Hydrodynamics and Thermodynamics of Ice Particle Accretion

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Keywords: Aircraft icing, Numerical computation, Phase change, Multiphase flows, Heat transfer

Description of the work

Icing in warm environments, e.g. in aircraft engines or heated measurement probes, occurs if airplanes fly through areas with high amounts of atmospheric ice crystals. Ingested into the warm engine, they start to melt, resulting in an airflow laden with mixed-phase particles consisting of water and ice. Liquid water deposits on component surfaces, which enables ice particles to adhere to them, forming ice accretion of considerable thickness. Such accretion reduces reliability, power and efficiency of the engine and impedes the function of probes. While light icing reduces the aircraft's economic viability and environmental-friendliness by increasing fuel consumption, it may also lead to engine failure and damage, or probe malfunction in severe cases, which all threaten aircraft safety significantly. The aviation industry is highly interested in eliminating this problem and in developing accurate ice accretion models to be able to predict engine icing and detect icing hazards. As the comprehension of the underlying physics of ice accrection is still rudimentary, the accuracy of current prediction tools is rather limited. The goal of this work is to investigate the physical mechanisms leading to ice accretion by developing theoretical models and the implementation of them in numerical codes.

List of relevant journal publications (plus 10 conference presentations, not listed)

2/2016 Kintea, D.M., Roisman, I.V., Tropea, C., *Transport processes in a wet granular ice layer: model for ice accretion and shedding*. International Journal of Heat and Mass Transfer, 97, 461-472

1/2016 Kintea, D.M., Breitenbach, J., Thammanna Gurumurthy, V., Roisman, I.V., Tropea, C., *On the influence of surface tension during the impact of particles on a liquid-gaseous interface*. Physics of Fluids 28, 012108 (2016).

9/2015 Kintea, D.M., Hauk, T., Roisman, I.V., Tropea, C., *Shape evolution of a melting nonspherical particle*. Physical Review E 92 (2015): 033012.

11/2013 Criscione, A., Kintea, D., Tuković, Ž., Jakirlić, S., Roisman, I. V., Tropea, C., *Cristallization of supercooled water: A level-set-based modeling of the dendrite tip velocity.* International Jounal of Heat and Mass Transfer, 66, 830-837.

6/2013 Rauschenberger, P., Criscione, A., Eisenschmidt, K., Kintea, D., Jakirlić, S., Tuković, Ž., Roisman, I. V., Weigand, B., Tropea, C., *Comparative assessment of Volume-of-Fluid and Level-Set methods by relevance to dendritic ice growth in supercooled water.* Computers & Fluids, 79, 44-52.

Scientific Summary

Within the scope of this work, three main phenomena related to the process of ice crystal accretion are studied: the melting of non-spherical particles, the impact of small particles on a liquid surface and the accretion and shedding of ice layers.

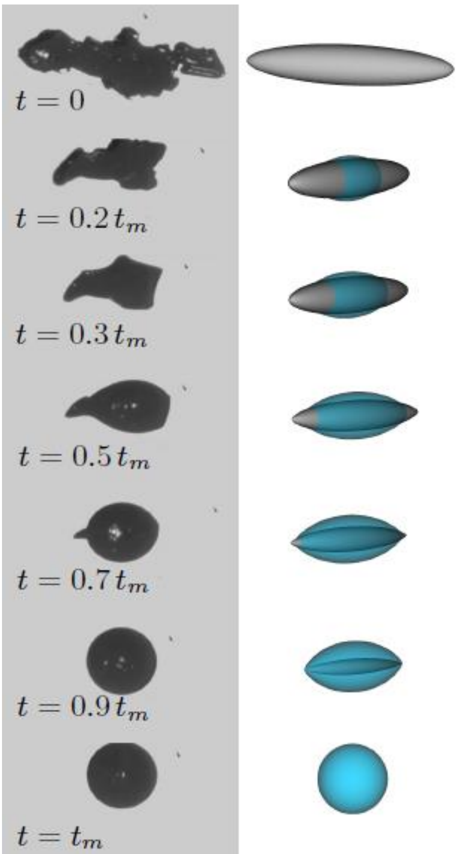

Figure 1: Comparison between experimental data and theoretical prediction.

A crucial dependence of the engine icing severity on the ratio of liquid to solid water content carried by the airflow renders an accurate prediction of this ratio extremely important for the prognosis of engine icing. In current codes, the ice particles are assumed to be spherical allowing an effective one-dimensional consideration of the melting process. However, atmospheric ice particles tend to be highly non-spherical, taking the shape of needles, plates or dendrites. In order to investigate the melting of such non-spherical particles, a theoretical model is developed based on an approximation of the particle shape as a spheroid (right-hand side of Figure 1). Due to capillary forces, the arising meltwater is presumed to accumulate in the particle mid-section, where the curvature is minimal. Numerically realized with a Level-Set approach, the model is able to predict the evolution of the shape of the melting particle and the time of its melting with high accuracy. Figure 1 shows the shape evolution of a melting irregular ice particle on the left, while on the right the corresponding modeled shapes are shown. The model yields results which confirm the model's superiority over currently employed melting models. In comparison with experimental data of melting non-spherical particles, the accuracy of the theoretical predictions was improved over the currently employed sphere-model by 58 %.

The particle impact onto a liquid surface determines whether ice particles stick to a liquid film which has accumulated on component surfaces or rebounds. Thus, it influences the accretion growth rate and thereby the icing severity. In current icing codes, this process is usually accounted for using empirical correlations lacking a detailed physical foundation. Within the scope of this work, the particle impact is studied numerically in order to gain insights into the predominant physical phenomena. In addition to pressure and viscous forces acting on the particle, the capillary forces arising at the three phase contact line are taken into account by a Finite-Volume algorithm. An appropriate mesh motion allows for the movement of the particle, which constitutes a boundary on the domain, while the liquid-gaseous interface is accounted for by a Volume-of-Fluid method. The code accurately predicts the impact behavior of high Weber number processes as well as low Weber impacts in which surface tension and the contact line force resulting from it prevails. By means of data obtained with the algorithm and a dimensional analysis, a simple correlation is found which is able to predict whether particles stick or rebound. Figure 2 shows a comparison between experimental data and the numerical predictions of this work of an impact of a sphere at a velocity of 2.17 m/s of a diameter of 25.4 mm on a free water surface.

Figure 2: Comparison between experimental data of the impact of a polypropylene sphere on a liquid surface (left-hand side of each picture) with the numerical results (right-hand side).

As the connection strength and the sticking of incoming particles principally depend on the accretion composition, it plays a central role in the growth of the ice/water layer and the accretion behavior, i.e. whether the accretion is rather loosely attached, well-adhered or no ice accretes at all. The computation of the composition, which in typical icing codes is not accounted for, is approached in this work in two steps: A detailed numerical investigation, in which individual ice crystals and liquid droplets are numerically resolved is used in the first approach while the behavior of a melting porous ice accretion is modeled in the second approach based on the results obtained by means of the first approach.

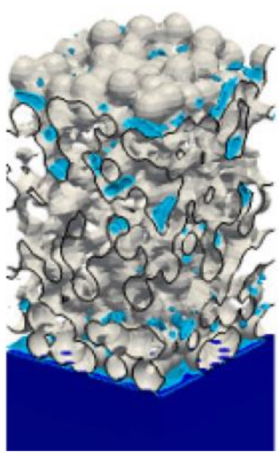

Figure 3: Graphical representation of the numerically obtained ice layer composition.

In the first approach, a detailed three-dimensional thermal model which resolves ice particles and liquid droplets is developed. It demonstrates that a porous ice/water layer behaves differently than solid ice. Figure 3 shows the numerically computed composition of the ice layer with the detailed approach. White surfaces correspond to ice and light-blue regions denote liquid regions, the wall on which the ice accretes is shown in dark-blue.

Theoretical modeling of the effective thermal properties and accounting for the transport of heat and mass in the ice layer is the basis of the second approach. It yields a numerical algorithm which efficiently predicts the composition of the accretion, which is then utilized to anticipate the instant of ice plate shedding. The obtained results agree very well with experimental data, but with significantly less computational effort than the detailed model.

Significant progress has been made within the scope of this work in all of the three sub-processes. Developed models and algorithms presented in this work are a significant step towards a new generation of predictive tools for ice crystal accretion. The development of such tools is a crucial milestone on the way towards safer and more economic air traffic.