International Journal of Heat and Mass Transfer 122 (2018) 1024–1039

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Dropwise condensation patterns of bismuth formed on horizontal and vertical surfaces

Praveen M. Somwanshi, K. Muralidhar, Sameer Khandekar *

Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

ARTICLE INFO

Article history:
Received 11 September 2017
Received in revised form 26 January 2018
Accepted 13 February 2018

Keywords:
Bismuth
Coalescence
Condensation cycle
Dropwise condensation
Mathematical modeling
Wall heat flux
Wall shear stress

ABSTRACT

Simulation of dropwise condensation of bismuth vapor on a subcooled hydrophobic surface is discussed in the present study. The process starts from nucleation of drops, followed by their growth and coalescence, resulting in drop instability that removes them from the surface. Fresh nucleation occurs at the exposed nucleation sites, thus creating a cycle of vapor condensation and liquid removal. The drop size distribution over the surface determines the instantaneous surface averaged wall heat flux. Wall shear stresses are generated during coalescence process and also when large drops start moving due to instability, which is gravitational in origin; hence, the largest drop diameter achieved depends on the surface orientation. Near-horizontal and vertical surfaces have been studied in the present work. Drop instability affects the periodicity of the condensation process and the average drop size and thus, the wall heat flux and wall shear stress. Coalescence of adjacent drops is a momentary step with a timescale of milliseconds, but the velocities generated are substantial. Coalescence velocities and time intervals have been determined by scale analysis, and the sensitivity of wall heat flux and wall shear stress to these ensuing velocities are delineated. The multiscale model developed is computationally intensive and has been simulated on large condensing surface areas using MPI on a parallel architecture. Bismuth condensation properties have been compared with water. Large heat fluxes and shear stresses are seen to be attained sporadically during coalescence for short time instants and do not contribute significantly to the surface-averaged values. On the other hand, wall shear stresses are found to be large enough to damage the hydrophobic coatings and degrade surface wettability, thereby hindering dropwise mode of condensation.

1. Introduction

Condensation occurs on a solid wall when the surface temperature falls below the local saturation temperature of the adjoining mass of vapor. On specially treated surfaces, condensing liquid droplets will appear at specific nucleation sites. As the phase-change process proceeds, these droplets grow by direct condensation from the vapor phase, coalesce with neighboring drops, and may fall-off or start to slide down the substrate. The process is cyclic and intermittent drop instability will prevent the formation of a continuous liquid film. Such a phase-change process, termed as dropwise condensation [3], is heterogeneous in which vapor condenses in the form of discrete liquid drops on, or underneath, a cold solid substrate [9,28].

Dropwise condensation can be sustained only on specially textured hydrophobic surfaces [23,33,21]. The heat transfer coefficient during dropwise condensation can be quite high, for example, up to 15 to 30 times greater than the filmwise mode, when tested with Langmuir-Blodgett surfaces [23] and 5–20 times better when a promoter layer is used [12]. Leaching of the coated or textured substrate can change its wettability characteristics and result in its aging. Hence, apart from heat fluxes, it is important to estimate the wall shear stresses created during bulk drop movement, as well as coalescence occurring during dropwise condensation [9,28].

Drops are expected to form at individual nucleation sites, while the area between the growing drops remains inactive with respect to condensation [13]. The diameter of the smallest drop at nucleation can be estimated from thermodynamic considerations [3]. Subsequently, the drop grows by direct condensation at a rate determined by the conduction/diffusion resistance through the drop, interfacial heat transfer coefficient, and the available temperature difference. Larger drops also grow by coalescing with their neighboring drops. When a certain critical size is reached, drops become gravitationally unstable, fall-off, or slide along the substrate surface, wiping other drops along their flow path. Fresh nucleation sites are thus revealed and the condensation process repeats in a quasi-cyclic manner.

* Corresponding author.
E-mail address: samkhan@iitk.ac.in (S. Khandekar).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.052
0017-9310/

Nomenclature

A	surface area, m^2
C_p	specific heat of condensate at constant pressure, J/kg K
F	force acting on drop, N
h	heat transfer coefficient, $q''/(T_{sat} - T_w)$, W/m^2 K
h_{lv}	latent heat of vaporization, J/kg
k	thermal conductivity of condensate, W/m K
L	distance between two nucleation sites, m
N	nucleation site density, cm^{-2}
p	pressure, N/m^2
q	surface heat transfer, W
q''	surface heat flux, W/m^2
r_b	base radius of drop (diameter d_b), m
r_{max}	base radius of drop at instability due to fall-off, m
r_{crit}	base radius of drop at instability due to slide-off, m
T_{avg}	average temperature of condensation = $(T_{sat} + T_w)/2$
T_{sat}	saturation temperature in vapor phase, K
T_w	substrate temperature, K
ΔT	degree of subcooling, $(T_{sat} - T_w)$, K
Δt	time step, s
U	relative velocity between substrate and drop, m/s
V	volume of liquid drop, m^3

Dimensionless quantities

$C_f, \overline{C_f}$	local and surface-averaged skin friction coefficient, $\tau_w/(1/2)\rho U^2$
Pr	Prandtl number of condensate, $\mu C_p/k$
Re	Reynolds number related to drop sliding, $\rho U d_b/\mu$
$(Nu)_{sd}$	Local Nusselt number of single sliding drop, hr_b/k

Greek symbols

α	inclination angle, radians
υ	specific volume, m^3/kg
μ	dynamic viscosity of liquid phase, Pa s
ρ	liquid density, kg/m^3
σ	surface tension coefficient at liquid-vapor interface, N/m
$\tau_w, \bar{\tau}_w$	local and average wall shear stresses, N/m^2
θ	contact angle, deg
θ_{adv}	advancing contact angle, deg
θ_{avg}	average contact angle, deg
θ_{rcd}	receding contact angle, deg
$\Delta\theta$	contact angle hysteresis, $(\theta_{adv} - \theta_{rcd})$, deg

Vemuri and Kim [32] and Kim and Kim [11] developed mathematical models of dropwise condensation based on a single condensate drop, combined with a population balance model for the entire surface. The condensate drop was assumed to be hemispherical with a circular base. Leipertz [14] discussed the importance of the drop shape on local heat transfer and instability. In the work of Chatterjee et al. [5], heat transfer coefficient was affected by the inlet vapor velocity. Hydrophilic island patterns distributed on a hydrophobic surface were seen to enhance the condensation heat transfer coefficient.

Nucleation site density has been inferred from indirect measurements of water vapor condensation in the literature. The size of a thermodynamically stable drop at nucleation is of the order of a few nanometers at preferred nucleation sites and corresponds to a nucleation site density of around 10^6 cm^{-2}. Leach et al. [13] reported nucleation site density in the range of 10^4–10^6 cm^{-2}. Rose [23] quoted 10^6 cm^{-2} as a possible nucleation site density. In previous studies of the authors, simulations were found to be in good agreement with experiments for wall heat flux during condensation of mercury at this nucleation site density [9]. However, careful determination of nucleation site density for metal vapor condensation has not been reported.

Liu and Cheng [15] and Niu et al. [17] reported in their work a correlation for the available nucleation site density during the condensation process. Liu and Cheng [15] studied theoretically the effect of subcooling, contact angle, thickness and thermal conductivity of the coating layer on nucleation site density and condensation heat flux during dropwise condensation. The nucleation site density ($N_s = 0.037/r_{min}^2$) predicted by Rose [22] for water vapor based on minimum radius (r_{min}) was seen to be an overprediction. The nucleation site density predicted by Liu and Cheng [15] matched with the experiments when the minimum radius was replaced with critical radius (r_c) derived by minimizing the free energy. Niu et al. [17] studied the effect of liquid-solid interfacial thermal resistance on dropwise condensation through modeling and experiments. The nucleation free energy derived by Liu and Cheng [15] was minimized to find the critical radius, by including the effect of the temperature distribution in the bulk droplet on the liquid-solid interfacial thermal resistance, incorporation of which increased the critical nucleation radius and reduced the nucleation density. The literature quoted above is for water; a study on nucleation site density, including experimental validation for liquid metals, has not been reported.

Some recent studies on other geometries/wetting conditions include that by Chen et al. [4], in which flow condensation inside a hydrophobic micro-channel was experimentally studied. Wu et al. [35] numerically studied condensation in annular rectangular micro-channels. Zhang et al. [39] studied experimentally the flow condensation of ethanol-water mixture inside a hydrophobic micro-channel. Deng et al. [6] numerically studied dropwise condensation of vapor on a wettability gradient surface. Post-condensation, the drop acquired an equilibrium shape on the substrate. The drop deformed to a semi-spherical shape to adjust for the contact angle hysteresis, resulting in contact angle of 90° on left and right sides of the drop. The instantaneous contact angle was greater than advancing and smaller than the receding angle, resulting in unbalanced wetting forces that, in turn, induced motion to the drop. The condensation of saturated vapor, first in the form of a thin film, became dropwise later on smooth gradient surfaces. Larger wettability gradient of the substrate caused larger amplitude oscillations of condensation rate and some variation in area coverage.

A multiscale dropwise condensation model, starting from the atomic scale, progressing towards the growth of droplets, coalescence, and drop instability has been reported by Sikarwar et al. [25–27] for condensation of water vapor. The model is comprehensive and the deformed drop shape is determined by the 2-circle approximation. In addition, the process of coalescence is taken to be instantaneous. In the present study, the original model is extended by including the characteristics of coalescence of the droplets. While condensation of bismuth is the primary focus, results for water are also generated for comparative purpose. The effect of drop coalescence on wall shear stress and heat transfer rates in dropwise condensation is determined. In addition, the mathematical model is parallelized using MPI to run for large condensing surface areas on a high performance computing system [28].

The choice of bismuth as the working fluid is motivated by the range of applications where liquid metals are encountered. These