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Condensation heat transfer on patterned surfaces

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ABSTRACT

An experimental study of condensation heat transfer was carried out on a 25.4 mm diameter surface using steam as the condensing fluid. Three surface conditions were studied: hydrophilic, hydrophobic, and a surface with patterns of distinct hydrophilic and hydrophobic regions. The effects of inlet vapor velocity, mass flux, and hydraulic diameter on the heat transfer coefficients were investigated. The inlet vapor velocity was varied from about 0.05 m/s to about 5 m/s and the hydraulic diameter was varied from 4.5 mm to 32.5 mm. Depending on the surface condition, the heat transfer coefficients showed different responses to the varying parameters of the experiments. For the hydrophilic surface, the heat transfer coefficient was observed to be up to 2.5 times lower than that for the hydrophobic surface with all other parameters unaltered. On the other hand, the surfacewith a pattern of distinct hydrophobic and hydrophilic regions showed heat transfer coefficients that were higher than that of the hydrophilic surface and lower than that of the hydrophobic surface. In both the patterned and the hydrophobic surfaces, the heat transfer coefficient was observed to increase significantly with mass flux, while for the hydrophilic surface, the heat transfer coefficient was observed to be affected much less by the mass flux. In all cases, the heat transfer coefficients increased with increasing heat flux and decreased with increasing wall sub-cooling. The effect of average quality of the steam showed little effect on the heat transfer coefficients.

1. Introduction

Condensation is an important research area because of its wide range of applications like in the power generation industry, distillation industry and in industrial cooling operations both at macro and micro scales. Likewise, enhancement of heat transfer coefficients for condensation is an active area of research. Conventionally, some of the methods employed to enhance condensation heat transfer coefficient are chemical treatment of the condensation surface, exploiting surface texture to drain the condensate, and adding chemicals to the vapor to affect its interaction with the surface [1–3]. The choice of the methods involved to enhance heat transfer depends on the conditions in which condensation takes place.

Heat transfer coefficients due to condensation can vary significantly depending on the operating conditions [4]. When the vapor velocities are high and interfacial shear stress on the condensate is influenced by the flowing vapor, condensation can be classified as *flow condensation* or *convective condensation*. On the other hand, for low vapor velocities, when interfacial stress is small or non-existent, surface tension effects of the condensate become important and condensation is classified as *vapor space condensation* [4]. However, the parameters that set flow condensation apart from vapor space condensation are not clearly defined.

In vapor space condensation the interaction of the condensate with the condensation surface is an important factor controlling the heat transfer process [5]. If the condensed fluid quickly coalesces, forms a thin film, and wets the entire surface, *filmwise condensation* (*FWC*) is said to have taken place [6]. This is a result of high surface energy of the condensation surface and is observed on surfaces which are hydrophilic. On the other hand, *dropwise condensation* (*DWC*) occurs in the form of liquid droplets on surfaces which are not wetted by the liquid and is a result of low surface energy of the condensation surface; such surfaces are said to be hydrophobic. *DWC* is characterized by higher contact angle of the droplets when compared to that of *FWC* [6].

For *FWC*, the effects of acceleration due to gravity and shear at the interface of the condensate and the vapor have been reported [7]. Analytical equations for heat transfer coefficients have been developed for condensation on a flat plate where there is either only the force of gravity or there is only shear forces (Eqs. (1) and (2)); when both forces are present, the heat transfer coefficient can be estimated by combining the heat transfer coefficients from the individual equations using Eq. (3) [7].

$$h_{gv} = 1.1\mathrm{Re}_{\Gamma}^{-1/3} k_l \left[\frac{\rho_l(\rho_l - \rho_v)g}{\mu_l^2}\right]^{1/3} \tag{1}$$

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Nomenclature

A	surface area of the condensation surface
ΔG	free energy barrier
g	acceleration due to gravity
h	heat transfer coefficient
h_{gv}	transfer coefficient only due to gravity
h_{sv}	heat transfer coefficient vapor-condensate interfacial shear
i_f	specific enthalpy of saturated liquid
i_{fg}	specific enthalpy of vaporization
i_i	specific enthalpy of inlet vapor
J	nucleation rate condensate
J_0	kinetic constant of nucleation rate condensate
K	Boltzmann constant
k_{cu}	thermal conductivity of oxygen free copper
k_l	thermal conductivity of the condensate
$\dot{m}$	vapor mass flow rate
Q''	heat flux
Re_Γ	Reynolds number based on the condensate flow rate
dT/dy	heat temperature gradient along the copper cooling block
T	absolute temperature
T_w	calculated wall temperature
T_1	temperature of the thermocouple closest to the condensation surface
x	steam quality
y	distance of thermocouple
Greeks	
μ_l	viscosity of the condensate
ρ_l	density of the condensate
ρ_v	density of the vapor
τ_i^+	non-dimensional shear stress at the interface of the condensate and the vapor

$$h_{sv} = 1.1\mathrm{Re}_\Gamma^{-1/2} k_l \left[\frac{\rho_l(\rho_l - \rho_v)g}{\mu_l^2}\right]^{1/3} (\tau_i^+)^{1/2} \tag{2}$$

$$h^2 = h_{gv}^2 + h_{sv}^2 \tag{3}$$

where, h_{gv} is the heat transfer coefficient only due to gravity, h_{sv} is the heat transfer coefficient due to shear force on the interface of the condensate and the vapor, h is the heat transfer coefficient due to the effects of both gravity and shear forces, Re_Γ is the Reynolds number based on the condensate flow rate, k_l is the thermal conductivity of the condensate, ρ_l is the density of the condensate, ρ_v is the density of the vapor, μ_v is the viscosity of the vapor, g is the acceleration due to gravity, and τ_i^+ is the non-dimensional shear stress at the interface of the condensate and the vapor.

Mobility of the condensate on the condensation surface also greatly affects the heat transfer. The diameter at which a droplet slides down a vertical condensation surface due to the effect of external forces is called the departure diameter; this typically occurs when the droplet is large. When a condensation surface is washed by higher frequency of falling droplets the heat transfer coefficient increases. McCormick and Baer [8] reported that droplet growth and dynamics significantly affected the heat transfer performance. Thus, droplet mobility becomes an important factor in condensation heat transfer. When a large drop moves away from the point of incipience, the moving drop washes away smaller drops in its path due to the cohesive nature of the liquid [9]. In *DWC*, droplets are readily able to be removed from their nucleation sites [10] and, hence, for *DWC* heat transfer coefficients have been observed to be up to an order of magnitude higher than that of *FWC* [6].

While it is accepted that *DWC*, which is observed in hydrophobic surfaces, results in high heat transfer coefficients [5], it has been observed that the nucleation rate is larger with hydrophilic surfaces [11]. This is due to the fact that the nucleation rate depends on the free energy barrier of the condensation surface, which in turn is a strong function of surface wettability [4]. The relationship between the nucleation rate and the free energy barrier can be expressed as [11]:

$$J = J_0 e^{-\Delta G/KT} \tag{4}$$

where, J is the nucleation rate, J_0 is the Kinetic constant, ΔG is the free energy barrier, K is the Boltzmann constant, T is the absolute temperature.

Since, hydrophilic surfaces have a smaller free energy barrier when compared to hydrophobic surfaces, they have higher rates of nucleation, as can be concluded from Eq. (4) and discussed by Varanasi et al. [11]. Thus, it is inferred that a while hydrophobic surface is necessary for *DWC* and high heat transfer coefficient, a hydrophilic surface is necessary to achieve high condensation rate.

While hydrophobic surfaces are associated with higher heat transfer coefficients when compared to that with hydrophilic surfaces, using a pattern of distinct hydrophobic and hydrophilic regions on the condensation surface may or may not enhance heat transfer coefficient. A study by Leu et al. [12] shows that some condensation surfaces with specific patterns of distinct hydrophobic and hydrophilic regions can result in higher heat flux than that of completely hydrophobic surfaces, while other patterns can result in lower heat flux when compared to completely hydrophilic surfaces.

Previous studies on condensation heat transfer on hydrophilic surfaces, hydrophobic surfaces, and surfaces with distinct patterns of hydrophilic and hydrophobic regions have been conducted. However, the effect of vapor velocity and dimensions of the flow chamber have not been adequately investigated, especially in the case of vapor space. Hence, the present study investigates the effect of vapor velocity and the dimension of the condensation chamber for surfaces that are hydrophilic, and hydrophobic. For surfaces with patterns of distinct hydrophilic and hydrophobic regions, certain patterned surfaces have the potential to enhance the heat transfer coefficient for condensation, others may not be able to do so [12]. Hence, a surface with patterns of distinct hydrophobic and hydrophilic regions has also been investigated.

2. Experimental apparatus and procedure

A chamber with a variable hydraulic diameter with an open steam loop was constructed as shown in Fig. 1(a). The loop consisted of a steam supply line at 445 kPa, a filter, a steam separator, a valve, an immersion heater, a test section, a heat exchanger, a flow meter and a drain. The entire flow loop was insulated to minimize heat loss. After the steam exits the test section, a heat exchanger was employed to completely condense the steam to allow steam mass flow rate measurement using a rotameter.

The test section consisted of a vapor chamber, a piston, a vertical condensation surface, the test section, and a visualization window (Fig. 1(b)). The vapor chamber was constructed from a translucent