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Local convective condensation heat transfer in horizontal double-layer three-dimensional dimple-grooved tubes

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ABSTRACT

An experimental study on local condensation heat transfer characteristics in two three-dimensional double-layer dimple-grooved tubes (2EHT tubes) and a smooth tube is performed using refrigerant of R410A. The smooth tube has an outer diameter of 12.7 mm and inner diameter of 11.07 mm. The 2EHT tubes have a nominal outer diameter of 12.7 mm and wall thickness of 0.8 mm. The enhanced surface areas of two 2EHT tubes are 1.02 and 1.03 times of the smooth tube, respectively. The present experiments are conducted to measure the local wall temperature when the mass flux ranges from 65 kg/(m^2·s) to 210 kg/(m^2·s), heat flux ranges from 10 kW/m^2 to 35 kW/m^2 and vapor quality ranges from 0.9 to 0.1. The saturation temperature is maintained at 40 °C. 248 experimental HTC data points are obtained and compared with six correlations. The results show that the measured local HTCs increase with increasing mass fluxes and decrease with increasing heat fluxes, and that the present correlations have a good predictability with smooth tube but cannot predict the HTC of 2EHT tubes. The proposed condensation correlation for 2EHT tubes is validated, and it predicts all experimental points within an error band of ±30%, and 94.25% of all test points within an error band of ±20%.

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1. Introduction

High efficient and compact condensers are common devices in many industrial applications and family equipment such as refrigeration, air conditioning and other power plants. In this regard, the technology of fabricating heat transfer enhanced tube and surface has been developed rapidly. These enhanced tubes and surfaces can be categorized into two groups due to the geometry size of roughness. One is two-dimensional enhancement (micro-fin, herringbone, corrugated and surface coating tubes), the other is three dimensional enhancement (dimpled, helically dimpled and groove-dimpled tubes). The type and geometry size of roughness have a great impact on the heat transfer coefficient (HTC). Zhao et al. [1] reported that the three-dimensional dimple-grooved tubes surface structure was more suitable for the condensing tubes with lower thermal conductivity, and that condensation heat transfer of R404A was more sensitive to the surface structure and conductivity than that of R134a. Publications on tube side flow condensation with different types and sizes of roughness were summarized as follows:

Micro-fin tube served effectively as the first type of enhanced tube in two phase flow area and caught the most researcher's attention. Jung et al. [2] experimentally studied the R22, R134a, R407C and R410A condensation inside a micro-fin tube with outer diameter of 9.52 mm and an equivalent smooth tube. The results showed that micro-fin tube provided 2–3 times higher heat transfer coefficient (HTC) than that of smooth tube, and the heat transfer enhancement factor decreased with increasing mass flux. Kim and Shin [3] investigated condensation performance inside seven micro-fin tubes with same outer diameter of 9.52 mm and reported the local HTC and average HTC results compared with the smooth tube. They found that the average condensation HTC of R22 and R410A for micro-fin tube was 1.7–3.19 and 1.7–2.94 times larger than that of smooth tube, respectively. Han and Lee [4] experimentally studied condensation heat transfer characteristics in four micro-fin tubes with different outer diameter and geometric roughness. Their results indicated that the variation of heat transfer enhancement factors with quality and mass flux had a similar tendency as those of pressure drop penalty factors. Other condensation experiments performed by Li et al. [5] and Wu et al. [6]. Li et al. [7] and Yildiz et al. [8] also implied that micro-fin roughness had a significant impact on liquid drainage and phase interaction between liquid film and fin tips compared with the smooth tubes.

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Nomenclature

A_i	inner surface area of test tube, m^2
A	cross-sectional area, m^2
c_p	specific heat, J/(kg·K)
D	hydraulic diameter, m
d_i	inner diameter, m
d_o	outer diameter, m
G	mass flux, kg/(m^2·s)
g	gravity acceleration, m/s^2
h	heat transfer coefficient, W/(m^2·K)
h_{lv}	latent heat of vaporization, J/kg
L	tube length, m
q	heat flux, kW/m^2
S_{par}	projected surface area, mm^2
S_{dar}	developed surface area, mm^2
S_a	arithmetical mean height, $Sq = \frac{1}{A}\iint_A \lvert z(x,y)\rvert dxdy$
S_q	root mean square height, $Sq = \sqrt{\frac{1}{A}dxdy}$
S_v	maximum pit height from mean plane, um
S_z	maximum height, $Sz = Sp + Sv$
S_{sk}	skewness of the height distribution
T	temperature, K
x	vapor quality
V	voltage, V
I	electric current, A
X_{tt}	Lockhart-Martinelli parameter
W	mass flow rate, kg/s

Greek symbols

λ	thermal conductivity of copper, W/(m·K)
μ	viscosity, Pa·s
ρ	density, kg/m^3
η	efficiency of the electric power

Subscripts

in	inlet section
IA	transition from intermittent to annular
out	outlet section
l	liquid phase
v	vapor phase
ref	refrigerant
cond	condensation
lv	liquid to vapor phase change
sat	saturation
pre	preheating section
water	water
local	local parameters

Except micro-fins tubes, condensation with many other types of roughness was studied in the past twenty years. Turbo C tubes had integral-fins on outer surface with fin height less than 1 mm and internal rib roughness with different helical angles. Jung et al. [9] experimentally studied the condensation heat transfer of R22 and R410A in turbo-C tubes. They reported that the HTC of turbo-C tube was 3–8 times higher compared to the smooth tube. Kang et al. [10] studied three turbo-C tubes with different roughness and proposed a heat transfer correlation. They found that turbo-C tube provided a 3.5–4.0 times higher HTC than that of the smooth tube, and it was more effective in the higher wall subcooling region. Fernández-Seara et al. [11] and Park et al. [12] studied the outside condensation of turbo-C tubes they found that HTC for R417A, R422A and R422D underwent a rapid increase when wall subcooling was less than 3 K, and increased slightly when wall subcooling was greater than 3 K. Based on the above studies, tube side condensation in turbo-C tubes was benefit from the heat transfer enhancement of annular side, and the condensation HTC was affected by the surface tension forces on the roughness that promoted the drainage process of the condensate flim. Based on the literatures [9–12], larger fin pitches were more effective for high surface tension refrigerants, and there must be a optimal fin height for vapor condensation and liquid drainage. The other types of surface roughness, herringbone tube, were known as V-type and W-type micro-fins on tube surface. Olivier and Liebenberg [13] observed the condensation flow patterns, and studied the heat transfer and pressure drop characteristics inside the herringbone tubes. Their results revealed that fins had an effect to prolong the annular flow region, delaying the transition region to a much lower vapor quality; and that herringbone tube provided a 70% higher heat transfer coefficient and 27% higher pressure drop gradient compared with the micro-fin tube. Guo et al. [14] investigated the convective condensation and evaporation of R22, R32 and R410A inside a herringbone tube and an EHT tube with same inner diameter of 11.5 mm at low mass fluxes. The inner surface of the EHT tube is enhanced by dimple/protrusion and secondary petal arrays. For condensation, the HTC of herringbone tube was 2–3 times higher than that of the smooth tube. They also indicated that the herringbone tube had the ability to extend the annular flow region to relatively low vapor quality and low mass flux condition, which was consistent with Olivier and Liebenberg [13]. Laohalertdecha and Wongwises [15] studied the effects of pitch and depth of corrugation on heat transfer coefficient using three corrugated tubes. The results showed that condensation HTC increased with increasing depth of corrugation and decreasing pitch due to the enhanced mixing of condensate film in the boundary layer. Similar results were reported by Fernández-Seara and Uhía [16]. Yarmohammadi and Farhadi [17] used the artificial neural network and multi-objective genetic algorithm method to find the optimal operational conditions for R404A condensation inside the corrugated tubes. Their findings showed that the average corrugation pitch and depth for optimum condensation were close to 5 mm and 1.5 mm, respectively.

Unlike the two-dimensional roughness, dimple-grooved tubes which have dimples on the outer surface and protrusions on the inner surface seems to have more potential to enhance the two phase heat transfer process. Vicente and GarcíA [18] experimentally studied the single phase flow using 10 dimpled tubes. They found that the dimple structure accelerated transition to critical Reynolds number down to 1400 and the hydraulic behavior of dimpled tubes mainly depended on dimple height parameters.

Publications on local condensation performance in dimpled tubes were very limited. Sarmadian and Shafaee [19] experimentally studied the R600a condensation inside a horizontal dimpled tube. They found that the HTC of the dimpled tube was 20–100% higher than that of plain tube, and the flow region transition from intermittent flow to annular flow took place at a relatively lower vapor quality compared to the smooth tube. The author's group, Li et al. [20] experimentally studied local heat transfer of flow evaporation in three-dimensional double-layer dimple-grooved tubes as the tubes in this study, and they found that dimpled tubes with other enhancement solution would provide much higher heat transfer coefficient than smooth tubes if the dimples were properly selected and arranged. This is mainly due to the heat transfer

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