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Abstract. It is well known that dropwise condensation (DWC) can achieve heat transfer coefficients (HTCs) up to 5-8 times higher as compared to filmwise condensation (FWC). The interaction between the condensing fluid and the surface defines the condensation mode. Coatings that present low surface energy and high droplet mobility are a solution to promote DWC instead of FWC on metallic substrates. In the present paper, the effect of vapor velocity during DWC has been investigated over a sol-gel coated aluminum surface and a graphene oxide coated copper surface. Heat transfer coefficients and droplets departing radii have been measured at constant saturation temperature and heat flux, with average vapor velocity ranging between 3 m s^{-1} and 11 m s^{-1}. A recent method developed by the present authors to account for the effect of vapor velocity on the droplet departing radius is here presented. The results of the proposed method, when coupled with the Miljkovic et al. [1] heat transfer model, are compared against experimental data.

1. Introduction

The promotion of dropwise condensation (DWC) in place of the traditional filmwise condensation (FWC) is a passive solution to enhance the efficiency of heat exchangers. DWC involves the formation of discrete liquid droplets on the condensing surface that must be removed by an external force as gravity or vapor drag force. The presence of droplets, instead of a continuous liquid film, allows to increase the heat transfer coefficient (HTC) by 5-8 times as compared to FWC [2]. The overall heat transfer during DWC depends on both the heat flow rate through a single drop and the droplet population [1,2]. Since most of heat exchanged is associated to small droplets [3], promoting droplets sweeping by reducing the departing radius r_{max} can lead to an increase of the condensation HTC. The departing radius is the outcome of a force balance between gravity, drag and adhesion forces. With the goal to reduce r_{max}, the drag force can be increased by acting on the vapor velocity. In the literature, there is a lack of data dealing with the influence of the vapor velocity on DWC and the available studies show that an increase of the steam velocity leads to an increase of the condensation HTC [4–6].

In the present paper, DWC has been experimentally investigated on aluminum and copper substrates at different values of steam velocity. A new approach developed by Tancon et al. [4] for the calculation of the droplet departing radius in presence of non-negligible vapor velocity is here presented. The new formulation of r_{max}, coupled with the Miljkovic et al. [1] heat transfer model, has been used to predict the effect of the vapor velocity on the heat transfer coefficient during DWC. Calculated values have

been assessed considering present data and other independent data sets by Sharma et al. [5] and Tanner et al. [6].

2. Experimental measurements

The test rig is a two-phase thermosyphon loop (figure 1). Pure saturated steam is produced in the boiling chamber where four adjustable electrical heaters can be regulated up to 4 kW in order to control the vapor velocity. Measuring the electrical power supplied to the boiling chamber, it is possible to determine the mass flow rate of steam and thus the mean vapor velocity (v_v) at the inlet of the test section. The boiling chamber is connected to the test section by steel pipes with heated walls to avoid vapor condensation prior the test section. The steam enters the test section in saturated conditions and then it condenses over a vertical metallic surface (50 mm x 20 mm). Six thermocouples are placed inside the specimen at two different depths from the condensing surface (z_1 = 1.3 mm and z_2 = 2.8 mm). Based on the thermocouples readings, the Fourier law is used to evaluate the local heat flux (q_{loc}) at three longitudinal locations along the specimen and to extrapolate the local surface temperature ($T_{wall,loc}$). The local HTC is obtained from the following three equations:

$$q_{loc} = \lambda_{al} \frac{\Delta T}{\Delta z} \tag{1}$$

$$T_{wall,loc} = T_{z1} + (T_{z1} - T_{z2}) \frac{z_1}{z_2 - z_1} \tag{2}$$

$$\mathrm{HTC_{loc}} = \frac{q_{loc}}{(T_{sat} - T_{wall,loc})} \tag{3}$$

In equation (1), λ_{al} is the aluminum thermal conductivity, T_{z1} and T_{z2} in equation (2) are the temperatures measured respectively at depths z_1 and z_2 and, in equation (3), T_{sat} is the steam saturation temperature. In the present paper, the arithmetical mean of the three local HTCs (average HTC) is considered over the whole surface of the specimen. The average heat flux over the sample can be also checked considering the heat balance at the secondary cooling fluid ("Cooling water 1" circuit in figure 1). Each experimental data here reported is the mean of 480 readings taken at 1 Hz frequency; uncertainty bars are calculated with a coverage factor k = 2. Additional information about the experimental apparatus and the data reduction technique can be found in [7].

DWC has been investigated over two metallic samples: an aluminum sol-gel coated sample (Tancon et al. [4]) and a copper substrate on which a reduced graphene oxide coating has been deposited (Colusso et al. [8]). The two surfaces have been characterized by means of dynamic contact angles measured by sessile drop method. After functionalization, the two surfaces were weakly hydrophobic displaying different droplet mobility. The advancing contact angles were similar ($\theta_a \approx 90°$), but the receding contact angles were $\theta_r \approx 65°$ for the coated aluminum and $\theta_r \approx 30°$ for the copper sample. Due to the lower contact angle hysteresis, water droplets present a greater mobility in the case of the sol-gel coated aluminum sample. Condensation tests have been performed maintaining a constant saturation temperature (107 °C), a constant heat flux (335 kW m^{-2} and 520 kW m^{-2} respectively for the aluminum and the copper specimen) and varying the vapor velocity between 3 m s^{-1} and 11 m s^{-1}. A high-speed camera coupled with a LED illumination system has been used for the visualization of the DWC process.

Images reported in figure 2 have been recorded on the coated copper sample at two different values of the vapor velocity (v_v = 3 m s^{-1} and v_v = 11 m s^{-1}). The departing droplets are highlighted with red circles. When the vapor velocity increases from 3 m s^{-1} to 11 m s^{-1}, the droplet departing radius decreased by 35% in the case of the aluminum sample and by 25% in the case of the copper sample (figure 2). Furthermore, the droplet shape becomes less elongated due to the drag force of the vapor that pushes the drop. Because of the different values of contact angle hysteresis, the measured departing radius, at both vapor velocities, is found to be higher in the case of the copper sample.

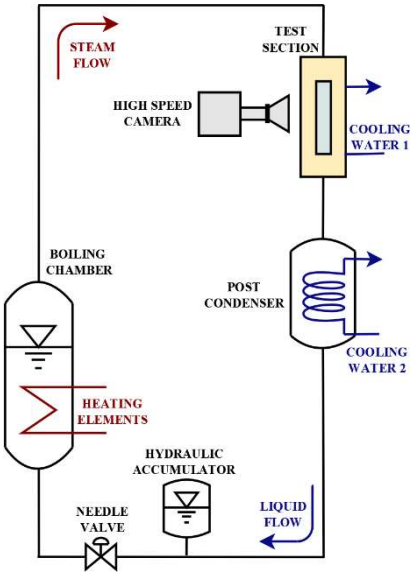
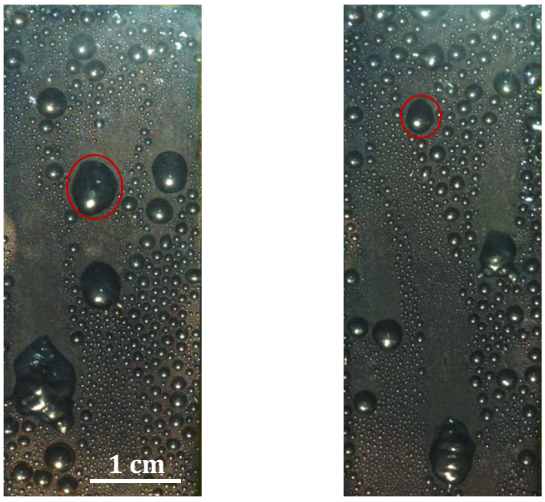


Figure 1. Schematic of the thermosyphon loop used during dropwise condensation tests.



$v_v = 3$ m s^{-1}
$r_{max} = 2.1$ mm

$v_v = 11$ m s^{-1}
$r_{max} = 1.6$ mm

Figure 2. Images of DWC taken on the copper sample at two steam velocities (3 m s^{-1} and 11 m s^{-1}). The departing droplets are marked with red circles. For each v_v, the respective value of departing radius r_{max} is reported.

3. Modeling the effect of vapor velocity on the sweeping mechanism

Steady-state dropwise condensation heat flux can be evaluated by integrating the product of individual droplet heat transfer rate and drop size density function between r_{min} and r_{max}. When the drag force induced by vapor velocity is added into the balance of forces acting on a single droplet, the departing radius can be calculated, as described in Tancon et al. [4], from equation (4):

$$r_{max} = \frac{-C + \sqrt{C^2 + 4AB}}{2B} \qquad \begin{aligned} A &= 2k_c\sigma \sin\theta_e \,(\cos\theta_r - \cos\theta_a) \\ B &= \pi \rho_l g \,(2 - 3\cos\theta_e + \cos^3\theta_e)/3 \\ C &= \rho_v v_v^2 C_d \,(\theta_e - \sin\theta_e \cos\theta_e)/2 \end{aligned} \tag{4}$$

where σ is the surface tension of the condensing fluid, k_c is the retention factor, θ_e is the equilibrium contact angle (θ_e in radians), ρ_l and ρ_v are respectively the density of the liquid and vapor phase, g is the gravitational acceleration and C_d is the drag coefficient. The drag coefficient, for the specific case of a droplet placed over the wall of a rectangular cross section channel (characterized by a large width-to-height ratio), was estimated in [4] from numerical simulations as:

$$C_d = 5.6053 \left[(L_c/l_{dr})^{-4/3} \, \mathrm{Re}_{dr}^{-1/6}\right] + 0.1754 \tag{5}$$

where L_c/l_{dr} is the ratio of channel height to droplet height and Re_{dr} is the droplet Reynolds number.

Heat transfer results are reported in figure 3 where the experimental HTC is plotted against vapor velocity. Both the aluminum and the copper surface were able to promote and sustain DWC exhibiting heat transfer coefficients respectively higher than 100 kW m^{-2} K^{-1} and 170 kW m^{-2} K^{-1}. An increase of the vapor velocity leads to a reduction of the average drop size (figure 2), with an improvement of the condensation HTC (figure 3) due to the presence of more small droplets on the condensing surface [3]. The HTC was increased by about 15% when increasing the vapor velocity from 3 m s^{-1} to 11 m s^{-1}.

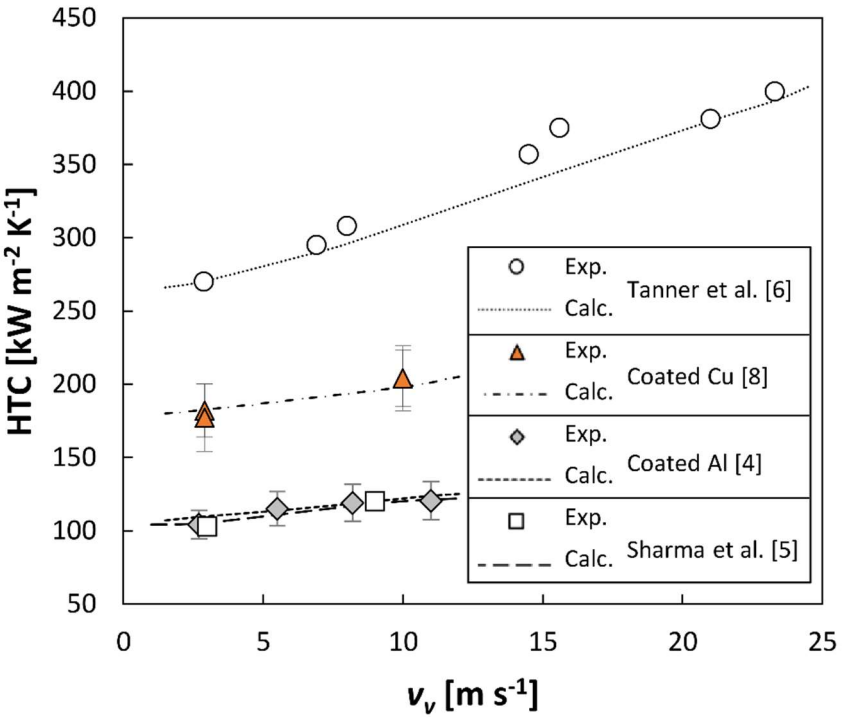


Figure 3. Heat transfer coefficients measured during DWC on the aluminum sample [4] and on the copper sample [8] plotted vs vapor velocity. Data by Sharma et al. [5] and data by Tanner et al. [6] are also reported. Dotted lines show HTC values predicted by the present equation for the droplet departing radius coupled with the Miljkovic et al. [1] model.

As a further step, the present formulation for the droplet departing radius has been coupled with the Miljkovic et al. [1] model to predict the HTC in presence of vapor velocity. Calculated values have been assessed using the present experimental data and those by Sharma et al. [5] and Tanner et al. [6]. The proposed calculation method is able to predict the HTC increase due to vapor velocity, with a mean relative deviation between the calculated and the experimental values below 5%.

4. Conclusions

The effect of steam velocity during DWC has been experimentally investigated over two different specimens: a sol-gel coated aluminum sample ($\theta_a \approx 90°$, $\theta_r \approx 65°$) and a graphene oxide coated copper sample ($\theta_a \approx 90°$, $\theta_r \approx 30°$). Flow visualizations and HTC measurements have been performed at a constant heat flux (335 kW m^{-2} and 520 kW m^{-2} respectively for the aluminum and copper sample), saturation temperature equal to 107 °C and vapor velocity between 3 m s^{-1} and 11 m s^{-1}. On both the surfaces, due to the drag force of the vapor, the droplet departing radius decreases as the vapor velocity increases, while the HTC increases. A new equation to account for the effect of vapor velocity on the droplet departing radius has been proposed. Predicted values of HTC obtained coupling the departing radius equation with the Miljkovic et al. [1] heat transfer model have been compared against present HTC measurements and against two other datasets by Sharma et al. [5] and Tanner et al. [6]. The HTC calculation procedure provides an accurate prediction of the effect of vapor velocity.

Acknowledgments
This work is supported by the European Space Agency through the MAP Condensation program ENCOM (AO-2004–096) and by the Department of Industrial Engineering through the project BIRD187743.

References
[1] Miljkovic N, Enright R and Wang E N 2013 *J. Heat Transfer* **135** 111004
[2] Rose J W 2002 *Proc. Inst. Mech. Eng. Part A J. Power Energy* **216** 115–28
[3] Parin R, Sturaro M, Bortolin S, Martucci A and Del Col D 2019 *Int. J. Therm. Sci.* **144** 93–106
[4] Tancon M, Parin R, Bortolin S, Martucci A and Del Col D 2021 *Int. J. Heat Mass Transf.* **165** 120624
[5] Sharma C S, Stamatopoulos C, Suter R, Von Rohr P R and Poulikakos D 2018 *ACS Appl. Mater. Interfaces* **10** 29127–35
[6] Tanner D W, Potter C J, Pope D and West D 1965 *Int. J. Heat Mass Transf.* **8** 419–26
[7] Parin R, Tancon M, Mirafiori M, Bortolin S, Moro L, Zago L, Carraro F, Martucci A and Del Col D 2020 *Appl. Therm. Eng.* **179** 115718
[8] Colusso E, Tancon M, Cazzola L, Parin R, Agnoli S, De Boni F, Pelizzo M G, Della Gaspera E, Del Col D and Martucci A 2021 *Nano Sel.* **2** 61–71