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Numerical simulation of dropwise condensation over hydrophobic surfaces using vapor-diffusion model

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Abstract. Dropwise condensation of humid air over hydrophilic and hydrophobic surfaces is numerically investigated using a phenomenological, Lagrangian model. Mass flux through droplets free surface is predicted via a vapor-diffusion model. Validation with literature experimental data is successfully conducted at different air humidities and air velocities. The accuracy of the implemented condensation model is compared with a standard analogy between convective heat and mass transfer, showing that the latter is not able to predict heat transfer performances in the investigated air velocity range.

1. Introduction

Dropwise condensation (DWC) is involved in several engineering applications, such as the evaluation of the performances of HVAC finned dehumidification devices [1, 2] or safety issue related to visibility through fogged automotive windshields and projector parabolas [3]. New technologies, including micro and nano-structured hydrophobic surfaces, has been developed in the last few decades, in order to promote DWC [4]. The simulation of heat transfer in HVAC devices may help during design process, but requires a multiscale approach, going from the molecular scale, related to the interaction between drops and solid surface, up to the macroscale related to the fluid flow around the device. Here, an efficient phenomenological model, based on a simplified modeling of the smaller scale physics, is used to investigate moisture condensation over a solid substrate. The model, already applied by the authors to pure steam condensation [5], is here updated, with a vapor-diffusion model used to estimate the mass flux through drop free surface. Validation with literature experimental data involving DWC over hydrophilic and hydrophobic surfaces is conducted. The analysis confirms that, at least in the considered flow conditions, the condensate estimate via vapor diffusion model is more accurate than a standard analogy between convective heat transfer at the wall and mass transfer on the droplet surface.

2. Mathematical model

The droplet evolution is simulated via a phenomenological model, that approximates the main physical mechanisms through the following procedure: generation of nuclei at random locations (only dry spots are active); growth of the whole droplet population due to condensation; coalescence check; droplet movement check, taking into account coalescence along moving path; next time step. Nucleation step requires the knowledge of the number of nucleating sites. Since coalescence becomes significant when droplet radius approaches a critical value



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$r_{cr} \sim (2\sqrt{\rho_{nuc}})^{-1}$ [6], which is usually much higher than the characteristic nucleation radius r_{nuc} , the initial radius of newly nucleated droplets is set to a safe value of $r_0 = r_{cr}/4$. The integration time step is, thus, defined by the interval needed by the droplets to grow from r_{nuc} to r_0 ,

$$\Delta t_0 = \frac{r_0 - r_{nuc}}{u_r}, u_r = \frac{dr}{dt} = \frac{\dot{m}''}{\rho} \frac{2}{(2 + \cos\theta)(1 - \cos\theta)} \quad (1)$$

where θ is the droplet averaged contact angle and \dot{m}'' is the condensation mass flux. After nucleation, droplets grows due to condensation occurring at liquid-air free surface and coalescence between adjacent droplets.

2.1. Momentum balance

The actual contact angle ranges between θ_{max} and θ_{min} along contact perimeter, according to [7, 8], due to deformation induced by external forces. In condensation, it can be assumed that θ_{max} approaches the advancing contact angle θ_{adv} , while θ_{min} derives from the balance between gravitational force, drag and rigidity force:

$$\cos\theta_{min} = \cos\theta_{adv} + \frac{|\mathbf{F}_g + \mathbf{F}_D|}{F_\sigma} \quad (2)$$

Fully derivation of F_σ and F_g can be found in [9, 10], while F_D is estimated from the known air velocity u_a and drag coefficient c_D for a flow around a leaning spherical cap. The droplet contact angle used in the computation is the average between θ_{max} and θ_{min} . Droplet motion is triggered when θ_{min} is lower than the receding contact angle θ_{rec} . In such a case, $\theta_{min} = \theta_{rec}$ and the droplet velocity is computed from a power balance between gravity force work Φ_g , surface tension work Φ_σ , drag force work Φ_D and viscous dissipation Φ_μ , given by core and wedge contributions [11, 1].

2.2. Thermal energy balance

The thermal energy balance is solved for each droplet, assuming uniform temperature T_w of the solid substrate. Thus, conduction through liquid droplet equals the sum of latent heat of condensation and sensible heat flux due to forced convection,

$$\lambda_l r (T_i - T_w) = \dot{m}'' S_i h_{lat} + h_c S_i (T_\infty - T_i) \quad (3)$$

where T_i is the free surface temperature, T_∞ is the environmental temperature, h_{lat} is the latent heat of condensation and h_c is the convective heat transfer coefficient. According to [12, 13], \dot{m}'' is evaluated assuming that the growth of droplets is governed by diffusion of water molecules to the liquid-vapor free surface:

$$\dot{m}'' = \eta f(\theta) \frac{D(c_\infty - c_i)}{r}, f(\theta) = 0.5 + 0.3105 \frac{\pi}{\theta} \quad (4)$$

$$c = \frac{\rho_v x}{\rho_v/\rho_a + x}, x = 0.622 \frac{\phi p_{sat}}{p_{atm} - \phi p_{sat}} \quad (5)$$

where c_i is the mass concentration of vapor at droplet free surface, calculated assuming saturated vapor at interface temperature, and c_∞ is the vapor concentration far away. The correction coefficient η , computed according to [12], models the interactions between neighbour droplets, that reciprocally affect the vapor concentration distribution.

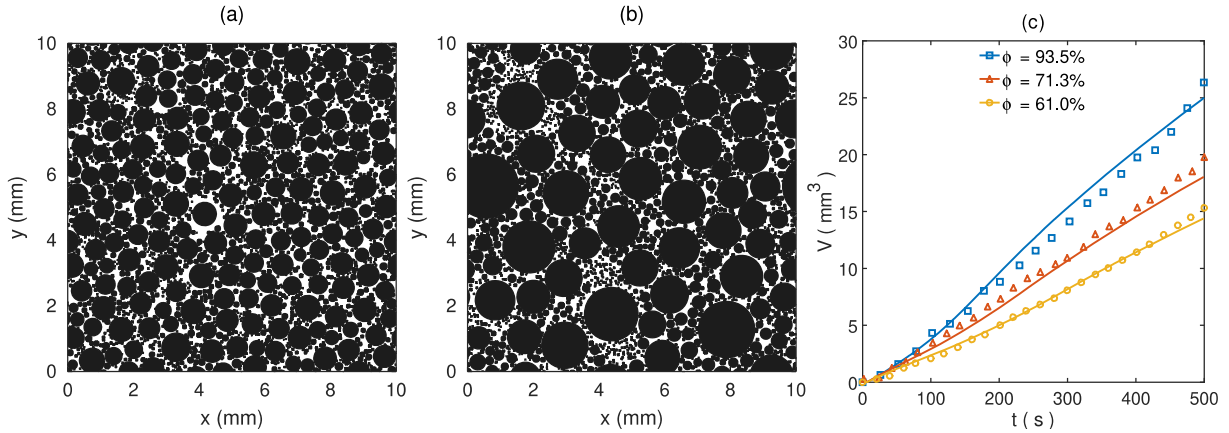


Figure 1. Drop population at $t = 250$ s (a) and $t = 500$ s (b): $\phi = 93.5\%$. Validation with experimental results (markers) of [14]: condensate volume evolution for different humidities (c). Horizontal plate, $\theta_s = 85^\circ$, $\rho_{nuc} = 1.3 \times 10^8 \text{ m}^{-2}$.

3. Results

The vapor-diffusion-driven condensation model is validated with experimental results involving DWC of humid air over both hydrophilic and hydrophobic surfaces. The `OpenMP` library is used in order to parallelize the source code and, thus, speed up computations on a shared memory machine. The experimental setup of [14] is first replicated. Thus, a horizontal flat plate, characterized by a solid-liquid static contact angle equal to $\theta_s = 85^\circ$, is considered and different air humidities ϕ are investigated. The initial plate temperature is set to $T_w = 1.55^\circ\text{C}$, while environmental temperature is $T_\infty = 28^\circ\text{C}$. Periodic conditions are applied through the boundaries of the computational domain. The density of nucleating sites, which is the only free parameter, is set to $\rho_{nuc} = 1.3 \times 10^8 \text{ m}^{-2}$. The evolution of the condensate volume is shown in figure 1(c): the predicted trends agree with experimental results, that are reduced to the simulated plate dimension, for all the investigated values of ϕ . However, only 500 s can be simulated, due to occurrence of deformed drops and puddles, with eventual switch to filmwise mode, experimentally observed in [14]. Figures 1(a) and 1(b), qualitatively similar to experimental frames [14], show the evolution of the droplet population, with heterogeneous droplets of increasing size forming due to combined effect of condensation and coalescence. The experiments of [15] are also replicated. Thus, a hydrophobic $350 \times 250 \text{ mm}^2$ vertical plate, characterized by $\theta_s = 125^\circ$ and crossed by an horizontal flow of humid air, is considered. The air relative humidity is set to $\phi = 85\%$, while characteristic air velocity u_a up to 5 m/s is investigated. Substrate and environmental temperatures are respectively set to $T_w = 10^\circ\text{C}$ and $T_\infty = 30^\circ\text{C}$, according to [15]. A portion of $20 \times 20 \text{ mm}^2$ vertical plate, with periodic conditions applied at lateral boundaries, is simulated to reduce computational costs. The time averaged heat flux,

$$q'' = \frac{h_{lat}}{S_{plate}} \frac{\sum_n \dot{m}_n \Delta t_n}{\sum_n \Delta t_n} + h_c (T_\infty - T_w), \quad \dot{m} = \sum_k^{n_{drop}} \dot{m}_k'' S_{i,k} \quad (6)$$

is computed and the corresponding global heat transfer coefficient plotted in figure 2(c) as a function of undisturbed air velocity, showing almost a perfect agreement with literature experimental data of [15]. On the other hand, a standard analogy with the convective heat flux through the wall leads to a qualitatively different heat transfer coefficient profile, as shown in the same figure 2(c). Droplet motion, which is triggered as shown by figures 2(a) and 2(b), is driven by gravitational forces, while the effect of shear induced by the horizontal air flow is

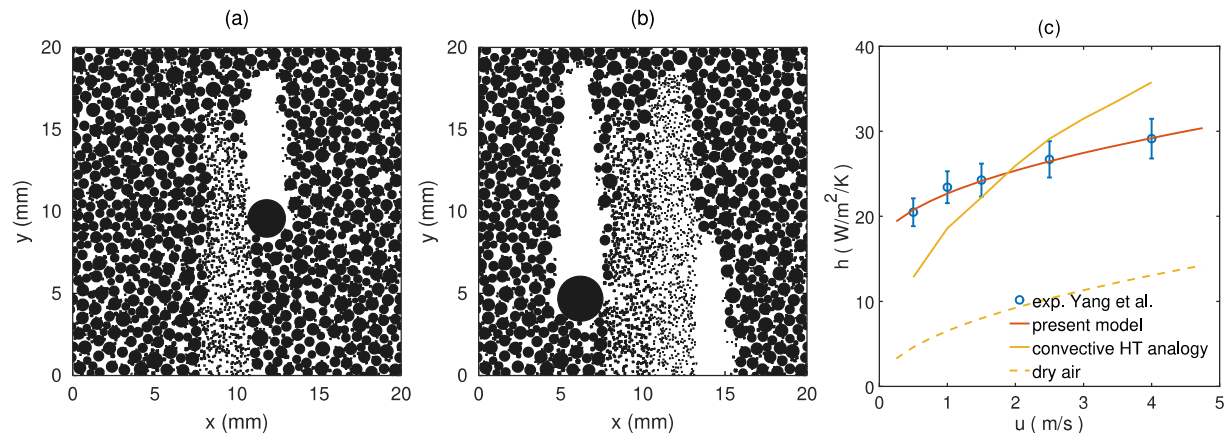


Figure 2. Drop population at two successive instants, time elapse of about 30 s, $u_a = 1$ m/s (a), (b). Validation with experimental results of [15]: global heat transfer coefficient versus air velocity (c). Vertical plate, $\theta_s = 125^\circ$, $\phi = 85\%$, $\rho_{nuc} = 10^7$ m⁻².

negligible, as also observed in [15].

4. Conclusion

A phenomenological model for the prediction of droplet pattern evolution is validated with experimental data involving DWC on both hydrophilic and hydrophobic surfaces. The model, which is an evolution of a numerical scheme previously applied to DWC of pure steam, is here extended to moisture condensation. In addition, a thermal energy balance is implemented for each droplet and the resulting condensation flux estimated through a vapor-diffusion model. The results show a good agreement with experimental data and, thus, the model is able to reproduce important features of the physical problem, including droplet motion, coalescence and condensation mechanism. A critical point is the definition of condensing rate on the droplet surface: under the present condition of low velocities, a vapour diffusion approach is more accurate than a standard analogy with the convective heat transfer. Future work will focus on the proper definition of condensing mass flow under different air velocity conditions and on the optimization of hybrid hydrophilic-hydrophobic surfaces.

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