Droplet Growth Model for Dropwise Condensation on Concave Hydrophobic Surfaces

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ABSTRACT: In this paper, mathematical models for predicting the droplet growth and droplet distribution of dropwise condensation on hydrophobic concave surface are developed and a theoretical analysis of the results of the model simulation is made. Under the assumptions of the Cassie–Baxter wetting mode and the consideration of noncondensable gases, the droplet growth model is not only established by heat transfer through a single droplet but also considered the thermal conductive resistance of the surface promoting layer. In addition, a droplet distribution model has been built based on the population balance theory. According to the calculation, the main thermal resistance in the droplet growth process is the conductive resistance inside the droplet. With the increase of contact angle, the above-mentioned thermal resistance increases; thus, the higher the hydrophobicity is, the slower the droplet growth and the less the droplet density are. Besides, the lower the temperature of the condensing surface is, the faster the droplets grow and the less the droplet density is. The models provide a mathematical tool for predicting the droplet radius at the initial stage of dewing on the concave surface and contribute to the design of functional surfaces in the field of water harvesting.

1. INTRODUCTION

Water nucleation and growth of water droplets are an important phenomenon both in nature such as dewing on surfaces of plants and in many fields of technologies such as on textured surfaces for water harvesting1–6 or surface self-cleaning7–9 purposes. In the field of water harvesting materials treated with surface modification, the wettability and structure of the surface have a remarkable influence on the efficiency of droplet formation and droplet collection. Hydrophobic or superhydrophobic surface with a water contact angle (CA) higher than 90 and 150°, respectively,10–12 has attracted much attention and been investigated by researchers due to its low sliding angle of droplets and high surface renewal rate13,14 for their special objective, such as collecting liquid water rapidly. On the other hand, it is verified that the tiny pits or grooves on surfaces enhance the water nucleation15 and droplet motion. Dai16 has found in his research that a directional slippery rough surface is capable of fast droplet removal. Many studies have also found that biomimetic micromorphology structure on the surface of materials exhibits excellent water harvesting rate.17,18 By roughening the material surfaces or surface micro/nanofabrication technology, cavities or channels of different wettabilities can be constructed, which are suitable for droplet growth19 and transportation.20–22 Therefore, hydrophobic concave surfaces may lead to facilitation of dewing2 and droplet removing, which displays considerable potential for investigation of water collection or anticorrosion.

To design surfaces with efficient water condensation rate and surface renewal rate, mathematical models that simulate the droplet growth process are desirable for predicting the droplet distribution on hydrophobic concave surfaces in the first place. Bintein measured and summarized the condensation rate on surfaces with grooves and reported that submillimetric grooves accelerate dew shedding.1 It is worth noting that Kim14 and Lu23 quantified the growth of a single droplet on hydrophobic flat surfaces and grooves, respectively. To the best of our knowledge, there were a few studies on establishing a droplet growth model on hydrophobic concave surfaces. In view of this, the objective of the current study is to develop a mathematical model for droplet growth calculation on hydrophobic concave surfaces while the thermodynamical influence of surface roughness and noncondensable gases is taken into consideration as parameters. Furthermore, the drop size distribution on concave surfaces with various hydrophobicities is to be found and the effect of the surface wettability on water condensation is to be explored by simulation in terms of contact angle and population density at certain drop size.

Received: July 2, 2020
Accepted: August 13, 2020
Published: August 27, 2020
2. DROPLET GROWTH MODEL

Water condensation is a process through which vapor molecules accumulate and form initial condensation nuclei. The nuclei grow mainly by adsorbing ambient vapor molecules until two adjacent nuclei contact and merge into a larger nucleus. The process above is usually omitted and the calculation is directly started, from where each nucleus has its initial droplet radius. During droplet growth, each drop contributes to the condensation by transferring heat through itself. In this section, with consideration of noncondensable gases, a growth model of the radius of a single droplet by water condensation on a concave hydrophobic surface will be established based on thermodynamics theory.

Consider a droplet with radius \( r \) on a hydrophobic concave surface with radius \( R \) and contact angle \( \theta \), as shown in Figure 1.

![Figure 1. Geometric structure of the droplet growth model.](https://dx.doi.org/10.1021/acsomega.0c03187)

The contact angle \( \theta \) is divided into two parts, \( \theta_u \) and \( \theta_d \), where the subscripts \( u \) and \( d \) indicate the upper and bottom parts of the droplet, respectively. \( H_l \) represents the height from the bottom of the concave surface to the midpoint of the boundary line that separates \( \theta_u \) from \( \theta_d \). As the droplet radius is increased by \( \Delta r \), \( \theta_d \) is assumed to be constant and the tangent of \( \phi \) can be calculated by \( \frac{R}{R + \Delta r} \). The vapor temperature and surface temperature are indicated as \( T_v \) and \( T_s \) respectively. Water condensation is an exothermic process by which vapor forms liquid water on surfaces and releases heat. In this process, the condensation is an exothermic process by which vapor forms liquid water on surfaces and releases heat. In this process, the condensation is an exothermic process by which vapor forms liquid water on surfaces and releases heat.

The nuclei grow mainly by adsorbing ambient vapor molecules and the solid conduction is neglected. By simplifying the shape of the bottom part of the droplet to a cylinder instead of a spherical sector, the height of the cylinder is assumed to be \( H_l/2 \), as shown in Figure 1, for which case, the temperature drop for the bottom part of the droplet can be written as

\[
\Delta T_{d,d} = \frac{q \times \theta_u}{4\pi k_c \sin \theta_u} \sin \theta_u \left( \tan \theta_u \right)^2
\]

and the total temperature drop through the droplet is given by

\[
\Delta T_{d} = \Delta T_{d,u} + \Delta T_{d,d}
\]

The curvature of the vapor–liquid interface leads to an equilibrium saturation temperature, which is lower than the saturation temperature at a flat interface. The temperature drop due to the droplet curvature is found to be

\[
\Delta T_c = \frac{2T_v \sigma}{H_l \rho}
\]

where \( \Delta T_c \) corresponds to the difference in the equilibrium temperature of vapor in saturated state at a convex interface, \( \sigma \) is the surface tension of water, \( H_l \) is the latent heat of vaporization, and \( \rho \) is the water density. The minimum viable radius of a droplet can be written as

\[
r_{\min} = \frac{2T_v \sigma}{H_l \rho \times \Delta T}
\]

Eq 5 can be reduced to

\[
\Delta T = \frac{r_{\min}}{r} \Delta T
\]

All surfaces are rough to some extent, and therefore, only a portion of surfaces comes into contact with the droplet, as shown in Figure 3. The heat flow from the droplet to the surface is therefore retarded by this incomplete contact, and the thermal conductive resistance of the rough promoting layer.
is given by combining the thermal resistance of solid phase of the condensing surface and the thermal resistance of the air trapped in grooves of the surface microstructure.

The way in which the droplet wets the concave surface is simplified to the Cassie–Baxter mode, that is, the cavities are not wetted by the droplet, and the temperature drop due to the thermal conductive resistance is given by:

$$\Delta T_{\text{ca}} = \frac{q \delta_e}{k_e S_w}$$  \hspace{1cm} (8)

$$k_e = f_k k_w + (1 - f_k) k_s$$  \hspace{1cm} (9)

where $k_e$ is the effective thermal conductivity, $f_k$ is the fraction of surface area occupied by solid phase, $k_w$ and $k_s$ are thermal conductivities of the solid phase and air, respectively, $\delta_e$ represents the average height of the micromorphology on the surface, and $S_w$ indicates the contact area between the bottom part of the droplet and the concave rough surface. To reduce the calculation steps, $S_w$ is idealized as the area of a circle with the diameter of $2R_w$, as shown in Figure 3, and thus is given as:

$$S_w = \pi R_w^2 \times (\sin \theta_e)^2$$  \hspace{1cm} (10)

In addition to thermal effect, microstructure on surface also enhances the vapor nucleation at the beginning of condensation under special conditions, that is, the surface characteristics (e.g., the arithmetic mean deviation of the surface roughness) and the ratio between droplet size and the size of the cavity should be in certain ranges. At present, investigations on the mathematical expression between surface roughness and the droplet radius are insufficient, as the result of which, the geometrical influence of the surface roughness is not within the scope of this study.

The droplet growth process is driven by the temperature drop $\Delta T$ between ambient and surface temperatures. The total temperature difference between the vapor and the surface is the sum of the four temperature drops found in eqs 1, 4, 7, and 8, and is given as:

$$q = \frac{(1 - \frac{\delta_e}{r}) \Delta T}{A}$$  \hspace{1cm} (11)

where

$$A = \frac{1}{\rho H_v} \left[ \frac{1}{h_1} \times 2\pi r^2 (1 - \cos \theta_e) + \frac{\theta_u}{4\pi k_c \sin \theta_e} + \frac{\theta_u}{2 \tan \phi} \frac{r}{k_c \pi r^2 \sin \theta_e} \right]$$  \hspace{1cm} (12)

The total heat transfer rate through a droplet of radius $r$ equals the change of energy required for the formation of an infinitely small amount of droplet volume in an infinitely small amount of time,

$$H_v \frac{dV}{dt} = q$$  \hspace{1cm} (13)

where the droplet volume $V$ and the derivative of the droplet volume with respect to time are, respectively, given in eqs 14 and 15

$$V = \pi r \left( \frac{2}{3} - \cos \theta_u + \frac{(\cos \theta_u)^3}{3} \right) + \frac{r \sin \theta_u}{2 \tan \phi} \times (\pi r^2 \sin \theta_e)^2$$  \hspace{1cm} (14)

$$\frac{dV}{dt} = \pi \left( 2 - 3 \cos \theta_u + (\cos \theta_u)^3 \right) + \frac{3(\sin \theta_u)^3}{2 \tan \phi} \times r^2 \times \frac{dr}{dt}$$  \hspace{1cm} (15)

Substituting eqs 11 and 14 into eq 13, and the droplet growth rate as a function of droplet radius $r$ is given as

$$J(r) = A_1 \times \left( 1 - \frac{\delta_e}{r} \right) \times \frac{\pi r^2 \times A_2 \times (\frac{1}{r} \times A_3 + \frac{1}{r} \times A_4)}{A}$$  \hspace{1cm} (16)

with

$$J(r) = \frac{dr}{dt}$$  \hspace{1cm} (17)

$$A_1 = \frac{\Delta T}{\rho H_v}$$  \hspace{1cm} (18)

$$A_2 = \frac{\pi r^2}{A_1} \times (\frac{1}{r} \times A_3 + \frac{1}{r} \times A_4)$$  \hspace{1cm} (19)

$$A_3 = \frac{1}{h_1 \times 2\pi (1 - \cos \theta_e)} + \frac{\delta_e}{4\pi k_c \sin \theta_e}$$  \hspace{1cm} (20)

$$A_4 = \frac{\theta_u}{2\pi k_c \sin \theta_e}$$  \hspace{1cm} (21)

3. DROPLET SIZE DISTRIBUTION MODEL

The purpose of establishing the droplet growth model is to calculate the amount of droplets with different drop sizes when condensation on hydrophobic concave surface reaches equilibrium. The condensation efficiency of a material surface can be evaluated by the distribution of the droplets number. Condensation occurs at proper nucleation sites. The initial droplet forms mainly by direct deposition from the vapor phase onto the surface and grows by absorbing ambient water molecules. As the droplet becomes larger and the distance between neighboring droplets becomes closer, coalescence starts to be the dominating mechanism for droplet growth until
The falling droplets sweep away other droplets in its path so that the condensing surface is cleaned and new initial droplets can be formed. During water condensation, there are droplets of different sizes on the condensing surface. For large droplets, the drop size distribution \( M(r) \) was established by Wen\(^3\)

\[
M(r) = \frac{1}{3\pi r^2} \left( \frac{r}{r_{\text{max}}} \right)^{-1/3}
\]

(22)

The maximum droplet radius \( r_{\text{max}} \) which indicates the size of the departure drop, can be calculated based on the force balance between gravity that acts on the droplet and liquid−solid interfacial capillary force. The latter can be approximately calculated as

\[
F_c = 6 \pi r \sigma \left( \cos \theta_i - \cos \theta_f \right)
\]

(23)

where \( \sigma \) is the constant that relates to the steepness of the surface and the drop shape.\(^2\) \( \theta_i \) and \( \theta_f \) represent the receding and advancing contact angles, respectively. By assuming that the condensing surface is perpendicular to the horizontal direction, the gravitational force on the body of the droplet is approximately calculated as follows

\[
F_g = \rho g \frac{2}{3} r^3 \cos \theta + \frac{1}{3} \left( \cos \theta \right)^2 \rho g
\]

(24)

By balancing between eqs 23 and 24, the radius of the departure droplet can be derived as

\[
r_{\text{max}} = \left( \frac{6 \pi (\cos \theta_i - \cos \theta_f) \sin \theta \times \alpha}{\pi (2 - 3 \cos \theta + (\cos \theta)^2) \rho g} \right)^{1/2}
\]

(25)

In this study, an experimental value of \( r_{\text{max}} \) has been adopted to improve the calculation efficiency by reducing the calculation steps of advancing and receding contact angles on different structures. The concept of the experiment and the experimental setup is given in Figure 4. A spherical shell made of stainless steel with a diameter of 5 cm was used to provide the condensing surface. The inner surface of the spherical shell was deposited with a hydrophobic material (solution of polysiloxane and propylamine polymer) and fixed on a frame, which is attached to an electronic condenser. The contact angle of the condensing surface was 108°. The ambient temperature and the temperature of the condenser were 30 and 0 °C, respectively. The condensation experiment lasted 4 h, and the radius of every departure droplet was observed by a camera. The statistical value of the size of droplets that rolled off from the condensing surface was approximately 2 mm by taking the average of the sizes of departed droplets in the whole period of the test.

For small droplets that grow mainly by absorbing surrounding vapor molecules, the population balance theory can be applied to determine the drop size distribution.\(^30\) The idea of the theory is that when the condensation reaches steady state, the derivative of the number of droplets with a certain radius is kept in conservation, that is, the number of droplets enters a certain drop size interval equal to the number of droplets leaving that size interval. By denoting the population density of droplets, i.e., the number of droplets with radius \( r \) per unit area as \( m(r) \), the number of droplets that enter an arbitrary size range \( (r_1, r_2) \) in an infinitely small amount of time \( dt \) can be written as \( Am_i(r)J_i(r) \, dt \), while the number of droplets leaving that range can be written as \( Am_s(r)J_s(r) \, dt \), where \( A \) is the area of an arbitrary section of the condensing surface. Considering the sweep off effect by departure droplets, the number of drops be swept off can be written as \( Sm_{12} (r_2 - r_1) \, dt \), where \( S \) is defined as the sweeping rate at which the surface is renewed by falling droplets and \( m_{12} \) is the average population density in the range from \( r_1 \) to \( r_2 \). According to the population balance theory, the number of droplets entering the size range by droplet growth must be equal to the sum of the number of droplets leaving by growth and the number of droplets be swept off

\[
Am_i(r)J_i(r) \, dt = Am_s(r)J_s(r) \, dt + Sm_{12}(r_2 - r_1) \, dt
\]

(26)

when \( \Delta r \) approaches zero, \( m_i \) approaches infinitely close to \( m_s \) and thus \( m_{12} \) becomes an exact value; thus, eq 26 can be simplified as

\[
\frac{d}{dr} (Jm) + \frac{m}{f} = 0
\]

(27)

where

\[
f = \frac{A}{S}
\]

(28)

Integrating eq 27 with respect to \( r \) gives

\[
\int_{r_{\text{max}}}^{r_{\text{min}}} \frac{dJm}{Jm} = \int_{r_{\text{min}}}^{r_{\text{max}}} - \frac{dr}{f} = \frac{J_{\text{min}}}{J_{\text{max}}}
\]

(29)

By solving eq 29, the population density of droplets with radius \( r \) is given as
\[
m(r) = \frac{(fm)_{\text{min}}}{f(r)} \exp \left[ \frac{-1}{f} \int_{r_{\text{min}}}^{r} \left( -\frac{1}{f(r)} \right) dr \right]
\]  

(30)

The boundary between the size of small droplets and large droplets\(^4\) is defined as \(r_e\)

\[
r_e = \left(4N_s\right)^{-1/2}
\]  

(31)

where \(N_s\) is the number of nucleation sites on unit area of condensing surface.\(^3\) The population density \(m(r)\) and \(M(r)\) are equivalent at \(r_e\), i.e., \(m(r) = M(r)\) at \(r = r_e\); furthermore, the derivatives of \(\ln(m(r))\) and \(\ln(M(r))\) with respect to \(r\) are equivalent at \(r_e\). The above two boundary conditions are, respectively, shown in eqs 32 and 33

\[
m(r_e) = M(r_e)
\]  

(32)

\[
d \ln(m(r)) \bigg|_{v} \quad = \quad \frac{d \ln(M(r))}{dr} \bigg|_{v}
\]  

(33)

With eq 32, \((fm)_{\text{min}}\) can be solved, and the expression of \(m(r)\) is shown as follows

\[
(fm)_{\text{min}} = f(r_e) \times \frac{1}{3\pi r_{\text{max}}^3} \times \left( \frac{r_e}{r_{\text{max}}} \right)^{-1/3} \times \left[ \exp[-B(r_e)] \right]
\]  

(34)

\[
m(r) = \frac{1}{3\pi r_{\text{max}}^2} \times \left( \frac{r_e}{r_{\text{max}}} \right)^{-1/3} \times \frac{1}{f(r)}
\]  

\[
\times \exp[-B(r_e) + B(r)]
\]  

(35)

where

\[
B(r) = \frac{-A_2\pi}{fA_1} \times \left\{ A_3[r + r_{\text{min}} \ln(r - r_{\text{min}})] 
\right.
\]

\[
+ \left. A_1 \left[ r_{\text{min}} \ln(r - r_{\text{min}}) + r \times r_{\text{min}} + \frac{r^2}{2} \right] \right\}
\]  

(36)

\(f\) can be calculated using eq 33 as

\[
f = \frac{C}{D}
\]  

(37)

where

\[
C = \frac{A_2A_3\pi + A_2A_4\pi r_{\text{min}}}{A_1} + \frac{A_1A_2\pi r_{\text{min}} + A_2A_4\pi r_{\text{min}}}{A_1(r_e - r_{\text{min}})}
\]

\[
+ \frac{A_1A_2\pi r_e}{A_1}
\]  

(38)

\[
D = \frac{8}{3r_e} + \frac{A_3 + 2A_4r_e}{A_1r_e^2 + A_4r_e^2} - \frac{1}{r_e - r_{\text{min}}}
\]  

(39)

Using eqs 22 and 35, the drop size distribution of water condensation in equilibrium on hydrophobic concave surface can be solved numerically.

4. RESULTS AND DISCUSSION

Using eqs 16, 22, and 35 from the previous section, the variation of droplet size with respect to time and the distribution of droplet number on a hydrophobic concave surface can be calculated.

The variation of droplet radius with respect to time is shown in Figure 5a. The calculation was executed under the condition where the vapor and surface temperature are 21 and \(-8\) °C, respectively, the contact angle of the surface is 108°, and the initial droplet radius is 1.1 times \(r_{\text{min}}\). The comparison between results using the prior growth model\(^27\) and results using the current droplet growth model is illustrated in the figure. It is demonstrated that the current droplet growth model has a higher accuracy compared to the prior model, as the thermal conductive resistance of the lower part of the droplet has been considered. The curve also shows that the droplet size on the surface increases with time, and the droplet size obtained by simulation increases faster than that of the measurement. The reason for this is that in the theoretical model, the initial value of the droplet radius was set to 1.1 times larger than that of the minimum viable radius for the purpose of initiation of the numerical iteration;\(^27\) therefore, the simulated value of the droplet radius was larger than that in experiment at time 0 s. Second, the results of radius increase in the model were calculated by iterative summation at every time step, while under real conditions, phase transition from vapor to liquid is required before the increase of the droplet radius, resulting in delay of nucleus growth. As shown in Figure 5a, the deviation between the results of the experiment and those of the current growth model is still large, due to the above-mentioned initial value of droplet growth and influence of the phase transition, and also the assumptions made by modeling. In the current model, the liquid—solid interfacial thermal resistance has been
neglected and the shape of the lower part of the droplet has been considered as a cylinder to avoid the nonintegrable in eqs 29 and 30 when modeling the droplet distribution; the thermal contact resistance between droplet and the condensing surface has also been neglected for lacking of the mathematical expression that relates the heat flux and the temperature drop.

By configuring the initial condition as $T_e = 30 \degree C$, $T_i = 0 \degree C$, and contact angle = 108°, Figure 5b illustrates the proportions of thermal resistance to total thermal resistance with respect to time. The result shows that the ratio of each thermal resistance to the total thermal resistance can be arranged in a decreasing order as follows: thermal conductive resistance due to the droplet, thermal conductive resistance of the promoting layer, interfacial thermal resistance, and thermal resistance due to curvature. The sum of the proportion of the conductive resistance of the droplet and the promoting layer accounts for more than 90% of the total thermal resistance.

The results of the droplet radius on surfaces with various hydrophobicities are shown in Figure 6a with $T_e = 30 \degree C$ and $T_i = 0 \degree C$. The corresponding interfacial thermal resistance and thermal resistance of heat conduction inside the droplet with respect to time are plotted in Figure 6b,c. As demonstrated in Figure 6a, the higher the hydrophobicity on the concave surface is, the slower the droplet radius increases. The reason is that, during water condensation, as shown in Figure 6b,c, the larger the contact angle is, i.e., the higher the hydrophobicity of the surface is, the larger the interfacial thermal resistance and internal thermal conductive resistance of the droplet are.

At time $t = 0$ s, the interfacial thermal resistance and the conductive resistance inside the droplet of the surface which has a contact angle of 145° are the largest, resulting in a decline of the droplet growth. As the condensation proceeds, the droplet radius on the surface with 145° contact angle is always smaller than that on surfaces of 120 and 108° contact angles, which leads to a smaller area for heat transfer. A small heat transfer area makes interfacial and conductive resistances higher than those of the 120 and 108° surfaces at a later stage. High thermal resistance in turn restrains droplet growth. Therefore, it is concluded that the larger the contact angle is, the higher the vapor–liquid interfacial resistance and internal thermal conductive resistance are, which reduce the increment of the droplet radius at the beginning of the condensation.

Figure 7a–c demonstrates the influence of hydrophobicity on the droplet density and the influence of subcooling on droplet density and droplet size under the condition where contact angle equals 108°. The correlation between the amount of droplets at each droplet size and the hydrophobicity of the surface is shown in Figure 7a. The result indicates that the larger the contact angle is, the less the droplet amount can be found. This can be explained by Figure 6a, which shows that high hydrophobicity leads to a low droplet growth rate, thus resulting in a low droplet density. Figure 7b,c shows the tendencies of droplet radius and droplet density by different subcoolings with respect to time and droplet size, respectively. As shown in Figure 7b, the lower the surface temperature is, the higher the droplet growth rate is. This is because a lower surface temperature represents a higher driving force of phase transition, which makes vapor condensation easier and thus the droplet growth becomes faster. Sequentially, as shown in Figure 7c, the larger the subcooling is, the less the droplet density is. The explanation is that a high subcooling provides more driving force supply to the droplet growth. While the vapor pressure is limited, more vapor is consumed by droplets with a high growth rate, resulting in a lack of vapor for condensation and growth of new drops, thus less droplets can be spotted.

5. CONCLUSIONS

In this study, a droplet growth model was developed for water condensation on hydrophobic concave surface based on thermodynamics theory. The wetting behavior between liquid and the surface was assumed to be the Cassie–Baxter mode, and the effect of noncondensable gases was considered. In comparison to the prior model, the current model takes into account the thermal conductive resistance in the lower part of droplets, which makes the current model more compatible for simulation of droplet growth on concave hydrophobic surfaces.
Furthermore, based on the droplet growth model, the population density model for condensation in steady state was established. The models provide effective mathematical tools for the prediction of condensation on hydrophobic concave surfaces, which will reduce the consumption in surface design.

According to the simulation of the models, the following results were obtained:

1. By droplet growth process in the early stage of condensation, the main thermal resistance includes the heat conductive resistance inside the droplet. With the increment of the surface contact angle, i.e., the increment of the surface hydrophobicity, the thermal conductive resistance of the droplet and the interfacial thermal resistance increase, resulting in a decrease of droplet growth rate and droplet density on the concave surface. Therefore, the higher the surface hydrophobicity is, the slower the droplet growth and the less the amount of droplets are.

2. The lower the surface temperature is, the higher the droplet growth rate is, which leads to the decrease of water concentration above the droplet surface. This retards the nucleation and condensation of new initial nuclei, so the amount of droplets decreases by lower surface temperature. In conclusion, by reducing the surface hydrophobicity and restricting the surface temperature, an enhancement to the droplet amount and droplet growth on hydrophobic concave surfaces will be achieved.

**Figure 7.** Droplet radius and droplet density by various hydrophobicities and subcoolings. (a) Relationship between droplet density and hydrophobicity; (b) relationship between subcooling and droplet size; and (c) relationship between subcooling and droplet density.

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**Notes**
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**
The authors acknowledge National Natural Science Foundation of China (50772131), National High-tech R&D Program of China (2011AA322100), and Key Project of Chinese Ministry of Education(106086) for support.

**REFERENCES**

1. Bintein, P.-B.; Henri, L.; Anne, M.; Laurent, R.; Daniel, A. B. Grooves Accelerate Dew Shedding. *Phys. Rev. Lett.* 2019, 122, No. 098005.
2. Daniel, B. *Dew Water*; River Publishers: Denmark and The Netherlands, 2018; pp 82–85.
3. Wen, R. F.; Ma, X. H.; Lee, Y. C.; Yang, R. G. Liquid-Vapor Phase-Change Heat Transfer on Functionalized Nanowired Surfaces and Beyond. *Joule* 2018, 2, 2307–2347.
4. He, M.; Ding, Y.; Chen, J.; Song, Y. L. Spontaneous Uphill Movement and Self-Removal of Condensates on Hierarchical Tower-like Arrays. *ACS Nano* 2016, 10, 9456–9462.
5. Zhang, S. N.; Huang, J. Y.; Chen, L.; Yang, K. Bioinspired Special Wettability Surfaces: From Fundamental Research to Water Harvesting Applications. *Small* 2016, 13, No. 1602992.
6. Yu, Z. W.; Yuan, F. F.; Wang, Y. Q.; Yao, L.; Dou, S. X.; Liu, K. S.; Jiang, L.; Wang, X. L. Desert Beetle-Inspired Superwettable Patterned Surfaces for Water Harvesting. *Small* 2017, 13, No. 1701403.
7. Nayshevsky, I.; Xu, Q. F.; Lyons, A. M. Hydrophobic-Hydric Surfaces Exhibiting Dropwise Condensation for Anti-Soiling Applications. *IEEE J. Photovoltaics* 2019, 9, 302–307.
8. Wang, S. F.; Liu, M. S.; Feng, Y.; Bu, Y. R.; Huyuh, S. H.; Ng, T. W.; Gu, F.; Yu, A. B.; Jiang, X. C. Bioinspired hierarchical copper oxide surfaces for rapid dropwise condensation. *J. Mater. Chem. A* 2017, 5, 21422–21428.
(9) Orejon, D.; Askounis, A.; Takata, Y.; Attinger, D. Dropwise Condensation on Multiscale Bioinspired Metallic Surfaces with Nanostructures. ACS Appl. Mater. Interfaces 2019, 11, 24735−24750.

(10) Liang, Y. J.; Ju, J. G.; Deng, N. P.; Zhou, X. H.; Yan, J.; Kang, W. M.; Cheng, B. W. Super-hydrophobic self-cleaning bead-like SiO2@PTFE nanofiber membranes for waterproof-breathable applications. Appl. Surf. Sci. 2018, 442, 54−64.

(11) Pinheiro, R. A.; Silva, A. A.; Trava, A. V. J.; Corat, E. J. Water vapor condensation and collection by super-hydrophilic and super-hydrophobic VACNTs. Diamond Relat. Mater. 2018, 87, 43−49.

(12) Long, J. Y.; He, Z. J.; Zhou, P. Y.; Xie, X. Z.; Zhou, C. X.; Hong, W. J.; Hu, W. Low-Cost Fabrication of Large-Area Broccoli-Like Multiscale Micro- and Nanostructures for Metallic Super-Hydrophobic Surfaces with Ultralow Water Adhesion and Superior Anti-Frost Ability. Adv. Mater. Interfaces 2018, 5, No. 1800353.

(13) Li, J.; Wei, Y.; Huang, Z. Y.; Wang, F. P.; Yan, X. Z.; Wu, Z. L. Electrohydrodynamic behavior of water droplets on a horizontal superhydrophobic surface and its self-cleaning application. Appl. Surf. Sci. 2017, 403, 133−136.

(14) Kim, S. W.; Kim, K. J. Dropwise Condensation Modeling Suitable for Superhydrophobic Surfaces. J. Heat Transfer 2011, 133, No. 081502.

(15) Yan, D. M.; Zeng, Q.; Xu, S. L.; Zhang, Q.; Wang, J. Y. Heterogeneous Nucleation on Concave Rough Surfaces: Thermodynamic Analysis and Implications for Nucleation Design. J. Phys. Chem. C 2016, 120, 10368−10380.

(16) Dai, X.; Sun, N.; Nielsen, S. O.; Stogin, B. B.; Wang, J.; Yang, S. K.; Wong, T. S. Hydrophilic directional slippery rough surfaces for water harvesting. Sci. Adv. 2018, 4, No. eaao9019.

(17) Hira, Y.; Mayama, H.; Matsuo, Y.; Shimomura, M. Uphill Water Transport on a Wettability-Patterned Surface: Experimental and Theoretical Results. ACS Appl. Mater. Interfaces 2017, 9, 15814−15821.

(18) Cao, M. Y.; Xiao, J. S.; Yu, C. M.; Li, K.; Jiang, L. Hydrophobic/Hydrophilic Cooperative Janus System for Enhancement of Fog Collection. Small 2015, 11, 4379−4384.

(19) Marie, G. M.; Anne, M.; Laurent, R.; Daniel, B. Edge effects on water droplet condensation. Phys. Rev. E 2014, 90, No. 062403.

(20) Yin, K.; Du, H. F.; Dong, X. R.; Wang, C.; Duan, J. A.; He, J. A simple way to achieve bioinspired hybrid wettability surface with micro/nanopatterns for efficient fog collection. Nanoscale 2017, 9, 14620−14626.

(21) Lee, D. K.; Choi, S. Y.; Park, M. S.; Cho, Y. H. Wetting properties of hybrid structure with hydrophilic ridges and hydrophobic channels. Appl. Phys. A 2018, 124, No. 192.

(22) Lee, D. K.; Cho, Y. H.; Lee, J. W.; Park, M. S. Wettability of microstructured Pyrex glass with hydrophobic and hydrophilic properties. Surf. Coat. Technol. 2017, 319, 213−218.

(23) Lu, C. H.; Beckmann, M.; Unz, S.; Gloess, D.; Frach, P.; Holst, E.; Lasagni, A.; Bieda, M. Heat transfer model of dropwise condensation and experimental validation for surface with coating and groove at low pressure. Heat Mass Transfer 2016, 52, 113−126.

(24) Tanasawa, I. Advances in Condensation Heat Transfer. Adv. Heat Transfer 1991, 21, 55−139.

(25) Singh, M.; Pawar, N. D.; Kondaraju, S.; Bahga, S. S. Modeling and Simulation of Dropwise Condensation: A Review. J. Indian Inst. Sci. 2019, 99, 157−171.

(26) Glicksman, L. R.; Hunt, A. W. Numerical Simulation of Dropwise Condensation. Int. J. Heat Mass Transfer 1972, 15, 2251−2269.

(27) Wu, X. M.; Chu, F. Q.; Chen, Y. G. Theoretical analysis of droplets growth in early stage of frosting on hydrophobic surfaces. CIESC J. 2015, 66, 60−66.

(28) Klemm, P.; Klemm, A. J.; Ibrahim, I. The effect of geometrical microstructure of solid surfaces on the kinetics of water vapour condensation process. Energy Build. 2006, 38, 1468−1476.

(29) ElSherbini, A. I.; Jacobi, A. M. Retention forces and contact angles for critical liquid drops on non-horizontal surfaces. J. Colloid Interface Sci. 2006, 299, 843−845.