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Dropwise condensation theory revisited Part II. Droplet nucleation density and condensation heat flux

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ABSTRACT

An improved dropwise condensation heat transfer model modified from previous models is proposed in this paper. The critical radius for onset of droplet condensation is determined in the preceding paper (Part I), leading to a more accurate determination of droplet nucleation density and the coalescence radius in this paper (Part II). Effects of subcooling, contact angle, thickness and thermal conductivity of the coating layer on droplet nucleation density, condensation heat flux, and critical condensation heat transfer rate for onset of droplet condensation are illustrated. The predicted droplet nucleation density and dropwise condensation heat flux are shown in excellent agreement with existing experimental data.

1. Introduction

The study of dropwise condensation heat transfer has attracted a great deal of attention [1,2] since Schmidt [3] performed his experiment on dropwise condensation heat transfer in 1930. Le Fevre and Rose [4] developed the first dropwise condensation heat transfer model in 1966, in which the average condensation heat transfer was obtained by an analysis for heat transfer through a single droplet combined with the drop size distribution. In this single droplet model, three thermal resistances including conduction resistance, vapor–liquid interfacial resistance and surface resistance were considered in series. Wu and Maa [5] obtained an expression for calculation of dropwise condensation heat transfer by dividing the droplets into two groups: small droplets before coalescence and large droplets after coalescence; they used a population balance model to obtain drop size distribution of small droplets before coalescence which grow mainly by direct condensation. Abu-Oriba [6] improved Wu and Maa's model [5] by taking account of the thermal resistance of promoter coating based on a single droplet heat transfer model given by Le Fevre and Rose [4]. A dropwise model similar to Abu-Oriba [6] was recently proposed by Kim and Kim [7], who included the effect of contact angle on heat conduction in a single droplet. Although Kim and Kim's model [7] for dropwise condensation heat transfer is a most comprehensive dropwise condensation model, it has a few shortcomings: (i) the critical radius was determined from the critical radius for classical heterogeneous droplet nucleation condensation, which did not take into consideration effects of contact angle and coating layer, (ii) the value of droplet nucleation density is unknown which had to be assumed in the range of 10^9–$10^{15}\ \mathrm{m}^{-2}$, and (iii) the model is unable to predict the critical heat transfer for onset of dropwise condensation.

In this paper, we propose an improved dropwise condensation model which is based on the modification of Kim and Kim's model [7] by using the more accurate expression for the critical radius for onset of droplet condensation derived in the preceding paper [8] to determine (i) the minimum droplet nucleation radius and (ii) the droplet nucleation density. Effects of contact angle, degree of subcooling, contact angle hysteresis, thickness and thermal conductivity of the coating layer and the saturated vapor pressure on dropwise condensation heat flux are analyzed. The predicted droplet nucleation density and dropwise condensation heat flux are shown in excellent agreement with existing experimental data [9–15].

2. Previous models for dropwise condensation

In this section, we will briefly review previous models for dropwise condensation on a subcooled surface. Wu and Maa [5] assumed that droplets condense on a subcooled surface can be divided into two groups: a group of small size droplets (with radius from $r_{\min}$ to r_e) having a number density $n(r)$, and a group of large size droplets (with radius from r_e to $r_{\max}$) having a number density $N(r)$ and gave the following expression for dropwise condensation heat transfer:

$$Q = \int_{r_{\min}}^{r_e} q_{drop}(r)n(r)dr + \int_{r_e}^{r_{\max}} q_{drop}(r)N(r)dr, \quad (1)$$

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Nomenclature

h_{fg}	specific latent heat (kJ kg^{-1})
h_i	interfacial heat transfer coefficient (W m^{-2} K^{-1})
g	gravitational acceleration (m s^{-2})
$n(r)$, $N(r)$	drop size distribution (m^{-3})
N_s	nucleation density (m^{-2})
p	pressure (Pa)
q	heat transfer rate (W)
Q	condensation heat flux (W m^{-2})
r	radius (m)
r_0	classical heterogeneous nucleation radius (m)
r_c	critical radius for heterogeneous nucleation (m)
r_e	coalescence radius (m)
$r_{\max}$	maximum droplet radius (m)
R_g	specific gas constant (J kg^{-1} K^{-1})
T	temperature (°C)
v	specific volume (m^3 kg^{-1})

Greek symbol

Ψ	availability (J)
ρ	density (kg m^{-3})
δ	coating thickness (m)
σ_{lv}	liquid vapor surface tension (N m^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
θ	contact angle (°)
φ	angle (°)
τ	sweeping period (s)

Subscripts

sub	subcooled
drop	droplet
coat	coating
l	liquid
g	gas (or vapor)
s	saturated
w	wall (or surface)

where $r_{\min}$ is the minimum droplet radius, r_e is the coalescence radius, and q_{drop} is the heat transfer rate through a single droplet given by Kim and Kim [7] as

$$q_{drop}(r) = \frac{\Delta T_{sub}\pi r^2(1 - r_{\min}/r)}{\frac{\delta}{\sin^2\theta\lambda_{coat}} + \frac{\theta r}{\sin\theta\lambda_{drop}} + \frac{1}{2(1-\cos\theta)h_i}}, \tag{2a}$$

where θ is the contact angle; δ is the thickness of the coating; λ_{coat} is its thermal conductivity, and h_i is the interfacial heat transfer coefficient is given by [1]

$$h_i = \frac{2\alpha}{2-\alpha}\frac{1}{\sqrt{2\pi R_g T_s}}\frac{h_{fg}^2}{v_g T_s}, \tag{2b}$$

where α is the accommodation coefficient ($0 < \alpha \leqslant 1$). Graham and Griffith [16] assumed the minimum radius $r_{\min}$ of the droplets to be equal to the critical radius r_0, which can be obtained from the classical heterogeneous droplet nucleation theory [1] as

$$r_{\min} = r_0 = \frac{2T_s\sigma_{lv}}{\rho_l h_{fg}\Delta T_{sub}}. \tag{2c}$$

where $\Delta T_{sub} = T_s - T_w$ is the degree of subcooling with T_s being the saturated temperature of the vapor; ρ_l is the liquid condensate density, and σ_{lv} is liquid–vapor surface tension, and h_{fg} is the latent heat. It should be noted that Eq. (2a) has taken into consideration of the thermal resistances of the promoter, the liquid/vapor interface, and the curvature depression of the equilibrium interface temperature.

In the first integral of Eq. (1), $n(r)$ is the drop size distribution of small droplets with radius from r_0 to r_e, which is given by [6]

$$n(r) = \frac{1}{3\pi r_e^3 r_{\max}}\left(\frac{r_e}{r_{\max}}\right)^{-2/3}\frac{r(r_e - r_{\min})}{r - r_{\min}}\frac{A_2 r + A_3}{A_2 r_e + A_3}\exp(B_1 + B_2), \tag{3a}$$

with parameters A_1, A_2, A_3, B_1 and B_2 given by

$$A_1 = \frac{\Delta T_{sub}}{2\rho_l h_{fg}}, \tag{3b}$$

$$A_2 = \frac{\theta(1-\cos\theta)}{4\lambda_{drop}\sin\theta}, \tag{3c}$$

$$A_3 = \frac{1}{2h_i} + \frac{\delta(1-\cos\theta)}{\lambda_{coat}\sin^2\theta}, \tag{3d}$$

$$B_1 = \frac{A_2}{\tau A_1}\left[0.5(r + r_e - 2r_{\min})(r_e - r) + 2r_{\min}(r_e - r) - r_{\min}^2\ln\left(\frac{r - r_{\min}}{r_e - r_{\min}}\right)\right], \tag{3e}$$

$$B_2 = \frac{A_3}{\tau A_1}\left[r_e - r - r_{\min}\ln\left(\frac{r - r_{\min}}{r_e - r_{\min}}\right)\right]. \tag{3f}$$

where the sweeping period τ is calculated as

$$\tau = \frac{3r_e^2(A_2 r_e + A_3)^2}{A_1(11A_2 r_e^2 - 14A_2 r_e r_{\min} + 8A_3 r_e - 11A_3 r_{\min})}, \tag{3g}$$

where $r_{\min} = r_0$ in Eqs. (3a)–(3g) and in all previous models [5–7].

The lower limit of the first integral is the critical radius $r_{\min}$ for droplet nucleation, and the upper limit in the first integral is the coalescence radius r_e given by [5]:

$$r_e = (4N_s)^{-0.5}, \tag{4a}$$

Rose [17] has derived a theoretical expression for droplet nucleation density which is given by

$$N_s = \frac{0.037}{r_{\min}^2}, \tag{4b}$$

where $r_{\min} = r_0$ is in all previous models. Although Eq. (4b) was derived in 1976, it has seldom been used in practice since Eq. (4b) is known to be overestimating the droplet nucleation sites if $r_{\min} = r_0$ where r_0 is given by Eq. (2c). On the other hand, experimental values of droplet nucleation density N_s were found in the range from 10^9 m^{-2} to 10^{15} m^{-2} [2], and this value was used in previous dropwise condensation models [5–7].

In the second integral of Eq. (1), $N(r)$ is the number density of large drops with radius from r_e to $r_{\max}$ which is given by [4]

$$N(r) = \frac{1}{3\pi r^2 r_{\max}}\left(\frac{r}{r_{\max}}\right)^{-2/3}, \tag{5a}$$

where $r_{\max}$ is maximum drop radius, which can be obtained according to the force balance between surface tension and gravity as [18]

$$r_{\max} = \left(\frac{6(\cos\theta_r - \cos\theta_a)\sin\theta}{\pi(2 - 3\cos\theta + \cos^3\theta)}\frac{\sigma_{lv}}{\rho_l g}\right)^{0.5}, \tag{5b}$$

with θ_r being the receding contact angle and θ_a the advancing contact angle. Eqs. (1)-(5) with $r_{\min} = r_0$ is Kim and Kim's model [7] for dropwise condensation heat transfer. It should be noted that the critical condensation heat flux from Eq. (2a) gives $q_{drop}(r_o) = 0$, which is unrealistic since the critical heat flux is not equal to zero for bubble nucleation [19].