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Effect of hydrophobic coating on optimization of dropwise condensation of steam on hybrid surfaces

Nicola Suzzi and Giulio Croce

DPIA - Dipartimento Politecnico di Ingegneria e Architettura - Universitá di Udine - Via delle Scienze - 33100 - Udine (UD) - Italy

E-mail: nicola.suzzi@uniud.it

Abstract. Dropwise condensation of pure vapor on hybrid surfaces, characterized by alternate hydrophobic-hydrophilic regions, is numerically investigated via phenomenological, Lagrangian modelization of dropwise condensation on hydrophobic regions. The drop size distribution over the hydrophobic domain, which knowledge is crucial for development of accurate simplified, statistically based models, is computed. Comparison with literature correlations shows that the theoretical correlation for size distribution of small droplets gives an inaccurate estimate, while the improved correlation, derived from the droplet population balance, better describes the numerical size distribution and, if incorporated in the statistically based model, allows to accurately predict the condensing flux.

1. Introduction

Dropwise condensation (DWC) of steam is involved in heat exchanger design [1, 2, 3, 4, 5, 6, 7]. Hybrid surfaces, characterized by recursive hydrophobic-hydrophilic patterns, are getting more attention in recent years. Indeed, the hydrophilic pattern, which triggers capillary driven migration of droplets from the hydrophobic domain, ensures fast surface renewal and condensate drainage, if compared to a standard hydrophobic surface [1, 2]. Peng et al [1] conducted an experimental campaign on steam condensation over a vertical plate, composed of alternate hydrophobic-hydrophilic stripes, while a horizontal cylinder with vertical hydrophobic and less hydrophobic stripes was considered by Alwazzan et al [2, 3]. A more complex configuration, characterized by inverted V-shaped channels, was experimentally investigated by Yang et al [4] in case of moist air condensation. Proper design of the surface geometry allows control of the maximum droplet size over hydrophobic domain and reduces the risk of flooding on the hydrophilic domain, where a filmwise condensation (FWC) regime is usually observed [1, 5]. To avoid extensive experimental campaigns, Probability-Based Models (PBM), which rely on statistical information such as the droplet size distribution [8, 9], represent a powerful tool to predict heat transfer performances. Experimental evidence prove the goodness of Le Fevre and Rose correlation [10], which gives the size distribution of large droplet population (droplet growth driven by the coalescence process). However, the size distribution of the smallest droplets with size down to the nucleation radius, whose growth is driven by condensation, has not been experimentally investigated due to the difficult access to the microscale. Even the theoretical correlation of [11] is not able to accurately predict the size distribution of small droplets [5, 12], making the PBMs still not reliable for hybrid geometry optimization. Here, numerical analysis of DWC of steam over an hybrid surface such as the one investigated by [1] is conducted via Individual-Based Modelization (IBM). Thus, a Lagrangian approach is adopted to simulate the evolution of the condensing droplet population: the whole life of every droplet, including nucleation, growth (due to condensation and coalescence) and departure, is followed using an in-house, high fidelity code previously developed and validated. Furthermore, an updated correlation is derived from the drop population balance, in order to predict the size distribution of small droplets. The computed droplet size distribution is compared with the updated correlation. Since the final aim of this work is to improve the accuracy of the simplified modelization of DWC over hybrid surfaces, the updated correlation is included in the PBM and the predicted condensing flux is compared with the numerical result.

2. Mathematical model

2.1. Numerical IBM model

In order to investigate the size distribution of small droplets, whose growth is driven by condensation, a numerical campaign was conducted via Individual-Based Model (IBM) method. To do so, a Lagrangian code, previously developed in `FORTRAN90` language and validated in case of dropwise condensation of pure steam over a hybrid hydrophobic-hydrophilic surface [5], was used. The implemented physical mechanisms include: the generation of nuclei at random locations (only dry spots are active), growth of droplets due to condensation, coalescence check and implementation, hybrid surface implementation via dedicated boundary conditions. Details of the numerical procedure are explained in [5]. The condensation model, which gives the droplet growth in time, was derived in non-dimensional form, to generalize the problem. The hybrid surface implementation allows to investigate geometries characterized by alternate hydrophobic-hydrophilic vertical stripes, such as the one of [1]. In particular, it was assumed that droplets, whose base surface partially stands over the hydrophilic stripes, instantaneously migrate to the more wettable region.

Let's define the characteristic coalescence radius r_e and the time required by a newly nucleated droplet to grow from nucleation radius r_n to r_e,

$$r_e = \frac{1}{\sqrt{4\,\rho_n}},\; t_e = \left[(\xi_c+1)^2 - \left(\xi_c + \frac{r_n}{r_e}\right)^2\right] \frac{3}{2}\,\frac{\rho_l\, V_\theta\, h_{lv}\, {r_e}^2}{\lambda_l\, F_\theta\, \Delta T} \tag{1}$$

where ρ_n is the nucleation density, ξ_c is the ratio between coating thermal resistance and conductive thermal resistance through a droplet of radius r_e, V_θ is the droplet volume normalized by the cube of its radius, F_θ, which is correlated to conduction through droplet core, is a function of the static contact angle [5]:

$$\xi_c = \frac{\lambda_l\, F_\theta\, \delta_c}{\lambda_c\, r_e\, \sin^2\theta},\; V_\theta = \frac{\pi}{3}\,(1-\cos\theta)^2\,(2+\cos\theta)\,,\; F_\theta = \frac{4\,\pi\,\sin\theta}{\theta} \tag{2}$$

Further defining $\mathbf{x}^* = \mathbf{x}/r_e$, $r^* = r/r_e$, $t^* = t/t_e$, the droplet growth in time due to the condensation process can be expressed in a non-dimensional fashion [5]:

$$\frac{\mathrm{d}r^*}{\mathrm{d}t^*} = \frac{(\xi_c+1)^2 - (\xi_c + r_n^*)^2}{2}\,\frac{1}{r^* + \xi_c} \tag{3}$$

$$r^* = -\xi_c + \sqrt{(\xi_c + r_n^*)^2 + \left[(\xi_c+1)^2 - (\xi_c + r_n^*)^2\right]\, t^*} \tag{4}$$

The non-dimensional nucleation density reduces to $\rho_n^* = \rho_n\, {r_e}^2 = \frac{1}{4}$ and, thus, the only problem parameters are: the static contact angle θ; the ratio ξ_c between coating thermal resistance and reference droplet thermal resistance; the non-dimensional hydrophobic width $L_D^* = L_D/r_e$, which in turn gives the maximum radius as:

$$r_{max}^* = \frac{L_D}{2\, r_e\, \sin\theta} = \frac{L_D^*}{2\, \sin\theta} \tag{5}$$

2.2. Drop size distribution

As experimentally and numerically proved [1, 5], the size distribution of large droplets, characterized by $r^* \geq 1$, is accurately predicted by the empirical correlation of Le Fevre and Rose [10] when dropwise condensation over hybrid surfaces is considered:

$$N_r^* = N_r'''\, {r_e}^3 = \frac{1}{3\,\pi\, r^{*2}\, r_{max}^*} \left(\frac{r_{max}^*}{r^*}\right)^{2/3} \tag{6}$$

Following literature [11], the mass balance of a droplets population growing with speed G^* gives a differential equation, which unknown is the number of droplets n_r^* per unit surface and radius,

$$\frac{\mathrm{d}}{\mathrm{d}r^*}\left(G^*\, n_r^*\right) + \frac{n_r^*}{\tau_{swe}^*} = 0,\; G^* = \frac{\mathrm{d}r^*}{\mathrm{d}t^*} \tag{7}$$

where $\tau_{swe}^* = \tau_{swe}/t_e$ is the non-dimensional sweeping time, assumed constant in [11].
Solving the droplet population balance as shown in [11] yields the size distribution of small droplets, characterized by $r^* < 1$, in non-dimensional form:

$$n_r^* = n_r'''\, {r_e}^3 = N_r^*(1)\, \frac{r^* + \xi_c}{1 + \xi_c} \exp\left[\frac{A}{2}\left(1 - r^{*2}\right) + A\,\xi_c\,(1 - r^*)\right] \tag{8}$$

$$A = \frac{2}{\tau_e^*}\left[(\xi_c + 1)^2 - (\xi_c + r_n^*)^2\right]^{-1} \tag{9}$$

where $\tau_e^* = \tau_{swe}^*|_{r^*=1}$ is obtained imposing the boundary condition at $r^* = 1$ in order to match the size distribution of large droplets, given by Eq. (6), according to [11]:

$$\left.\frac{\mathrm{d}\log\left(n_r^*\right)}{\mathrm{d}\log\left(r^*\right)}\right|_{r^*=1} = -\frac{8}{3},\; \tau_e^* = \frac{6}{(\xi_c + 1)^2 - (\xi_c + r_n^*)^2}\, \frac{(\xi_c + 1)^2}{8\,\xi_c + 11} \tag{10}$$

However, it was numerically observed in [5, 12] that Eq. (8) is not reliable in the limit of droplet radius approaching the nucleation value. As proved in [12], this is due to the assumption that the renewal time τ_{swe}^*, associated to coalescence events, is a constant. Indeed, numerical results of [12] shows that the sweeping time linearly depends on the droplet radius. Assuming $\tau_{swe}^* = \tau_e^*\, r^*$ and solving the droplet population balance, Eq. (7), gives the updated size distribution of small droplets:

$$n_r^* = N_r^*(1)\, \frac{r^* + \xi_c}{1 + \xi_c} \exp\left[A\,(1 - r^*) + A\,\xi_c\,\log\left(\frac{1}{r^*}\right)\right] \tag{11}$$

where A, τ_e^* are the same as Eqs. (9) and (10).
Figure 1(a) shows the literature, theoretical correlation, Eq. (8), valid for small size distribution, while the updated correlation, Eq. (11), which assumes that the sweeping time is a function of the drop radius, is shown if Figure 1(b). Note that an higher number of droplets per unit surface (i.e. higher value of n_r^* for any $r^* < 1$) is always predicted, independently on the imposed ξ_c, by the updated correlation, Eq. (11), because the small droplets are renewed faster due to the higher sweeping frequency.

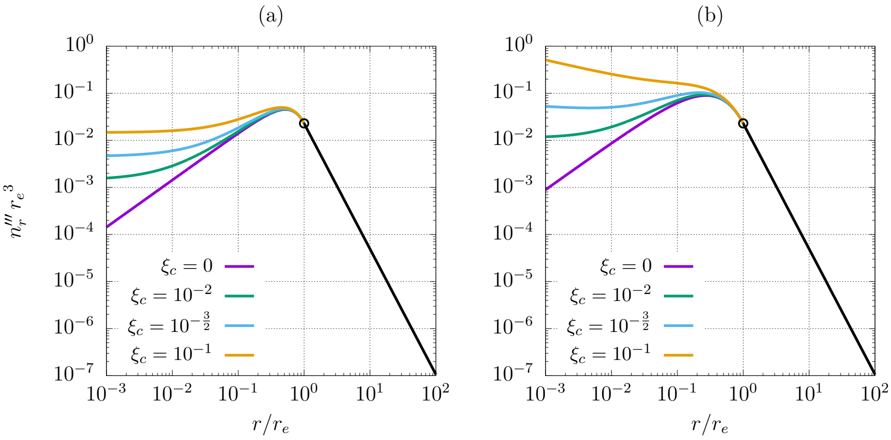

Figure 1. Small droplet population at different values of normalized coating thermal conductivity ξ_c: constant sweeping time (a), sweeping time varying linearly with droplet radius (b). Black line denotes the large droplet population. $r_n^* = 10^{-3}$, $r_{max}^* = 10^2$.

3. Result

Dropwise condensation over a hybrid surface, composed of alternate hydrophobic-hydrophilic vertical stripes, was numerically investigated. It was assumed that the solution of a localized portion of hydrophobic stripe is statistically representative of the whole hydrophobic domain. The hydrophilic stripes were implemented through sections $x^* = 0, L_D^*$ via the dedicated boundary condition, while periodic conditions were imposed through $y^* = 0, H^*$, with $H^* = H/r_e$ being the computational domain height. The integration time step was set to $\Delta t^* = 5 \times 10^{-3}$, in order to achieve accurate statistical information for the smallest droplets. The non-dimensional nucleation radius was set to $r_n^* = 10^{-2}$, while the non-dimensional coating resistance was set to $\xi_c = 10^{-1}$, which falls in the range of practical applications. The hydrophobic width was set to $L_D^* = 200$, which gives a dimensional value of $L_D = 1\,\text{mm}$ for reasonable nucleation density of $\rho_n = 10^{10}\,\text{m}^{-2}$, while $H^* = 3\,L_D^*$ ensures statistically relevant results. The static contact angle over hydrophobic domain was set to $\theta = 120°$, according to the experimental test case of [1]. The droplet population at successive instants is shown in Figure 2. Note that the migration of the largest droplet to the hydrophilic region, where a continuous film regime allows for fast condensate drainage, ensures hydrophobic surface renewal and, thus, enhances heat transfer. The time-averaged drop size distribution and the sweeping time are traced as a function of the drop radius:

$$n_r^*(r^*) = \frac{1}{n_t} \sum_{i=0}^{n_t} \frac{N_{dro}(r^*, r^* + \Delta r^*)}{L_D^*\, H^*\, \Delta r^*}, \; \tau_{swe}^*(r^*) = \left[\frac{1}{\Delta t^*} \sum_{i=0}^{n_t} \frac{N_{swe}(r^*,\, r^* + \Delta r^*)}{N_{dro}(r^*,\, r^* + \Delta r^*)} \right]^{-1} \tag{12}$$

where N_{dro} is the actual number of droplets with radius ranging in $[r^*,\, r^* + \Delta r^*]$ and N_{swe} is the number of droplets with radius ranging in $[r^*,\, r^* + \Delta r^*]$ coalescing during i−th time step. The numerical drop size distribution is compared with the theoretical correlations in Figure 3(a). The empirical correlation of Le Fevre and Rose [10] (black line) is able to accurately predict the size distribution of large droplets, while Eq. (8), derived following [11] under the assumption of constant sweeping time, underestimates the effective size distribution of the small droplets. On the other hand, an accurate prediction of the numerical small size distribution is achieved via the updated correlation, Eq. (11), which assumes the sweeping period τ_{swe}^* to be proportional to the drop radius. As a proof of the goodness of Eq. (11), Figure 3(b) verifies that the computed sweeping time due to coalescence linearly depends on the droplet radius when

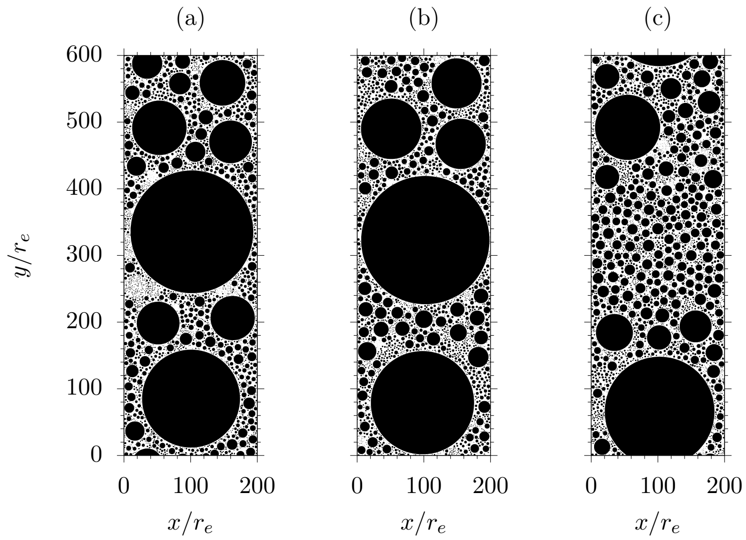

Figure 2. Droplet population over hydrophobic domain at successive instants: $t^* = 1180$ (a), $t^* = 1215$ (b), $t^* = 1250$ (c). $L_D^* = 200$, $\theta = 120°$, $\xi_c = 10^{-1}$.

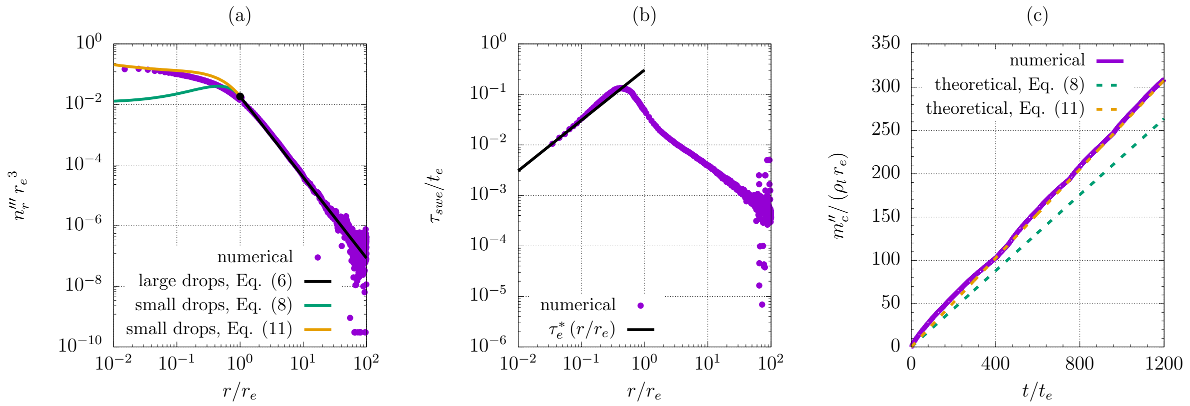

Figure 3. Numerical drop size distribution (markers) versus correlations (lines) (a); sweeping time due to coalescence as a function of droplet radius (b); computed condensate mass as a function of time (continuous line) versus PBM (dashed lines) (c). $L_D^* = 200$, $\theta = 120°$, $\xi_c = 10^{-1}$.

$r^* \leq 1$. Figure 3(c) compares the computed cumulative condensate mass with the one predicted via the Probability-Based Model (PBM),

$$\dot{m}_c^* = \frac{\dot{m}_c''}{(\rho_l \, r_e / t_e)} = 2\,\pi\,(1 - \cos\theta) \left[\int_{r_n^*}^{1} n_r^* \, G^* \, r^{*2} \, \mathrm{d}r^* + \int_{1}^{r_{max}^*} N_r^* \, G^* \, r^{*2} \, \mathrm{d}r^* \right] \tag{13}$$

where n_r^* was evaluated both via Eq. (8) and via Eq. (11), proving that the latter provides a better estimate of the effective condensing flux, while a discrepancy of about 20% was observed if the literature correlation, Eq. (8), is used.

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4. Conclusion

Numerical investigation of dropwise condensation of steam over a hybrid surface, characterized by alternate vertical hydrophobic-hydrophilic stripes, was conducted via a high fidelity, in-house Lagrangian code, previously developed and validated. The numerical size distribution of small droplets was successfully compared with the updated correlation, Eq. (11), derived from the solution of the population balance assuming that the droplet sweeping time is proportional to its radius. On the other hand, it was shown that the literature correlation, Eq. (8), does not provide an accurate estimate. The physical robustness of the assumption that the sweeping time linearly depends on the droplet radius was also verified via postprocess of numerical results. Furthermore, it was shown that appropriate statistical information is crucial for the development of robust Probability-Based Models (PBM), which allow an estimate of the heat transfer performances of hydrophobic surfaces and potentially represent an interesting tool for the design of the hybrid surface geometry. Indeed, PBMs have the advantage of low computational cost, compared to numerical approach based on Individual-Based Models (IBM), and do not require extensive experimental campaigns, but still fail in the solution of complex problems such as hybrid surface optimization. In perspective, the frequency of the droplets migrating to the hydrophilic region should also be analyzed, since it allows the prediction of the condensate flow rate removed by hydrophilic stripes. Coupled with a dedicated modelization of the film regime over the hydrophilic stripes, such an analysis would provide an accurate prediction of the flooding threshold (i.e. liquid overflowing the hydrophilic stripes), which negatively affects the heat transfer performance of the hybrid surface. This would allow the full modelization of hybrid hydrophobic-hydrophilic surfaces via simplified, statistically based models such as PBMs.

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