Moist Air Condensation on Inclined Hydrophobic Metallic Surfaces: Simulation & Experiments

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Abstract. Atmospheric Water Generators (AWGs) are popularly used for harvesting portable water from atmospheric air of hot, humid and arid regions of the world. Hydrophobic metallic surfaces are preferred in AWGs systems because condensation of moist air on/underneath these surfaces have high efficacy. There are several issues to fabricate hydrophobicity on metallic surfaces. Although with the advent of Nanotechnology and thin film coating technologies, the fabrication of hydrophobicity on metallic surfaces has become easier and realizable in the recent era. In this manuscript, a comprehensive mathematical model is developed for simulating the moist air condensation in the form of droplets on various substrates and in different environmental conditions. The experiment is carried out for validation of the present model. Post validation, the effect of surface hydrophobicity, relative humidity and degree of sub-cooling on the condensation rate are addressed. The simulation results show that vertically orientated metallic surfaces having a high contact angle along with low contact angle hysteresis are efficient for condensing unit. Larger condensation rates are observed at higher relative humidity and a high degree of sub-cooling. This research is helpful for designing efficient and effective AWGs for the hot and humid region.

1. Introduction

Earth’s atmospheric air contains more than 12,800 trillion liters water in the form of moisture (1). This amount of water is enough to fulfill the requirements of entire flora and fauna living on the Earth if it is extracted effectively and efficiently. It is a green technology, feasible, portable, compatible with existing systems and it does not produce any concentrated hypersaline wastewater discharge. However, high energy requirements (2260 Kilojoules/Kg of water) and low transport coefficients of the condensation process hinders its deployment in large scale applications. With the advent of advanced instrumentation and fabrication processes, extraction of water via condensation from moist air is a possible and reliable technology (2). With the acquaintance of the fact that the transport coefficients of dropwise condensation are higher as compared to filmwise condensation (3). Emphases are been laid on the fabrication of hydrophobicity on metallic surfaces because they promote condensation in drop mode and have high thermal conductivity (4). Several studies have been carried out to demonstrate the dropwise condensation of pure vapor however, the literature is limited on moist air condensation in the form of drop for procuring fresh water from the atmosphere.

In contrast to the pure vapor, condensation of moist air is a complex process because of NCGs. The vapor-liquid interface is impermeable to the NCGs and these gases get accumulate during condensation near the interfaces forming NCG diffusion layer (5). Hence, NCGs plays a crucial role in moist air condensation for water harvesting applications. Several researcher and scientists (6, 7) have
experimentally and theoretically demonstrated condensation of steam. They reported that the heat transfer coefficient of dropwise condensation process reduces due to the presence of NCGs in the air-steam mixture. Recently, some researchers (8-10) have reported the effect of NCGs in moist air at controlled environmental conditions. Baghel et al. (8) experimentally investigated the effect of static contact angle on the moist air condensation rate. Fouda et al. (9) experimentally and theoretically investigated the condensation of water vapor present in moist air around the horizontal pipe. Their study shows that condensation rate increases with increase in moist air mass flow rate, relative humidity and degree of sub-cooling. Zheng et al. (10) developed a mathematical model for dropwise condensation of moist air for hemispherical droplet using the kinetic theory of gases and law of continuum fluid dynamics formulated by the Knudsen layer and continuum region.

To the best of author’s knowledge, a holistic mathematical model for moist air condensation in drop mode is not reported in the literature. In this context, a comprehensive mathematical model is developed to simulate the moist air condensation in the form of droplets on the vertical cold surface under atmospheric conditions. The skeleton of the mathematical model is similar to the one reported by other elsewhere (11) for pure vapor condensation in drop mode. Current moist air condensation model is an extension of the author’s previous work (12) in which the presence of NCG is also taken into consideration in the simulation of dropwise condensation. An additional resistance acts due to the formation of the Knudsen layer near the three-phase contact line due to the accumulation of NCGs at the interface. Author’s previous drop growth model is modified as given in Equation 1, considering the various assumptions as reported previously (12).

$$\frac{dr}{dt} = \frac{4(T_a - T_r)}{\rho_d (H_o)} \times \left[ \frac{r_r \beta \theta_{avg} (1 - \cos \theta_{avg})}{k_c (r_r + \beta \theta_{avg})} + \frac{1 - \cos \theta_{avg}}{r_r} \right] \times \left[ \frac{1 - \cos \theta_{avg}}{2 - 3 \cos \theta_{avg} + \cos^2 \theta_{avg}} \right]$$

(1)

**Figure 1.** Flow diagram of dropwise condensation of moist air along with drop COALESC and SLIDE-OFF subroutines.
The water vapor present in moist air is sensibly cooled till the dewpoint before it starts to condense in unsaturated moist air. The value of the $H_v$ in equation 1 for unsaturated air is as follow;

$$H_v = h_v + C_p(T - T_{sat})$$

(2)

The interfacial heat transfer coefficient $h_{int}$ in equation 1 is,

$$h_{int} = \left[\frac{2\beta}{2 - \beta}\right] \left[\frac{h_s^2(\rho_d - \rho_m)}{T_{sat}}\right] \left[\frac{M_m}{2\pi RT_{sat}}\right]^{1/2} \left[1 - \frac{P_v}{2h_s(\rho_d - \rho_m)}\right]$$

(3)

where $\beta$ is the accommodation coefficient, in this study $\beta = 0.001$ is considered for moist air condensation. $T_{sat}$ is the dew point temperature and $T$ is the temperature of moist air. $M_m$, $K_m$ and $\lambda_m$ are molecular weight, thermal conductivity and mean free path of moist air respectively. The properties of moist air are calculated as reported in the literature (13). $\rho_d$, $K_d$ and $r_d$ are density, thermal conductivity, and radius of the droplet.

The presence of NCGs in moist air also alters the droplet size ($r_{crit}$) and terminal velocity ($U$) during drop sliding on a vertically hydrophobic surface. The modified equations are as:

$$r_{crit} = \left[\frac{k \sin \theta_{avg}}{2 - 3 \cos \theta_{avg} + \cos^3 \theta_{avg}}\right] \left[\cos \theta_t - \cos \theta_a\right] \left[\frac{\sigma}{g(\rho_d - \rho_m)}\right]^{1/2}$$

(4)

$$U = \left[\frac{2(F_\parallel - F_\perp)}{C_f \rho_d \pi r_{avg}^2 (1 - \cos^2 \theta_{avg})}\right]^{1/2}$$

(5)

Where $k$ is a coefficient whose value is considered as 0.5 for moist air condensation, $\theta_{avg}$, $\theta_t$ and $\theta_a$ are static, receding and advancing contact angles for droplet respectively. The $C_f$ is evaluated by the law of continuum fluid dynamics where the droplet is considered stationary with respect to moist air surrounding the droplet. The moist air flow at a velocity equal to the terminal velocity of the droplet.

In the present model, primarily various variables are initialized. These variables are thermophysical properties of moist air, physio-chemical properties of condensing surfaces, nucleation site density, relative humidity, time step and a total time of the simulation. In this study nucleation sites of $10^6 \text{ cm}^2$ are randomly distributed on the surface by a random number generator. All the nucleation sites are instantaneously occupied by the droplet of minimum radius ‘$r_{min}$’ on the virgin substrate. Subsequently, droplet whose radius is more than or equal to $r_{min}$ further grow by direct condensation as per equation 1 (solved by 4th order Runga-Kutta method) and coalesce with the neighboring droplets. However, droplets with a radius less than minimum radius evaporate and vanish. Due to direct condensation and coalescence phenomena the size of droplet increases to a limit that the gravity forces eventually surpass the limiting surface tension force at the triple phase contact line of the condensed droplet. This creates an imbalance in forces and as a result, droplet deforms to achieve necessary static balance. In the course of time, the droplet reaches a critical radius and incipient sliding from the vertical hydrophobic condensing surface. It then re-activates the exposed sites created due to drop coalescence and slide-off and provide a minimum radius drop on newly exposed sites. The aforementioned procedure repeats until a dynamic steady-state is reached. The flow diagram of the numerical algorithm is shown in Figure 1. The C++ program is written to carry out simulation as per the proposed algorithm.
Figure 2. Moist air condensation experimental setup (a) schematic diagram (b) photograph of the condensing unit.

The moist air condensation experiments are carried out on chemically etched irradiated metallic surfaces for generating data for code validation. Figure 2 shows the schematic diagram and photograph of the moist air condensation experimental setup. The surface fabrication and experimental procedures are as reported by the author elsewhere (8).

3. Results and discussion
The moist air condensation experiments are carried out on chemically treated irradiated surfaces for validation of the code. Figure 3 and 4 shows the qualitative and quantitative comparison of experiment and simulation results respectively. Both the studies were performed at atmospheric pressure and degree of sub-cooling of 10°C. The controlled temperature and humidity of 30°C and 95% are maintained throughout the studies. In this work, a vertically oriented, 40×40 mm surface is considered for moist air condensation. The static contact angle and contact angle hysteresis on this surface are measured as 154° and 7.5° respectively. Validation results show that the simulation results are in good agreement with the experimental data. Hence the model is appropriate and credible. Figure 3 shows the spatiotemporal droplet distribution on the superhydrophobic condensing surface. Droplet imaging at t = 10 min shows droplet growth by direct condensation and coalescence. However, re-nucleation after droplet slide-off is visualized at time t = 60 min. Figure 4 shows the comparison of experimental and simulation condensation rates. The value of simulation condensation rate is higher than the experimental values due to various assumptions made in the simulation study.

Figure 3. Spatio-temporal drop distribution of moist air condensation experiment and corresponding simulation results.

Figure 4. Quantitative comparison of experimental and simulation results.
Post validation, simulations are carried out for a range of parameters which are not covered in the experimental study. Here the effect of static contact angle, Relative humidity and degree of sub-cooling on condensation rate are investigated. The effect of static contact angle on the condensation rate is shown in Figure 5. The simulation is performed for the controlled operating condition, various values of contact angle and corresponding contact angle hysteresis. The results show that as the static contact angle of surface increases, contact angle hysteresis decreases, drop pinning on surfaces reduces and results into enhanced droplet shedding. Therefore, the condensation rate increases as the static contact angle of the condensing surfaces increases and becomes highest for superhydrophobic surfaces as compared to hydrophilic and hydrophobic surfaces. Figure 6 and 7 shows the effect of relative humidity and degree of sub-cooling on condensation rate respectively. Results show that the condensation rate becomes twice as the relative humidity of moist air increase from 40% to 95%. It is because as the amount of water vapor present in moist air increases, the condensation rate augments with increasing relative humidity. To investigate the effect of degree of sub-cooling the condensation rate is simulated by varying the condensing surface temperature keeping moist air temperature and humidity constant. Results show that the condensation rate linearly increases with increasing degree of sub-cooling.

**Figure 5.** Variation of condensation rate with respect to static contact angle of the condensing surface. Simulation carried out considering \( T_{\text{sat}} = 30^\circ \text{C}, \Delta T = 10^\circ \text{C} \) and RH = 95%.

**Figure 6.** Variation of condensation rate with respect to relative humidity of moist air. Simulation performed considering \( T_{\text{sat}} = 30^\circ \text{C}, \Delta T = 10^\circ \text{C}, \theta = 154^\circ \text{and CAH} = 7.5^\circ \).

**Figure 7.** Variation of condensation rate with respect to degree of subcooling. Simulation performed considering \( T_{\text{sat}} = 30^\circ \text{C}, \text{RH} = 95\%, \theta = 154^\circ \text{and CAH} = 7.5^\circ \).
4. Conclusion
The moist air condensation is a process for extracting the fresh water from the atmosphere of hot and humid regions. The dropwise condensation of water vapor present in moist air is distinct from the condensation of pure water vapor due to the presence of NGCs in moist air. In this work, a mathematical model is developed to simulate the condensation of water vapor present in moist air in the form of droplets. The simulation results were validated against the data obtained from experimental study and good agreement was found between them. Post-validation, parametric studies were carried out to know the effect of static contact angle, relative humidity and degree of sub-cooling on condensation rate. The study concludes that the surfaces of higher contact angle and low contact angle hysteresis are more efficient for the condensation process. Superhydrophobic surfaces with contact angle hysteresis less than 10° promote efficient dropwise condensation and exhibit enhanced droplet shedding. Large condensate rate is estimated at higher relative humidity and a higher degree of sub-cooling.

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References
[1] Bagheri F. Performance investigation of atmospheric water harvesting systems. Water Resources and Industry. 2018;20:23-8.
[2] Clarke NP, C. Camarillo, Atmospheric moisture collection device1992.
[3] Schmidt VE, W. Schurig, and W. Sellschopps. Versuche über die Kondensation von Wasser dampf in Film- und Tropfenform. Forsch Ingenieurwes. 1930;1:53-63.
[4] Lee A, Moon MW, Lim H, Kim WD, Kim HY. Water harvest via dewing. Langmuir: the ACS journal of surfaces and colloids. 2012;28(27):10183-91. Epub 2012/06/27.
[5] Luo X, Fan Y, Qin F, Gui H, Liu J. A new model for the processes of droplet condensation and evaporation on solid surface. International Journal of Heat and Mass Transfer. 2016;100:208-14.
[6] Ma X-H, Zhou X-D, Lan Z, Li Y-M, Zhang Y. Condensation heat transfer enhancement in the presence of non-condensable gas using the interfacial effect of dropwise condensation. International Journal of Heat and Mass Transfer. 2008;51(7-8):1728-37.
[7] Lan Z, R. Wen, A. Wang, and X. Ma. A droplet model in steam condensation with noncondensable gas. International Journal of Thermal Sciences. 2013;68:1-7.
[8] Baghel V, Sharma DK, Sikarwar BS, Kumar R, Avasthi DK. Tailoring the hydrophobicity of copper surface with ion beam irradiation. Radiation Effects and Defects in Solids. 2019:1-13.
[9] Fouda A, M. G. Wasel, A. M. Hamed, E.-S. B. Zeidan, and H. F. Elattar. Investigation of the condensation process of moist air around horizontal pipe. International Journal of Thermal Sciences. 2015;90:38-52.
[10] Zheng S, Eimmann F, Philipp C, Fieback T, Gross U. Modeling of heat and mass transfer for dropwise condensation of moist air and the experimental validation. International Journal of Heat and Mass Transfer. 2018;120:879-94.
[11] Sikarwar BS, Battoo NK, Khandekar S, Muralidhar K. Dropwise Condensation Underneath Chemically Textured Surfaces: Simulation and Experiments. Journal of Heat Transfer. 2011;133(2):021501.
[12] Sikarwar BS, Khandekar, S., and Muralidhar,K. Mathematical modelling of dropwise condensation on textured surfaces. Sadhana. 2013;38:1135-71.
[13] Tsilingiris PT. Thermophysical and transport properties of humid air at temperature range between 0 and 100°C. Energy Conversion and Management. 2008;49(5):1098-110.