Three dimensional numerical simulation of ice crystal melting under different influencing factors

Jiachen Zhang1,*, Weifang Chen1 and Lifen Zhang2

1School of Aeronautics and Astronautics, Zhejiang University, Hangzhou 310027, China.
2School of Power and Energy, Northwestern Polytechnical University, Xian 710072, China.

*Corresponding author e-mail: 18291447884@163.com

Abstract. The icing of the aeroengines caused by ice crystals has gradually become a research hotspot in recent years. In this study, the influence laws of different factors of ice melting on melting process of ice crystal were studied. Performed unsteady simulation of ice crystal melting under forced convection of air based on VOF method coupled with solidification and melting model in CFD simulation analysis. The influence laws of different factors of ice melting on melting process of ice crystal were revealed.

1. Introduction
The icing of the aeroengines caused by ice crystals has been confirmed and gradually become a research hotspot in recent years. The melting state of ice crystals directly affects icing of the inside of engines, and different factors of ice melting have an influence on melting of ice crystals [1]. The most common such as particle diameter, air temperature, air speed, particle shape and particle attitude.

The melting of ice crystals under different influencing factors creates different flow fields. The flow fields in melting of ice have been studied with experimental method and computational fluid dynamics (CFD) simulation [2-8]. In recent years, CFD analysis has been developed to be a useful and essential method on researching the flow field. Researchers [2] studied the mechanism of melting and attachment of ice crystals inside aeroengines. However, there are no relevant results yet on the influence laws of different factors on melting of ice crystals outside. In this paper, the flow fields in melting of ice crystals were numerical simulated by approach of CFD, three-dimensional model was built and the simulated flow field such as stream line and temperature distribution was correspondingly analyzed. Meanwhile, this paper showed the influence laws of different factors on melting of ice crystals.

2. The melting of ice crystals

2.1. Numerical Simulation
We used a calculation domain of a quarter or one-half of the total flow field due to the symmetrical characteristic of the field. The computational domain and the corresponding grids were created by ICEMCFD. The flow field was obtained by solving the N-S equations through the commercial
software FLUENT 16.0. The volume of fluid (VOF) method and solidification & melting model (SMM) [3-8] were applied to run the simulations. Laminar model was used due to simulation conditions that flow states were laminar. Pressure-velocity coupling used semi-implicit method pressure linked equation (SIMPLE) algorithm. Figure 1 shows the three-dimensional model of the ice crystals with different shapes and equal quality. Figure 3 shows the corresponding mesh dividing, hexahedral mesh and double O-grid blocks were applied in this model.

For the study on different attitudes of ice crystals with ellipsoid-shaped, the rotation angles 0°, 30°, 60° and 90° were only chosen due to the symmetrical characteristic of the angle, as shown in Figure 2. The calculation domain is large enough to not affect the melting of ice crystals.

2.2. Method Validation
In order to study the influence of the number of grids on the calculation results, the ice crystal with sphere-shaped was taken as an example to study the melting of ice crystals under four grids. Figure 4 shows the results, which verify the grid independence [9]. In addition, the experiment of melting of ice

Figure 1. Numerical simulated model of ice crystals. (a) is the ice crystal with sphere-shaped, (b) is the ice crystal with ellipsoid-shaped, (c) is the ice crystal with cylinder-shaped.

Figure 2. Rotation diagram of the ice crystal with ellipsoid-shaped.

Figure 3. The mesh dividing of the model for the whole flow field. (a) contains the ice crystal with sphere-shaped, (b) contains the ice crystal with ellipsoid-shaped, (c) contains the ice crystal with cylinder-shaped.
crystals [10] with sphere-shaped was numerically verified in order to verify the reliability of the simulation method. Table 1 shows the results, which indicates that the simulation method is feasible.

![Figure 4](image)

**Figure 4.** Comparison of liquid fraction under four grids.

**Table 1.** Comparison of numerical value.

| Comparative object                  | Time/s |
|------------------------------------|--------|
|                                    | 0.4    | 1.2  | 2.0  | 2.8  | 3.3  |
| Experiment/%                       | 16     | 50   | 68   | 80   | 96   |
| Numerical simulation/%             | 17     | 39   | 62   | 84   | 99   |
| Error value/%                      | 6.25   | 22   | 8.82 | 5    | 3.13 |

3. Result and discussion

The ice crystals with sphere-shaped was taken as an example (diameter is 0.3mm, air speed is 0.5m/s and temperature is 298K). Figure 5(a) shows the time evolution of temperature distribution in flow fields. It’s obvious that the inflow surface of ice crystals melts faster and the backflow surface melts slower. Figure 5(b) shows the velocity vector distribution cloud diagram of the flow field close to the backflow surface at a certain moment. There is a vortex formed close to the backflow surface which leaves the surface at some location, where it’s in the range of 120° to 150° that’s the point melting slowest.

![Figure 5](image)

**Figure 5.** Cloud diagram of flow fields. (a) is the temperature distribution, (b) is the velocity vector distribution.
Figure 6(a) shows the time evolution of liquid fraction of ice crystals with sphere-shaped under different diameters. Figure 6(b) shows the time evolution of liquid fraction of ice crystals with sphere-shaped under different air speeds. Figure 6(c) shows the time evolution of liquid fraction of ice crystals with sphere-shaped under different air temperatures. Figure 6(d) shows the time evolution of liquid fraction of ice crystals under different particle shapes. Figure 6(e) shows the time evolution of liquid fraction of ice crystals with ellipsoid-shaped under different attitudes.

Figure 6. The time evolution of liquid fraction. (a) is under different particle diameters, (b) is under different air speeds, (c) is under different air temperatures, (d) is under different particle shapes, (e) is under different particle attitudes.

4. Conclusion
Three dimensional numerical simulation models were built for simulating the flow field in melting of ice crystals. Meanwhile, the grid independence and the reliability of simulation methods were verified. The result shows that the larger the particle diameter, the longer the ice crystal melts completely. The air temperature has little effect on the melting of ice crystals, but the air speed has a great influence. In addition, the particle shape and the particle attitude are also important factors affecting the melting of ice crystals.

This study illustrated that the laws of different external factors affecting the melting of ice crystals are also different and the melting of ice crystals can be controlled by adjusting external factors.

Acknowledgments
This research was supported by the National Natural Science Foundation of China (Grant NO.11502232, 11572284 and 61627901) and the National Basic Research Program of China (Grant NO.2014CB340201).

References
[1] Sutton, M., and Hammond, D, “The Development of the Facilities for the Simulation of Ice Crystal Conditions”, Proceedings of the International Icing Symposium, Montreal, Canada.1995.
[2] Mason, J. G., “Current Perspectives on Jet Engine Power Loss in Ice Crystal Conditions: Engine Icing”, Seventh AIRA Research Implementation Forum Boeing.2008.
[3] L. Fan, “A Numerical Simulation on the Solidification and Melting of ice”, Publisher of Nanjing University of Aeronautics and Astronautics.2005.

[4] Y. J. Qiu, “Numerical Research of Solidification and Heat Transfer Characteristics for an Air-Cooling Molten Blast Furnace Slag Droplet”, Publisher of Chongqing University.2014.

[5] N. Qin, “The Experimental Study and Numerical Simulation of Ice Water Changing Between Solid and Liquid”, Publisher of Qingdao University of Science and Technology.2011.

[6] T. T. Guo, “The Theoretical Research on Transformation Between Solid and Liquid of Water and Ice”, Publisher of Qingdao University of Science and Technology.2011.

[7] X. H. Geng, “The experimental Study and Numerical Simulation on the Effect of Humidity and Temperature Between Solid and Liquid of Ice Water”, Publisher of Qingdao University of Science and Technology.2014.

[8] Y. Qin, “A Numerical Simulation on the Interaction of the Interface and the Convection Heat Transfer”, Publisher of Dalian University of Technology.2005.

[9] W. Q. Tao, “Numerical Heat Transfer”, Publisher of Xi’an Jiaotong University.1998.

[10] Sihong Yan, Jose Palacios, “Experimental quantification of partial melting in a single frozen droplet”, AIAA 2016-3741.