THE DESIGN OF A SERIES OF ELECTROTHERMAL ICE PROTECTION SYSTEMS

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Abstract

This paper focuses on the design of ice protection system of aircraft components under different inflight icing characters. A numerical simulation method based on Euler-Euler multiphase coupling model was adopted to design the electrothermal anti-icing system for aircraft components with atypical shapes such as radomes on fuselages. For the calculation of droplets impingement, 3D N-S equations and standard $k-\varepsilon$ *turbulence model were applied to improve the simulation precision of flow fields and droplets concentration fields of complex configurations. The Langmuir distribution model of droplet diameters was introduced and the numerical solutions are compared with that of uniform average diameter. Some representative validation examples are presented, including an airfoil, a 2-D cylinder and a 3-D sphere, by comparing our results with the dissertations' ones which come from experiments or numerical simulations of authoritative organizations. The calculated thermal loads of real components are compared with that of the previous used engineering method. The electrothermal anti-icing system designed as a product had been tested in engineering practice for a long time.*

1 Introduction

The icing phenomenon on a flying aircraft's surface is called inflight icing. When an aircraft flying in minus temperature atmosphere with super-cooling droplets, under the conditions of super-cooling droplets impingement, aerodynamic heating and surface heat emission, the super-cooling droplets impact, freeze and accrete on the windward surface of the aircraft components if the equilibrium temperature of the components is minus, and this phenomenon is called ice accretion. Ice accretion will deteriorate aerodynamic characters as well as endanger flight safety. The research regarding ice protection and deicing has been conducted for a long time. Comprehensive explanation on ice accretion theory and the practical anti-icing system have been improved by a large margin since 1950s. The research and design of anti-icing system of some typical aircraft components, such as spheres, ellipsoids, airfoils, and cylinders, have been basically settled thanks to the rich experiences in ice wind tunnel tests, numerical simulations and flight tests. An engineering method, which can accurately solve the anti-icing design problems for the similar shapes mentioned above, has been established by looking up tables. [1]

The global air traffic is ever-increasing since 1990s, especially in special meteorological regions. Meanwhile, with the introduction of CAD, the shapes of aircraft components tend to become more and more complex and diversified to meet the requirements of accurate aerodynamic design and a variety of special functions. Ice accretion problem becomes vital again and is attracting many eyes. Driven by the European EURICE plan as well as the cooperation between America and Canada, new meteorological standards, experimental and numerical simulation techniques, anti-icing methods and so forth, appeared one after another. With the development of CFD especially multi-phase flow simulation technologies, many anti-icing calculating softwares based 3D N-S equations, such as FENSAP, LEWICE, ANTICE, IMPING3D, etc, are growing up. [5]

There were stagnant decades in China on the research of inflight icing and anti-icing since 1960s. By the end of 1990s, ice accretion had not yet been considered by Chinese aviation circle unless the persistent increase of Chinese aviation activities, the outspread of air lanes and the continual demands on broadening the aeronautical meteorological limitations, especially a severe air disaster which caused two large aero transports crash in 2001.

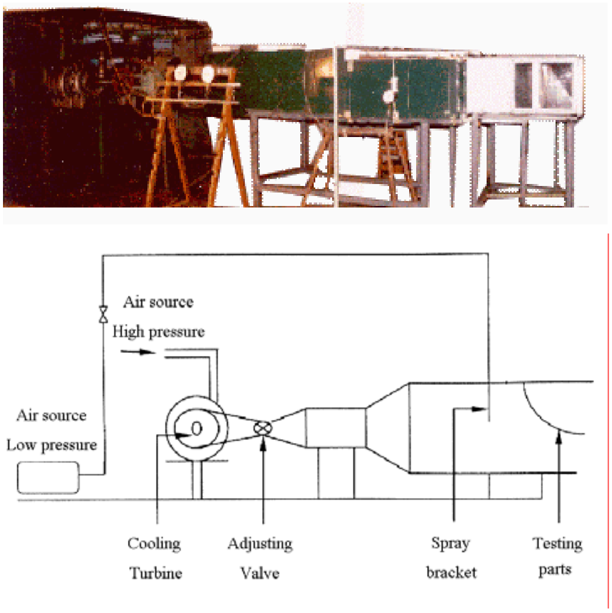

Fig. 1. Beihang IRT and its schematic

Beijing University of Aeronautics and Astronautics and Beijing Institute of Aeronautical Engineering served as a pioneer to develop an entire solution plan on the design of ice protection system. A simplified IRT, which is an open-circuit compressed-air-driven tunnel and refrigerated by cooling turbines, has been firstly founded in China. A 3D simulation program has been compiled, to determine the characteristics of droplet impingement and the heatflux demanded for ice protection. And a composite electrothermal ice protection system has been developed. This system can be applied to the forehead of composite radomes with the next advantages: it has little distortion on the shape of the original aircrafts; it has no effect on the strength properties of the basic composite materials; it can accurately control the temperature of the overall heating surface, it has little effect on EMC and maintains high reliability; and it can be easily mounted on today’s aircrafts. There have been four sets of products equipped on two kinds/four aircrafts and they all are operating well for many years.

2 Droplets Impingement Computation

2.1 Diverse Methods and Analysis

There are mainly two kinds of methods for the research of two-phase turbulent flow, Euler-Lagrange and Euler-Euler (two-fluid model). According to trajectory model, it is commonly acknowledged that the particles have pulse, but the discrete phases do not have the fluid-like turbulent behaviors; according to two-fluid model, the discrete phases, such as the pulse of particles, behave the turbulent character of liquid or gas. As time pasts, the concepts of particle turbulence, particle turbulent kinetic energy and particle Renault stress, which are proposed in two-fluid frame by borrowing ideas from single-phase turbulence, have been widely acknowledged and used in multiphase flows.

In case of complex aircraft components, foreign researches on ice protection show that it is necessary to take the coupling and interaction of momentum and energy of both flow field and droplets into account. Then the two-way coupling of discrete phrase as well as continuous phrase is a must, furthermore, the droplet-droplet interaction should be considered, viz. quadri-coupling. The way, which the distribution of droplet size in cloud layer acquired by flight tests as well as a comprehensive consideration of the effects of different diametric droplets are considered, is better than the way, which a uniform average diameter is adopted, to figure out the droplets impingement similar to reality inflight status.

The droplets impingement computation is based on the 3D N-S equations and the two-way momentum-coupling Eulerian-Eulerian two-phase fluid model, and the simple algebraic coupling $\kappa-\varepsilon-\kappa_p$ turbulence model is applied for the continuous and discrete phrases. Therefore the computational code can solve practical problems with complex shapes. To validate the code, some computations are compared with the results in some authorized dissertations, and some numerical results are also assessed by IRT tests. The meteorological conditions chosen from FAR and CCAR together with the Langmuir distribution of droplets diameters, makes the computation more close to reality than that of the uniform average diameter. But the coupling of droplet-droplet interaction (quadri-coupling) has not yet been come up with. [2]

2.2 Mathematic Model

The continuity, momentum and energy equations for multiphase two-fluid model are given bellow:

$$\frac{\partial(r_\alpha \rho_\alpha)}{\partial t}+\nabla\cdot(r_\alpha \rho_\alpha u_\alpha)=0$$

$$\frac{\partial(r_\alpha \rho_\alpha u_\alpha)}{\partial t}+\nabla\cdot\left(r_\alpha(\rho_\alpha u_\alpha u_\alpha)\right)= \qquad (1)$$

$$-r_\alpha \nabla p_\alpha+\nabla\cdot\left(r_\alpha \mu_\alpha\left(\nabla u_\alpha+(\nabla u_\alpha)^T\right)\right)+M_\alpha$$

$$\frac{\partial(r_\alpha \rho_\alpha h_\alpha)}{\partial t}+\nabla\cdot\left(r_\alpha(\rho_\alpha u_\alpha h_\alpha-\lambda_\alpha \nabla T_\alpha)\right)=Q_{\alpha\beta}$$

Where the subscript α denote the continuous phrase; and the equations for discrete phrases are identical to them only with different subscript β; r_α is volume fraction, viz. the proportion of the phrase to the whole volume; M_α and $Q_{\alpha\beta}$ denote the momentum interchange and energy interchange between different phrases respectively. The heat transfer of droplet condensation only appears at the flow field borders (so does the mass transfer) because of the slight temperature difference between phrases during the ice accretion calculation, in general, $Q_{\alpha\beta}$ is zero. The momentum coupling M_α is a function of drag coefficient C_D of droplets, inter-phase contact area $A_{\alpha\beta}$ and droplet's diameter d, the function is:

$$M_\alpha=C_{\alpha\beta}(u_\beta-u_\alpha)$$

$$C_{\alpha\beta}=\frac{C_D}{8}A_{\alpha\beta}\rho_\alpha\left|u_\beta-u_\alpha\right|= \qquad (2)$$

$$\frac{3}{4}\frac{C_D}{d}r_\beta \rho_\alpha\left|u_\beta-u_\alpha\right|$$

The Grace model is applied here for the drag force of droplets, where U_T can be acquired by solving a complex experimental equation.

$$C_D=\max\left(C_D(Sphere),\ C_D(ellipse)\right)$$

$$C_D(Sphere)=$$

$$\min\left(\frac{24}{\mathrm{Re}_{\alpha\beta}}\left(1+0.15\,\mathrm{Re}^{0.687}\right),0.44\right) \qquad (3)$$

$$C_D(ellipse)=\min\left(\frac{4}{3}\frac{gd}{U_T^2}\frac{\Delta\rho}{\rho_\alpha},\frac{8}{3}\right)$$

The standard $k-\varepsilon$ turbulence model can be applied here for continuous phrase, and the viscosity coefficient of discrete phases is supposed to have a simple algebraic relation to $\mu_{t\alpha}$ of the continuous phase or can be simplified by the zero-equation algebraic turbulence model:

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha k_\alpha)+\nabla\cdot\left(r_\alpha\left(\rho_\alpha u_\alpha k_\alpha-\left(\mu+\frac{\mu_{t\alpha}}{\sigma_k}\right)\nabla k_\alpha\right)\right)=$$

$$r_\alpha(P_\alpha-\rho_\alpha \varepsilon_\alpha)+T_{\alpha\beta}^{(k)}$$

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha \varepsilon_\alpha)+\nabla\cdot\left(r_\alpha \rho_\alpha u_\alpha \varepsilon_\alpha-\left(\mu+\frac{\mu_{t\alpha}}{\sigma_\varepsilon}\right)\nabla \varepsilon_\alpha\right)= \qquad (4)$$

$$r_\alpha \frac{\varepsilon_\alpha}{k_\alpha}(C_{\varepsilon 1}P_\alpha-C_{\varepsilon 2}\rho_\alpha \varepsilon_\alpha)+T_{\alpha\beta}^{(\varepsilon)}$$

$$\mu_{t\beta}=\frac{\rho_\beta}{\rho_\alpha}\mu_{t\alpha}$$

Finally, the collect coefficient β and its synthesis under a Langmuir distribution conditions are:

$$\beta=\frac{-r_\beta(u_\beta\cdot n)}{r_{\beta 0}|u_0|} \qquad (5)$$

$$\beta_{LWC}=\sum \beta_i\cdot LWC_i\%$$

2.3 Results and Validation

Some impingement calculation results of cylinders and airfoils are compared with the ones in dissertations.[6][7]

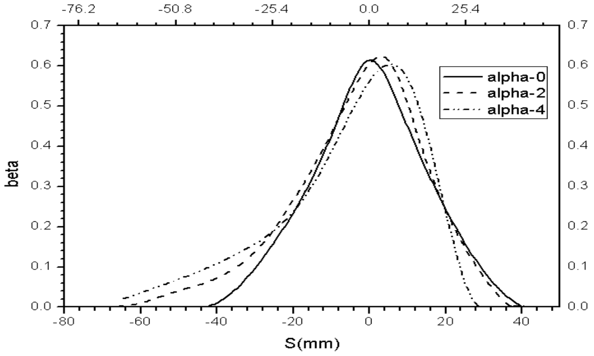

Fig. 2. Beta(local collection efficiency) distribution for comparison on NACA0012

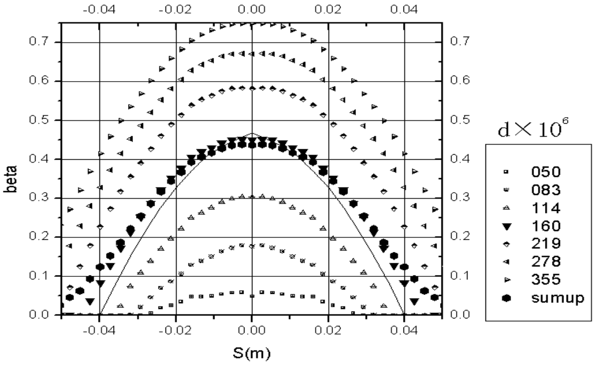

Fig. 3. Beta distribution for comparison on a cylinder

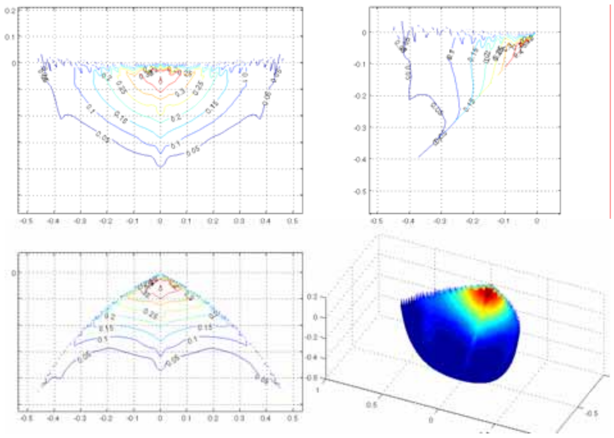

Fig. 4. Distribution of beta on a remote sensing radome

3 Heatflux Computation

3.1 Method

While the distribution of local collection efficiency on radome surface is determined, in order to accurately calculate the heatflux for ice protection/anti-icing, we also take the following thermodynamic facts into consideration: heatflux to melt the ice, water heating, convection, friction, evaporation, kinetic energy of droplets, etc. The surface heat equilibrium equation for an aircraft under ice accretion is:

$$q_\alpha + q_e + q_w + q_r - q_v - q_{w_v} - q_i = 0 \qquad (6)$$

where q_α is the convection heatflux, q_v the heatflux from surface friction, q_e the heaflux for evaporation, q_w the heatflux for heating the droplets, q_{w_v} the heatflux from the kinetic energy, q_r the lost heatflux by atmospheric radiation of the anti-icing surface, q_i the heatflux from the droplets freezing. Because the anti-icing system will prevent the droplets from freezing down, q_i is zero. Because the temperature of radome surface is not allowed very higher than the ambient temperature for the sake of energy saving, the radiant heatflux q_r can be also ignored. Now, the anti-icing heatflux q_n can be written as:

$$q_n = q_\alpha + q_e + q_w - q_v - q_{w_v} \qquad (7)$$

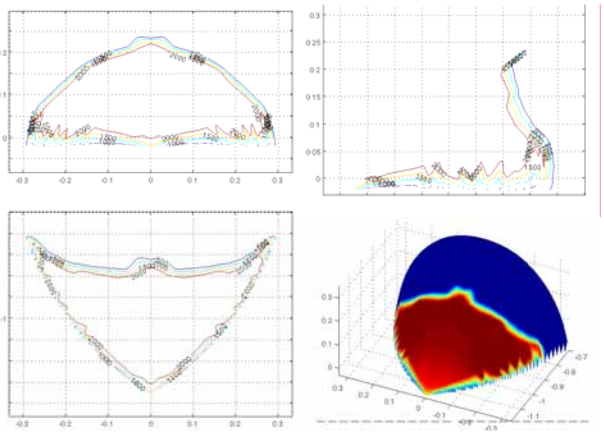

Fig. 5. Heat demand on the radome, wet anti-icing

3.2 Actualization

The heating wires in the composition interlayer can be arranged base on the numerical heatflux results, meanwhile, the magnetic field generated by the electric current of heating wires can be cancelled by carefully arranging the heating wires, which can reduce the electromagnetic irradiancy.

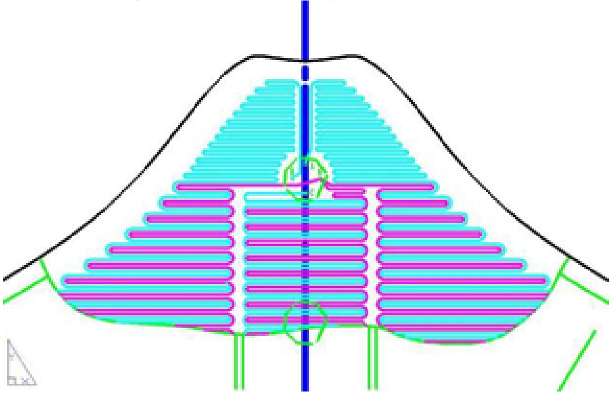

Fig. 6. Winding heating wires to reduce the radiancy

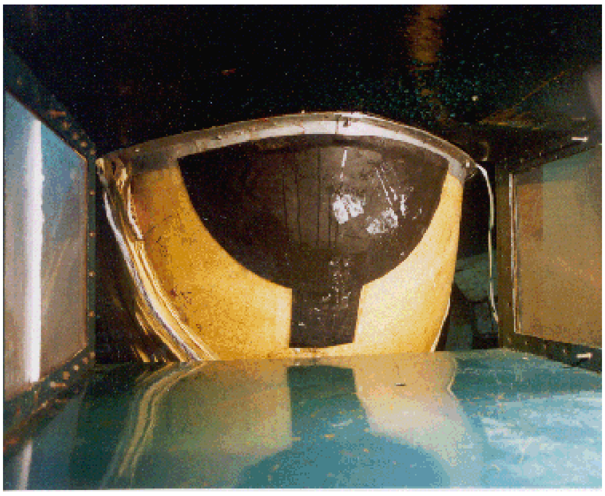

Fig. 7. Anti-icing systems on radome in IRT

4 Applications

The radome of a satellite communication antenna fitted on the back of an aircraft is easy to accumulate a mass block of ice. It is necessary to equip an ice protection system to the head of the radome because the leading edge of the vertical tails on its downwind ward cannot tolerate the strike of such a block ice.

On another remote sensing aircraft, there are two radomes one following another under the fuselage; the backer is cellular structure so that not even a tiny ice cast from the former will smash the backer. To avoid this kind of incident, an ice protection system is needed too.

Some simulation figures of the droplets impingement character and the heatflux for anti-icing are presented here.

Our results as well as the results in the bibliography show that, under the conditions of multi-phrase coupling with turbulence and Langmuir distribution model of droplet diameters, the numerical results are more comparable to experimental ones, however, under the uniform average diameter, the computation tends to come out with offsetting peak values and small scopes.

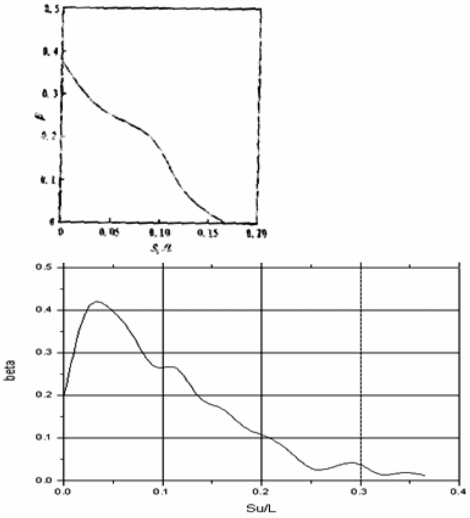

Fig. 8. Comparison of results of beta distributions on symmetry plane via current method(down) and previous engineering method(up)

In the old days, the droplet impingement coefficients are acquired by the USSR’ engineering method, [3][4] in which radomes are approximated by ellipsoid heads. Not only the shape is quite different, but also the body boundary layer effects and flow field disturbances are not included. In fact, fuselage has great impact on the concentration distribution of droplets in a flow field. The droplet impingement coefficients of the symmetry plane, acquired by the old engineering method and our new method, are shown in the next figure. The upper curve is the result of engineering method. We can find that its scope is small and its peak value appears at the most leading edge. Our new method, which has taken the fuselage effect (defilading and pushing aside droplets, boundary layer influence) into account, enlarges the scope and makes the peak value moving backward, and our results agree well with the theoretical analysis and the experimental results.

During the thermal load computation, a close study of the heatflux of each part shows that convection and evaporative play dominate roles in most of the anti-icing regions while having little relation to droplet impingement coefficient. Then the thermal load distribution is not perfectly consistent with the droplet impingement coefficient other than the scope. The calculated surface heat rate demanded for anti-icing is mostly 2kw/m^2. Compared with the needed thermal load acquired by the engineering method given in the bibliographies, more than a half of power is saved no matter the heat efficiency and two times safety factor. This greatly lowers the design requirement of anti-icing system.

5 Reviews and Prospects

While this investigation is going on, some other institutes in China are also concentrating on the same theme and some small IRT had been settled, and a larger advanced IRT has been established in 2005 in CARDC in Mianyang. Many relevant projects had been initiated.

The method presented in this paper can solve the thermal load problem for ice protection system of aircraft components with complex shapes, and it can yield comparable accurate results to the ones in the dissertations, and the computational accuracy of thermal load can also meet the demand of engineering design. The electrothemal ice protection is just a first fruit and it still has many shortages. Its energy demand is higher than electroexpulsive system, and the protection surface will shield the electromagnetic waves so that it only suited to the inner antenna working upward or sideward. A comprehensive validation processes for the code are necessary in order to establish a more accurate icing model for ice accretion simulation. So the properties of ice roughness and ice structure, such as variety, density, strength and heat transfer rate, can be simulated more elaborately.

The continuous increasing of Chinese aviation must seek more safety guarantees from the research of ice protection.

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