. Therefore, correction to the annular flow friction factor was proposed for the flattened tubes and now the method predicts 83.7% of the flattened tube pressure drop data within ±30%. The model is applicable to the flattened tubes in the test condition range in the present study. Extension of the model to other conditions should be verified with experimental data.

1. Introduction

Flattened tube heat exchangers have a potential use in a wide range of industrial applications: air-conditioning, heat pump and refrigeration systems, automotive radiators, and fuel cell engines, etc. Compared to a circular tube, a flattened tube has a higher surface-to-cross-sectional flow area ratio, which may be used to enhance the heat transfer rate and increase the compactness of heat exchangers. For example, flattened heat transfer tubes can greatly reduce the refrigerant charge in direct-expansion evaporators and condensers and thus provide more compact heat exchanger design. Furthermore, potential advantages of flattened tube profiles are reduced air-side pressure drop and increased air-side heat transfer. Flattened heat transfer tubes in the present study refer to plain round tubes that have been extruded flat on top and bottom and remain round at the two ends as shown by the photo in Fig. 1.

So far, there are very limited studies on two-phase flow and heat transfer in flattened tubes in the literature. Wilson et al. [1] investigated refrigerant charge, two-phase pressure drop and heat transfer during condensation of refrigerants R134a and R410A in several flattened tubes. Their results show significant reduction in refrigerant charge as a tube is flattened. They also indicate enhancement of condensation heat transfer and an increase of pressure drop in the flattened tubes. Krishnaswamy et al. [2] investigated condensation heat transfer of steam-air mixtures in a horizontal flattened tube. They also proposed a simple heat transfer model. Their model predicts their data satisfactorily. Koyama et al. [3] conducted experiments on two-phase pressure drop and heat transfer of condensation of refrigerant R134a in multi-port extruded flattened tubes with hydraulic diameters of 1.114 and 0.807 mm. They concluded that to establish a prediction method of the pressure drop and heat transfer characteristics of pure refrigerant condensing in a small diameter tube, more experimental data for small diameter tubes should be investigated by considering the following terms: (1) flow patterns, (2) the effect of tube diameter, and (3) the interaction effect among the vapor shear stress and the gravitational acceleration and the surface tension. As for flow boiling in flattened tubes, however, there is no study available in the

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Nomenclature

A	cross-sectional area of flow channel (m^2)
C	correction factor
c_p	specific heat at constant pressure (J/kg K)
D	internal tube diameter (m)
$\frac{di_{wat}}{dz}$	water enthalpy change over distance, dz (J/kg)/m
f	friction factor
G	total vapor and liquid two-phase mass flux (kg/m^2 s)
g	gravitational acceleration (=9.81 m/s^2)
H	height of flattened tube (m)
i	enthalpy (J/kg)
i_{LV}	latent heat of vaporization (J/kg)
L	tube length (m)
m	mass flow rate (kg/s)
N	number of data points
P	perimeter of test tube (m)
p	pressure (bar)
p_r	reduced pressure ($=p/p_{crit}$)
Q	transferred heat (W)
q	heat flux (W/m^2)
Re_V	vapor phase Reynolds number ($=GxD_e/\mu_V\varepsilon$)
T	temperature (K)
t	tube wall thickness (m)
u	mean velocity (m/s)
W	width of flattened tube (m)
We_L	liquid Weber number ($=\rho_L u_L^2 D_e/\sigma$)
x	vapor quality
z	distance from the tube inlet (m)

Greeks

Δp	pressure drop (Pa)
δ	liquid film thickness (m)
ε	cross-sectional vapor void fraction
μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m); standard deviation (%)
ξ_i	relative error (%)
$\bar{\xi}$	average error (%)
$\lvert\bar{\xi}\rvert$	mean error (%)

Subscripts

A	annular flow
crit	critical
e	equivalent
exp	experimental
ext	external
f	frictional
h	hydraulic
i	data point
in	inlet
L	liquid
LV	liquid–vapor
m	momentum
out	outlet
pred	predicted
preheater	preheater
ref	refrigerant
s	static
sat	saturation
t	total
V	vapor
wat	water
wet	wetted

literature. In order to design a flattened tube evaporator, it is important to understand and predict the two-phase flow and flow boiling heat transfer characteristics inside horizontal flattened tubes. In particular, in the case of a flattened tube having a very small height between the top and bottom, the confinement of such a tube will greatly affect two-phase pressure drop and heat transfer characteristics [4–7]. In the present study, experimental investigation of two-phase pressure drops and flow boiling heat transfer with refrigerants R22 and R410A in four flattened smooth copper tubes with 2 and 3 mm heights is performed. In Part I, experimental results of two-phase frictional pressure drops are presented and analyzed. Furthermore, a modified flow pattern based phenomenological two-phase flow frictional pressure drop model for these flattened tubes is presented. Experimental investigation of flow boiling heat transfer characteristics of these fluids and an updated flow pattern based flow boiling heat transfer model are presented in Part II.

Flow patterns are very important in understanding the very complex two-phase flow phenomena and heat transfer trends in flow boiling [8]. As the predictions of two-phase flow frictional pressure drops with the leading methods often cause errors of more than 50% [9], efforts are increasingly being made to improve the accuracy of two-phase flow pressure drop predictions. In addition, the empirical two-phase pressure drop prediction methods do not contain any flow pattern information, which is intrinsically related to the two-phase frictional pressure drop. As opposed to such completely empirical two-phase pressure drop methods, a flow pattern based phenomenological model relating the flow patterns to the corresponding two-phase flow pressure drops is a more promising approach [8,9]. A new flow pattern based phenomenological model of two-phase frictional pressure drops was recently developed by Moreno Quibén and Thome [10–12]. The model physically respects the two-phase flow structure of the various flow patterns while maintaining a degree of simplicity as well.

Fig. 1. Photograph of round and flattened tubes.