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Droplet departure modeling and a heat transfer correlation for dropwise flow condensation in hydrophobic mini-channels

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ABSTRACT

Droplet nucleation, growth, coalescence, and departure control dropwise condensation heat transfer. Smaller droplets are associated with higher heat transfer coefficients due to their lower liquid thermal resistances. Unlike quiescent dropwise condensation with gravity-driven droplet departure, droplet departure sizes in flow condensation are governed by flow-droplet shear forces and droplet-solid adhesive forces. This research models droplet departure, droplet size distributions, and heat transfer through single droplets under different flow conditions. Heat transfer through single droplets includes the thermal resistances at the vapor-liquid interface, temperature depression across the curved surface, conduction in the liquid droplet, and conduction through the surface promoter (e.g., Teflon). Droplet size distributions were determined for two ranges using the population balance method and power law function for small and large droplets, respectively. Droplet departure sizes (e.g., 10–500 μm) were derived using force balances between drag forces (obtained using FLUENT) and droplet-solid adhesive forces (determined using a third-order polynomial for contact angle distribution along contact line). The analytical model was compared to experimental flow condensation heat transfer data in a Teflon AF™-coated rectangular mini-gap with hydraulic diameters of 0.95 and 1.8 mm. The correlation was compared against experiments with a steam mass flux range of 35–75 kg/m^2 s and quality of 0.2–0.9. There was good agreement between the model and experimental data; without any curving fitting, the mean absolute errors of the heat transfer correlation were 9.6% and 8.8% respectively for the 0.95-mm and 1.8-mm mini-gaps.

1. Introduction and literature review

Due to large latent heat of water, steam condensation is an important process in industries such as thermal power plants [1,2], desalination [3], fuel cells [4], air conditioning systems [5], water harvesting [6], and electronic device cooling [7]. An improved fundamental understanding of steam-side condensation can improve heat transfer performance and reduce the size of condensers [8]. Changing condensation modes from filmwise condensation, typically observed on hydrophilic, metallic surfaces, to dropwise condensation on hydrophobic or superhydrophobic surfaces can greatly increase heat transfer. Schmidt et al. [9] first recognized 5–7 times higher heat transfer coefficients in dropwise condensation rather than filmwise condensation.

Subsequent research investigated many parameters impacting dropwise condensation, including nucleation mechanisms [10], nucleation density [11–13], subcooling degree [14], droplet size [14–16], surface structures [17,18], channel geometry [19], steam velocity [8,20], heat flux [20], and saturation pressure [16,21]. Lee et al. [13] numerically studied dropwise condensation on a nano-pin-structured surface on which nucleation density was tunable by changing nano-pin dimensions and spacing. Higher condensation heat fluxes were achieved as nucleation sites increased. Tanasawa and Ochiai [15] obtained time-averaged steady-state dropwise condensation by wiping the surface periodically. Various sweeping periods generated different maximum droplet sizes, where higher time-averaged heat transfer coefficients were associated with smaller maximum droplet sizes and higher wiping rates. Immediately after the surface was cleared, extremely high transient heat transfer coefficients (greater than 1 MW/m^2 K) were measured. Hatamiya and Hiroaki [21] experimentally studied dropwise condensation of steam on a variety of surfaces (e.g., gold-plated copper, ultra-finished gold disk, gold-vapor deposited silicon disk, and chromium plated copper) at different saturation pressures. Under the same conditions, smaller

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Nomenclature

A	area
a	droplet size distribution
D	channel diameter
d	droplet diameter
f	flow
G	flow mass flux
$\bar{h}$	average heat transfer coefficient
i	evaporative enthalpy
k	thermal conductivity
Pr	Prandtl number
$\dot{Q}$	heat transfer rate
q''	heat flux
R	thermal resistance
Re	Reynolds number
R_g	steam vapor gas constant
Su	Suratman number
T	temperature
x	quality

Greek

α	void fraction
γ	specific heat ratio
δ	thickness
θ	contact angle
μ	dynamics viscosity
ρ	density
σ	surface tension
τ	sweeping period
Φ	two-phase flow multiplier
X_{tt}	turbulent-turbulent Martinelli parameter

Subscripts

Cond	condensation
co	cutoff droplet diameter (i.e., 50 μm)
DW	dropwise condensation
FW	filmwise condensation
l	liquid
s	surface
sat	saturation
st	steam
t	total condensation areas
v	vapor
vo	vapor only flow

droplets seemed to be more densely populated on the gold-plated surface and provided higher heat transfer coefficients. With similar droplets sizes, similar heat transfer coefficients were observed on two surfaces.

In dropwise condensation, a periodic motion of droplet nucleation, coalescence, and departure can be driven by gravitational or shear forces. This cyclical process promotes nucleation and reduces the liquid film thermal resistance, which provides order-of-magnitude-higher heat transfer coefficients than filmwise condensation. Heat transfer coefficients were found to decrease with increasing droplet contact angle hysteresis, which generally corresponds to higher contact angle and easier droplet rolling [22]. Ma et al. [23] proposed that dropwise condensation heat transfer coefficients were related to the surface free energy difference between the condensate and the solid surface. Lower surface energies, associated with higher contact angles, promoted dropwise condensation. Surface modifications such as organic polymer coatings [24–30], self-assembled monolayers (SAM) [13,31–36], ion implantation [37–40], electroplating [41], mini/micro/nano-structures [17,42,43] and biphilic patterns [8,14,18,44,45] decreased surface energy and eased droplet roll-off, thereby promoting dropwise condensation and increasing heat transfer coefficients compared to filmwise condensation.

In dropwise condensation, saturated vapor deposits on condensation surfaces and forms small droplets, which grow until external forces (i.e. gravity or shear forces) sweep them away. Few studies have created correlations to predict dropwise condensation. Le Fevre and Rose [46] analyzed condensation heat transfer through single droplets using an electrical resistor analogy. The results agreed with gravity-driven dropwise condensation on vertical films at heat fluxes of 0.3–1.8 MW/m^2. They also proposed the idea of determining heat transfer rates through single droplets, and then integrating over the range of droplet sizes to obtain the average heat transfer rate on condensation surfaces. They visualized dropwise condensation and correlated a power-law function for droplet size distribution with heat transfer coefficient obtained in their previous work [47], through which they developed the first dropwise condensation heat transfer coefficient correlation with four experimentally determined coefficients. Graham and Griffith [48] derived the minimum stable droplet size through mechanics and thermodynamics analysis, and Tanaka [49] observed that the power-law function works well for droplets growing through coalescence but not for smaller droplets growing through direct condensation. Population theory [11,22,49–51] considers conservation of droplet numbers in certain ranges of droplet sizes as well as sweeping effects.

Due to the importance of modeling and predicting dropwise condensation, the objectives of this paper are to develop a model for internal flow dropwise condensation where shear forces drive droplet incipient motion.

2. Correlation development

2.1. Overall heat transfer coefficient modeling approach

Depending on flow conditions (e.g., mass flux and quality), rivulets and liquid streams can form on hydrophobic surfaces concurrent with dropwise condensation [52], as shown in Fig. 1. Filmwise

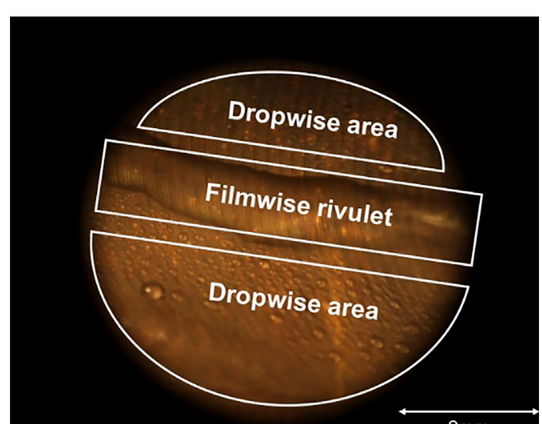

Fig. 1. Filmwise condensation region and dropwise condensation region during steam condensation on hydrophobic surfaces.