Computational and Experimental Study on the Freezing Characteristics of Supercooled Water Droplets: Postprint

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Abstract

Aiming at the special solidification process of aircraft icing, an improved icing characteristics prediction model and numerical calculation method were developed based on the Enthalpy-porosity model, and the established model and prediction method were validated through solidification experiments. The results demonstrate that, compared with the traditional Enthalpy-porosity method, the developed approach can effectively characterize the non-equilibrium solidification process, thus offering significant improvement in representing the solidification characteristics of cold water droplets. Based on the established method, an analysis of factors influencing droplet solidification characteristics was performed, obtaining the temperature distribution and phase interface evolution features during droplet solidification under various supercooling conditions. This research can provide important references for improving icing thermodynamic models and enabling refined prediction of icing characteristics.

Full Text

Computational and Experimental Study on Freezing Characteristics of Supercooled Water Droplet

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Abstract

An improved icing prediction model and numerical method are developed for the special freezing process of aircraft icing based on the Enthalpy-porosity model. The proposed method can effectively characterize the non-equilibrium freezing process, thereby providing better representation of supercooled water droplet freezing characteristics. Using the developed method, an analysis of influencing factors on droplet freezing characteristics is conducted, obtaining the temperature distribution and phase interface evolution features under different supercooling conditions. This research can provide important reference for improving icing thermodynamic models and enabling refined prediction of icing characteristics.

Key words: supercooled water droplet; aircraft icing; freezing; phase change

Aircraft icing is a special liquid-solid phase change phenomenon where supercooled water droplets impact aircraft surfaces and freeze, representing a significant safety hazard for flight operations [1-3]. The freezing of supercooled water droplets in aircraft icing typically occurs in two distinct stages [4]. The first stage begins with nucleation, representing the transition of water droplets from a thermodynamic non-equilibrium state to equilibrium—known as the dendrite formation stage or partial freezing stage [6]. The second stage is the complete solidification phase, where the liquid-solid interface advances from the liquid phase toward the solid phase until freezing is complete [7]. In aircraft icing, heterogeneous nucleation induced by impact makes the first stage significantly faster than the second [5]. Due to the complexity of the icing physics, most research on supercooled water droplet freezing has focused on the second stage, particularly the interface advancement process [4, 5]. Consequently, most studies have employed equilibrium freezing theories and methods for icing prediction, such as the Enthalpy-porosity method used by many researchers [8, 9] to investigate liquid-solid phase change behavior during solidification. However, this method primarily addresses equilibrium freezing and cannot capture the non-equilibrium effects characteristic of the first freezing stage.

In recent years, increasing demands for icing prediction accuracy have drawn greater attention to non-equilibrium freezing effects in supercooled water droplets [10-13]. Nevertheless, due to the complexity of the solidification process, predictive capabilities for non-equilibrium freezing characteristics remain limited, and prediction accuracy needs improvement, resulting in relatively weak understanding of supercooled water droplet freezing behavior. This paper addresses the non-equilibrium effects in supercooled water droplet freezing during aircraft icing by developing a prediction method for freezing characteristics and building an experimental system for validation. This research provides valuable reference for improving icing thermodynamic models and enabling refined icing prediction.

Experimental studies have shown that the freezing process of supercooled water droplets consists of two typical stages. In the first stage—the dendrite formation stage—the droplet temperature rises from the supercooled state to the freezing point, accompanied by partial release of latent heat, representing a non-equilibrium freezing process. The second stage is the interface advancement phase driven by thermal diffusion, which occurs isothermally as an equilibrium freezing process. Although the first stage is relatively short compared to the second, different icing conditions create different initial conditions for the second stage at the end of the first stage, thereby affecting subsequent freezing characteristics. Therefore, effective prediction of the entire freezing process must consider both the non-equilibrium effects of the first stage and the equilibrium effects of the second stage. Given these characteristics, a key challenge in accurately predicting the complete freezing process is how to incorporate the non-equilibrium effects of the first stage into the prediction of interface advancement.

[Figure 1: see original paper] Two typical freezing stages of supercooled water droplet

Since partial latent heat has already been released during the first stage when the mixed state forms, the prediction of the second stage should incorporate corrected characteristic parameters from the first stage. The dimensionless supercooling is expressed as:

where is the specific heat capacity of the solid phase and is the latent heat of solid-liquid phase change. The calculation expression for is:

Therefore, the latent heat of solid-liquid phase change for the mixed state can be expressed as:

The relevant physical property parameters of the mixed state can be expressed as: and represent the corresponding liquid and solid phase properties, respectively.

Once the physical property parameters for the first-stage freezing process are obtained, the phase change problem considering non-equilibrium freezing effects during supercooling can be transformed into an equilibrium freezing problem. To adopt prediction methods for liquid-solid phase change heat transfer under equilibrium conditions, the following assumptions are made: 1. Deformation of water droplets during freezing is neglected. 2. Due to heterogeneous nucleation from impact, the first freezing stage is significantly shorter than the second stage. 3. The liquid region during the freezing process is essentially a mixed state that has undergone partial phase change during the first stage; therefore, physical property parameters in the liquid region during the second-stage calculation are replaced by mixed-state parameters.

Based on these assumptions and drawing from the Enthalpy-porosity method, the flow and heat transfer governing equations for the freezing process can be described as:

where is the liquid phase freezing temperature and is the supercooled temperature. Here, and represent velocities in different directions, and and represent coordinates (for three-dimensional problems,). and correspond to pressure and temperature variables, respectively, is the reference temperature satisfying the Boussinesq approximation, and is enthalpy. , , , and correspond to physical parameters including density, viscosity, thermal expansion coefficient, and thermal conductivity. is gravitational acceleration in different directions, and is the source term in the two-phase zone during the second freezing stage, which can be described as [9]:

where is a parameter characterizing the two-phase zone features during freezing, and is the liquid fraction ratio in the second freezing stage of icing, expressed as:

where and are the temperatures for complete melting and complete solidification during the liquid-solid phase change process, respectively.

The finite volume method is employed to discretize the governing equations, with first-order accuracy in time for the unsteady term and solution via the strongly implicit iteration method. Based on fixed-grid technology, the two-phase interface is not tracked directly; instead, the interface position at different times is calculated indirectly through the relationship between temperature and enthalpy, avoiding difficulties associated with direct interface tracking. Using this approach, the phase-change heat transfer code developed previously by our team [14] was improved and applied to typical case studies.

2. Non-equilibrium Freezing Model

Taking a supercooled water droplet with a diameter of 4 mm and height of 2.5 mm as an example, the temperature distribution and phase zone evolution during freezing are analyzed. The droplet bottom surface serves as the cooling surface. In the calculations, the bottom is an isothermal boundary while the surface employs a convective boundary. Physical properties used in the calculations are shown in Table 1 .

Table 1. Physical properties of water and ice [5]

Material	(kg · m ^{3})	c (J · kg ^{1} · K ^{1})	(W · m ^{1} · K ^{1})	L (kJ · kg ^{1})
Water	1000	4187	0.6	334624
Ice	920	2031	2.3	-

Figure 2 [Figure 2: see original paper] shows the temperature distribution characteristics during supercooled water droplet freezing, while Figure 3 [Figure 3: see original paper] shows the phase zone distribution characteristics. In the initial freezing stage, the phase interface and isotherms are approximately parallel to the bottom cooling surface. As freezing progresses, both the phase interface and isotherms gradually curve toward the droplet top.

Figure 4 [Figure 4: see original paper] compares the freezing rates with and without considering non-equilibrium freezing effects at a supercooling of -10°C, and Figure 5 [Figure 5: see original paper] shows the influence of different droplet supercooling levels on the phase interface evolution rate. The results demonstrate that the freezing rate is higher when non-equilibrium freezing effects during supercooling are considered. This is because the developed model accounts for partial latent heat release during nucleation and dendrite growth in the supercooling stage, reducing the amount of latent heat released during the interface advancement stage and consequently increasing the interface propagation speed compared to traditional methods. Figure 5 shows that under the same conditions, greater droplet supercooling produces larger phase change driving forces and thus higher freezing rates.

3. Experimental Validation

3.1 Experimental System Design

To validate the developed model and method, an experimental system was built and corresponding experimental studies were conducted. The experimental system diagram is shown in Figure 7 [Figure 7: see original paper], consisting of a semiconductor refrigeration system, Agilent 34970A multi-point data acquisition unit, ANV TF100 PID temperature monitor, temperature controller, MotionXtra HG-100K high-speed camera, FLIR E60 infrared camera, LED shadowless light source system, industrial computer, and voltage-regulated power supply. During experiments, the semiconductor refrigeration platform provides the freezing environment, with the PID temperature control system maintaining the platform surface at the required experimental temperature. Using an interface tracking method, the high-speed camera records the temporal evolution of the droplet freezing phase interface, while the infrared camera records real-time temperature changes during freezing.

3.2 Comparison of Experimental and Computational Results

In droplet freezing experiments, during the nucleation and dendrite growth stage in the supercooled period, the droplet gradually transitions from a transparent to a blurred state under supercooled conditions. When the droplet reaches equilibrium temperature, the solid-liquid interface emerges and moves from the liquid zone toward the solid zone. Taking the moment when the solid-liquid interface first appears as the starting point of the second freezing stage, a high-speed camera records the temporal variation characteristics of the phase interface while an infrared thermal imager simultaneously records the temperature distribution patterns at different moments. Figure 8 [Figure 8: see original paper] shows the phase interface evolution over time during the second freezing stage at a supercooling of -10°C, and Figure 9 [Figure 9: see original paper] shows the corresponding temporal evolution of the droplet' s infrared temperature field. The results reveal that during the second freezing stage, the phase interface advances from the liquid zone toward the solid zone under thermal diffusion, while the low-temperature region gradually develops from the bottom to the top of the droplet.

Figure 10 [Figure 10: see original paper] compares the computational and experimental phase interface movement characteristics, while Figure 11 [Figure 11: see original paper] compares the calculated surface temperatures with experimental infrared temperature variations at supercooling levels of -10°C and -14°C. Figure 10 demonstrates that under the same supercooling conditions, the improved prediction model shows better agreement with experimental results than the traditional Enthalpy-porosity model. Notably, the improved model considering supercooling effects predicts higher freezing rates than the traditional model. The comparison reveals good agreement between computational and experimental phase interface movement over time, while computational and experimental temperature histories show some deviation but similar trends, confirming the validity of the developed model.

4. Conclusions

This paper investigates the computational and experimental aspects of supercooled water droplet freezing characteristics, focusing on non-equilibrium freezing effects in aircraft icing. The main conclusions are:

1. Based on the Enthalpy-porosity model, an improved prediction model and numerical method for supercooled water droplet freezing characteristics were developed. An experimental test rig was built to validate the numerical method. Compared with traditional methods, the developed model and method can effectively characterize non-equilibrium freezing effects and are thus suitable for predicting supercooled water droplet freezing characteristics.
2. During the icing process, greater supercooling leads to higher droplet freezing rates. However, when non-equilibrium freezing effects are considered, the freezing rate of supercooled water droplets is higher than in cases where these effects are neglected. Therefore, the freezing characteristics of supercooled water droplets in aircraft icing exhibit features distinct from equilibrium freezing processes. Effective characterization of non-equilibrium freezing phenomena during icing is essential for improving icing thermodynamic models and enhancing prediction accuracy.

References

[1] BLAKE J, THOMPSON D, RAPS D, et al. Simulating the freezing of supercooled water droplets impacting a cooled substrate[J]. AIAA Journal, 2015, 53(7): 1725-1739. [2] FUMOTO K, KAWANAMI T. Study on freezing characteristics of supercooled water droplets impacting on solid surfaces[J]. Journal of Adhesion Science and Technology, 2012, 26(4-5): 463-472. [3] KING W D. Freezing rates of water droplets[J]. Journal of the Atmospheric Sciences, 1975, 32(2): 403-408. [4] TABAKOVA S, FEUILLEBOIS F, RADEV S. Freezing of a suspended supercooled droplet with a heat transfer mixed condition on its outer surface[C]//1st International Conference on Applications of Mathematics in Technical and Natural Sciences, AIP Publishing, 2009, 1186(1): 240-247. [5]

FEUILLEBOIS F, LASEK A, CREISMEAS P, et al. Freezing of a subcooled liquid droplet[J]. Journal of Colloid and Interface Science, 1995, 169(1): 90-102. [6] BURTNETT E. Volume of fluid simulations for droplet impact on dry and wetted hydrophobic and superhydrophobic surfaces[D]. Mississippi: Mississippi State University, 2012. [7] JUNG S, DORRESTIJN M, RAPS D, et al. Are superhydrophobic surfaces best for icephobicity?[J]. Langmuir, 2011, 27(6): 3059-3066. [8] Voller, V. and Prakash, C. A Fixed Grid Numerical Modelling Methodology for Convection-Diffusion Mushy Region Phase-Change Problems[J]. International Journal of Heat and Mass Transfer, 1987, 30(8): 1709-1719. [9] Crank, J. Free and Moving Boundary Problems[M]. New York: Oxford University Press, 1987. [10] Worster M G. Solidification of fluids[J]. Perspectives in fluid dynamics, 2000, 742: 393-446. [11] ELLEN N, JACCO M H, EDWIN W, et al. Aircraft icing in flight: effects of impact of supercooled large droplets[C]//29th Congress of the Aeronautical Sciences St. Petersburg, Russia, September 7-12, 2014. [12] Tabakova, S., and Feuillebois, F., On the Solidification of a Supercooled Liquid Droplet Lying on a Surface[J]. Journal of Colloid and Interface Science, 2004, 272(1): 225-234. [13] Szimmat J. Numerical simulation of solidification process in enclosures[J]. Heat Mass Transfer 2002, 38: 279-293. [14] Du Yanxia, Xiao Guangming, Gui Yewei, et al. Study on Heat Transfer Characteristics of Phase-Change Energy Storage Unit for Thermal Management[J]. International Journal of Thermophysics, 2014, 35(8): 1577-1589

Note: Figure translations are in progress. See original paper for figures.

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