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Heat transfer measurement during dropwise condensation using micro/nano-scale porous surface

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ABSTRACT

Unique micro/nano-scale porous surfaces were fabricated on the surfaces of steam condensers to promote dropwise condensation which can exhibit higher heat transfer rate than that of filmwise condensation. Steam condensation tests were conducted to evaluate heat transfer performance of the fabricated micro/nano-scale porous surfaces. The micro/nano-scale porous surfaces were prepared using a self-assembly technique, polymer based thin coatings, and a surface etchings technique. The resulting surface morphologies and the wetting characteristics were investigated using SEM and the liquid contact angle measurements to quantify important parameters for enhancing the dropwise condensation. From visual observations, it was deduced that the micro/nano-scale porous surfaces can effectively initiate dropwise condensation by generating smaller condensates and limiting the growth of 'large' condensate drops and by improving surface renewal rate.

1. Introduction

There have been many efforts to obtain a higher condensation heat transfer rate by promoting "drop-wise" condensation mode (DWC) comparing to the traditional "film-wise" condensation mode (FWC) [1]. The greatest portion of the thermal resistance in FWC comes from the liquid condensate layer due to its poor thermal conductivity. In DWC mode, condensates do not fully occupy the heat transfer surface and form a layer, but forms separate drops across the surface. Droplets then make a continuous cycle of drop generation and departure which reduces the effect of thermal resistance of liquid condensate layer in FWC. In DWC mode, vapor impinges on to the condensing surface and numerous droplets are formed, which release the latent heat of condensation, and increase a heat transfer rate. Droplets grow very rapidly due to continuous and direct condensation of vapor onto them. As the drops reach a critical radius by growing and coalescing adjacent drops, they depart from the condensing surface taking in other droplets within their path. This motion sweeps the condensing surface, where new droplets are generated again. However, it is difficult to maintain DWC conditions for a long-term operating period especially at a high surface subcool condition.

Common methods to promote "dropwise" condensation are surface treatments on condensing surfaces, which can shift condensation modes from a filmwise (FWC) to a dropwise (DWC). Blackman et al. [2] reported two critical characteristics of successful coating compounds: a hydrophobic group and a chemical group with a high affinity for the metal. To achieve these characteristics, a number of methods have been employed. Early methods used an organic promoter to foster DWC [3,4], though these surface treatments developed into more complex coatings including nanostructure in polymer matrix [5] and Self-Assembled Monolayers (SAMs) of organic material [6,7]. Das et al. [8] used organic SAMs as a DWC promoter for horizontal tubes and carried out condensation experiments with a number of different samples.

It is considered that super- or ultra-hydrophobicity conditions accelerate water droplet rolling off motions (called self-cleaning) and improve condenser performances by refreshing condensing surfaces more frequently. Highly fluorinated monomer/polymers have been widely used to improve the hydrophobicity of the surface utilizing low surface energy characteristics of fluorinated polymers such as PTFE [9,10] and others [5] which could dramatically

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Nomenclature

A	area (m^{2})
c_p	thermal capacity (kJ kg^{-1} K^{-1})
D	diameter (mm)
f	friction factor
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1}) or enthalpy (kJ kg^{-1})
Ja	Jacob number
k	thermal conductivity (W m^{-1} K^{-1})
m	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer rate (W)
q	heat flux (kW m^{-2})
R	thermal resistance (K W^{-1})
r	radius (mm)
Re	Reynolds number
T	temperature (°C)
U	overall heat transfer coefficient (W m^{-2} K^{-1})

Greek symbols

γ	surface energy (mJ m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^{2} s^{-1})
θ	contact angle (°)
ρ	density (kg m^{-3})

Subscripts and superscripts

ave	averaged
c	coolant
cond	condensation
d	dispersion
fg	latent
h	hydrogen bonding and dipole–dipole interactions
i	in
l	liquid
o	out
sat	saturation
subcool	subcooling
t	tube
tot	total
w	wall

reduce the wettability of the surface. In addition, organic materials like hydrocarbons and polyvinylidene chloride coatings received considerable attention for their hydrophobic capabilities in promoting DWC [11]. Carbon Nano Tubes (CNT) based DWC promoters have also been considered [5,9]. Erb and Thelen [12] used coatings using inorganic compounds such as metal sulfides and found that a sample of sulfided silver on mild steel showed excellent DWC mode. Many studies [13–15] showed micro- and nano-hybrid structures can create super hydrophobic surfaces. Recently developed technology can enable for researchers to tune condensation surfaces for increasing nucleation sites, changing condensate contact angles, and accelerating surface renewal rates [7,16,23].

Although each of these methods showed some degrees of success to promote a DWC mode, knowing the surface properties by surface treatments is a key to govern condensation heat transfer rates. This includes that thin coatings would benefit in an overall heat transfer rate, but can lead to weak hydrophobicity and a failure to get an acceptable life span, while thick coatings reduce or eliminate the merits of promote a DWC mode due to additional thermal resistances introduced by the coatings. Thus, the objective of this study is to promote a DWC mode and enhance condensation heat transfer performances using micro/nano-scale porous surfaces by polymers base coatings, a self-assembled layer, and an etching and then inspect these surface properties.

2. Experiments

Four different types of micro/nano-scale porous surfaces have been applied and tested experimentally to promote DWC mode. These surfaces included two types of polymer based coatings, self-assembled layer and an etched surface. Initially, the surface morphologies and surface contact angles under ambient condition were analyzed using Scanning Electron Microscopes (SEM) and a contact angle measurement apparatus, respectively. Later, condensation heat transfer tests were performed with visual observations for steam. Details of the test surfaces and the condensation experimental setup are described in this section.

2.1. Test samples

The substrates for testing surfaces are copper alloy 122 tubes with an outside diameter of 15.9 mm, a wall thickness of 0.813 mm, and a length of 914 mm. The four different types of surfaces are prepared using PolyPhenylene Sulphide (PPS) and PolyTetraFluoro Ethylene (PTFE) based polymer coatings, a self-assembled layer, and an etching, respectively. The copper used as the substrates, because of its good thermo-physical properties and cost-effectiveness for heat transfer applications. The four different types of surfaces are applied on the middle of the substrate with a length of 533 mm and the other substrate portions without the surfaces are used for connections of the heat transfer test setup.

Before applying coatings and self-assembled layer, the substrate surfaces are polished with a 150 grid sand paper and then cleaned with ethanol and acetone solutions.

For the polymer based coatings, two different solutions were prepared. One solution is with PPS (PolyPhenylene Sulphide) and CNT (Carbon Nano Tube), and the other solution is with PTFE (PolyTetraFluoro Ethylene).

PPS, a thermoplastic polymer is used for the coating compound to promote DWC, which has outstanding high-temperature stability, good chemical resistance, and excellent friction properties. CNT is added on the PPS compound solution to increase the thermal conductivity of coating, because PPS has a lower thermal conductivity of 0.3 W/m-K.

PolyTetraFluoro Ethylene (PTFE) is also used to promote DWC, because it has excellent properties such as non-sticky, chemical resistance, thermal stability at high temperatures, although PTFE has a poor thermal conductivity, poor abrasion resistance and adhesion to metal substrate. For the polymer based coatings, PEG (PolyEthlylene Glycol) is used as a binder solution mixed in $(NH_4)_2CO_3$ solution. A nano-porous network can be formed by escaping gases from the solutions on the condenser surfaces with decomposing of the solution $(NH_4)_2CO_3$ into CO_2 and NH_3 during a melting process of PPS compounds in an oven at 340 °C for four hours. The compositions of PPS based coating are summarized are listed in Table 1.