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Internal convective jumping-droplet condensation in tubes

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ABSTRACT

Water vapor condensation governs the efficiency of a number of industrial processes. Jumping-droplet condensation of water has recently been shown to have a 10× heat transfer enhancement compared to filmwise condensation due to the removal of condensate at much smaller length scales (~1 μm diameter). However, the removal efficiency of jumping droplets can be limited by return to the surface due to gravity, entrainment in bulk convective vapor flow, and entrainment in local condensing vapor flow. If used appropriately, convective condensation has the potential to entrain droplets and impede their return to the surface. In this work, a comprehensive model of internal convective jumping-droplet condensation in a superhydrophobic tube has been developed for constant heat flux boundary conditions. Laminar boundary layer theory was used to model the vapor flow inside the tube with condensation modeled as vapor suction. We analyzed the effects of jumping droplet size ($1 < R_d < 100$ μm), condensation heat flux ($0 < q < 10$ W/cm^2), initial jumping location axially along the tube ($0 < x < 5$ m) and radial position ($0 <$ theta $< 2\pi$), entering vapor mass flux ($0.05 < G < 1.5$ kg/m^2 s), and pipe radius (1 mm $< a <$ 30 cm), on droplet trajectory, overall heat transfer performance, and pressure drop. By linking droplet return with droplet jumping (multi-hop), we develop a framework to predict macroscopic droplet motion along the tube, and offer guidelines for the minimization of drag force and maximization of overall condensation heat transfer. The reduced theoretical pressure drop and enhanced heat transfer performance of convective internal jumping-droplet condensation shows potential of applicability in air-cooled condensers, and presents a framework for novel flow humidification and dehumidification technologies with appropriate design and flow separation.

1. Introduction

Water vapor condensation is an important industrial and natural process. In an effort to more rapidly remove condensate for enhanced phase-change heat transfer, researchers have created non-wetting surfaces for dropwise [1] and jumping-droplet condensation [2], whereby millimetric droplets shed due to gravity or micrometric droplets spontaneously jump away from the surface [3], respectively. A number of recent works have fabricated superhydrophobic surfaces to achieve jumping-droplet condensation [4–14] for a variety of applications including self-cleaning [15–17], thermal diodes [18], anti-icing [19–22], vapor chambers [23,24], energy harvesting [25–27], and heat transfer enhancement [28–43].

The efficient removal of jumping droplets along with the heat transfer enhancement can be limited by droplet return to the surface due to (1) gravitational force (2) entrainment in a bulk convective vapor flow, and (3) entrainment in the local condensing vapor flow towards the surface [2,23]. The first two return mechanisms can be mitigated with suitable geometric design of the macroscale condensing surface and vapor supply. However, local vapor flow driven droplet return is more difficult to eliminate due to the need to conserve mass of the condensing vapor flowing towards the surface.

While the removal of the droplets by electric fields offers a method to remove condensate [27,44], practical difficulties exist, mainly related to the need for energized electrodes that require condensate to be removed from their surfaces [41]. Here, we present a solution to the aforementioned limitations by utilizing forced bulk vapor flow to remove jumping-droplets, in what we term convective jumping-droplet condensation. We provide a comprehensive modeling framework of internal convective jumping-droplet condensation inside a tube. Utilizing hydrodynamic boundary layer analysis, we couple the droplet motion to the internal vapor flow fields to calculate droplet trajectories and surface interactions. We study the jumping droplet traveled length

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Nomenclature

Symbols

a	pipe radius
Bo	Bond number
Ca	Capillary number
C_D	drag coefficient
d	diameter
$\vec{e}$	unitary vector
f	similarity function, friction factor
$\vec{F_G}$	gravitational force
$\vec{F_D}$	drag force
$\vec{F_{SL}}$	Saffman lift force
G	mass flux
h_{fg}	vaporization latent heat
L	traveled length
N	number of droplets
P	pressure
q	heat flux
r	radial coordinate
R_d	droplet radius
R	suction based Reynolds number
Re	Reynolds number
R_g	individual ideal gas constant
t	time
u	axial velocity
U_0	vapor inlet velocity
v	radial velocity
V_w	wall suction velocity
We	Weber number
x	Cartesian coordinate, vapor quality
y	Cartesian coordinate
z	Cartesian coordinate, axial coordinate
α	void fraction
γ	surface tension
Δ	change
μ	dynamic viscosity
ν	kinematic viscosity
θ	angle between vector and x-axis in xy plane
ϕ	angle between vector and Cartesian z-axis
ρ	density
η	similarity variable
τ	wall shear stress

Subscripts

none	vapor flow
0	initial
avg	average
d	droplet
G	gradient
hom	homogeneous
i	index
l	liquid
lo	liquid only
r	position
rel	relative
S	Saffman
sat	saturation
t	total
tp	two-phase
v	vapor, velocity

Superscripts

$'$	derivative with respect to independent variable

along the tube as a function of the condensation heat flux, tube entrance vapor velocity, jumping droplet size, location of droplets along the tube, and radial location of jumping. By linking droplet return with droplet jumping (multi-hop), we develop a framework to predict macroscopic droplet motion along the tube axis, and offer guidelines for the minimization of drag force and maximization of overall condensation heat transfer. We also develop a framework for analyzing internal flow jumping-droplet condensation pressure drop and compare it to conventional two-phase flow pressure drop calculations for homogeneous and separated flows. The modeling framework shown here outlines the first treatment of internal convective jumping-droplet condensation which has the potential to be implemented in air-cooled steam condensers for energy and water applications.

2. Internal convective jumping droplet model

2.1. Assumptions

Our model for the convective jumping droplet condensation in a tube is based on several assumptions:

(1) Jumping droplets are much smaller ($R_d < 250$ μm) than the radius of the pipe ($a > 1$ cm), hence the droplets have a negligible effect on the vapor velocity field in the pipe.
(2) The condensation at the pipe inner wall can be modeled mathematically as a suction velocity (equivalent to a porous pipe) due to the negligible change in volume during the process ($\rho_v \ll \rho_l$) [45,46]. The suction velocity V_w can be expressed in terms of the heat flux q, vapor density ρ_v and latent heat of vaporization of water h_{fg} as:

$$V_w = \frac{q}{\rho_v h_{fg}} \tag{1}$$

(3) The flow is laminar. Although we consider transitional Reynolds numbers ($Re \approx 11,000$) at the pipe inlet, the wall suction is assumed to retard transition to turbulence [47].
(4) The flow is fully developed, meaning the axial velocity of the vapor has a self-similar profile along the tube, and the radial velocity does not depend on the axial location.
(5) Heat flux is assumed to be uniform along the circumference of the pipe and along the axial location. Because of constant velocity around the circumference of the pipe, the flow is axisymmetric.

2.2. Velocity field

Fig. 1 shows a schematic of the internal flow problem coupled with jumping droplet condensation. The problem is treated in cylindrical coordinates, z and r representing the axial and radial coordinates, respectively. The pipe considered has a radius a and the axial and radial velocities are represented by u and v, respectively. The suction velocity at the wall due to vapor condensation and the circular droplet (blue circle) are contributions from jumping droplet condensation.

The problem of a fully developed laminar flow in a porous tube has been solved analytically and numerically via series solutions by Terrill and Thomas [48]. We will present only the main findings here. Considering the non-dimensional similarity variable:

$$\eta = \frac{r^2}{a^2}, \tag{2}$$