STUDY ON THERMODYNAMIC COUPLING BEHAVIOR OF NON-NEWTONIAN DEICING FLUID DROPLETS IMPINGING ON SOLID WALLS AT LOW TEMPERATURE

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Abstract：*Icing on key aircraft parts is one of the major hidden dangers of flight safety in winter. To eliminate the hidden danger caused by icing, deicing liquid jet deicing is the most common deicing operation method in most airports in our country. The deicing liquid jet is sprayed on the surface of the fuselage to melt the ice and snow of the aircraft skin, and then the film is applied on the surface of the fuselage, which can inhibit the accumulation of ice in the fuselage for a certain period. Deicing fluid is a typical non-Newtonian fluid, and its film distribution characteristics are affected by various factors. This paper studies the film distribution characteristics of Type II deicing fluid impacting aluminum plates and relies on commercial code Fluent simulation software to build a droplet wall impact model to analyze the data of droplet spreading and rebound under different droplet diameters and different initial velocities. The high-speed camera is used for comparative analysis and verification. The coupling effect mechanism of droplet physical property parameters on droplet wall impact behavior and spreading film behavior was revealed, which provided theoretical guidance for airport deicing operation parameter regulation and accurate determination of deicing fluid retention time. Under the same initial conditions, the larger the initial velocity of the droplet, the larger the kinetic energy of the droplet, the larger the maximum dimensionless diameter of the droplet, and the larger the length of the spreading film. The larger the droplet diameter, the larger the droplet falling inertia, the larger the maximum dimensionless diameter, the smaller the thickness, and the longer the spreading film.*

Keywords：*Non-newtonian fluid、The droplet hit the wall、Spread the cloth film*

1 Introduction

Safety is a top priority in the civil aviation sector, General Secretary Xi Jinping made important instructions many times："Air transport security concerns national security and national strategy". Snow removal in winter has an important impact on civil aviation safety. There are numerous flight accidents caused by ice on the surface of aircraft in the world, and the problem of ice removal has become an important research issue in the field of civil aviation. A deicing liquid jet is often used to deice aircraft surfaces in Chinese airports. The deicing liquid jet is sprayed on the surface of the aircraft and spreads on the skin to form a thin liquid film. The retention time of the liquid film has a great impact on the anti-snow and ice operation. Deicing fluid is a non-Newtonian fluid, and the droplet impact on the solid surface is affected by many factors, such as droplet velocity, droplet diameter, droplet concentration, impact Angle, impact surface difference, etc., which will have an important impact on the retention time. Different fields and applications have different requirements for droplet film spreading and rebound behavior mechanisms. For aircraft surface deicing, the spreading performance of deicing drops is required to be good. When a droplet touches a solid wall and begins to spread, the maximum diameter of the droplet during the process can reflect the maximum area of contact between the droplet and the solid, which is one of the important parameters studied in this paper. Compared with the currently published research results, the study of droplet spreading behavior in this paper can achieve accurate regulation of the droplet collision spreading mechanism, which is of great significance for civil aviation safety.

The mechanism of non-Newtonian droplet collision has been studied by many scholars at home and abroad. According to four different state points, Park et al. [1] divided the impact process into five parts: pre-impact stage, spreading stage, retraction or rebound stage, oscillation to equilibrium stage, and equilibrium stage. By using a high-speed camera, Bi Feifei et al. [2] investigated the different effects of droplet impact parameters on droplet morphology by conducting experiments on three droplets with different physical properties. Chen Feng et al. [3] found that the greater the viscosity of the droplet, the greater the surface tension and the lower the maximum spreading length of the droplet. Regilling [4] studied the splashing behavior of Newton fluid droplets hitting low-temperature aluminum alloy plates and analyzed the influence of droplet temperature and solid contact surface temperature on the spread of the droplet film. Zheng Nuo [5] found through experiments that with the decrease of the power law index, the maximum spreading length of the droplet after hitting the wall increased, which promoted the rebound of the droplet. With the decrease of droplet surface tension or the increase of solid surface wettability, the maximum dimensionless diameter will also increase, which will inhibit droplet rebound.

According to the thermal dynamic physical process of deicing liquid jet spraying to the film on the surface of aircraft skin, non-Newtonian droplets' behavior impacting the low-temperature solid wall is abstracted. Based on the hypothesis of continuum and the principle of fluid dynamics (CFD), a model of droplet impact on a solid surface was constructed. Based on the model, a numerical study was carried out to analyze the dynamic behavior mechanism of droplet impact and spreading under different conditions. The VOF method is a kind of two-phase flow simulation technology in a fluid medium, which improves the traditional porous solid finite difference technique. VOF technique uses fluid volume fraction to describe the control of fluid phase, and can fully grasp the evolution of two-phase flow, and has been applied in many fields. This paper uses the implicit solution of the VOF method for analysis. In addition, experiments were carried out with shear-thinning Type II deicing liquid and aluminum plate as research objects, recorded by high-speed camera to verify the model analysis results, strengthen the reliability of numerical simulation, and provide theoretical and data support for the optimization of deicing operation parameters.

2 Mathematical model

The physical process of the impact of high-temperature deicing liquid droplets on the low-temperature solid wall involves multi-phase flow and heat transfer, including spreading, retracting, and rebounding, which is accompanied by energy, momentum, and viscosity loss. In this paper, the VOF method is used to simulate, and the mathematical model needs to be analyzed including the mass conservation equation, momentum conservation equation, energy conservation equation, phase volume fraction governing equation, and phase interface governing equation.

3. Physical model

3.1 Model simplification and assumptions

The high-temperature deicing liquid jet sprayed onto the surface of the aircraft can be regarded as the interaction process between the droplet and the aircraft skin. The model constructed in this paper simplifies the problem as a circular droplet with diameter d, v is the initial velocity, and T is the temperature, with gravitational acceleration, hitting an aluminum plate with a surface temperature of Twall. The dynamic characteristics and the change of physical parameters during the impact are studied, and the influencing factors are analyzed

The numerical example adopts a two-dimensional plane model of droplet impact on an aluminum plate. The calculation area of the numerical model is a two-dimensional structure. The physical model established is shown in Fig 1:

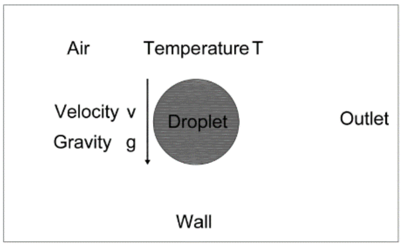


Fig 1. Schematic diagram of the numerical model of droplet impact on a solid wall

3.2 Physical parameters of deicing liquid

The selection of deicing liquid needs to consider many factors, including temperature change, viscosity change, shear rate change, etc. The Type of deicing liquid selected in this paper is Type II deicing liquid, type II deicing liquid is an alcohol or olefin organic matter. Its rheological properties belong to shear-thinning non-Newtonian fluids, and its viscosity is greatly affected by shear rate and temperature changes. The specific parameters of the simulated Type II deicing liquid droplet are shown in Tab 1:

Tab 1 Physical parameters of Type II de-icing fluid

Parameter	Symbol (unit)	Numerical value

Diameter	$\mathrm{d(mm)}$	1
Density	$\rho(\mathrm{kg}\cdot m^{-3})$	1150
Viscosity	$\eta(\mathrm{pa}\cdot \mathrm{s})$	0.5-3
Temperature	$\mathrm{T(K)}$	353.15
Droplet velocity	$\mathrm{v}(\mathrm{m}\cdot s^{-1})$	2-8
Surface tension	$\sigma(\mathrm{mN}\cdot m^{-1})$	48.4
Consistency coefficient	$\mathrm{K}(\mathrm{kg}\cdot s^{n-2}\cdot m^{-2})$	14.741
Flow characteristic index	$\mathrm{m(1)}$	0.5175

3.3 Power law model

The viscosity η of a non-Newtonian fluid varies with the shear rate $\dot{\gamma}$ and the shear stress τ, and is normally expressed as the ratio of τ to γ. To influence the coupling shear thinning characteristic on the droplet impact on the solid wall, a power law model (Ostwald-De Wale power law) is adopted in the numerical model in this paper to describe the dynamic change of droplet shear viscosity with shear rate. The equation is shown as follows:

$$\eta(\dot{\gamma}) = \mathrm{K}\dot{\gamma}^{m-1} \qquad \text{eq.(7)}$$

η is the apparent viscosity, $\dot{\gamma}$ is the shear strain rate, K is the consistency coefficient, K value is a measure of shear viscosity, the higher the apparent viscosity, the higher the K value. m is a power law exponent, that is, a non-Newtonian exponent, which is theoretically a parameter related only to the properties, temperature, and concentration of the fluid.

4. Numerical simulations

4.1 Model solving

The PISO algorithm is widely recognized as a typical multi-step correction time-splitting algorithm for solving unsteady pressure-velocity coupled problems in complex discrete regions. The PISO algorithm is divided into one prediction and two correction implementations at each time stratum, while the second correction takes into account the velocity correction values of the neighboring points, which allows the velocity and pressure values solved in each time stratum to better satisfy the momentum equation and the continuity equation. The non-Newtonian droplet impact on the solid wall studied in this paper needs to solve the coupled equations of velocity and pressure fields, so the pressure correction solution process of the PISO algorithm is used, and the solution flow chart is shown in Fig 2:

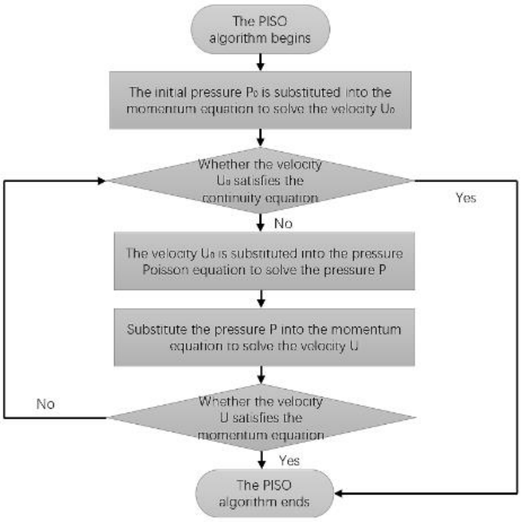


Fig 2. Separate solution time iteration method

4.2 Initial conditions

The initial conditions of the numerical simulation are set as follows: the initial velocity of droplet v=2m/s, the initial temperature of the droplet is 353.15K, the radius of the droplet is 1mm, the initial pressure of droplet is 0Pa, the initial temperature of the environment and the wall is 273.15K, the acceleration of gravity g=9.8m/s2, this paper addresses the problem of de-icing liquid jet spraying onto the fuselage surface, which can be regarded as the interaction process of each droplet individually with the aircraft skin surface. To simulate the impact of the de-icing fluid on the aircraft surface, except for the bottom surface (Wall), which is a non-slip walled aluminum plate, the rest of the boundary is an open boundary with a pressure outlet. The physical parameters of aluminum are shown in Tab 2:

Tab 2 Physical parameters of Aluminum plates

parameters	Symbol (unit)	numerical value
intensity	$\rho(\mathrm{kg}\cdot m^{-3})$	2719
specific heat	C_p（$\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$）	871
heat conductivity	$\mathrm{W}\cdot m^{-1}\cdot \mathrm{K}^{-1}$	202.4

4.3 Experimental validation

The experiment uses Type Ⅱ de-icing fluid to impact the aluminum plate, and the dynamic process of a droplet impacting the wall is recorded by the high-speed camera. The numerical model is as follows: consistency coefficient K= 0.208Pa·sn, power-law index m= 0.4, to simulate the behavior of shear-thinning droplet impacting the solid wall, and the simulation results are compared with the experimental results to verify the accuracy of the numerical model in predicting the behavior of a non-Newtonian fluid impacting on a wall.

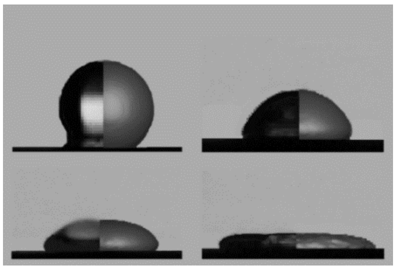


Fig 3. Comparison of numerical simulation results with experimental results (experimental results on the left, simulation results on the right)

From Fig 3, it can be seen that the numerical simulation results at different moments are consistent with the experimental results, which shows that the VOF numerical model established in this paper has a certain degree of realism in simulating the non-Newtonian fluid droplet impact on the wall.

4.4 Grid independence verification

For the numerical simulation results, it is necessary to select the appropriate mesh size. For the numerical simulation of multiphase flow, the accuracy of the grid is relatively high. When the mesh size is large, its accuracy will be affected to a certain extent, while when the mesh size is small, the calculation amount will be significantly increased. Therefore, grid independence verification is often required before numerical simulation. In this paper, the behavior of the shear-thinning droplet impacting the solid wall under different mesh densities is simulated, and the change curve of the dimensionless diameter with time is compared by gradually increasing the mesh density, and a suitable mesh density is found. The mesh density of 4 different mesh densities (M1, M2, M3, M4), M1, M2, M3, M4 is 12.5×12.5, 30×30, 50×50, 120×120, respectively.

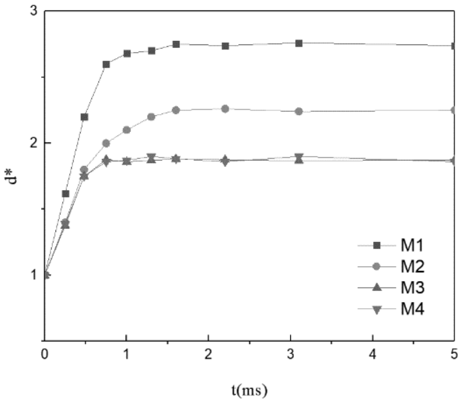


Fig.4 Dimensionless diameter curves of droplets over time at different grid densities

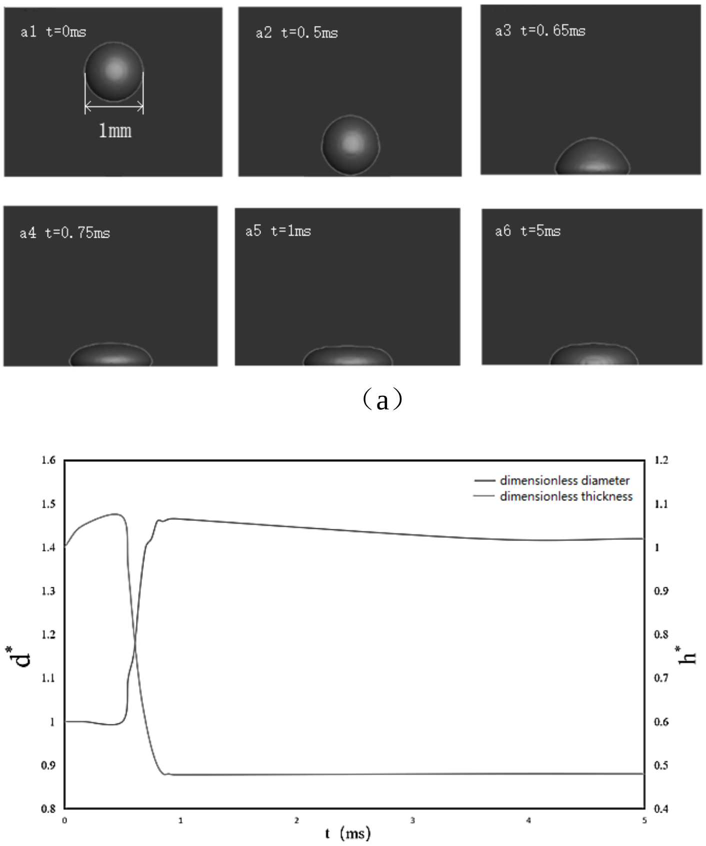
As can be seen from Fig 4, with the increase of mesh density, the calculated results gradually converge, and the simulation results of M3 and M4 are consistent. Therefore, to save calculation time, a grid with a mesh density of 50×50 was selected to carry out subsequent numerical simulation.

5. Numerical simulation

5.1 Numerical results of the kinetic properties of the droplet impact wall

The maximum dimensionless diameter is one of the most important research parameters in the process of droplet impact on the wall when the spreading length is maximum, the contact area between the droplet and the solid wall is maximum, the interaction is the strongest, and it has a great influence on the anti-icing, and the modeling algorithm investigates the kinetic properties of the droplet impact on the wall. The numerical simulation conditions for this example: non-Newtonian fluid de-icing droplet consistency coefficient K=0.208 Pa·sn, the non-Newtonian fluid de-icing liquid droplet radius is 0.5mm, the power law index m=0.4, the initial temperature is 353.15K, the initial falling speed v=3m/s, the environment and the initial temperature of the wall T=273.15K, and the angle of inclination of the droplet hitting the wall is 0°.

Numerical simulation of the impact of a single droplet of deicing liquid on the skin of a cryogenic aircraft is carried out to continuously and dynamically monitor the trend changes of the velocity field, viscosity field, and temperature field, as well as the changes of the dimensionless diameter d* and the liquid film thickness h* with the time t in the process of droplet descent and impact, and to explore and summarize the laws. The changes of velocity field and dimensionless diameter d* and liquid film thickness h* during the impact process of a non-Newtonian droplet vertically striking a solid wall are shown in Fig 5（b）:



（a）

（b）

Fig 5. Numerical simulation results of the dynamic characteristics of droplets hitting the wall(a)

Phase interface evolution (b) dimensionless diameter *d and dimensionless thickness *h with time t.

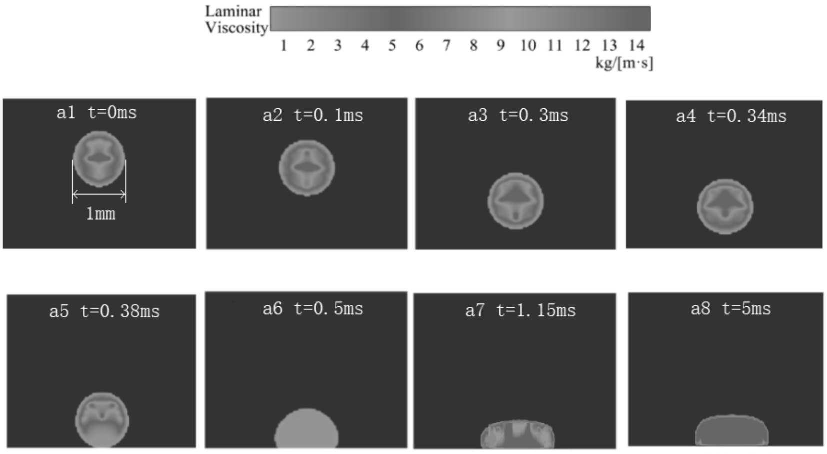
As can be seen from Fig 5, t=0ms to t=0.5ms is the initial stage of droplet impact on the solid wall. From the contact between the lower part of the droplet and the wall surface, the lower part of the droplet is squeezed and becomes flat, but the upper part of the droplet is still in a spherical state and maintains a downward flow trend. Due to the obstruction of the horizontal wall, the lower part of the droplet begins to shift in the horizontal direction, and the middle part of the droplet is affected by the liquid at the bottom, and then moves diagonally down along the liquid film formed at the bottom.

t=0.5ms to t=1ms is the spreading stage of droplet impact on the wall. After the droplet impacts the wall, the upper liquid continues to move downward under the action of inertial force, and the lower part of the droplet is hindered by the impact force, and the work done by the impact force is gradually transformed from gravitational potential energy to kinetic energy, making the upper liquid spread along the lower liquid, and the maximum non-dimensional diameter of the droplet is reached at t=1ms. Due to the high viscosity of the non-Newtonian fluid deicing solution, the internal flow rate of the droplet will gradually decrease during the spreading process, and the dimensionless diameter will be the largest at this time. t=1ms to t=2.5ms is the retraction stage of the droplet impact on the wall. Under the action of surface tension, the droplet shrinks back, and the dimensionless diameter of the droplet decreases slightly, while the dimensionless thickness of the droplet increases slightly. Due to the high viscosity of non-Newtonian fluid, the droplet retraction is not obvious, and the droplet retraction inhibition of non-Newtonian fluid appears.

5.2 Numerical study of droplet impact viscosity and temperature

Aiming at the research on the variation trend of droplet viscosity and temperature during droplet impact on a solid wall, a 2D model is adopted in this section. The droplet falling velocity v=4m/s, initial temperature 353.15K, initial ambient and wall temperature T=273.15K, and other initial conditions remain unchanged and the same.

Retraction inhibition is a unique dynamic characteristic of non-Newtonian fluid droplets. To better study the wall bumping behavior of non-Newtonian fluid, the change of the apparent viscosity of Type II deicing fluid droplets with time will continue to be studied. Fig 6 shows the numerical simulation results of the viscosity of non-Newtonian fluid droplets after impinging on a solid wall.



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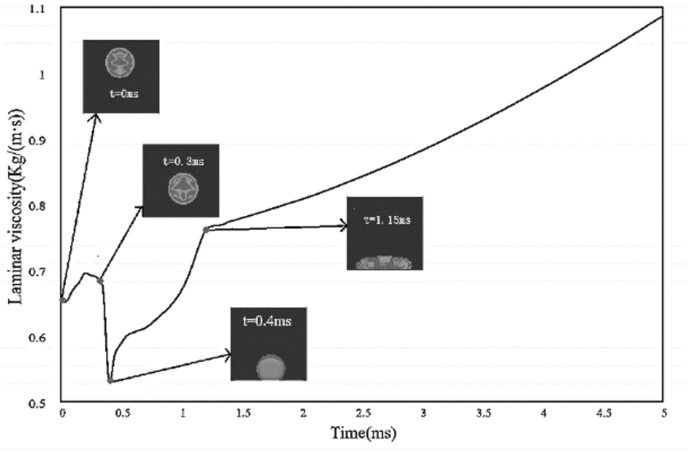


（b）

Fig 6. Numerical simulation of viscosity of non-Newtonian fluid droplets after impacting solid wall (a)Phase interface evolution and droplet viscosity distribution (b) Droplet average viscosity vs. time curve.

As can be seen from Fig 6 (b), the apparent viscosity of the droplet of Type II deicing solution is low at the beginning, drops sharply at the moment when the droplet collides with the wall, rises gradually during the spreading process, and the rising speed decreases gradually when the droplet reaches the maximum dimensionless diameter. The falling stage is affected by the air resistance and the intermolecular viscous force. Due to gravity, the falling speed of the droplets gradually increases, thus increasing the air resistance and gradually increasing the viscosity. When the droplet is in contact with the solid wall, the kinetic energy of the droplet is the maximum value and the viscosity is the minimum value. Subsequently, due to the viscous force between the two, the droplet movement rate gradually decreases, the shear rate decreases, and the viscosity gradually increases. When the liquid film spreads to the maximum, the kinetic energy is completely transformed into the potential energy of the surface tension and the viscous dissipation work. At this time, the droplet begins to shrink, and the shear rate gradually decreases and then becomes stable, while the apparent viscosity gradually increases and becomes stable. There is a heat loss behavior in the process of a high-temperature droplet impacting the low-temperature wall, so the temperature field distribution of a single droplet impacting the wall of the Type II deicing solution is shown in Fig 7.

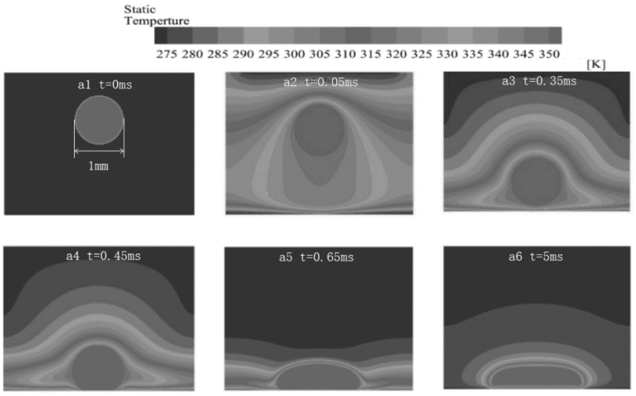


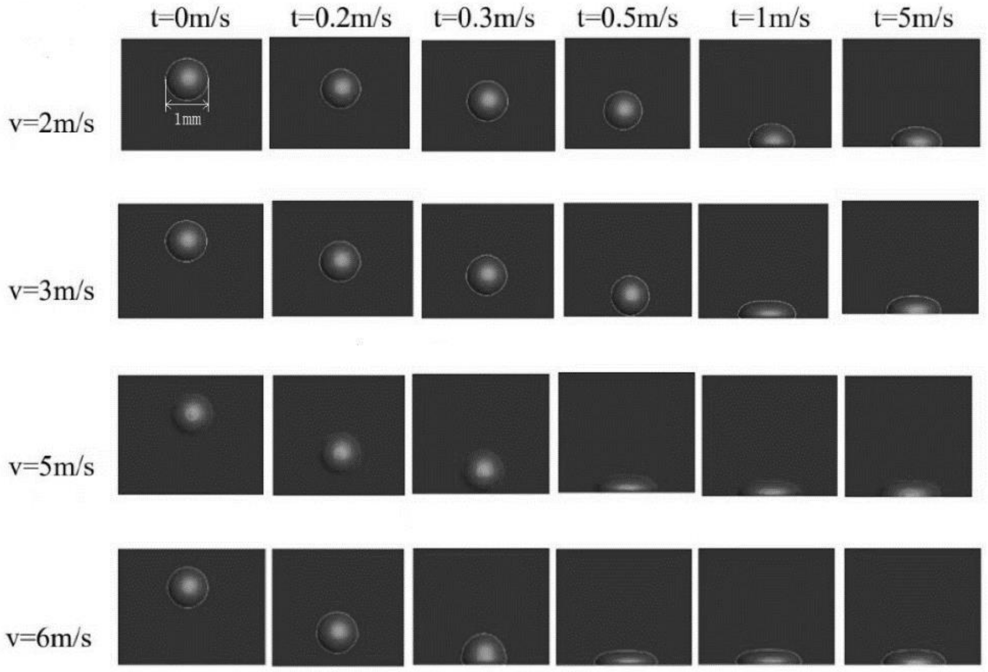
Fig 7. Numerical simulation results of non-Newtonian fluid single droplet impact wall temperature field

As can be seen from Fig 7, the temperature of the liquid drop at the beginning is 353.15K, and the temperature of the surrounding air and solid wall is 273.15K. At the beginning of the simulation, the average temperature of the droplet is significantly higher than that of the surrounding atmosphere, and the temperature of the surrounding space gas increases due to the heat transfer of the droplet to the air. The material of the wall is aluminum. When the liquid drop touches the wall, the heat transfer between the liquid drop and the wall is higher than that between the air because the thermal conductivity of the solid wall is higher than that of the air. Since the numerical simulation area is an open boundary, the hot air around the droplet gradually transfers heat to the low-heat air. In the process of the impact between the droplet and the solid wall, the heat transfer mode between the droplet and the wall is mainly heat conduction, and the heat transfer mode between the droplet and the air is mainly convection heat transfer. The drop temperature and wall heat flow temperature decrease with the increase of time. However, due to the small time scale of the spreading process studied in this paper, the temperature change of the droplet is not obvious, so the change of shear stress caused by temperature change is ignored.

5.3 Influence of different factors on the behavior of droplet collision and spreading

5.3.1 Effect of droplet impact velocity on droplet spreading behavior

To further explore the dynamic behavior of the non-Newtonian droplet, this section studied different initial velocities v=2m/s, v=3m/s, v=4m/s, v=5m/s, v=6m/s (corresponding to We=95, We=214, We=383, We=595, We=862, respectively). Movement of Type II deicing liquid droplet impacting horizontal aluminum wall.



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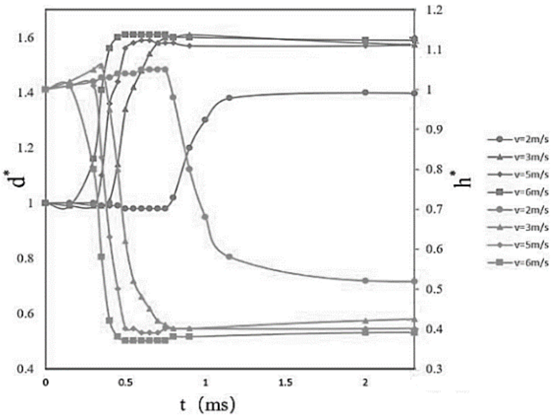


（b）

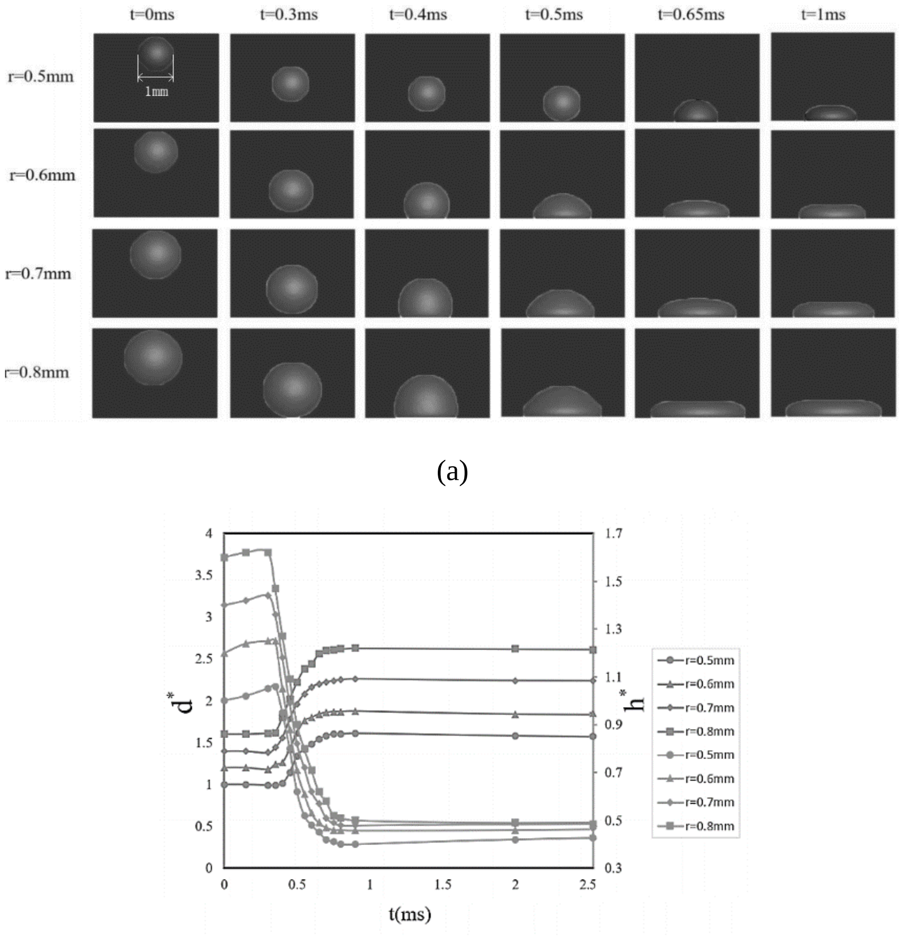
Fig 8. Dynamics of liquid impact walls(a) Motion diagram of droplets impacting level wall (b) The dimensionless diameter *d and the dimensionless thickness *h of the droplet impacting the horizontal wall at different initial velocities v versus time t.

As can be seen from Fig 8 (b), with the increase of the initial velocity, the minimum thickness of the liquid film decreases correspondingly, the dimensionless spreading length of the droplet increases, the phenomenon of shrinkage inhibition occurs, and the droplet does not break, and the maximum spreading length of the droplet still has room to increase.

With the increase of the initial velocity of the droplet, the inertia force and kinetic energy of the droplet increase, the shear rate of the droplet when it hits the wall is accelerated, and the apparent viscosity decreases, resulting in the increase of the dimensionless diameter of the droplet and the decrease of the dimensionless thickness. The time for droplets with different velocities to reach the maximum spreading length is almost the same, which indicates that the increase in the initial velocity leads to the simultaneous increase of the spreading speed of the liquid film.

5.3.2 Effect of droplet diameter on droplet spreading behavior

The diameter of a single droplet of Type II deicing liquid is different in practice, and different droplet diameters have a certain influence on the spreading effect. In this section, the motion of a droplet impacting the horizontal wall under different initial droplet radius r=0.5mm, r=0.6mm, r=0.7mm, r=0.8mm is studied.



(a)

（b）

Fig 9. Dynamics of liquid impact walls(a) Motion phase diagram of a droplet impacting on the wall with different initial diameters(b) The variation curves of dimensionless diameter *d and dimensionless thickness* h of droplets impacting on the wall with different initial diameters with time t.

As can be seen from Fig 9(a), the droplet enters the spreading state after touching the wall surface. As the droplet diameter increases, the droplet volume also increases. Under the influence of gravity, the droplet with a larger volume of pure concentration deicer drops falls faster gains more kinetic energy, and increases the viscous dissipation work during droplet wall collision and spreading. With the increase of the initial diameter of the droplet, the dimensionless spreading length of the liquid film also increases, which can be obtained by appropriately increasing the droplet diameter, which is conducive to efficient deicing work.

As shown in Fig 9 (b): with the increase of the initial droplet diameter, the maximum dimensionless diameter and the minimum dimensionless liquid film thickness also increase. With the increase of the initial droplet diameter, the dimensionless diameter increases disproportionately in the stable period, while the dimensionless liquid film thickness increases significantly. The increase of liquid film thickness can inhibit the recurrence of ice accumulation on the aircraft skin surface for a longer time, but the retention time of deicing liquid cannot be increased by increasing the droplet diameter indefinitely.

6. Conclusion

In this paper, the behavior of non-Newtonian high-temperature droplets impacting the low-temperature wall is numerically studied, and the following conclusions are drawn:

(1) After the non-Newtonian fluid Type II deicing liquid drops hit the solid wall, the droplet gradually spread to the maximum dimensionless diameter d_{max}, and then the droplet shrinkage phenomenon occurred, and the shrinkage inhibition phenomenon was obvious, and finally reached the equilibrium state. High viscosity coefficient and high shear rate are the main causes of droplet shrinkage inhibition.

(2) Most of the kinetic energy and potential energy obtained by Type II deicing fluid of non-Newtonian fluid during the falling process are consumed by viscous dissipation work during the spreading process, which results in the shrinkage inhibition of drops of non-Newtonian fluid.

(3) For Type II deicing liquid droplets with the same droplet diameter and temperature, with the increase of initial droplet velocity, the inertial force of droplet falling increases, the kinetic energy obtained by droplet increases, the maximum dimensionless diameter of wall collision spreading increases, and the dimensionless thickness of liquid film decreases accordingly. The faster the component migration rate of water droplets in liquid film, the more obvious the viscosity loss of liquid film. However, the droplet does not break, and the initial droplet velocity can be continuously increased to obtain a larger single droplet film spreading length.

(4) With the increase of droplet diameter at moment 0 of the same speed and temperature, the droplet falling inertia increases slightly, the maximum dimensionless diameter increases obviously, and the minimum dimensionless liquid film thickness increases accordingly. Therefore, the deicing liquid with a larger droplet can be appropriately selected under the condition of considering the influence of other factors.

Acknowledgment

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