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Experimental study of condensation heat transfer on hydrophobic vertical tube

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ABSTRACT

Condensation heat transfer on surfaces can be enhanced by altering the surface topography. Surface modification technology can promote dropwise condensation which can exhibit higher heat transfer rate than filmwise condensation. This paper presents experimental data on the condensation of steam on vertical bare copper tubes and lead coated copper tubes for degree of sub-cooling in the range $0.5\ ^{\circ}\mathrm{C} \leq \Delta T \leq 20\ ^{\circ}\mathrm{C}$. The chemical texture of the tube surface was altered by coating with lead of thickness 10 μm and the physical texture of the surface was transformed by providing four grooves each having equal depths 0.10 mm, 0.15 mm and 0.30 mm. The condensation heat transfer characteristics of the tube surface is explained based on contact angle hysteresis and sliding velocity of the droplet. The results of the study reveal that for the tubes tested the average condensation heat transfer coefficient decreases with increase in degree of sub-cooling. It is also found that for copper tubes, providing grooves aids condensation heat transfer for the range of sub-cooling. However, for lead coated copper tube with/without grooves the heat transfer performance at $\Delta T < 2\ ^{\circ}\mathrm{C}$ shows marked difference in contrast to $\Delta T > 2\ ^{\circ}\mathrm{C}$.

1. Introduction

Vapour condensation has been a process of significant interest due to its applications in the field of power generation, water desalination and HVAC [1–3]. Mainly, there are two types of surface condensation processes- filmwise (FWC) and dropwise condensation (DWC). Typically filmwise condensation is observed on hydrophilic surfaces which has high surface energy resulting in high wettability. However, on hydrophobic surfaces with low surface energy the liquid condenses in the form of droplets causing dropwise condensation. Recently researchers have tried several modifications on surfaces to promote dropwise condensation, which lead to higher heat transfer rates compared to filmwise condensation. Dropwise condensation on surfaces can be achieved by changing the surface morphology and surface chemistry [4]. Even though dropwise condensation leads to higher heat transfer, in spite of sustained research over the last decade the mechanism behind the formation of droplet and its transport is still not well understood and remains a challenge.

The role of changing the chemical texture of the surface, so as to promote dropwise condensation (DWC) has been investigated by many researchers [5–12]. It is also important to mention here that few of the researchers [13–15] have also studied the influence of physical texturing on surfaces to enhance condensation heat transfer. However, recently a combination of chemical texturing along with physical texturing as a method of enhancing condensation heat transfer has also been well documented in literature [16]. A study was conducted by Izumi et al. [17] on condensation heat transfer characteristics of a vertical copper plate surface with round shaped grooves coated with ethanol solution of oleic acid. The study revealed that there exist an optimum groove width corresponding to maximum heat transfer. Experiments were conducted by Lara et al. [18] on vertical naval brass and copper plates with Ni-P-PTFE and without coatings. Ni-P-PTFE coated brass and copper plates showed better heat transfer performance.

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Nomenclature

A	effective condensation area, constant in Eq. (3) [m^2]
C_p	specific heat at constant pressure, [kJ/kg K]
d_0	outside diameter of the cylindrical test specimen, [m]
d_i	inside diameter of the cylindrical test specimen, [m]
h_c	condensation heat transfer coefficient, [kW/m^2 K]
k_{Cu}	thermal conductivity of copper tube, [W/m K]
L	length of the cylindrical test specimen, [m]
$\dot{m}$	mass flow rate of cooling water, [kg/s]
Q	heat transfer rate of cooling water, [kW]
R	dependent variable
r	distance measured radially, [m]
S_{surf}	surface entropy, [J/m^2 K]
T	temperature, [K]
T_{co}	outlet temperature of cooling water, [K]
T_{ci}	inlet temperature of cooling water, [K]
T_{wo}	average outer wall surface temperature of copper tube, [K]
T_{wi}	average inner wall surface temperature of copper tube, [K]
T_{vap}	vapour temperature, [K]
ΔT	degree of sub-cooling, (T_{vap}-T_{wo}), [K]
U_{surf}	surface internal energy, [J/m^2]
V	volume flow rate, [l/h]
α_1	receding contact angle, [deg]
α_2	advancing contact angle, [deg]
γ	surface free energy, [N/m]
σ_R	standard deviation of independent variable, $\sigma_R = \pm\left\{\sum_{i=1}^{n}\left[\left(\frac{\partial R}{\partial X_i}\right)^2 \sigma_{X_i}^2\right]\right\}^{\frac{1}{2}}$
σ_{X_i}	standard deviation of dependent variable
X_i	dependent variable
θ	contact angle hysteresis, (α_2-α_1)

Experiments were conducted on dimpled titanium plate and vertical grooved copper plate by Lara et al. [19]. Copper was coated with lead containing and lead free Ni-P-PTFE while the titanium plate was kept bare. The overall heat transfer coefficient was experimentally measured for all cases. Condensation heat transfer of steam on three vertical titanium plates was investigated by Baojin et al. [20] by tuning the surface energy. Two titanium plates used for the tests were subjected to modification which include chemical etching on one plate and the other subjected to a combination of chemical etching and hydrogen peroxide solution treatment. It was observed that on unmodified surface, both filmwise and dropwise condensation was found to coexist, whereas filmwise condensation was achieved on plate modified with chemical etching and Dropwise condensation was achieved on plate subjected to combination of chemical etching and hydrogen peroxide solution treatment.

Lee et al. [21] conducted experiments on micro/nano scale porous surfaces made by polyphenylene sulphide (PPS), and PTFE based polymer coatings, SAM and etching on the plain surfaces of steam condenser tubes. It was found that etched surface gives the highest transfer coefficient due to its lowest surface energy. Condensation heat transfer outside horizontal plain and finned copper tubes with different surface wettability was experimentally studied by Hu et al. [22]. Investigations were conducted on plain copper tube, hydrophobic copper tube, hybrid (hydrophilic-hydrophobic) finned copper tube, hybrid (hydrophilic-super hydrophobic) finned tube. The tests were conducted in presence of non-condensable gases and also in vacuum. It was reported that in the presence of non-condensable gases hybrid (hydrophilic-super hydrophobic) hybrid finned tube achieved the highest condensation heat transfer performance. However, in vacuum hybrid (hydrophilic-hydrophobic) finned copper tube showed the highest condensation heat transfer performance. Huang et al. [23] compared the condensation heat transfer performance on a pure copper surface with a super hydrophobic-modified copper surface. The super hydrophobic surface was prepared using a hydrogen peroxide immersion and fluorosilane polymer coating. It was found that super hydrophobic modified copper surface performed better than the pure copper surface. Condensation heat transfer on tube bundles having three different surface structures plain, 2-D finned and 3-D finned tubes was tested by Hu et al. [24]. Comprehensive study on the effect of Reynolds number of cooling water, Reynolds number of air vapour mixture and volume fraction of water vapour on convective condensation heat transfer coefficient and number of tube rows was conducted.

In addition to the above techniques, different types of geometrically enhanced tubes have also been used for many years to enhance condensation heat transfer. These tubes may be simple two dimensional rectangular integral fin tubes, three dimensional pin fin tubes or wire rapped tubes. The condensation heat transfer on these types of tubes has received considerable attention in heat transfer research because of its wide industrial application especially in industrial condensers. Ali and Briggs [25,26] reported data for the condensation of R-113 and ethylene glycol at near atmosphere pressure and low velocity on five three dimensional pin fin tubes. They studied the effect of circumferential pin spacing and thickness on the condensate retention on the pin fin tubes. The results of the study showed that among all the pin fin tubes considered in this work, for R 113, the best performing pin fin tube gave a heat transfer enhancement of 14% higher than the equivalent two dimensional integral fin tube, having the same fin root diameter, longitudinal fin spacing, thickness and fin height. However, for ethylene glycol, the best performing pin fin tube gave a heat transfer enhancement of 20% higher than the equivalent two dimensional integral fin tube. The same authors [27] extended their work to systematically study the influence of pin geometry on enhancement of heat transfer during condensation of ethylene glycol on eleven different pin fin tubes and plain tube. It was reported that the best performing pin fin tube gave a heat transfer enhancement of 5.5: 17% higher than obtained from optimised two dimensional fin tube reported in literature and 24% higher than equivalent two dimensional integral fin tube. Ali and Briggs [28] further reported the experimental data for condensation of ethylene glycol and R113 at near atmospheric pressure and low velocity on three identical pairs of pin fin tubes made of copper, brass and bronze. The study revealed that copper pin fin tubes showed better heat transfer performance in comparison with brass and bronze tubes. The above experimental studies of Ali and Briggs have shown that heat transfer performance of integral pin fin tubes are superior than equivalent integral fin tubes.

It is worth to mention here that the major factor that affects the heat transfer from integral pin fin tubes is condensation retention or flooding as reported by few researchers [29–31]. Ali and Briggs [32] measured the liquid retention angles on 15 rectangular pin fin tubes under static conditions (without condensation) using water, ethylene glycol and R-113. It was found that condensate retention