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 that 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...
\[ r_{cr} \sim \left( 2 \sqrt{\frac{1}{\rho_{nuc}}} \right) \] [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 \( r_0 \),

\[ \Delta t_0 = \frac{r_0 - r_{nuc}}{u_r}, \quad u_r = \frac{\dot{m}''}{\rho \left( 2 + \cos \theta \right) \left( 1 - \cos \theta \right)} \] (1)

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

\[ \cos \theta_{min} = \cos \theta_{adv} + \frac{|F_g + F_D|}{F_\sigma} \] (2)

Fully derivation of \( F_\sigma \) 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 \( \theta_{max} \) and \( \theta_{min} \). Droplet motion is triggered when \( \theta_{min} \) is lower than the receding contact angle \( \theta_{rec} \). In such a case, \( \theta_{min} = \theta_{rec} \) and the droplet velocity is computed from a power balance between gravity force work \( \Phi_g \), surface tension work \( \Phi_\sigma \), drag force work \( \Phi_D \) and viscous dissipation \( \Phi_\mu \), 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,

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

where \( T_i \) is the free surface temperature, \( T_\infty \) 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:

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

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

where \( c_i \) is the mass concentration of vapor at droplet free surface, calculated assuming saturated vapor at interface temperature, and \( c_\infty \) is the vapor concentration far away. The correction coefficient \( \eta \), computed according to [12], models the interactions between neighbour droplets, that reciprocally affect the vapor concentration distribution.
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 $\phi$ are investigated. The initial plate temperature is set to $T_w = 1.55^\circ$C, while environmental temperature is $T_\infty = 28^\circ$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 $\rho_{nuc} = 1.3 \times 10^8$ 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 $\phi$. 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 $350 \times 250$ 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 $T_w = 10^\circ$C and $T_\infty = 30^\circ$C, according to [15]. A portion of $20 \times 20$ mm$^2$ vertical plate, with periodic conditions applied at lateral boundaries, is simulated to reduce computational costs. The time averaged heat flux,

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

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
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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