NUMERICAL SIMULATION OF ICE ACCRETION ON AIRFOILS

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Summary An approach to numerically simulate ice accretion on airfoils has been developed and used to characterize ice accretion on a NACA0012 airfoil. In this paper we present the background and motivation for the investigation, the techniques used, and then the main results are presented. The validation of the simulation approach developed in this paper is also discussed. Finally, the conclusions are presented based on our analysis of the results presented.

BACKGROUND INTRODUCTION

Ice accretion on airplane wings can be a hazard to flight safety. The cause of the accretion is due to supercooled water droplets impinging to the windward face of the wings. Ice accretion can modify the designed aerodynamic shape of airfoils and considerably degrade their aerodynamic performance. Thus, being able to evaluate the mechanisms and consequences of ice accretion is of great importance to anti-icing and de-icing.

Different icing conditions form different type of ice accretions. Depending on the icing mechanism, ice accretions can be classified as: rime ice, glaze ice or mixed ice. Rime ice occurs in a low temperature environment and forms because supercooled droplets freeze simultaneously when they impinge onto the airfoil surface. Glaze ice occurs in an environment with relatively high temperature (while still lower than freezing point) under which the droplets freeze partially at the impingement location and then freeze gradually during the flow along the airfoil surface caused by airflow. Mixed ice is defined as a mixture of rime and glaze ice. Glaze ice and mixed ice can corrupt the designed aerodynamic shape of airfoils more significantly than rime ice.

These forms of ice accretion can be investigated by several means, including flight test, experimental simulation, engineering method and numerical simulation. Flight test and experimental simulation can obtain exact ice shape but are usually too expensive to be widely adopted. The engineering method uses the typical experimental data and empirical formulae but could hardly analyze the ice accretion process. Therefore, numerical simulation is widely adopted because it is economical and can simulate the icing process and so provide a relatively exact evaluation of ice accretion. Several codes for simulating ice accretion have been developed internationally, such as: LEWICE (USA), ONERA (France), DRA (UK), FENSAP-ICE (Canada), CIRAMIL (Italy).

TECHNIQUES DESCRIPTION

This paper develops an approach to numerically simulate ice accretion on airfoils which is based on four modules: (1) air flowfield solution, (2) droplets collection efficiency calculation, (3) boundary layer characteristics evaluation, and (4) ice accumulation evaluation via a thermodynamic model.

Air flowfield solution

The air flowfield can be obtained by using the panel method to solve the Euler equations or directly solving the compressible Navier-Stokes equations. The panel method can calculate the air velocity at any point in the flowfield directly but usually lacks accuracy in computing the complete flowfield. In contrast, the solution of the compressible Navier-Stokes equations can provide a more accurate flowfield computation but is time consuming. In order to synthetically consider the computational precision and efficiency, an Euler flow computation is adopted in this paper.

Droplets collection efficiency calculation

The droplets' collection efficiency on the airfoil surface is important in numerically simulating ice accretion and two computational methods are available: Lagrangian and Eulerian two-phase flows methods. The Lagrangian method obtains the collection efficiency by solving the motion equation of droplets to track each droplet's trajectory in the flowfield. Eulerian two-phase flow methods consider the droplets in the airflow as a form of pseudo fluid which interpenetrates with the air and the collection efficiency is obtained through solving the velocity and apparent density distribution of droplets. There are advantages in using the Eulerian two-phase flow method compared with a Lagrangian approach since the same mesh can be used to solve the governing equations for the airflow and droplets. Also, the droplets' collection efficiency may be obtained based on the solution of the droplets' flowfield directly, meaning that particles don't have to be tracked. For these reasons the Eulerian two-phase flows method has been adopted here.

The governing equations for supercooled droplets have as unknowns the apparent density and velocity of the droplets. In the Eulerian two-phase flows method, the droplets' collection efficiency is determined by the apparent density and velocity of droplets near the wall. Therefore, the wall boundary condition is important in solving the droplets' flowfield. Previous literature [1,2] set the initial solution of the droplets' apparent density and velocity on the wall to be zero and no special techniques were employed to deal with the wall boundary. This can result in oscillations in the solution of the droplets' flowfield (especially near the wall boundary) and extra stabilization terms must be added. In fact, because of the particular nature of the impingement between the droplets and wall, supercooled droplets adhere to the wall after they inelastically impinge on it. Before droplets reach the wall, they have quite high normal velocity relative to the wall and this velocity becomes zero instantaneously when the droplets impinge on the wall inelastically. If the droplets velocity on the wall is set to be zero, this is equivalent to the droplets having no impingement with the wall because the net flux of droplets on the wall is nil. Nor can the droplets apparent density on the wall be set to be zero. Otherwise it is equivalent to a fact that no droplets impinge onto the wall. Based on the above analysis, this paper proposes a permeable wall to simulate the droplets impingement on airfoils. Another problem in Eulerian two-phase flows method is the computation of the governing equations for the droplets. A numerical computational technique has been developed to deal with this and the accuracy and convergence of the numerical computation improved remarkably on using this technique combined with the permeable wall.

Boundary layer characteristics evaluation

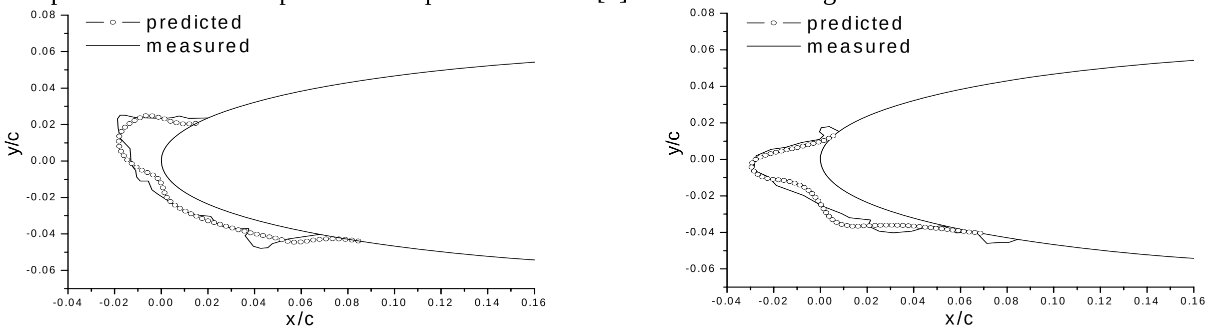
The convective heat transfer coefficient is an essential parameter in the thermodynamic process of ice accretion. It primarily depends on the boundary layer properties, such as momentum thickness and skin friction coefficient. An integral boundary layer method corrected to account for roughness effect, based on LEWICE and CIRAMIL codes, has been employed to evaluate the boundary layer properties and calculate the convective heat transfer coefficient.

Ice amount evaluation via thermodynamic model

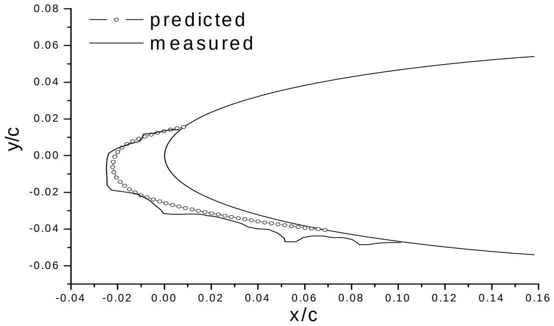
The thermodynamic model of ice accretion is based on the classical Messinger model employed by most of the ice accretion codes. The ice amount is evaluated using mass and energy balances. The shape of ice accretion is found using the assumption that ice grows in the direction locally normal to the airfoil surface.

MAIN RESULTS

This paper investigates the ice accretions on NACA0012 airfoil under different icing conditions. Figure 1 shows the typical predicted results compared with experimental data [3] under similar icing conditions.



T_∞=-6.1 ℃ T_∞=-14.13 ℃



T_∞=-28.3 ℃

Figure 1 Comparison of ice accretion between the predicted results and experimental data

AOA=4°, V_∞=67.05m/s, LWC=1.0g/m^3, MVD=20μm, Accretion time=360s

CONCLUSIONS

An approach to numerically simulate ice accretion on airfoils has been developed. Based on the evaluated results, the following conclusions can be drawn: (1) ice accretion can greatly corrupt the designed aerodynamic shape of airfoils, which will result in degradation of the aerodynamic performance; (2) the new simulation approach developed in this paper appears effective in predicting the geometry of this ice accretion.

References

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