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A dropwise condensation model using a nano-scale, pin structured surface

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ABSTRACT

In this paper, a dropwise condensation model using innovative "nano-scale, pin structured surfaces" is presented. The surfaces are porous surfaces oriented with nano- or sub micro-scale pins randomly designed or structurally arranged on extended and/or porous surfaces. These surfaces can promote a dropwise condensation showing a higher heat transfer rate than that of "filmwise" condensation by increasing the number of nucleation sites on the condenser surface and providing tunable surface properties such as surface wetting conditions. The developed model is consisted of a heat flux estimation of a single condensate drop based on thermal resistance analysis and a population theory for small and large condensate drops. The results of heat flux of a single condensate drop indicate that a smaller condensate drop with higher contact angle has a higher condensation heat flux; however, when it combined with population theory, a hemispherical shape of condensate with Wenzel surface wetting mode and a higher pin density can increase dropwise condensation heat transfer rates. In addition, a thinner nano- or sub micro-scale pins surfaces is required to increase condensation heat fluxes, when it is applied.

1. Introduction

There have been many efforts to enhance a condensation heat transfer process (vapor-to-liquid phase), because the condensation process is a critical heat transfer mechanism that improves the efficiencies of energy systems used in many industrial processes. "Dropwise condensation" (DWC), which has been studied for over 70 years [1–7], shows a much higher heat transfer rate than those of "filmwise condensation" (FWC). The greatest thermal resistance of the filmwise condensation comes from a thick liquid condensate layer covering the condensing surface. However, the dropwise condensation mode can minimize the thermal resistances of the liquid condensate layer by the continuous cyclic process of generating small condensate drops and rolling-off motion on the condenser surface. Thus, the heat transfer rate of dropwise condensation is substantially higher than that of the filmwise condensation [8].

Dropwise condensation is a multiple-staged process: the generation of the initial drops on a condensing surface, the growth to larger drops, and rolling off motion and departure from the condensing surface due to gravity. The dropwise condensation starts with forming initial nucleate size drops on the condensing surfaces by phase change from vapor to liquid. The sizes of drops increase as the amount of vapor condensed on the surfaces of condensate drops increases. The small drops become large drops and the large drops start to collapse neighboring drops and then sweep the surface. Once the volume of drops is large enough to fall against the surface tension, drops are dripping off the condensing surfaces by gravity. During the sweeping motion, the falling drops absorb other drops on their paths and clean the condensing surfaces, allowing new condenser surface for initial drops development.

The population of drops on the condenser surfaces is also important to increase condensation heat fluxes, because the condensing process simultaneously generates many drops and the growth rates of the drops are varied. Many mathematical models for dropwise condensation have been developed based on the ideas of combining a heat transfer in a single condensate drop as well as drop population models on the condenser surface [9–16].

There are, however, some limitations using the developed dropwise condensation models, because the condensate shapes were assumed to be hemispherical [10–15] or larger than a hemispherical shape [16]. Although the efficiency of the dropwise condensation heat transfer is closely related to the properties of the condenser surface [17] and the promoters used on the condenser surface for accelerating dropwise condensation [18,19], the

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Nomenclature

A	area of the condensing surface, m^2
b	fin layer thickness, m
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_{fg}	latent heat, $J\,kg^{-1}$
$N(r)$	population density of large drops, m^{-3}
$n(r)$	population density of small drops, m^{-3}
N_s	number of drops, m^{-3}
q	heat transfer rate, W
q''	heat flux, $W\,m^{-2}$
r	radius of drop, m
S	sweeping rate, $m^2\,s^{-1}$
T	temperature, °C or K

Greek symbols

α	tilted angle of condenser surface, degree
Δ	difference
ε	porosity
θ	contact angle, °
θ_a	advancing angle, °
θ_r	receding angle, °
ρ	density, kg/m^3
σ	surface tension, N/m
τ	sweeping period, s

Subscripts and superscripts

c	condensate
curv	curvature
drop	drop
e	effective
i	interfacial
max	maximum
min	minimum
p	porous
pin	pin
s	solution or surface
sat	saturation
subcool	subcooling
total	total

hysteresis of the water contact angle due to the angle of the tilted condensation surface, was not considered. In addition, previously developed models did not consider recently developed, modern technology which can enable researchers to tune condensation surfaces for increasing nucleation sites, changing condensate contact angles, and accelerating surface renewal rates [20,21]. Therefore, the objective of this study is to develop a mathematical model for dropwise condensation using a nano-scale, pin structured surfaces as a promoter for dropwise condensation with conducting parametric study for a pin density, a condensate contact angle, surface wetting mode and a surface tilted angle.

2. Model approach

Although the actual condensation is a highly unsteady process in nature, it is important to note that the dropwise model used in this study attempts to obtain the mean of the heat flux of the condensing surface using combinations of steady thermal resistances of a single condensate drop and the steady population of the drops on the surface, similar to previously developed models [11–16].

Fig. 1(a) shows schematic images of the condensate drops on a condenser surface with a hydrophilic ($\theta < 90°$) [21] and hydrophobic ($\theta > 90°$) [15,20,21], or a hemispherical ($\theta = 90°$) shapes [11–14] depending on the surface tension of the condensates and surface properties. Note that the radius of a condensate drop is r, however the radius of the condenser surface contacting with the condensate is $r\sin\theta$.

In general, a condensate drop sitting on a tilted plate with an angle of α, shown in Fig. 1(b), can have an advancing contact angle, θ_a and a receding contact angle, θ_r, respectively.

Varanasi et al. [21] showed that condensate drops can sit on micro scale fins which serve as nucleation drop sites and dropwise condensation promoters. In addition, Lee et al. [22] used a nano-scale, pin structured, and copper oxide surface for evaporation. Based on the geometry used by Varanasi et al. [21], pin structured surfaces on a condenser was considered in this study and it is assumed that the height of a condensate is equal to the pin height. Fig. 2 shows the schematic image of nano-scale, pin structured surface used by Lee et al. [22] with the dimensions and considering pins as rectangular bars constructed upright on the condensing surface.

Note that the surface wetting of condensates on a nano-scale pin structured surface will be Cassie or Wenzel, or Cassie–Wenzel mixed modes. For Wenzel mode, condensates fill the gaps between the pin structured surfaces and non-condensable gases fill the gaps for Cassie mode. In the aspect of heat transfer analysis, the concept of using an effective thermal conductivity is applied for thermal network method to simplify these modes. The effective thermal conductivity (k_e) of the nano-scale, pin structured surface can be obtained from the conductivities of a pin structured surface and the condensate or air filling the pores between the pins, which is given by,

$$k_e = \varepsilon k_c + (1-\varepsilon)k_p \tag{1}$$

where ε is the porosity of pins structured surface, and k_p is thermal conductivities of a pin and k_c can either be thermal conductivity of condensate for Wenzel mode and air for Cassie mode. In addition, k_c can be in the range of those of Cassie and Wenzel modes for the mixed mode.

Note that the thermal conductivity of a water condensate (0.666 W/m-K) is higher than that of air (0.0313 W/m-K).

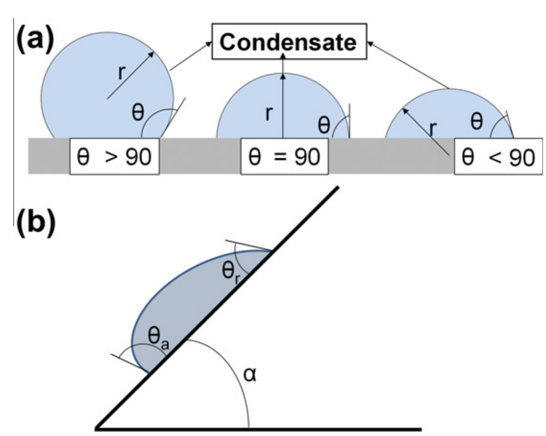

Fig. 1. Condensate contact angles on condensing surface and condensate drop on tilted surface.