Numerical Study on Dynamic Behavior of Non-Newtonian De-icing Liquid Film Impacted by Water Droplets

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Abstract: In freezing rainy weather, physical processes, such as sputtering, spreading, and miscibility, will occur after the supercooled large water droplets hit the liquid film of the de-icing liquid, the temperature and concentration of the liquid film of the de-icing liquid will decrease, the freezing point of the liquid film will rise and the viscosity will decrease, causing the liquid film to slide and detach and greatly shortening the anti-icing holding time. Based on the volume of fluid (VOF) method and combined with the component transport equation, a dynamic behavior model of multi-phase, multi-component, multi-system, multi-field coupled water droplet hitting non-Newtonian de-icing liquid film is constructed. Based on this numerical model, the kinetic behavior of water droplet hitting the unsteady state process and the non-Newtonian rheological characteristics, such as dilution and viscosity reduction of liquid film, are studied. The results show that the higher the initial concentration of the liquid film, the greater the degree of inhibition of the growth of the water droplet crown, the smaller the spreading diameter of the water droplet after impact, the more obvious the water transport migration phenomenon in the collision area of the water droplet and the de-icing liquid film, and the more obvious the viscosity decrease of the de-icing liquid film under the coupling effect of shear dilution and concentration reduction. The larger the initial diameter of the water droplet, the larger the range of the water droplet on the liquid film, and the greater the decrease in the viscosity of the liquid film. The greater the falling impact speed of the water droplet, the faster the migration rate of the components of the water droplet in the liquid film, and the more obvious the viscosity loss of the liquid film.

Key words: de-icing liquid film; multiphase and multi system; non-Newtonian; shear dilution; component migration

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0 Introduction

During the anti-icing operation at the airport, the ground crew needs to spray the aircraft fuselage with de-icing fluid to form a liquid film of de-icing fluid to prevent and delay the re icing of the aircraft surface within a certain period of time. However, in freezing rain weather, the holding time of this layer of de-icing liquid film will be greatly reduced. In addition, the existing de-icing fluid holding schedule has a large time span, and if the aircraft waits longer than the holding time on the ground, it will seriously jeopardize aviation safety[1-3]. De-icing fluid is a kind of alcohol or alkene organic matter. Its rheological properties belong to shear-thinned non Newtonian fluid, and its viscosity is greatly affected by changes in the shear rate and temperature. In freezing rain weather, the impact force generated by falling water droplets hitting the liquid film will produce a large shear rate, reduce the viscosity of the de-icing liquid, and accelerate the sliding and falling off of the liquid film under the action of gravity. In addition, the water droplets hit the liquid film to sputter, rebound, sag and other behaviors. The water droplets are partially dissolved in the alcohol organic solution, which will reduce the concentration of the de-icing liquid in the liquid film, resulting in a decrease in the viscosity of the liquid film and fur-

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ther accelerating the slippage of the liquid film. It can be seen that the anti-icing failure behavior of liquid film in freezing rain weather is a complex microphysical process of the dynamic behavior of supercooled water droplets impacting the non-Newtonian de-icing liquid film and the non-Newtonian rheological coupling of the liquid film, involving the complex behavior characteristics and evolution mechanism of the Newtonian fluid (water droplet), non-Newtonian fluid (de-icing liquid), two medium coupling rheological characteristics, and the thermal fluid phase's three field co evolution characteristics. It is necessary to study the dynamic behavior of large water droplets impacting on non Newtonian fluid film in order to accurately predict the holding time of de-icing fluid.

Droplet impingement on liquid film is a classical problem of heat and mass transfer of multiphase fluid, which has been studied by many scholars. At present, the research and quantitative analysis of this process are mainly realized through high-speed cameras and computer simulation.

Many researchers have conducted research in this area, because droplets usually form splashes or liquid crowns when they hit the liquid film. Rioboo et al.[4] observed three different results of droplet impinging on the liquid film through experiments, namely, deposition, liquid cap without splash and splash. Cossali et al.[5] experimentally studied the influence of single droplet on thin liquid film, and found that viscosity has a great influence on splash form and impact dynamics. Pan et al.[6] found that increasing the viscosity can delay the boundary transition of various transition states after the droplets hit the liquid film, and reducing the surface tension can promote these transitions. Zhong et al.[7] studied the development process of the wall liquid film after a single droplet hit the thin liquid film when the incident droplet and the wall liquid film were of different components and were miscible. Through experiments, it was found that the increase of the droplet Weber number and the decrease of the liquid film viscosity promoted the breakup process of the droplet, and the breakup type evolved from splash breakup to hole breakup and mixed breakup. Although the experimental method can directly and accurately observe the morphological changes of liquid droplet and liquid films during the impact process, it involves a series of changes in the velocity, pressure, viscosity and other parameters of the flow field during the impact process, especially when the impact on the liquid film is difficult to determine specifically through experiments.

Therefore, many scholars use numerical simulation methods to study the impact of droplets on the liquid film. Nikolopoulos et al.[8] used the finite volume method to study the impact of droplets on the liquid film. In the simulation process, the axisymmetric simulation method was used. The research results showed that in the initial stage of droplet impact, viscosity did not play a significant role, but it would have a greater impact on the jet development of the collision interface and the secondary droplet in the later stage; when the thickness of the liquid film was small, the produced liquid ring mostly contained the liquid of the liquid film on the wall. Lee et al.[9] first used the free energy model to simulate the process of a single droplet impacting the liquid film under the condition of a large density ratio. Shiladitya et al.[10] introduced multiple relaxation (MRT) collision operator on the basis of Lee et al.[9] model and studied the influence of the density ratio and viscosity coefficient ratio on the evolution of liquid crown. Cheng et al.[11] further converted the Shiladitya et al.[10] two-dimensional model into a three-dimensional model to simulate the process of liquid droplet impacting the moving liquid surface. Wu et al.[12] used the Lattice Boltzmann method (LBM) method to study the kinetic process of multiple droplets hitting the liquid film. Kharmiani et al.[13] and Hao et al.[14] used the LBM pseudo potential model to study the influence of different parameters on the evolution of liquid crown when a single droplet vertically impacts the liquid film. Chen et al.[15] used the coupled level set and volume of fluid method (CLSVOF) method to analyze the influence of droplets on the liquid film with different thicknesses, studied the morphology, velocity field and pressure field distribution of the liquid crown in the liquid film, and analyzed the changes of the morphology, velocity field and pressure field when continuous droplets impacted the liquid film. Shao et al.[16] combined the LBM and VOF methods to explore the droplet splash state in different air environments. Zhao et al.[17] used the CLSVOF method to establish a numerical model of single droplet hitting the flowing liquid film. Wang et al.[18] used the finite volume method and the VOF method to numerically simulate the process of droplet impacting the liquid film, and studied the influence of the thickness of the liquid film on the impact force.

In terms of numerical simulation of non Newtonian fluids, based on the diffusion interface method, Han et al.[19] studied the dynamic behavior of viscoelastic fluid droplet impacting hydrophobic walls described by the Oldroyd-B model. Their numerical simulation results pointed out that fluid viscoelasticity had no significant impact on the spreading process of the droplet, and the elastic stress at the interface and moving contact line was the main reason for the inhibition of the rebound behavior of the droplet. Eunjeong et al.[20] captured the movement of the phase interface through the VOF method, used the Herschel-Bulkley model to couple the yield stress shear thinning characteristics of the fluid, and studied the behavior of the yield stress shear thinning droplet impacting the solid wall. Their research results show that the power law index, non-Newtonian Reynolds number and Weber number determined the spreading stage of the impact droplet, while the non-Newtonian capillary number played a major role in the retraction stage of the droplet. Wang et al.[21] used the phase field method to capture the movement of the phase interface, coupled the rheological properties of the fluid with the Giesekus model, and studied the behavior of viscoelastic shear thinning liquid droplet impacting the solid wall. They pointed out that the inertial force, the viscosity and elasticity of the fluid jointly affected the motion state of the liquid droplet after they hit the wall. Shen et al.[22] used the modified power law model to build a numerical model of droplet impact on the wall, and analyzed the mechanism of the influence of shear thinning characteristics on the behavior of droplet impact on different wetted walls.

At present, the research on the impact of liquid droplet on liquid film focuses on the morphology evolution, splash and rebound mechanism of the impact droplet, while the relevant numerical simulation research focuses on the impact process of Newtonian fluid with the same physical property, such as the impact of water droplet on the water film. Due to the complex rheological characteristics of non-Newtonian de-icing liquid, further investigation still needs on what changes will happen when a droplet hits the non-Newtonian de-icing liquid film, what factors will affect the evolution process of the liquid film, and the spreading rule of the impacted droplet. The above issues are of great significance for revealing the internal mechanism of the phenomena related to the impact of a droplet on the non-Newtonian liquid film.

In this paper, the VOF method combined with the component transport model is used to study the morphological evolution and physical properties of the liquid film impacted by droplet under different working conditions. The influence of initial concentration of the liquid film on the evolution of droplet morphology is discussed based on the numerical calculation of the spreading length and splash time of the droplet impacting the liquid film. The influence of falling parameters of the droplet on the diffusion velocity of the droplet is discussed by calculating the mass diffusion time of the droplet in the liquid film.

1 Mathematical Model

When a large supercooled water droplet hits the liquid film of the de-icing liquid, it will undergo physical processes such as sputtering, spreading, mutual dissolution, etc. The temperature and concentration of the liquid film of the de-icing liquid will decrease, the freezing point of the liquid film will rise, and the viscosity of the liquid film will drop, which will cause the liquid film to accelerate sliding and detaching, and the ice suppression will fail. This complex behavior process is a complex microphysical process of multiphase (liquid (supercooled large water droplet), liquid (de-icing/anti-icing liquid film), solid (fuselage surface)), multi-fields (flow field-temperature field-phase field), multi-components (water de-icing liquid), and multi-systems (Newtonian fluid (water droplet), non Newtonian fluid (de-icing/anti icing liquid)), which involves the migration and capture of the interface between the liquid phase and the gas phase of the immiscible fluid, and the mass transfer and diffusion process between the liquid droplet and the liquid film of miscible fluids with different physical properties.

In order to describe this complex physical process, the constructed mathematical model includes not only the conventional mass conservation equation, momentum conservation equation and energy conservation equation, but also the following sub models: (1) Multiphase flow model. It uses the VOF method to solve the formation and migration of the phase interface between the droplet and the liquid film in the air during the impact process, and regards the droplet and the liquid film as the phases of the same material. (2) Component transport model. Since the droplet and the liquid film are regarded as mixtures with different components in the same liquid phase, the component transport model without chemical reaction is used to solve the mass transfer between the droplet and the liquid film during the impact process. (3) Turbulence model. Since the renormalization group(RNG) k-ε model is widely used and has a lot of data accumulation to better simulate complex flows such as jet impingement and swirling, the RNG model is selected due to its complex impingement process between the droplet and the non-Newtonian liquid film. The specific control equations are described as follows.

1.1 Multiphase flow model

The VOF equation tracks the interface between phases by solving the continuity equation of volume fraction of one or more phases. For the q phase, the equation is

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q v_q\right)=S_{\alpha q}+\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right) \tag{1}$$

where ρ_q is the density of phase q; v_q the velocity of phase q; $S_{\alpha q}$ the mass source term; $\dot{m}_{qp}$ the mass transfers from phase q to phase p; and $\dot{m}_{pq}$ the mass transfers from phase q to phase p. The volume fraction equation does not solve the initial phase, but provides constraints on the volume fraction of each phase

$$\sum\alpha_q=1 \tag{2}$$

In each control volume, the total volume fraction of all phases is 1. Therefore, the variables and properties in any given element represent either one of the pure phases or a mixture of phases, depending on the volume integral value. VOF only solves one momentum equation, and the velocity field obtained is shared by all phases

$$\frac{\partial}{\partial t}(\rho\boldsymbol{v})+\nabla\cdot(\rho\boldsymbol{v}\boldsymbol{v})=$$
$$-\nabla_p+\nabla\cdot\left[\mu\left(\nabla\boldsymbol{v}+\nabla\boldsymbol{v}^{\mathrm{T}}\right)\right]+\rho\boldsymbol{g}+\boldsymbol{F}+S_m \tag{3}$$

where S_m is the momentum source term caused by mass transfer; and $\boldsymbol{F}$ the additional volume force caused by the surface tension.

1.2 Component transport model

The component transport equation can be applied to the multiphase flow, where the conservation equation of species is solved. For each phase k, the local mass fraction Y_q^i of each species is predicted by solving the convection diffusion equation of species i. The generalized chemical species conservation equation can be expressed as

$$\frac{\partial\left(\alpha_q\rho_q Y_q^i\right)}{\partial t}+\nabla\cdot\left(\alpha_q\rho_q\boldsymbol{v}_q Y_q^i\right)=$$
$$-\nabla\cdot\left(\alpha_q\boldsymbol{J}_q^i\right)+\alpha_q R_q^i+\alpha_q S_q^i+\sum_{p=1}\dot{m}_{p^i q^j}+R \tag{4}$$

where R_q^i is the net rate of species i in the q phase chemical reaction; $\dot{m}_{p^i q^j}$ the source term of the mass transfers of species i and j from q phase to p; and R the heterogeneous reaction rate; α_q, ρ_q are the volume fraction and the density, respectively; and S_q^i is the productivity of the external resources; $\boldsymbol{J}_q^i$ the diffusion flux of species i in q phase, which is caused by the concentration gradient and temperature gradient. In turbulence, its diffusion flux can be expressed as

$$\boldsymbol{J}_q^i=-\rho\left(D_{i,m}+\frac{\mu_t}{S_{ct}}\right)\nabla Y_i-D_{T,i}\frac{\nabla T}{T} \tag{5}$$

where $D_{i,m}$ is the mass diffusion coefficient of component i in the mixture; $D_{T,i}$ the thermal diffusion coefficient; S_{ct} the turbulent Schmidt number, and μ_t the turbulent viscosity.

1.3 Turbulence model

The RNG k-ε model is derived by the statistical technique of the renormalization group theory. Its formal standard is similar to that of the k-ε model, but an additional term in the ε equation of the RNG model improves the accuracy of fast strain flow. An additional term in the equation improves the accuracy of fast strain flows. Compared with the standard equation with a high Reynolds number, it provides an effective viscosity differential formula to explain the effect of the low Reynolds number. The two equation turbulence model determines the length and time scale of the turbulence by solving two independent transport equations. The RNG k-ε Turbulent kinetic energy k and its dissipation rate through the model ε can be obtained from the following transport equation

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=G_k+G_b+\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{\text{eff}}\frac{\partial k}{\partial x_j}\right)-\rho\varepsilon-Y_M+S_k \tag{6}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{\text{eff}}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \tag{7}$$

where G_k is the turbulent kinetic energy due to the average velocity gradient; G_b the turbulent kinetic energy generated by buoyancy, Y_M the effect of wave expansion of compressible turbulence on the overall dissipation rate; $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are constants; α_k and α_ε the k and ε Turbulent Prandtl numbers; and S_k and S_ε the user-defined source items.

2 Physical Model

2.1 Model simplification and assumptions

In this paper, the physical process of a water droplet impacting on the liquid film of de-icing liquid is abstracted from the phenomenon of sliding and falling off of the liquid film of de-icing liquid in freezing rain weather, and its impact dynamic behavior and non-Newtonian rheological characteristics are analyzed. In order to simplify the calculation, the following assumptions are made: (1) The supercooled large water drop is spherical; (2) the temperature and humidity of external environment are constant; (3) the de-icing liquid membrane is a mixture of pure de-icing liquid and water.

Fig.1 is the physical model established in this paper. As shown in Fig.1(a), the calculation area is a rectangular area with a size of 10 mm × 8 mm. And the whole area is divided into three areas. The blue thin layer at the bottom is the liquid film of the de-icing liquid, which is set as the liquid phase including two component area (water and pure de-icing liquid). According to the initial concentration of the liquid film of the de-icing liquid, the mass fraction of its components is changed. The upper space is the external air, and the gas phase area (main phase) is set. The upper blue area is the supercooled large water drop, which is set as the liquid phase single component (water) area.

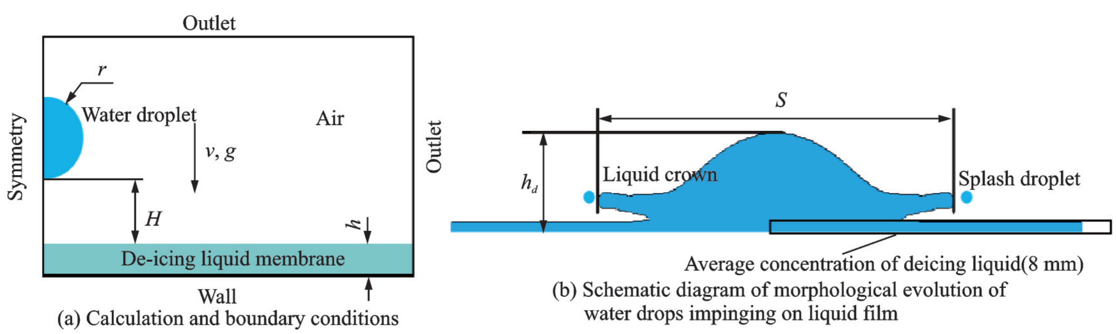


Fig.1 Physical model

2.2 Boundary conditions

The model boundary conditions are set, as shown in Fig.1(a). Considering the complex physical flow characteristics in the impact process, in order to speed up the calculation and reduce the calculation error, a two-dimensional axisymmetric model is adopted. The left boundary of the calculation domain is set as a symmetrical boundary. The bottom boundary is set as a solid wall without slip. And the other boundaries are gas boundaries. The surface at the bottom of the model is covered with a liquid film of non-Newtonian de-icing fluid with a thickness of h. Assume that the droplet is a standard sphere. The initial radius of the droplet is r. The falling velocity is v, and the acceleration due to gravity is g= 9.81 m/s^2. Considering the influence of the air bubbles generated by the entrained air when the droplet hits the liquid film, and the influence of gravity and surface tension on the shape of the droplet when falling, the drop height is defined as the distance between the bottom end of the droplet and the surface of the liquid film with H=0.7 mm. In this paper, t represents the time of the droplet movement, and t^* represents the time of the droplet contacting with the liquid film. Fig.1(b) is a schematic diagram of the morphological evolution of the droplet when it hits the liquid film. S is defined as the spreading length of the droplet, that is, the maximum diameter of the liquid crown (dimensionless diameter $S^*=S/2r$), and h_d is defined as the falling height of the droplet, that is, the distance between the top of the droplet and the solid wall. In order to explore the impact of the droplet impact behavior on the concentration of the liquid film of de-icing liquid, this paper defines the average concentration of de-icing liquid within the area of 0.8 mm^2 in the liquid film to characterize the change of the concentration of de-icing liquid, starting from the side of the symmetrical boundary, 8 mm long and 0.1 mm high as the initial height of the liquid film.

2.3 Physical parameters

The bottom liquid film is a type Ⅱ de-icing liquid film, and the droplets are water. Table 1 lists specific physical parameters. Wang et al.[23] and Zhang et al.[24] have tested and pointed out that the power-law model can better fit the rheological properties of type Ⅱ de-icing fluid, in order to explore the influence of non-Newtonian rheological properties of de-icing liquid film on the droplet impact process. This paper uses the power-law equation widely used in engineering to describe the change of rheological properties of de-icing liquid film. The equation is

$$\tau = kD^n \tag{8}$$

where τ is the shear stress; k the consistency coefficient, which is related to the consistency of the fluid; n the flow characteristic index.

Table 1 Physical parameters of materials

Parameter	Symbol	De-icing fluid	Water
Density	ρ/(kg·m^{-3})	1 150	998
Viscosity	η/(Pa·s)	0.5—3	0.001
Surface tension	σ/(mN·m^{-1})	48.4	78.2
Consistency	k	14.741	NIL
Power law	n	0.517 5	NIL

3 Numerical Simulation

3.1 Spatial discreteness

For the study of droplet hitting the liquid film, Shiladitya et al.[11] found that air has a certain influence on the impact process, so the influence of gas on the impact process is reduced by increasing the distance between the droplet and the gas boundary. Due to the symmetry of the flow field shape during the entire impact process, a two-dimensional axi-symmetric calculation is used to shorten the calculation time. The calculation domain is a quadrilateral area of 10 mm long and 8 mm high, divided by a square structured grid. The grid size has an important impact on numerical simulation. If the grid is too large, the calculation error is increased, and it is easy to show different phenomena. If the grid is too small, although it improves the accuracy of calculations, the consumption of computer resources and time increases. Therefore, it is important to choose an appropriate mesh size for different simulations. In this paper, the drop height of droplets with different grid sizes is measured with time under the impact conditions of droplet radius r of 1 mm, falling velocity v of 4 m/s, and initial concentration of liquid film de-icing solution of 50%. As shown in Fig.2, it is found that the drop height value of the droplet is close when the grid size is about 0.02 mm, and the mesh refinement has little effect on the spread and fall of the droplet, so the grid size is determined to be 0.02 mm.

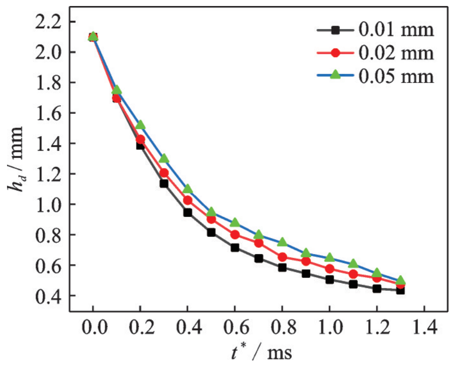


Fig.2 Grid independence verification (the initial concentration of liquid film is 50%, liquid film thickness h=0.1 mm, droplet radius r=1 mm, droplet speed v=4 m/s)

3.2 Flow solvement

This paper studies the unsteady flow problem of incompressible fluids, so the pressure-velocity coupling algorithm is selected for solving transient problems. The pressure implicit with splitting of operators (PISO) algorithm is developed on the semi-implicit method for pressure-linked equation (SIMPLE) algorithm, and its calculation steps are prediction, correction, and re-correction. Thus, this will accelerate the convergence speed of the calculation, and make calculations faster and relatively stable in transient calculation. The pressure solution adopts the PRESTO method. The volume fraction of the liquid phase is calculated using the Geo-Reconstruct. The momentum is discrete in the second-order windward interpolation format, and the discrete format of the other terms is the first-order interpolation format. In order to ensure the stability and convergence of the calculation results, the whole calculation process can be better converged when the time step is 1e−7 s according to the test. Fig.3 shows the solution process of the entire calculation process. The fluid of the entire calculation domain is initialized, and the air is defined as the main phase. The volume fraction is 0. The droplet and liquid film are the secondary phase, and the volume fraction is 1. The parameters are initialized through Path. The volume fraction of the liquid phase is 1. The mass fraction of water in the droplet area is 1, and the drop radius r, the falling speed v and the mass fraction of the water in the liquid film area are adjusted according to different working conditions.

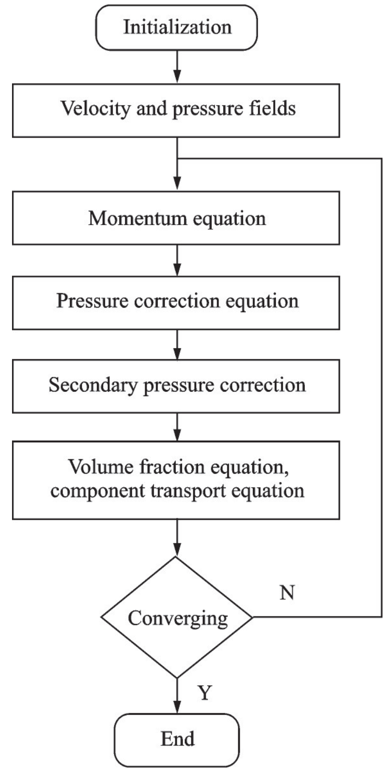
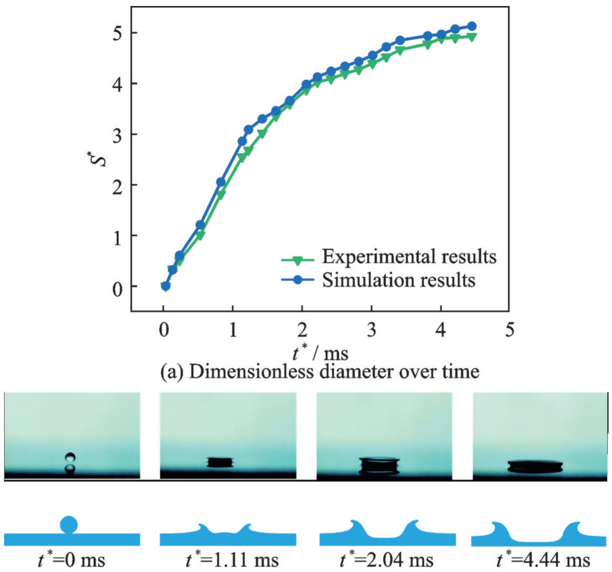


Fig.3 Calculation Flow Chart

After the initialization of the fluid properties is completed, and the iterative operations of each program are performed according to the algorithm.

3.3 Model validation

Pei et al.[25] experimentally studied the morphological evolution of droplets after impacting liquid films of different viscosities. In order to clarify the influence of the miscibility of droplet and liquid films on the impact phenomenon of different droplets and liquid films, the test of isooctane droplet hitting silicone oil film (phase miscibility) is carried out. In this paper, the droplet and film are set to the same physical parameters, and the numerical model is verified by the working conditions of the droplet falling velocity of 3.1 m/s, droplet radius of 1.1 mm, and the liquid film thickness of 1.54 mm. Fig.4(a) shows the dimensionless diameter of the liquid crown over time, and Fig.4(b) shows the change in the morphology of the liquid crown over time. By comparing the simulation results with the experimental results, it can be found that the experimental and simulated results have good consistency between the liquid crown growth morphologies, which verifies that the model can be used to simu-



(a) Dimensionless diameter over time

(b) Changes in morphology over time (experimental results on the above, simulation results on the below)

Fig.4 Simulation results and experimental results

late the morphological changes and mechanism analysis of the liquid film of droplets impacting under multi-component.

4 Calculation Results and Analysis

4.1 Dynamic process analysis of a water droplet hitting non-Newtonian fluid films

The impact of a water droplet on a non-Newtonian de-icing fluid film is a complex multiphase multi-component flow process. In order to explore the influence of a droplet on the liquid film and the morphological evolution of the droplet, this section calculates and analyzes the dynamic process of the impact under a single working condition. Fig.5 shows the dynamic process of a water droplet hitting the 20% concentration of de-icing liquid film. The drop speed v is 4 m/s, the droplet radius r is 1 mm, the thickness h of the liquid film is 0.1 mm, and the drop height H is 0.7 mm. Since the falling durations of contact with the liquid film when the droplets at different speeds are different, the initial contact time of the droplet with the liquid film is defined as the start time t^*=0 ms.

As shown in Fig.6(a), at t^*=0.5 ms, that is, the initial stage of impact, the gas around the impact site is carried into the liquid film by the droplet to form bubbles. This is because the droplet in the process of impact and fusion with the liquid film, the

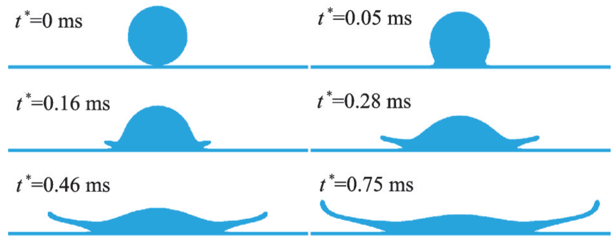
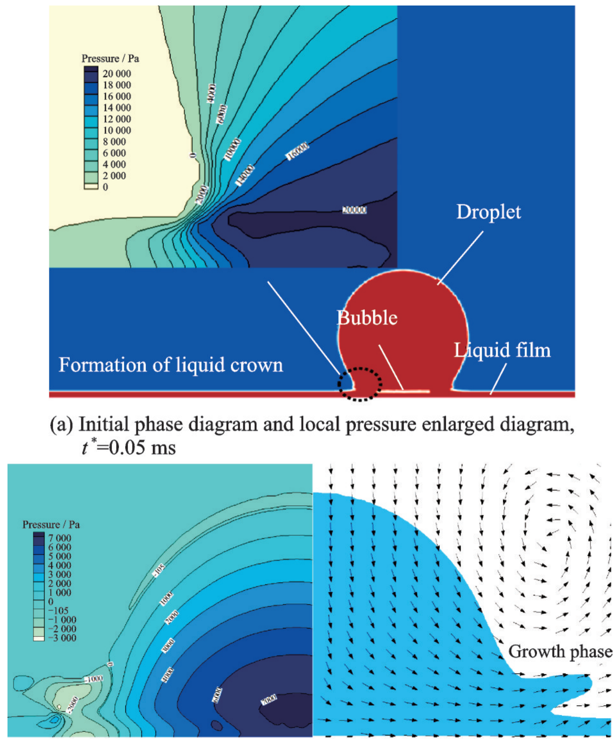


Fig.5 Dynamic process of the water droplet impacting on the liquid film of de-icing liquid (the initial concentration is 20%, h=0.1 mm, r=1 mm, v=4 m/s)



(a) Initial phase diagram and local pressure enlarged diagram, t^*=0.05 ms

(b) Pressure nephogram and velocity vector diagram, t^*=0.16 ms

Fig.6 Growth process of liquid crown

air on the surface of the droplet and the liquid film will be compressed, the increase of air pressure will make the liquid film form a depression, part of the gas is entrained by the falling droplet to the inside of the liquid film, and the small bubbles formed by the gas entrainment are mainly distributed on the boundary between the droplet and the liquid film.

From the local magnification of the pressure in Fig.6(a), it can be seen that when the droplet hits the liquid film, a large pressure is generated inside the fluid, and the closer to the impact center, the greater the pressure. The maximum is about 20 000 Pa. And the pressure at the interface of droplets, liquid film and air is approximately equal to atmospheric pressure, so a large pressure difference between the inside and outside of the liquid at the interface is generated. Driven by the pressure, the liquid at the intersection overcomes the action of surface tension and gravity, and begins to produce tiny bulges. Over time, the bulge gradually grows outward into a liquid crown, and when $t^*=0.16$ ms, a clear liquid crown structure can be seen.

However, the energy of the droplet falling is not entirely used for the growth of the liquid crown, and part is used for the movement of the fluid inside the liquid film. Fig.6(b) is a velocity vector diagram of the growth stage of the liquid crown. By observing the velocity direction of the fluid, it can be seen that when the droplet falls, the part of the fluid in the liquid film flows into the liquid crown in the tangential direction, and the part of the fluid near the solid wall moves horizontally to the right. The analysis indicates that the energy generated by the droplet hitting the liquid film can be regarded as two losses. Part of the energy is used to overcome the shear loss of the flow inside the liquid film and promote the mixing of the water of the droplets with the de-icing liquid in the liquid film. The falling droplets drive the fluid in the liquid film to move downward, and when this part of the fluid collides with the solid wall, the flow direction changes from the vertical downward to deflection to both sides. Therefore, the part of the fluid near the wall area flows horizontally on both sides, while transporting water from the collision area to the far part of the liquid film. The other part of the energy is used for the growth of the liquid crown, as shown in the pressure cloud in Fig.6(a). It can be seen that the pressure inside the liquid drops from 20 000 Pa at the initial stage of impact to the current 7 000 Pa.

However, at this time, there is still a large pressure difference between the droplet, liquid film and air. Due to the presence of a pressure difference, the fluid in the impact area is ejected from the liquid-gas junction into the air, manifested by the rapid growth of the liquid crown at an angle in the horizontal direction. And due to the movement of the liquid, a vortex of air flow is created above the liquid crown.

The above analysis reveals that in the initial stage of the water droplet hitting the de-icing liquid film, that is, the time period from $t^*=0$ ms to $t^*=0.28$ ms, the main factor for the generation and growth of liquid crowns is the local pressure difference between the droplet, liquid film and air during the impact process. Then, the liquid crown continues to grow, and the diameter gradually increases. When $t^*=0.46$ ms, a slight deflection can be observed at the tip of the liquid crown. At $t^*=0.75$ ms, the tip of the liquid crown begins to grow upward. The analysis reveals that when the liquid crown grows to a certain stage, the effect of pressure difference on the growth of the liquid crown tip begins to decrease, and the pressure at this time is not enough to support the liquid crown to continue to grow in the form of jets. Ref.[26] has tested the correctness of the motion discontinuity theory by simulating the process of water droplets hitting the water film. It points out that the discontinuity of the fluid velocity in the liquid film is the main reason for the expansion of the liquid crown. Affected by the movement of the fluid to both sides in the near-wall area, and under the action of the surface tension and gravity of the liquid, the growth direction of the liquid crown gradually transit to the vertical direction.

In order to explore the effect of the droplet impact behavior on the concentration of the de-icing fluid film, the average concentration of the de-icing fluid within 0.8 mm^2 of the liquid film in the impact area is used to characterize the change of de-icing fluid concentration. The line chart and concentration field map of the concentration change of the de-icing liquid in the liquid film are shown in Fig.7. Within 0—0.18 ms, the droplet does not contact the liquid film, and a brief increase in the concentration of

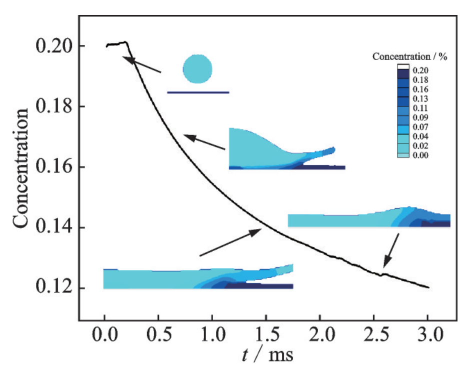


Fig.7 Concentration change of de-icing liquid in liquid film (initial concentration 20%)

de-icing liquid can be seen. This is because the falling droplets entrain some of the air and cause the depression of the liquid film, resulting in small fluctuations in the concentration of the de-icing fluid in this area.

After the droplets are in contact with the liquid film, the concentration of de-icing liquid shows an overall downward trend with the passage of time, and the decline rate gradually decreases. The de-icing fluid concentration drops from 20% to 14% within 0—1.5 ms, while within 1.5—3 ms, the de-icing fluid concentration decreases by only 1.5%. Combined with the mass distribution cloud of the de-icing liquid at various time points, it can be seen that at about 0.5 ms, the water in the droplet is transported to the liquid film with the impact behavior and mixed with the de-icing liquid. And the concentration of the de-icing liquid in this area decreases rapidly due to the violent convective movement of the droplet and the liquid film. At the same time, it can be seen that the liquid crown generated by the impact also carries a part of the de-icing liquid out of the liquid film. When t=1.5 ms, the mixed fluid of the droplet and the liquid film continue to expand to both sides along the wall, the liquid crown begins to fall under the action of gravity and surface tension, and the effect of convection motion on the concentration of de-icing liquid in the liquid film gradually decreases. When t=2.5 ms, the liquid crown falls back to the surface of the liquid film and gradually dissolves in the liquid film under the action of gravity.

4.2 Effect of initial concentration of liquid film on its failure behavior

Since in the actual process of spraying de-icing liquid for aircraft anti-icing, the initial concentrations of de-icing liquid used in anti-icing under different conditions are different, and the concentration of de-icing liquid in the liquid film after spraying is affected by different environmental conditions, it is necessary to explore the influence of the initial concentration of the liquid film on the impact behavior of the droplet. This section changes the initial concentration of the de-icing liquid of the liquid film to 30%, 40% and 50% under the condition that other parameters remain unchanged, and calculates and analyzes the movement law of the droplet in the liquid film. As shown in Fig.8(a), the spreading length S and drop height h_d of the droplet under different de-icing liquid concentrations of the liquid film change with time. It can be seen that the spreading length and falling height of the droplet under different working conditions show the same change trend in the entire time range, and their change speed gradually decreases with time. With the increase of the initial concentration of the liquid film, the spreading length of the droplet gradually decreases, and the drop height of the droplet gradually increases, which indicates that the concentration of the liquid film has a great influence on the morphological evolution process of the droplet.

The conclusion of Ref.[7] declares that the internal shear of the high-viscosity liquid film is large enough to maintain the stability of the crown structure, but when the droplet hits the low-viscosity liquid film, the internal shear force of the liquid film is not enough to resist the kinetic energy of the droplet. Since the de-icing liquid is a liquid with high viscosity, as the initial concentration of the liquid film increases, the viscosity of the liquid film also increases, and the high-viscosity de-icing liquid film will consume a lot of kinetic energy. As shown in Fig.8(b), the change of the velocity in the liquid film with time is described, and the changes of the droplets when they hit the liquid film with different initial concentrations are obtained. After the droplets contact the liquid film, the speed of the liquid film at different initial concentrations has the same change trend. Its speed peaks at about 0.2 ms, decreases rapidly, and then slowly declines after decreasing to a certain value. However, the lower the initial concentration, the higher the velocity peak, and it takes longer time to reach a steady state. This indicates that the higher kinetic energy dissipation the initial concentration, the higher the liquid film will cause. This will reduce the jet velocity generated by the impact, thereby inhibiting the formation and growth of the liquid crown.

Fig.9(a) shows the morphological evolution of droplets under different concentrations of the liquid film. It can be seen that bulges are produced at the

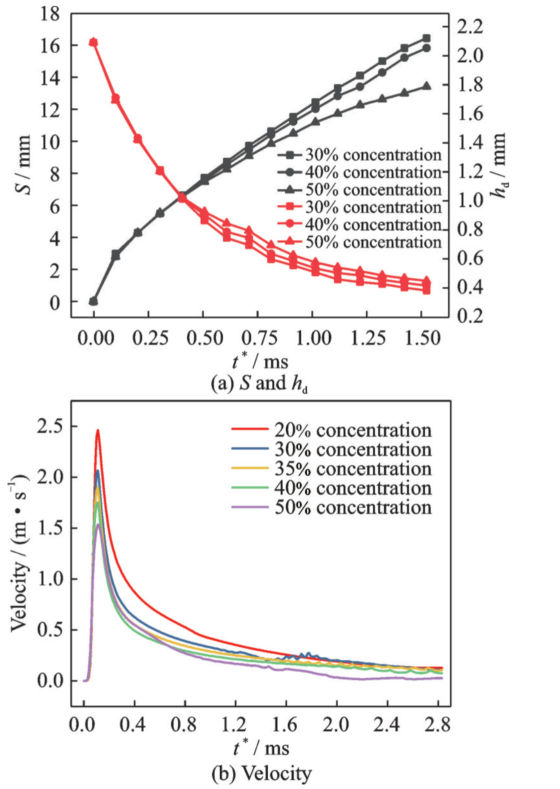


Fig.8 Droplets S and h_d and fluid velocity within the liquid film over time at different initial concentrations (liquid film thickness h=0.1 mm, droplet radius r=1 mm, droplet speed v=4 m/s)

junction of the three phases in the early stage of impact. However, when t^*=0.21 ms, the angles of the liquid crown produced at different concentrations are different from the horizontal direction, and with the increase of the initial concentration of the liquid film, the spray angle of the liquid crown in the initial stage gradually decreases, while the spreading length and falling height of the droplets are basically the same. Combined with the data in Fig.8(a), it can be seen that the spreading length of the droplet is about 5 mm at this time, and the droplet drop height is about 0.9 mm. This shows that in the initial stage of impact, the concentration of de-icing liquid in the liquid film has little effect on the spreading length and the drop height of the droplet, but has a greater influence on the subsequent development of the liquid crown. Due to the different spray angles of the liquid crown, small angle liquid crown will come into contact with the liquid film faster. It can be seen from Fig. 9 that at t=0.88 ms, the liquid crown under the condition of the initial concentra-

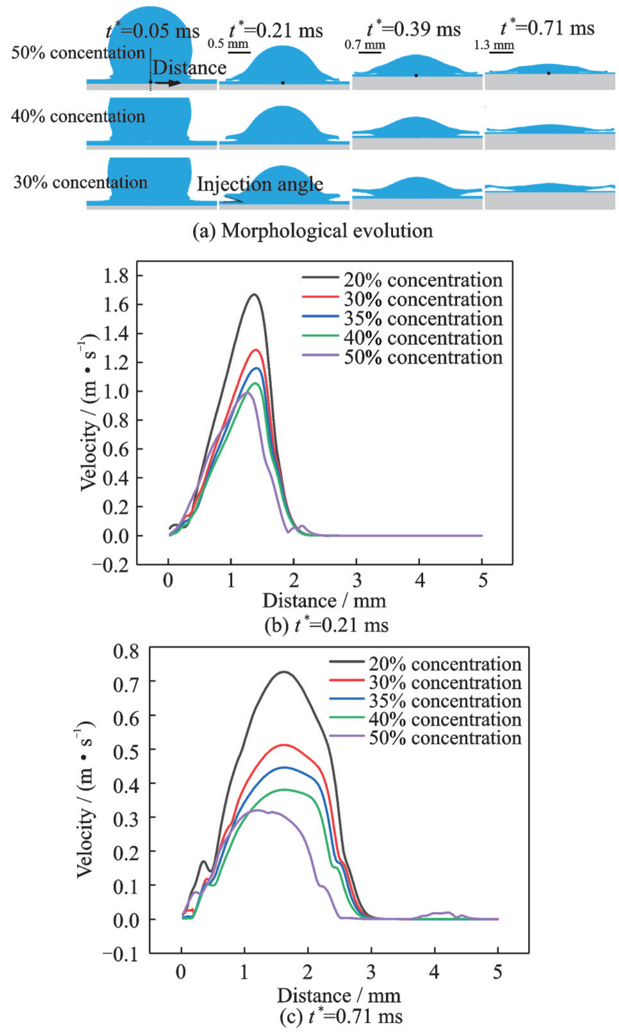


Fig.9 Morphological evolution of droplets under different concentrations of liquid film

tion of the liquid film of 50% has fallen to the liquid film surface, and the spreading movement is carried out on the liquid film surface. Due to premature contact with the liquid film, it can be seen from Fig. 8 that the spreading length of the droplet is significantly smaller than the other two conditions at a de-icing liquid concentration of 50%. The drop height in the whole process is relatively close, because the volumes of the impact droplet at different initial concentrations are the same, so with the increase of the initial concentration of the de-icing liquid in the liquid film, the falling droplets are more likely to accumulate in the liquid film in the impact area, thereby greatly reducing the concentration of the de-icing liquid in this area.

This can be verified by exploring the velocity in the liquid film, and the flow field velocity within

5 mm from the impact point is selected for analysis. From Figs.9 (b,c), it can be found that at t^*=0.21 ms and 0.71 ms, the velocity of the fluid in the liquid film increases first and then decreases with the increase of distance at any initial concentration, and there is a velocity peak. According to the conclusion of Section 4.1, the liquid crown is constantly expanding due to the intermittent velocity of the fluid in the liquid film. Therefore, the velocity peak moves further away from the impact center, which promotes the fusion of the droplet with the liquid film. And the higher the initial concentration of the liquid film, the smaller its speed, which further indicates that the high concentration of the liquid film will consume more kinetic energy. The decrease in velocity will inhibit the expansion of the liquid crown, and it can be seen that the higher the concentration of the liquid film, the higher the velocity peak, and the closer the velocity peak to the impact center, so the falling droplets are more likely to collect in the collision area.

The above analysis, reveals that in the initial stage of the water droplet hitting the de-icing liquid film, the liquid film concentration has little effect on the spreading length and falling height of the falling droplet, and has a greater influence on the spray angle of the liquid crown. This shows that in the early stage of impact, the initial parameters of the droplet may play a major role in the morphological evolution of the droplet, and the initial concentration of the liquid film determines the subsequent growth process of the liquid crown, and with the increase of the concentration of de-icing liquid in the liquid film, the growth of the liquid crown is inhibited. This will cause a large amount of water to accumulate in the initial collision area between the droplet and the liquid film, thereby greatly reducing the concentration of the de-icing fluid in this area, decreasing the holding time of the de-icing liquid, and causing the anti-icing failure of the liquid film.

4.3 Influence of droplet parameters on the failure behavior of liquid film

In the practical anti-icing work, the falling radius and falling speed of raindrops are not fixed due to the influence of the natural environment. And it can be seen from Section 4.2 that in the early stage of impact, the initial parameters of the droplet may play a major role in the morphological evolution of the droplet. Therefore, it is necessary to explore the influence of droplet parameters on the failure behavior of the liquid film. In this section, the three conditions of 0.5, 0.8 and 1 mm of the impact droplet and the three conditions of different droplet impact velocity of 2, 3 and 4 m/s are calculated and analyzed. Fig.10 shows a cloud map of the change of de-icing liquid concentration under different working conditions. When the droplets hit the liquid film under different falling radii (Fig.10(a)) and falling speeds (Fig.10(b)), there is no liquid crown with a certain spray angle. Since the growth direction of the liquid crown is horizontal and air is present on the surface of the liquid film, a brief slip of the liquid crown on the surface of the liquid film can be seen.

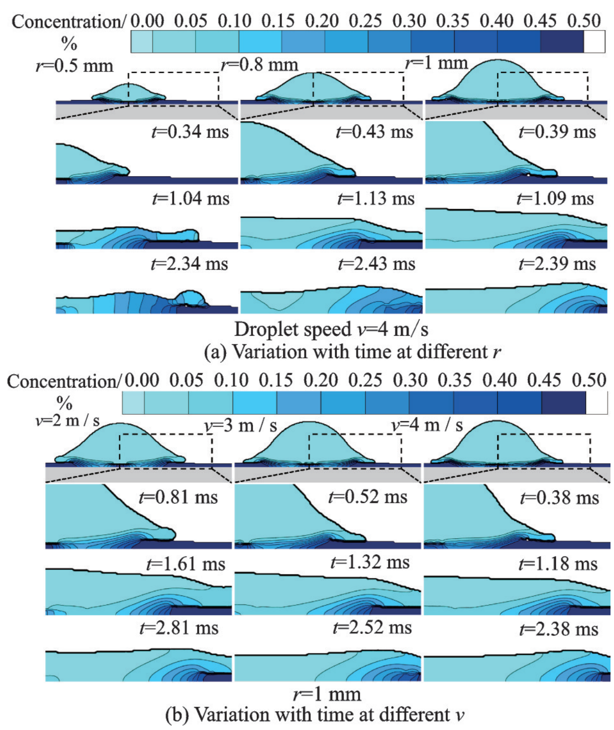


Fig.10 Cloud chart of de-icing liquid concentration under different working conditions(initial concentrations of liquid film is 50%, liquid film thickness h=0.1 mm)

Fig.11 shows the changes of the concentration and viscosity of the de-icing solution in the liquid film with time under different droplet radii r. The falling speed v of the droplet is 4 m/s. The initial concentration of the de-icing solution of the liquid

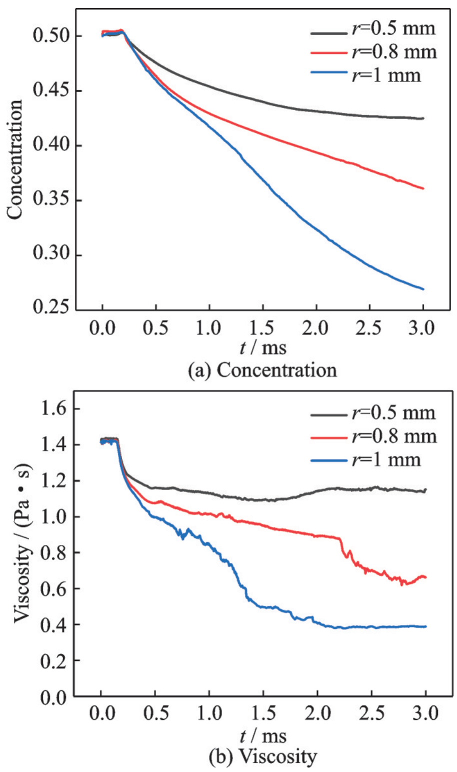


Fig.11　Changes of concentration and viscosity of liquid film de-icing solution with time under different droplet radii r

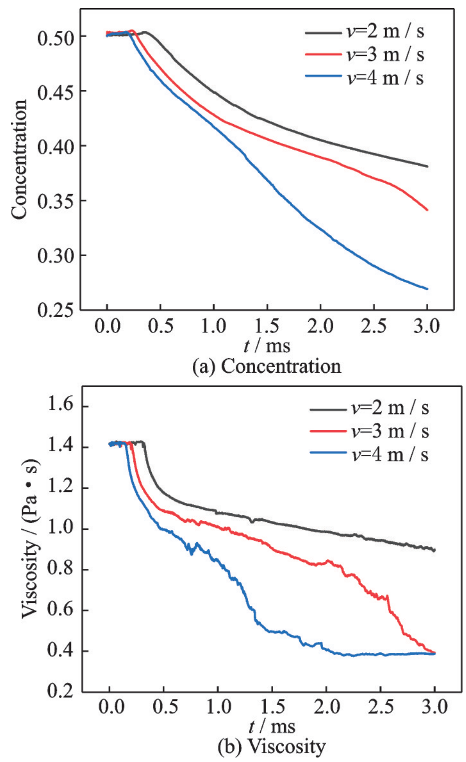


Fig.12　Changes of concentration and viscosity of liquid film de-icing solution with time under different droplet velocities v

film is 50%. The thickness h of the liquid film is 0.1 mm. And the drop height H of the droplet is 0.7 mm. It can be seen that the concentration and viscosity of the de-icing liquid in the liquid film have decreased significantly over time. As the drop radius r of the droplet increases, the concentration and viscosity of the de-icing liquid in the liquid film gradually increase.

Fig.12 shows the changes of the concentration and viscosity of the liquid film de-icing solution under different droplet velocities v with time. The drop radius r is 1 mm. It can be seen that with the increase of the droplet falling speed, the concentration and viscosity of the de-icing solution in the liquid film decrease faster.

From the line chart of the concentration of de-icing solution in Fig.11(a) and Fig.12(a), it can be seen that during the period when the droplet is not in contact with the liquid film phase at 0—0.18 ms, due to the extrusion of the air between the droplet and the liquid film, the concentration of the de-icing solution in the liquid film under different working conditions has a transient increase, which is the same as the conclusion of Section 4.1. The viscosity diagram in Fig.11(b) also reflects the change in the viscosity of the liquid film caused by air extrusion, because the de-icing fluid belongs to the non-Newtonian type shear thinning fluid, the de-icing liquid film should be in a static state during the non-collision period, and the viscosity of the liquid film is a fixed value, while the viscosity of the liquid film fluctuates at about 1.4 Pa•s in the initial stage. This is because the extrusion of air causes fluctuations on the surface of the liquid film, and when the shear-thinned fluid is subjected to a certain amount of shear, it shows a decrease in viscosity. After the droplet contacts the liquid film, the viscosity of the liquid film at different radii of about 0.28 ms drops rapidly from 1.4 Pa•s to 1.2 Pa•s. Combined with Fig.12(b), it can be found that in a short time after the impact, the viscosity of the liquid film decreases to a similar degree at different speeds, which indicates that the change of the viscosity in the liquid film in the initial stage of the impact is mainly caused by the dilution of the liquid film by the water in the droplet. As shown in Fig.11, under the condition of droplet radius r of 0.5 mm, when the viscosity of the liquid film drops to 1.2 Pa·s, the viscosity in the liquid film in 0.5—1.75 ms decreases, and then slowly increases and maintains a stable fluctuation. From the analysis of the first two subsections, it can be seen that the energy of the droplet after hitting the liquid film contributes to the growth of the liquid crown and the movement of the droplet in the liquid film, and the smaller the radius of the droplet, the less energy generated by the impact of the droplet, the more difficult it is to produce the ejected liquid crown. So the smaller radius of the droplet has a smaller range of action on the liquid film, and the faster time to reach the steady state. When the liquid film reaches a steady state without the shear action of droplet, the viscosity shows an upward trend after decreasing because the intrinsic viscosity of non-Newtonian fluids begins to recover slowly.

In the condition of radius r of 0.8 mm, the viscosity drops rapidly again after a period of slow decline. Combined with the cloud map of the change of the concentration of the de-icing liquid in Fig.10, it can be found that the initial angle of the liquid crown of the liquid crown is close to the horizontal direction under different working conditions, which leads to the movement of the fluid sprayed in the liquid crown along the surface of the liquid film, because there is air between the liquid crown and the liquid film. The tip of the liquid crown has carried out a short slip on the surface of the liquid film. The calculation area of viscosity in this paper is the liquid film area with a height of 0.1 mm. So during the time when the liquid crown is not mixed with the liquid film, the calculation of the concentration and viscosity of the liquid film ignores the liquid crown above the liquid film. When t=2.42 ms, the liquid crown is mixed with the liquid film under the action of gravity, and the viscosity of the liquid film is rapidly reduced again. The smaller the drop radius of the droplet, the more difficult it is to produce a sprayed liquid crown, resulting in a decrease in the liquid flowing into the liquid crown. Thus, most of the energy generated by the droplet impact contributes to overcoming the shear inside the liquid film. Due to the high shear effect in the liquid film, the liquid film tends to stabilize at a faster speed.

From the above analysis, it can be seen that the increase of the radius and speed of the droplet will significantly reduce the concentration and viscosity of the de-icing liquid in the liquid film, resulting in the deterioration of the anti-icing effect of the liquid film, and the liquid film is more prone to slip and fall off. Small radius droplets with a small range of action can make the impact process stabilize faster, which is conducive to the recovery of the viscosity of the liquid film and reduces the possibility of liquid film slip. The increase of droplet velocity will increase the shear effect on the liquid film, thereby accelerating the concentration and viscosity decline rate of the de-icing liquid in the liquid film. This will significantly reduce the anti-icing time of the de-icing fluid, which in turn increases the potential risk of anti-icing failure of the liquid film.

5 Conclusions

The flow analysis of the fluid during the impact reveals that the kinetic energy brought by the droplet falling will be converted and lost in two ways during the impact process: (1) To overcome the shear effect of the fluid inside the liquid film and promote the mixing of the water in the droplet with the liquid film de-icing liquid; (2) to generate liquid crowns, and the growth of liquid crowns is accompanied by the phenomenon of de-icing liquid detachment from the liquid film. These two effects will contribute to the decrease of the concentration of de-icing fluid.

When the droplets fall, the air entrained by the droplets has a shear effect on the surface of the liquid film and reduces the viscosity of the liquid film. After the water droplets hit the liquid film, the concentration of de-icing fluid in the impact area drops rapidly due to the effect of convective dilution. This indicates that the physical effects generated during the droplet's fall and impact collectively influence the changes in the physical parameters of the liquid film.

The higher the initial concentration of de-icing liquid in the liquid film, the smaller the spreading diameter of the water droplets after impact, and the greater the degree of inhibition of the growth of the liquid crown, leading to the more obvious the water migration phenomenon in the collision area. Therefore, by adjusting the initial concentration of de-icing liquid, the impact behavior of raindrops can be effectively affected, and the anti-icing effect of the liquid film can be improved.

The greater the speed of the droplet, the faster the migration rate of the components of the droplets in the liquid film, and the faster the average concentration and viscosity of the mixture decrease. The larger the drop radius, the larger the range of action of the water droplets within the liquid film, and the greater the average concentration and viscosity decrease of the mixture. This shows that the size and speed of the droplets are important factors affecting the interaction between the droplets and the liquid films, which can further optimize the anti-icing performance of the liquid film.

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水滴撞击非牛顿除冰液液膜动力学行为特性数值研究

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摘要：冻雨天气下，过冷大水滴撞击到除冰液液膜后会发生溅射、铺展、互溶等物理过程，除冰液液膜温度降低、浓度下降，液膜冰点上升、黏度下降，引发液膜滑落脱离，大幅缩短防冰保持时间。本文针对冻雨天气下飞机除冰液液膜失效行为开展数值研究，基于流体体积法，并结合组分输运方程，构建了多相、多组分、多体系、多场耦合的水滴撞击非牛顿除冰液液膜的动力学行为模型。基于该数值模型，研究了水滴撞击非稳态过程的动力学行为以及液膜的稀释、降粘等非牛顿流变特性。研究表明：液膜初始浓度越高，对水滴液冠生长抑制程度越大，撞击后水滴的铺展直径越小，水滴和除冰液液膜的碰撞区域的水分输运迁移现象越明显，除冰液液膜在剪切稀释和浓度降低的耦合作用下，黏度下降幅度越明显；水滴初始直径越大，水滴对液膜的作用范围越大，液膜黏度下降幅度越大；水滴的下落撞击速度越大，水滴在液膜内组分迁移速度越快，液膜黏度损耗越明显。

关键词：除冰液液膜；多相多体系；非牛顿；剪切稀释；组分迁移