Noname manuscript No.
(will be inserted by the editor)

Effect of Nucleation and Icing Evolution on Run-back Freezing of Supercooled Water Droplet

Mingming Sun, Weiliang Kong, Fuxin Wang, Hong Liu

Received: date / Accepted: date

Abstract Supercooled large droplet (SLD), which can cause run-back ridged ice, will affect the aerodynamic performance of aircraft and poses a serious threat to aircraft safety. However, there is little knowledge about the abnormal run-back icing mechanism, which is vital for the development of aircraft anti-icing technologies. The flow and freezing of supercooled droplet impinging on inclined surface can help us better understand the run-back icing of SLD, especially the coupling of water flow and phase change in the freezing process. This paper experimentally investigates the freezing behavior of supercooled water droplet impinging on inclined surface. By observing the processes of water flow, ice formation and growth with a high-speed camera, the overflow distance and the freezing time are recorded with different temperatures. Different from previous discoveries that droplet freezes as the form of two smaller droplets on an inclined surface, we found two new frozen morphologies under the condition of short nucleation time: ellipse and slender strip, when the supercooling is high and low respectively. The overflow distance and freezing time will increase with the decrease of ice growth rate, when supercooling decreases. And the freezing time will increase dramatically when the supercooling is low enough. Finally, the mechanism of run-back freezing of droplet based on nucleation and icing evolution is discussed. Droplet impact on the inclined surface will result in large overflow distance when it nucleates after its retraction stage.

M.Sun · W.kong · F.Wang · H.Liu
Institute of Aeronautics and Astronautics, Shanghai Jiaotong University, Shanghai, China
E-mail: mingmingsun@sjtu.edu.cn

W.kong
E-mail: kongwl@sjtu.edu.cn

F.Wang
E-mail: fuxinwang@sjtu.edu.cn

H.Liu
E-mail: hongliu@sjtu.edu.cn

Keywords supercooled droplet · impact freezing · overflow distance · nucleation · ice growth

1 Introduction

Aircraft icing is one of the serious threats to aircraft safety. The run-back ridged ice on wing surface, which is caused by supercooled large droplet (SLD), can change the aerodynamic shape of aircraft and seriously affect flight safety [1,2]. Although investigations have been carried out to understand the impact freezing of supercooled large droplet, the mechanism of run-back freezing of SLD is not well understood yet, and it can not satisfy the development of anti-icing technologies. Therefore, it is necessary to study the run-back freezing of supercooled droplet to better understand the icing accretion on aircraft.

Current studies on droplet freezing are mostly based on droplet impinging on horizontal surfaces. For instance, S. Tabakova and F. Feuillebois [3] modeled the solidification of a supercooled droplet as a one-phase Stefan problem, and solved numerically with an implicit finite-difference technique. Zhao et al. [4] numerically studied the impact and freezing of a droplet based on a newly developed triple-phase lattice Boltzmann method, and analyzed the effect of droplet velocity and temperature as well as surface property. In addition to these numerical simulations [3–7], many researches have also been done on droplet impact freezing experimentally.

Yang et al. [8] experimentally studied the freezing mechanism of supercooled droplet impinging on cold metal surfaces. The phenomena of instantaneous and non-instantaneous freezing of supercooled impinging droplet were identified and the conditional boundaries for these two kinds of freezing were found statistically. Xu et al. [9] investigated the shape changes of droplet impacting on a cold surface with a high-speed camera, and found that higher impact velocity expands the spreading diameter and promotes the retraction. Jin et al. [10,11] reported the observations of the freezing processes of water droplets on an ice surface, and their results showed once the droplet initial height is increased, the maximum spreading factor will increase while the height of the ice bead reduces significantly. Zhang and Liu [12] classified three types of freezing characteristics: spreading-freezing, recoiling-freezing and finishing-freezing through phenomenological reproduction. Besides, a physical explanation of unsteady heat transfer process was proposed theoretically based on the close-coupling between impact dynamics and phase change, which results in the rapid freezing of supercooled large droplet impinging onto surface. Wang et al. [13] found that droplet nucleates in different dynamic stages will freeze in different shapes: basin, pancake and semisphere, corresponding to instantaneous freezing, noninstantaneous freezing and quasi-static freezing respectively.

However, physics with the run-back freezing of SLD is more similar to impact freezing of supercooled droplet on inclined surface rather than horizontal surface. Although many researches have been carried out on water layer flow on inclined surface [14–18], the mechanism of water flow and phase change in the freezing process of droplet on inclined surface is not well understood yet.

Jin et al. [19,20] experimentally investigated the impact and freezing processes of a water droplet on different inclined surfaces and surfaces with different inclined angles. The results show that the increase of droplet size leads to the increase of spreading time, spreading maximum diameter, gliding maximum diameter and maximum displacement of foremost point [19]. The inclined angle of surface was found to have an apparent influence on the spreading time, and the water droplet would split into two smaller droplets once the inclined angle of the surface was high enough (e.g. 60.0^o) [20]. However, the droplet in their experiment is room-temperature rather than supercooled, the icing theory of which is different from that of supercooled water. Besides, the coupling of water flow and phase change is not considered in their research.

In conclusion, the impact freezing of supercooled large droplet on inclined surface is not well understood yet, which is helpful for the understanding of run-back icing of SLD. This work experimentally investigates the freezing process of supercooled droplet impinging on inclined copper. By observing nucleation and icing of supercooled droplet, the law of overflow distance and freezing time are analyzed, and the mechanism that nucleation and ice growth affect droplet impact freezing is discussed.

2 Experimental setup and conditions

The experimental setup of our research group [13] is adapted in this paper to observe the freezing process of supercooled droplet impact on inclined surface. As shown in Fig.1, the experimental setup consists of five components: the cooling circulatory system, supercooled droplet generation system, temperature measurement system, impact surfaces and the observation system.

The refrigerating water bath (AP15R-30-A12Y, PolyScience) can provide cooling liquid as cold as -20°C that circulates between the upper and lower chambers, to cool down droplet generator and impact surface respectively. The droplet generator is composed of a micro pump (LSP02-1B, Longerpump, Ltd.) and a nozzle made from Teflon tube. By adjusting injection volume and nozzle size, the droplet diameter can remain constant. Thermistors (PT100, Heraeus) are attached on the side of impact surfaces and the tip of droplet generator to measure the temperatures, as shown in Fig.1. The impact surface is copper with the inclined angle of 60^o. It is nickel electroplated and mirror polished to enhance the reflection of surface, and then the ice on surface can be clearly identified. The $1\mu m$ thick layer of hydrophobic coating is applied uniformly on the surface of copper and the contact angle of droplet on the surface is 121.8^o. A high-speed camera (Phantom VEO710, Vision Research Inc, USA) is used to record the whole freezing process of droplet impinging on the inclined surface. A spectroscope is fixed in front of the camera lens and a LED light is placed on the side of camera to provide a better observable light environment.

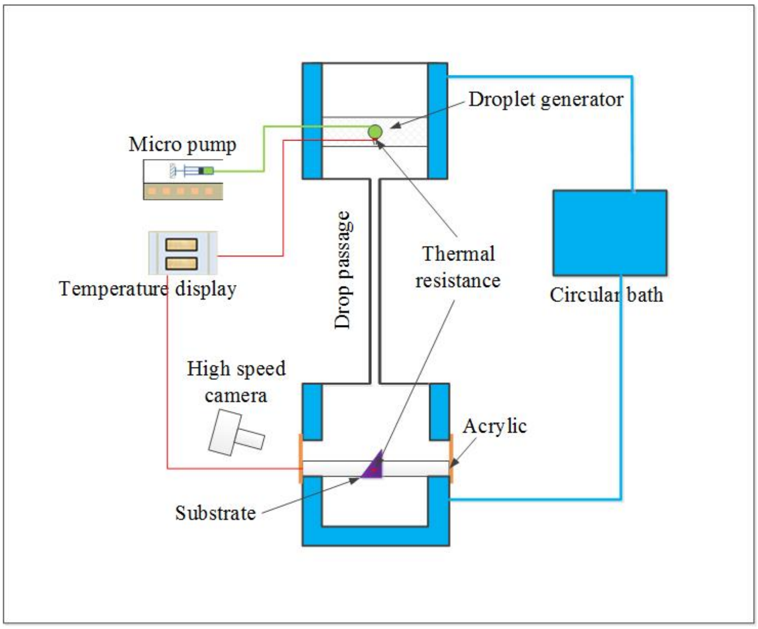

Fig. 1 Schematic of the experimental setup

During the experiment, the temperature and relatively humidity of laboratory are kept at 16°C±2°C and 56±4% respectively to minimize the influence of experimental fluctuation. The drop passage is constant as 66cm, and droplet impact velocity is 3.6m/s with the error less than 0.03m/s. The droplet is regarded as a sphere before it impact on surface and its diameter in this experiment is 2.8±0.5mm. The temperature range of droplet is −5°C∼−15°C, with the measurement error less than 0.1°C. Every experiment under same condition is conducted more than ten times to obtain the freezing results under different nucleation times and the average values.

3 Results and discussions

3.1 The freezing process of supercooled droplet impact on inclined surface

Fig.2 shows the freezing process of droplet in different temperatures impinging on inclined copper plate. The moment that droplet contacts the surface is defined as t=0. After droplet impacts on surface, it spreads out and flows downward. The droplet at -15°C nucleates at 3ms, during its spreading stage. Ice nucleus grows rapidly, which greatly affects the flowing of droplet. At 20ms, the liquid at bottom freezes and droplet stops retraction. Droplet is completely frozen at 186ms, in the shape of ellipse as a whole part. The -10°C droplet nucleates at 5ms, and the bottom liquid freezes at 28ms with high growth rate of ice. Finally, it freezes at 977ms in the shape of ellipse. As for the -6°C

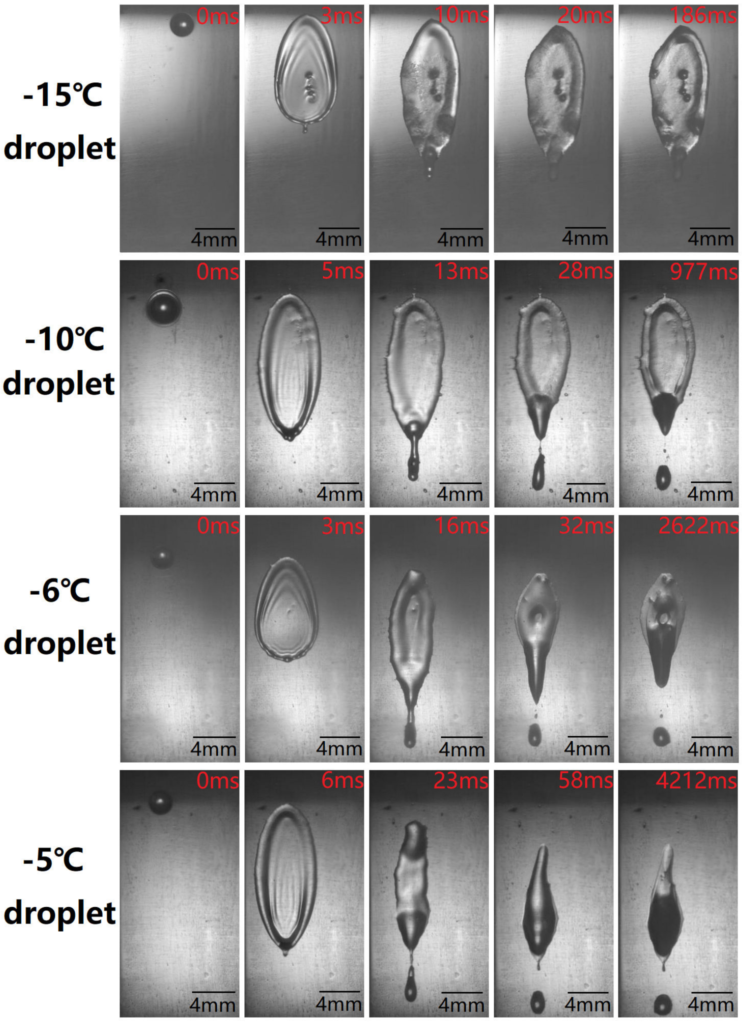

Fig. 2 The freezing process of supercooled droplet in different temperatures impinging on inclined copper plate

droplet, it nucleates at 3ms, but the low growth rate of ice makes it freezes in the shape of slender strip. The bottom liquid of droplet freezes at 32ms with liquid above ice layer. The freezing time of -6°C droplet is 2622ms, nearly ten times of that of -15°C droplet. The overflow distance (the distance from impact point to the lowest point of frozen droplet) of -6°C droplet is nearly the same with -10°C droplet, and longer than that of -15°C droplet. The overflow distance of -5°C droplet is the longest. After it impacts on surface, it spreads and then retracts, and keeps flowing downward. Droplet nucleates at 23ms and the bottom liquid freezes at 58ms. Finally, it is completely frozen at 4212ms, in the shape of slender strip.

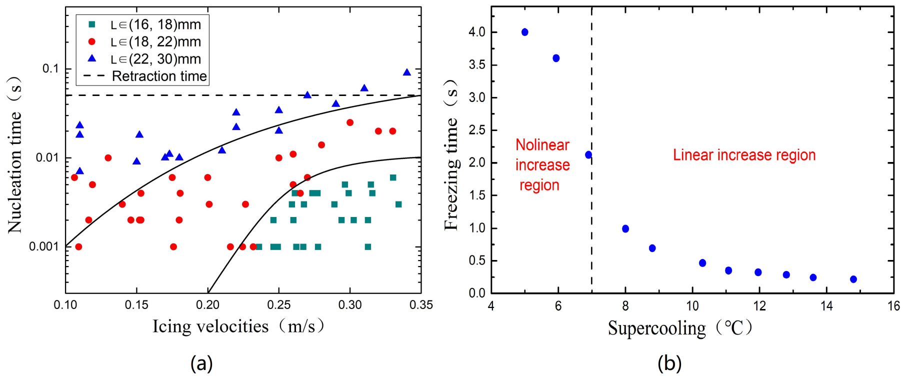

Fig. 3 The freezing law of supercooled droplet impinging on copper. (a) The overflow distance under different nucleation times and icing velocities. (b) The freezing time under different supercoolings.

3.2 The freezing law of supercooled droplet impinging on inclined surface

As can be seen from Fig.2, different nucleation time and icing velocity will lead to different freezing results of droplet. The overflow distance of droplet in different nucleation times and icing velocities is shown in Fig.3 (a). When the icing velocity is higher than 0.20m/s with nucleation time less than 0.01ms, the overflow distance is the shortest (16mm-18mm) and droplet freezes in the shape of ellipse under this condition. With the increase of nucletaion time under condition of high growth rate of ice, the overflow distance of droplet will increase. When the icing velocity is slower than 0.20m/s, the range of overflow distance is (18mm-22mm) and (22mm-30mm), corresponding to the condition of nucleation time shorter than 0.01s and nucleation time longer than 0.01s respectively. As the nucleation time increases, the overflow distance of droplet will increase as well. When the nucleation time of droplet is longer than its retraction time 0.05s (shown as the dotted line), the droplet will freeze as the form of two smaller droplets, which is consistent with the results of Jin [20], and the overflow distance will be longer.

Although some droplets with low icing velocity have the same overflow distance (18mm-22mm) as droplets with high icing velocity, their frozen morphologies and freezing times are much different. Droplet with high icing velocity freezes in the shape of ellipse ,corrsponding to short freezing time under high supercooling in Fig.3 (b). However, the droplet with short nucleation time and low icing velocity freezes in the shape of slender strip, corresponding to long freezing time under low supercooling in Fig.3 (b). It can be seen that the freezing time in Fig.3 (b) can be divided into two regions: nonlinear increase region and linear increase region. If the supercooling degree is larger than 7°C, the freezing time decreases linearly with the increase of horizontal growth rate of ice, when supercooling degree increases (Fig.4). But if the supercooling is smaller than 7°C, the freezing time of droplet is much longer and it increases dramatically when the supercooling decreases, which corresponds

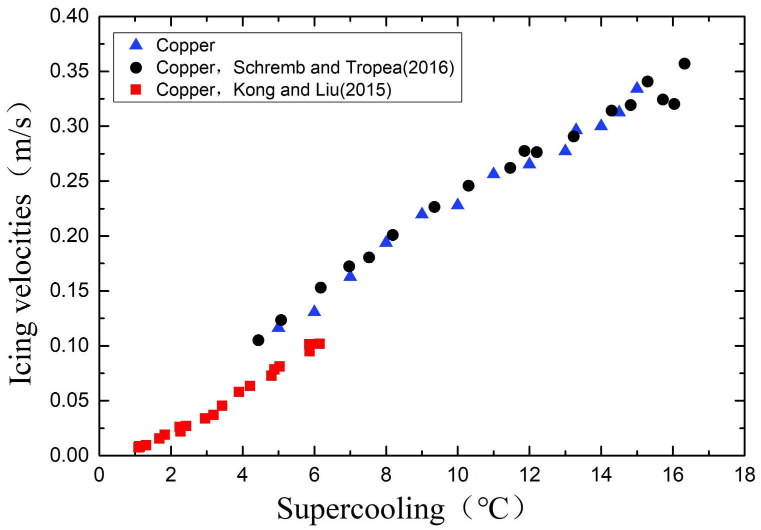

Fig. 4 The horizontal growth rate of ice under differnt supercoolings

with -5°C and -6°C droplet in Fig.2. According to the icing theory in supercooled water by Kong and Liu [21], vertical growth rate of ice will decrease dramatically when the supercooling degree is low enough, even though the horizontal growth rate of ice does not change much. The low vertical growth rate of ice will result in much longer freezing time when droplet freezes in the shape of thick strips, as shown in Fig.2. And the horizontal growth rate of ice under different supercoolings is shown in Fig.4. The horizontal growth rate of ice increases with the increase of supercooling, which corresponds with the results of Schremb and Tropea [22], but a little higher than the results of Kong and Liu [21]. Because Schremb and Tropea [22] obtained the results from supercooled droplet and their experimental conditions are more similiar to that of this paper. It can be seen form Fig.4 that the data of horizontal growth rate of ice in this experiment is close to previous studies.

3.3 The mechanism of impact freezing of supercooled droplet on inclined surface

The impact freezing of supercooled droplet on inclined surface is the coupling process of the dynamic process of water flow and the phase change of nucleation and ice growth. As shown in Fig.5 (a), after droplet impacts on inclined surface, it will spread, retract, and keep flowing downward, which is affected by droplet properties and surface inclined angle. The phase change is composed of nucleation and ice growth, as shown in Fig.5 (b). The nucleation of supercooled water is random and can be affected by many factors, such as dynamics, surface properties [23–25]. After droplet nucleates, the ice nucleus keeps growing, in horizontal and vertical directions, until the droplet

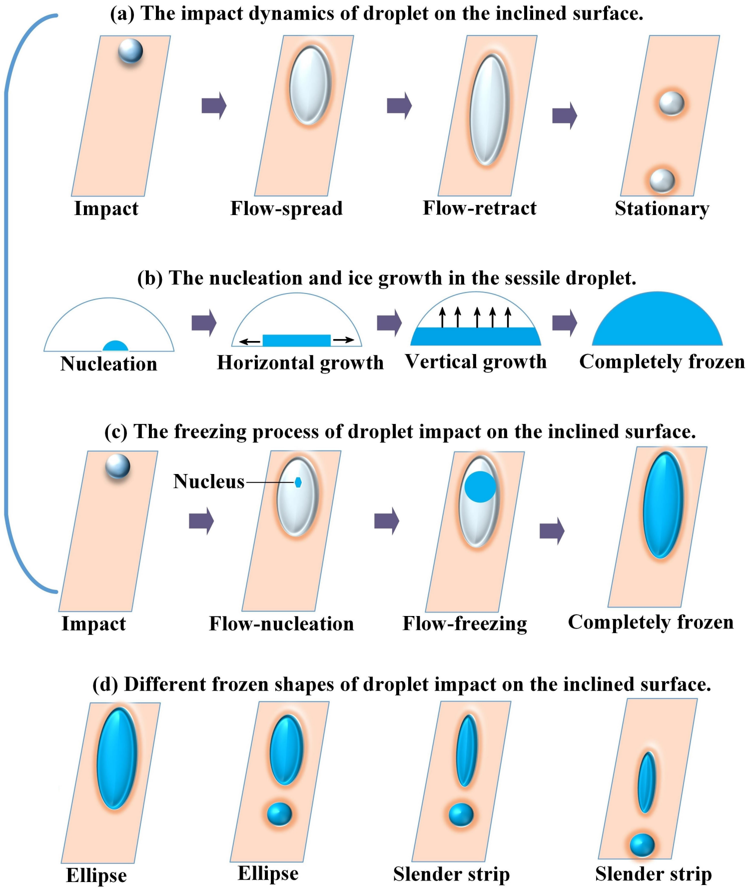

Fig. 5 Diagram of coupling process of droplet dynamics and phase change

is completely frozen on surface. The growth rate of ice is mainly affected by supercooling and substrate conductivities [21].

As for the coupling process of droplet impact on surface, the dynamic process of droplet is not only affected by droplet momentum, but also the nucleation and ice growth. The nucleation time and the ice growth rate have a decisive effect on the impact freezing of supercooled droplet, as shown in Fig.5 (c).

Different frozen shapes of droplet after its impact on the inclined surface are shown in Fig.5 (d). When the icing velocity is high, the retraction and flow of droplet will be inhibited by fast ice growth under the condition of short nucleation time, and droplet will freeze in the shape of ellipse. With the increase of nuceation time, the influence of ice growth on water flow falls down. Although droplet still freezes in the shape of ellipse, its overflow distance and freezing time will be longer. When the icing velocity is slow, droplet will freeze in the shape of slender strip due to large extent of retraction in horizontal direction, and the freezing time will be much longer due to low vertical growth rate of ice when the supercooling is low enough. As the nucleation time increases, the overflow distance will increase as well.

In conclusion, the water flow, nucleation and ice growth all influence the freezing of supercooled droplet impinging on inclined surface. The impact freezing of supercooled droplet is nucleation-dominated when the icing velocity is high, and it is ice growth-dominated in the opposite case. In terms of run-back icing of aircraft, the droplet with adequate water can keep flowing downward if the nucleation time is longer than its retraction time, and finally results in accumulated ridged ice on the wing with particularly large overflow distance.

4 Conclusions

The present work experimentally investigates the freezing of supercooled droplet impact on inclined copper. The frozen morphologies, overflow distance and freezing time are recorded with different supercoolings. And the mechanism of run-back freezing of supercooled droplet is analyzed. The conclusions are as follows:

(1) Different from previous discoveries that room-temperature water droplet freezes as the from of two smaller droplets on an inclined surface, two frozen shapes of supercooled droplet are found under the condition of short nucleation time: ellipse and slender strip. The former appears when the supercooling is high, while the latter occurs when the supercooling is low.

(2) When supercooling decreases, the overflow distance and freezing time will increase with the decrease of ice growth velocity. And the freezing time will increase dramatically when the supercooling is low enough.

(3) Theoretical analysis shows that the run-back freezing of supercooled droplet impinging on inclined surface will result in large overflow distance and long freezing time, if droplet nucleates after its retraction stage and the icing velocity is smaller than 0.20m/s.

References

1. National Transportation Safety Board Aircraft Accident Brief. Crash During Take-off in Icing Conditions Canadair, Ltd., CL-600-2A12, N873G Montrose, Colorado; [R]; NTSB/AAB-06/03, November 28, 2004.
2. National Transportation Safety Board. Accident Report Loss of Control on Approach Colgan Air, Inc. Operating as Continental Connection Flight 3407 Bombardier DHC-8-400, N200WQ Clarence Center, New York[R], NTSB/AAR-10/01 February 12, 2009.
3. Tabakova S , Feuillebois F . On the solidification of a supercooled liquid droplet lying on a surface[J]. J Colloid Interface Sci, 2004, 272(1):225-234.
4. Zhao J , Li X , Cheng P . Lattice Boltzmann simulation of a droplet impact and freezing on cold surfaces[J]. International Communications in Heat and Mass Transfer, 2017, 87:175-182.
5. Blake J D , Thompson D S , Raps D M , et al. Simulating the Freezing of Supercooled Water Droplets Impacting a Cooled Substrate[C]// Aerospace Sciences Meeting. 2015.

6. Mohammadi M, Tembely M, Dolatabadi A. Predictive model of supercooled water droplet pinning/repulsion impacting on a superhydrophobic surface: the role of gas-liquid interface temperature.[J]. Langmuir, 2017, 33(8):1816-1825.
7. Tembely M, Attarzadeh R, Dolatabadi A. On the numerical modeling of supercooled micro-droplet impact and freezing on superhydrophobic surfaces[J]. International Journal of Heat and Mass Transfer, 2018, 127: 193-202.
8. Yang G , Guo K , Li N . Freezing mechanism of supercooled water droplet impinging on metal surfaces[J]. International Journal of Refrigeration, 2011, 34(8):2007-2017.
9. Xu Q, Li Z, Wang J, et al. Characteristics of single droplet impact on cold plate surfaces[J]. Drying technology, 2012, 30(15): 1756-1762.
10. Jin Z , Cheng X , Yang Z . Experimental investigation of the successive freezing processes of water droplets on an ice surface[J]. International Journal of Heat and Mass Transfer, 2016:S0017931016323924.
11. Jin Z , Zhang H , Yang Z . Experimental investigation of the impact and freezing processes of a water droplet on an ice surface[J]. International Journal of Heat and Mass Transfer, 2017, 109(Complete):716-724.
12. Zhang C , Liu H . Effect of drop size on the impact thermodynamics for supercooled large droplet in aircraft icing[J]. Physics of Fluids, 2016, 28(6):260-42.
13. Wang L , Kong W ,Wang F , et al. Effect of Nucleation Time on Freezing Morphology and Type of a Water Droplet Impacting onto Cold Substrate[J]. International Journal of Heat and Mass Transfer, 2018, 130:831-842.
14. Hughes D T , Bott T R . Minimum thickness of a liquid film flowing down a vertical tube[J]. International Journal of Heat and Mass Transfer, 1998, 41(2):253-260.
15. Ozgen, S, Carbonaro M , Sarma G S R . Experimental study of wave characteristics on a thin layer of de/anti-icing fluid[J]. Physics of Fluids, 2002, 14(10):3391-3402.
16. Thiele U , Brusch L , Bestehorn M , et al. Modelling thin-film dewetting on structured substrates and templates: Bifurcation analysis and numerical simulations[J]. European Physical Journal E, 2003, 11(3):255-271.
17. Wang G , Rothmayer A P . Thin water films driven by air shear stress through roughness[J]. Computers and Fluids, 2009, 38(2):235-246.
18. Porombka P , HoHne T . Drag and turbulence modelling for free surface flows within the two-fluid Euler–Euler framework[J]. Chemical Engineering Science, 2015, 134:348-359.
19. Jin Z , Sui D , Yang Z . The impact, freezing, and melting processes of a water droplet on an inclined cold surface[J]. International Journal of Heat and Mass Transfer, 2015, 90:439-453.
20. Jin Z , Zhang H , Yang Z . The impact and freezing processes of a water droplet on a cold surface with different inclined angles[J]. International Journal of Heat and Mass Transfer, 2016, 103:886-893.
21. Kong W , Liu H . A Theory on the Icing Evolution of Supercooled Water near Solid Substrate[J]. International Journal of Heat and Mass Transfer, 2015, 91:1217-1236.
22. Schremb M , Tropea C . Solidification of supercooled water in the vicinity of a solid wall[J]. Phys.rev.e, 2016, 94(5).
23. Wakamoto S, Nakao K, Tanaka N. Study of the Stability of Supercooled Water in an Ice Generator[J]. ASHRAE Trans, 1996,Vol.102(2),142-150.
24. Young S W . Mechanical Stimulus to Crystallization in Supercooled Liquids[J]. Journal of the American Chemical Society, 2002, 33(2):726-30.
25. Lindinger B, Mettin R, Chow R, et al. Ice Crystallization Induced by Optical Breakdown.[J]. Physical Review Letters, 2007, 99(4):045701.