International Journal of Heat and Mass Transfer 85 (2015) 513–523

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation of condensation heat transfer on hybrid wettability finned tube with large amount of noncondensable gas

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 31 January 2015
Accepted 3 February 2015

Keywords:
Condensation heat transfer
Finned tube
Dropwise condensation
Experiment
Noncondensable gas

ABSTRACT

Condensation heat transfer outside horizontal plain and finned tubes with different surface wettability is experimentally studied. The methods of self-assembled monolayer coatings of n-octadecyl mercaptan with oxidation and etching treatments are employed to create the hydrophobic surfaces or superhydrophobic surfaces with nanostructures. The hydrophilic–hydrophobic (HH) hybrid and the hydrophilic–superhydrophobic (HS) hybrid surfaces based on the finned tubes are fabricated as well. The experimental results show that the HS hybrid finned tube achieves the highest condensation heat transfer performance in the presence of a large amount of noncondensable gas while it does not exhibit superior performance for the pure vapor condensation. The fraction of water vapor in the nitrogen–vapor mixture has significant influence on the condensation heat transfer coefficient. The dropwise condensation transforms gradually to the film condensation on both the superhydrophobic and the HS hybrid finned tubes with the increase of water vapor fraction.

1. Introduction

The vapor-to-liquid condensation is an essential process in a wide variety of industrial applications including energy conversion, power generation and water harvesting systems [1]. Advanced enhancement technologies of condensation heat transfer have the potential to significantly improve thermal efficiency and reduce the cost of energy consumption in these applications.

In general, the investigation of heat transfer enhancement is mainly concentrated on technology of increasing heat transfer area. The surface expansion technology using various fin types is one of the most popular methods for heat transfer enhancement. The condensation heat transfer performance of the water and R-134a in two types of finned tubes (circular integral-fin tubes and spine integral-fin tubes) was experimentally investigated by Kumar et al. [2]. They developed an empirical correlation to determine the condensation heat transfer coefficient. Namasivayam and Briggs [3] experimentally studied the forced convection condensation of the water vapor on the integral-fin tubes with different fin spacings. Wang and his colleagues [4–6] theoretically and experimentally studied the performance of various enhanced condenser tubes, including low finned tubes, microfin tubes and wire-wrapped enhanced tubes. Experimental study and theoretical analysis of the refrigerant R-134a condensation heat transfer characteristics for two types of three-dimensional (3D) enhanced and low finned tubes were carried out by Gstoehl and Thome [7,8]. They found that the liquid inundation rate affected the thermal performance of the 3D enhanced tubes greatly, whereas it had nearly no effect on the low finned tube. The ammonia condensation heat transfer for integral-fin titanium tube with 32 fpi was experimentally studied by Fernandez-Seara et al. [9]. Ji et al. also investigated the film condensation heat transfer characteristics of R134a on smooth horizontal tubes and various enhanced tubes experimentally [10].

Dropwise condensation exhibits much higher heat transfer characteristics [11,12] when compared with the film condensation. Promoting dropwise condensation on the hydrophobic or superhydrophobic surface is of great potential to enhance the condensation heat transfer. Recently, there has been significant interest in developing superhydrophobic surfaces to promote dropwise condensation. An increasing number of researchers have focused on fabrication of non-wetting surface with high contact angle using various surface modification techniques. Self-assembled monolayers of n-octadecyl mercaptan were employed to promote the dropwise condensation by Vemuri et al. [13,14]. They reported that the n-octadecyl mercaptan coated surface increased the condensation heat transfer rate by approximately eight times when the pressure

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.006
0017-9310/

Nomenclature

A	surface area (m^2)
C_p	specific heat capacity ($J/kg \cdot K$)
d	tube diameter (mm)
e	height of outside fin (mm)
f	friction factor
h	heat transfer coefficient ($W/m^2 \cdot K$)
h_{fg}	latent heat of water vapor (kJ/kg)
HH	hydrophilic–hydrophobic
HS	hydrophilic–superhydrophobic
k	overall heat transfer coefficient ($W/m^2 \cdot K$)
L	effective length of test tube (mm)
n	amount of substance (mol)
NCG	noncondensable gas
Pr	Prandtl number
q''	heat flux (W/m^2)
q_V	volume flow rate of cooling water (L/min)
Q	heat rate (W)
Re	Reynolds number
R_f	thermal resistance of fouling ($m^2 \cdot K/W$)
R_W	thermal resistance of tube wall ($m^2 \cdot K/W$)
SAM	self-assembled monolayers
t	temperature (°C)
x	mole fraction (%)

Greek alphabet

β	ratio of external surface area to internal surface area
ρ	density (kg/m^3)
λ	thermal conductivity ($W/m \cdot K$)
Δt	temperature difference (°C)
Δt_m	logarithmic mean temperature difference (°C)
μ	dynamic viscosity ($Pa \cdot s$)
φ	volume fraction (%)
σ	error

Subscript

g	nitrogen–vapor mixture
i	inside of tube
in	inlet of tube
l	water liquid
o	outside of tube
out	outlet of tube
s	saturation
v	vapor

was 101 kPa and it could maintain ideal dropwise condensation for more than 2600 h. By the self-assembled monolayer treatment, Ma et al. [15,16] experimentally investigated the effects of surface free energy and nanostructures on dropwise condensation. A new condensate wetting mode, i.e., the condensate sinkage mode was observed, when the dropwise condensation appeared on the roughness-induced superhydrophobic surface in the presence of noncondensable gas [17].

Recently, a fabrication method for biologically inspired superhydrophobic nanostructured surfaces made of a self-assembled copper oxide was presented, and the wetting behaviors of different shapes and scales of tier structures obtained by modulating wet chemistry was elucidated experimentally and analytically [18]. Miljkovic et al. [19] found that the condensate droplets on a superhydrophobic nanostructured copper tube of low super-saturations could jump from the surface due to the release of excess surface energy under pure water vapor. But they also found that high super-saturations would lead to surface flooding and weaken the condensation heat transfer performance. Then, the immersion condensation on oil-infused micro- and nanostructured surface was investigated experimentally, and it could drastically increase nucleation density. It is particularly attractive that this oil-infused heterogeneous nanostructured copper oxide surface demonstrated approximately 100% improvement in heat transfer coefficient compared to the typical hydrophobic surface [20]. Different micro- and nanoscale porous surfaces using self-assembly technique, polymer based thin coatings and surface etching technique were fabricated on the copper tube surfaces to promote dropwise condensation by Lee et al. [21]. Enright et al. [22] produced the superhydrophobic copper tube surface with functionalized nanostructures by direct deposition of a fluorinated silane molecular film or by sputtering a thin gold film before depositing a fluorinated thiol molecular film, which was capable of keeping superhydrophobic condensation. Their findings suggested that superhydrophobic condensation could not necessarily enhance heat transfer, if the parasitic thermal resistances of the functionalized nanostructured superhydrophobic surface were not minimized. Microfabrication techniques were employed to produce the chemical homogenous surfaces positioned horizontally with rectangular microgrooves by Zhong et al. [23], and wetting characteristics and the motion of condensing droplets were also observed.

Lau et al. [24] observed that droplets could suspend on the superhydrophobic surface, which was obtained by the nanoscale roughness inherent in a vertically aligned carbon nanotube forest together with a thin PTFE coating. In addition, Boreyko et al. [25,26] and Wisdom et al. [27] reported a continuous dropwise condensation on superhydrophobic surface with short carbon nanotubes deposited on micromachined posts, a two-tier texture based on bionic principle. In their study, the superhydrophobicity was retained during and after condensation, and rapid drop removal and self-propelled droplets could lead to a jumping motion due to the droplet coalescence. There have been some investigations on condensation heat transfer on mixed wettability surfaces. Zhai et al. [28] created the mixed wettability structure by depositing an array of hydrophilic spots with size of 750 μm onto the superhydrophobic surface using a poly-water/2-propanol solution. Derby et al. [29] examined the internal flow condensation heat transfer of pure vapor on different wettability surfaces, including hydrophilic copper, hydrophobic Teflon, and four surfaces with combined Teflon and hydrophilic patterns. They found that the condensation heat transfer coefficient on hydrophobic/hydrophilic patterned surfaces surpassed the hydrophilic surface by an order of magnitude.

Though significant interest and efforts have been devoted to develop the enhancement technology and mechanism on the condensation heat transfer, the enhancement technology of extended surface combined with wettability modification is rarely seen in the literature. In addition, it is rarely reported on the condensation heat transfer performance of water vapor on the hydrophilic, hydrophobic and superhydrophobic surfaces in the presence of a large amount of noncondensable gas. In this work, we study the condensation heat transfer characteristics of plain and finned tubes which are modified to be hydrophilic, hydrophobic and superhydrophobic in the pure vapor and nitrogen–vapor mixture, and the combined effects on condensation heat transfer outside the finned tube together with surface modification are presented. Furthermore, to the authors' best knowledge, for the first time, the hydrophilic–hydrophobic (HH) hybrid and hydrophilic–superhydrophobic (HS) hybrid finned tubes are proposed.