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Experimental study on condensation and evaporation flow inside horizontal three dimensional enhanced tubes

Wei Li [a,*], JingXiang Chen [a], Hua Zhu [a], David J. Kukulka [b], W.J. Minkowycz [c]

[a] Department of Energy Engineering, Zhejiang University, Hangzhou 310027, China
[b] State University of New York College at Buffalo, 1300 Elmwood Avenue Buffalo, New York 14222, USA
[c] Department of Mechanical and Industrial Engineering (M/C 251), University of Illinois at Chicago, 842 West Taylor Street, Room 2049 ERF, Chicago, IL 60607-7022, USA

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ABSTRACT

Experimental investigations of tube side condensation and evaporation in two 3-D enhanced heat transfer (2EHT) tubes were compared to the performance of a smooth surface copper tube. The equivalent outer diameter of all the tubes was 12.7 mm with an inner diameter of 11.5 mm. Both the inner and outer surfaces of the 2EHT tubes are enhanced by longitudinal grooves with a background pattern made up by an array of dimples/embossments. Experimental runs were performed using R410A as the working fluid, over the quality range of 0.2–0.9. For evaporation, the heat transfer coefficient ratio (compares the heat transfer coefficient of the enhanced tube to that of a smooth tube) of the 2EHT tubes is 1.11–1.43 (with an enhanced surface area ratio of 1.03) for mass flux rate that ranges from 80 to 200 kg/m^2 s. For condensation, the heat transfer coefficient ratio range is 1.1–1.16 (with an enhanced surface area ratio of 1.03) for mass flux that ranges from 80 to 260 kg/m^2 s. Frictional pressure drop values for the 2EHT tubes are very similar to each other. Heat transfer enhancement in the 2EHT tubes is mainly due to the dimples and grooves in the inner surface that create an increased surface area and interfacial turbulence; producing higher heat flux from wall to working fluid, flow separation, and secondary flows. A comparison was performed to evaluate the enhancement effect of the 2EHT tubes using a defined performance factor and this indicates that the 2EHT tubes provides a better heat transfer coefficient under evaporation conditions.

1. Introduction

Two-phase flow heat exchangers are commonly used in a variety of industries (HVAC, refrigeration, process, etc.); it is often desired to improve the heat transfer coefficient in those heat exchangers by utilizing enhanced tubes that can increase the heat transfer coefficient (HTC) and increase performance. Understanding of the heat transfer and pressure drop characteristics of these enhanced heat transfer tubes is required in order to implement them in high performance designs. Although there have been previous works that have examined this problem, more studies are needed since improved surface enhancement methods have been developed that produce new types of tubes.

Previous studies [1–9] have been performed to evaluate the tube side heat transfer and pressure drop characteristics of horizontal micro-fin tubes in two-phase flow field. Webb and Kim [1] summarized their and many previous authors' data results, and proposed many principles and correlations of enhanced heat transfer which can be applied to different situations including tube side condensation and evaporation with different tube geometry. Cavallini et al. [2] presented a detailed review of condensation heat transfer in smooth and enhanced tubes. They discussed the limitations of using previously reported semi-empirical correlations that are commonly used and accepted for some enhanced tubes to predict the performance of all enhanced or non-circular tubes; inaccurate results may be predicted when these correlations are used to predict the heat transfer performance of some brand new applications, such as flattened tubes and the newly designed three dimensional enhanced heat transfer tubes (2EHT) in this study. Rollmann et al. [3] studied the flow boiling of R407C and R410A in a horizontal micro-fin tube with saturation temperature ranging from −30 °C to 10 °C; heat flux values ranging from 1.0 to 20 kW/m^2; mass flux values ranging from 25 to 300 kg/m^2 s; with a vapor quality that ranged between 0.1 and 1.0. A new method to derive the heat transfer coefficient was presented in Wojtan et al. [4,5]; Olivier et al. [6] investigated tube side condensation of several tubes (smooth tube, helical micro-fin tube, and herringbone tube) using various refrigerants (R22, R134A, R407C). The result showed that x_{AI} (a transform criterion of flow pattern from annular flow to intermittent flow) of the herringbone tube was much smaller than a smooth tube; and for a micro-fin tube it decreased slightly. Compared with a smooth tube, the pressure drop of the herringbone tube was 80% higher; while only 27% higher than a micro-fin tube. The author's group [7–9] intensively studied the heat

* Corresponding author.
E-mail address: weili96@zju.edu.cn (W. Li).

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Nomenclature

A_i	inner surface area of test tube, m^2
A_o	outer surface area of test tube, m^2
c_p	specific heat, J kg^{-1} K^{-1}
d_i	inner diameter of test tube, m
d_o	outer diameter of test tube, m
d_h	hydraulic diameter, $d_h = D_i - d_o$, m
D_i	inner diameter of outer tube, m
f	Fanning friction factor
Fr	Froude number
g	gravitational acceleration, m s^{-2}
G	mass flux, kg/m^2 s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
h_{lv}	latent heat of vaporization, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	tube length, m
LMTD	logarithmic mean temperature, K
P	pressure, kPa
PF	performance evaluation factor
Pr	Prandtl number
Q	heat transfer rate, W
Re	Reynolds number
T	temperature, K
V	voltage, V
I	electric current, A
W	mass flow rate, kg s^{-1}
We	Weber number
x	vapor quality
X_{tt}	Martinelli parameter

Greek symbols

ΔP	pressure drop, kPa
λ	loss efficient of electricity power
μ	dynamic viscosity, Pa s
σ	surface tension, N m^{-1}
ρ	density, kg m^{-3}
ΔP_m	Pressure drop due to density change, kPa
ε	void fraction

Subscripts

exp	experimental
pre	preheating section
sens	sensible heat
lat	latent heat
wall	wall parameters
ref	refrigerant
sat	saturated
in	inlet
out	outlet
w	water
l	liquid phase
v	vapor phase
i	inner tube surface based parameters
o	outer tube surface based parameters
lv	liquid phase to vapor phase
EHT	enhanced tube
m	momentum
SL	sudden enlarge
SC	sudden contraction
ONB	onset of nucleate boiling
s	smooth tube

transfer characteristics of evaporation in micro/mini-channels. Li and Wu [7] presented a more accurate correlation for evaporative HTC by taking the combined effects (a non-dimensional parameter Bo$\cdot Re_l^{0.36}$) of liquid Reynolds number and Bond number into account, in the regime of Re_l < 2000 and Bo < 3. Subsequently, a new criterion for adiabatic two-phase pressure drop is also established by using Bound number and liquid Reynolds number to modify the Chisholm parameter in Li and Wu [8]; and the Chisholm parameter was distinguished into three ranges by the Bond number; when Bo < 1.5, the surface tension dominates the pressure drop; when Bo > 11, surface tension can be ignored; and when 1.5 < Bo < 11, surface tension, inertia and viscous forces are all important in the micro/mini-channels. Wu and Li [9] proposed a saturated critical heat flux correlation by combining the boiling number, length-to-diameter ratio and outlet quantity, which can predicts almost 97% of non-aqueous data (except R12 data) and 94% of the water data within the ±30% error band. Kattan et al. [10] updated the flow pattern map by editing and redefining the transition curves. Methods to distinguish different flow regimes are provided in Kattan et al. [10]. Liebenberg and Meyer [11,12] observed the refrigerant condensation flow regimes in enhanced tubes and evaluated the effect of enhancement on heat transfer coefficients and pressure drops for mass flux values that ranged from 300 to 800 kg/m^2 s; at a saturation temperature 313.15 K. Comparing condensation conditions of the enhanced tubes evaluated in [11,12] with smooth and micro-fin tubes, the two enhanced tubes produced an earlier transition from annular flow to intermittent flow. Moreover, the heat transfer coefficient (HTC) of the enhanced tubes is approximately 1.7 times of the smooth tube; with an 80% increase in pressure drop. A detailed review of condensation heat transfer and pressure drop characteristics of enhanced tubes are also presented by Dalkilic and Wongwises [13].

Only recently have condensation and evaporation empirical models been developed for single enhancement unit in tube side, such as rough surfaces, extended surfaces, and displaced insert swirl flow. Gregorig [14] discussed surface tension effects on 2-D enhanced condensation tubes, all models developed in the current study begin to take surface tension into account. Belghazi et al. [15] developed a theoretical condensation model for a complicated 3-D tube; whose geometry changes in both the axial and circumferential directions.

The author's group [16] conducted studies to evaluate the tube side convective condensation and evaporation heat transfer performance using three different refrigerants in three equivalent diameter copper tubes (a smooth tube, a herringbone tube and a 3-D 1EHT tube; with inner diameter 11.5 mm). Results indicated that the condensation heat transfer of the herringbone tube is 2–3 times larger than that of smooth tube and condensation heat transfer coefficient of the 1EHT tube is 1.3–1.95 times that of the smooth tube. Better performance of herringbone tube than EHT tube is mainly because of the larger surface area increase and efficiency of liquid drain due to the surface tension produced by the micro-channels between different fins. While for evaporation, their results indicated that EHT tube provided the best evaporation heat transfer coefficient (HTC); with the herringbone tube only producing a slightly higher evaporation HTC when compared to a smooth tube. Unlike the 1EHT tube in [16], heat transfer surface area enhancement ratio of 2EHT tubes tested in this study is much smaller. Vicente et al. [17] studied the heat transfer and friction factors of ten helically dimpled tubes and presented five performance evaluation criteria. However, they did not study the heat transfer and pressure drop performance under two phase flow conditions. In general, literature lacks two-phase flow studies and correlations to predict the heat transfer coefficient and pressure gradient for many newly developed enhanced tubes; currently there is no explanation of the physical mechanism of the 2EHT tubes evaluated in this study.

The two tubes (2EHT-1 and 2EHT-2) evaluated in this study are 3-D enhanced tubes. They have different configurations than previously investigated enhanced heat transfer tubes and have different surface characteristics from those Vipertex 1EHT tubes investigated in previous studies [17–19]. As shown in Fig. 1, the 2EHT tube surfaces are more of a