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Numerical simulation of three-dimensional ice accretion on an aircraft wing

Yihua Cao [a], Junsen Huang [a,*], Jun Yin [b]

[a] School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, People's Republic of China
[b] AVIC Chengdu Aircraft Industrial (Group) Co., Ltd., Chengdu, 610092, People's Republic of China

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ABSTRACT

A method based on the Eulerian two-phase flow theory and the extended heat transfer model for numerically simulating three-dimensional ice accretions on an aircraft wing is presented in this paper. The governing equations for supercooled droplets in three-dimensional applications are established by considering the droplet phase as pseudo-fluid and applying the conservation laws of mass and momentum for a fixed control volume. A permeable wall boundary condition is proposed to depict the physical phenomenon of droplet impingement more properly. The droplet collection efficiency distribution is readily obtained from the solution of the three-dimensional droplet flowfield. Ice accretions can then be simulated through performing the mass and energy balances for each icing control volume. Some concepts such as critical ice thickness and inner time step as well as an iterative solution procedure for runback water motion have been proposed to facilitate the simulation for three-dimensional case. For validation purpose, multistep simulation results for the droplet impingement and ice accretion under specified icing conditions are compared with the corresponding experimental data and some previously predicted results, showing some better agreement gained for the current method. Furthermore, the effects of some meteorological parameters on ice accretion have been investigated and analyzed individually.

1. Introduction

Icing has become one of the main meteorological hazards faced by the aviation industry. A number of air disasters have been proven to be related to ice accretion in the past few decades. Research on ice accretions occurred on various components of an aircraft has gained intensive attention with a lot of effort spent on it, but now still remains an issue far from being completely resolved [1]. Ice accretions may occur on aircraft wings during the flight when supercooled droplets within the cloud impinge on the surface whose temperature is below freezing. The ice buildup at the wing's leading edge may cause significant changes to the original aerodynamic configuration thus seriously threatening the flight safety. Several approaches have been used for the investigation of ice accretion including icing tunnel test, flight test, natural icing test and numerical simulation through CFD methods. Due to the limitations of the experimental study, the exploration for the entire icing envelope can be made possible only through the analytical methods [2]. That is probably the major reason for the popularity of the numerical simulation method in the icing community. Numerical methods have obtained considerable progress and been widely used with the rapid development of digital computer capability and advanced CFD theories. Several icing codes have been developed by some countries or organizations and the representative ones are listed as follows: LEWICE code of NASA [3–5], TRAJICE code of DRA [6], FENSAP-ICE code [7–9], the code of ONERA [10] and the code of CIRA [11–13].

The basic simulation procedures for the above icing codes are similar. The major modules include: (1) solution of the governing equations for air flow field; (2) droplet collection efficiency calculation based on the air flowfield solution from the previous module; (3) icing properties calculation and ice shape generation based on appropriate icing model. In practical applications, the coupling icing process, that is, the surrounding air flowfield and the associated droplet impingement characteristics are time-varying due to the ever-changing ice shape, is commonly regarded as quasi-steady in one single simulation step. Thus the whole icing process is divided into several intervals according to some certain criteria during which the air flowfield and droplet impingement characteristics are treated as constant.

* Corresponding author.
E-mail addresses: yihuacaobu@126.com (Y. Cao), huangjunsen124@163.com (J. Huang), yinjunbuaa@163.com (J. Yin).

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Nomenclature

B	ice layer thickness, m	R	temperature recovery factor
c	chord length, m	T_0	icing substrate temperature, K
c_{pw}	specific heat of water, J/kg	T_f	freezing point temperature, K
c_{pi}	specific heat of ice, J/kg	T_{sur}	upper surface temperature of ice layer, K
c_{pa}	specific heat of air, J/kg	T_{wq}	temperature of supercooled droplets K
h_{cv}	convective heat transfer coefficient, W/(m^2 · K)	T_e	temperature at the edge of boundary layer, K
k_i	thermal conductivity of ice, W/(m · K)	t_{ice}	total ice accretion time, s
LWC	Liquid Water Content, g/m^3	U_e	air velocity at the edge of boundary layer, m/s
l_f	specific latent heat of freezing, J/kg	U_d	velocity of impinging water droplets, m/s
l_s	specific latent heat of sublimation, J/kg	V_∞	free stream velocity, m/s
l_e	specific latent heat of evaporation, J/kg	β	local droplet collection coefficient
n_{step}	number of time steps in multistep procedure		

In module (1), namely, the air flowfield solution, different methods have been adopted. Earlier icing codes such as LEWICE and ONERA use a panel method (with appropriate compressibility correction) or an Euler method to calculate the inviscid flowfield. Usually for these earlier icing codes the calculation of boundary layer is combined with the flowfield solution to gain some parameters needed for the icing model, for instance, the convective heat transfer coefficient on a rough wall. Owing to the advancement in modern CFD approaches, current icing codes like FENSAP-ICE solve the set of Navier–Stokes equations directly without boundary-layer techniques involved.

Accurate calculation for droplet collection efficiency distribution is of great importance in icing simulation and two methods are available: Lagrangian tracking method and Eulerian two-phase flow method, The Lagrangian method computes the collection efficiency by tracking a number of droplets' trajectories released from the far field at different initial locations. The motion equation for each droplet is established by Newton's second law and numerically integrated to find the trajectory throughout the surrounding domain. The Eulerian method considers the droplet as a pseudo-fluid phase and solves the droplet-phase-related continuity and momentum equations. The collection efficiency can be readily obtained from the droplet flowfield properties near the wall. Due to its remarkable superiority in comparison with the Lagrangian method when applied to three-dimensional complex geometries, the Eulerian method is adopted in this paper for the droplet collection efficiency calculation.

Most icing codes based their icing model on the classical Messinger model [14] or its improved versions. As this kind of model was initially developed for two-dimensional cases like an airfoil, its implementation in three-dimensional case has met with some difficulties and some special measures have been taken to get them around. For example, the ONERA three-dimensional icing model defines the thermodynamic grid along the wall air streamlines thus requiring interpolation of some input parameters for the icing model. This obviously brings about a large amount of extra computational effort.

This paper presents a method to numerically simulate three-dimensional ice accretions on an aircraft wing based on the Eulerian two-phase flow theory and the extended heat transfer model proposed by Myers. The governing equations for supercooled droplets in three-dimensional applications are established according to the droplet pseudo-fluid model. A permeable wall boundary condition is proposed to depict the physical phenomenon of droplet impingement on the wall surface more properly. Based on the extended heat transfer model, some concepts have been proposed to give a better description of the overflow that might occur on the icing surface. To determine the existence of unfrozen runback water in a control volume, a criterion concerning the local ice layer thickness is given thus making it possible that the overflow calculation can be conducted simultaneously for all control volumes. For immediate update of the above criterion, the procedure of inner time step marching is presented. It makes the simulation of the time-variant icing process, namely, the ice growth and runback water motion more close to the physical reality. With the assumption that runback water closely follows the local air streamlines, the inflow and outflow runback water mass fluxes as well as the ice accretion rate for all icing control volumes are gained simultaneously through an iterative solution procedure during each inner time step. The ice shape is built under the assumption that ice grows in the direction normal to the surface. Furthermore, multistep simulation procedure has been employed for each case studied to improve the accuracy.

2. Three-dimensional Eulerian approach to droplet impingement simulation

2.1. Governing equations for droplet phase

Based on the Eulerian two-phase flow theory, a fixed control volume for applying the conservation law of mass and momentum to the droplet phase is illustrated in Fig. 1. Some assumptions need to be made for establishing the governing equations of the droplet phase [15]. They are listed as follows:

(1) The water droplets are treated as spheres with volumetric diameters.
(2) No collision, distortion or heat transfer is considered during the droplet's motion along its streamline before impingement or bypass.
(3) The turbulent fluctuations of the airflow have no effect on the droplet flowfield.

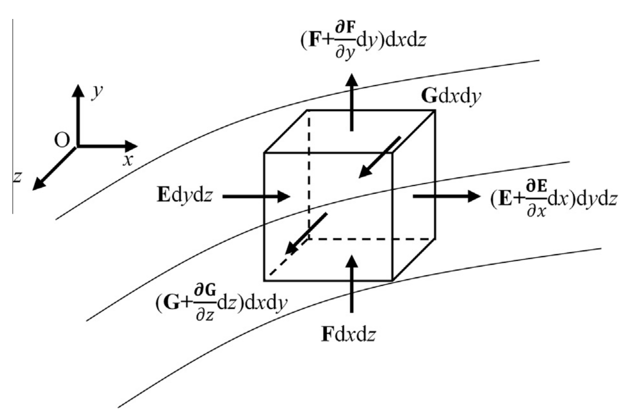

Fig. 1. Illustration for derivation of the conservation law of mass and momentum for the droplet phase.