

Article

Ice Object Exclusion Characteristics of Turboshaft Engine Inlet under Helicopter/Inlet Integration Conditions

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Abstract: In this study, the influence laws of different parameters on the exclusion characteristics of hailstone and ice flake, and on the aerodynamic performance of the inlet are studied by numerical method. The motion of the hailstone and ice flake is simulated using the 6-DOF method. Results show that the inhalation of hailstone in the inlet decreases total pressure distortion by about 20%, and the total pressure recovery coefficient is essentially unchanged. Icing of the upper lip decreases the total pressure distortion of the inlet by about 22%, and the total pressure recovery coefficient decreases by 0.6%. The ice flakes on the inner and outer lip, when shed and brake by collision with the center body, will cause damage to the engine duct. The shedding and breaking of ice flake at an angle of 150° to the lip can result in a large amount of ice flake debris entering the engine duct, threatening the performance and structure of the engine in the rear. The motion characteristics of hailstone and ice flake under helicopter fuselage/rotor/inlet integration conditions are revealed. It also provides a reference on the numerical methods for the numerical study of hailstone/ice flake exclusion characteristics of helicopter fuselage/rotor/inlet integration conditions.

Keywords: helicopter; turboshift engine inlet; computational fluid dynamics (CFD); ice object; ice flake; hailstone



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1. Introduction

Helicopter plays an important role in military and civil aircraft due to their characteristics of low altitude and low-speed flight, air hovering, and vertical take-off and landing [1]. Its excellent performance and unique take-off and landing methods enable it to work in harsh environments [2,3], such as deserts, mountains, and plateaus. With the development of aeronautical and astronautical science and technology, the performance requirements for new types of aircraft have become higher and higher. The aircraft is not only to be able to adapt to various flight environments but also to maintain excellent performance under adverse flight conditions. Due to its special operational environment and tactical characteristics, the helicopter is required to be able to take off and land on unimproved and improvised sites in the field (field, grass, beach, etc.) or hover at low altitudes. However, helicopters can encounter snow and ice during flight, resulting in the inhalation of hailstone into the engine inlet or icing on the aircraft [4]. And, as helicopters operate in severe cold weather, ice flakes shed from the propeller blades and from the lip of the inlet can enter the inlet causing engine surge and power loss [5]. In severe cases, this can lead directly to engine stalling, produce permanent power loss, or cause damage to major engine structures [6,7].

The inlet system is located at the front section of the helicopter turboshift engine duct. It is responsible for particle classification and delivering a certain amount of high-quality airflow to the compressor. It is also the aerodynamic link between the external flow field and the turboshift engine. Its characteristic performance has a direct impact on the power-to-weight ratio, fuel consumption, and operational reliability of the engine [8]. As the

operating environment of the helicopter is becoming more and more complex, its tasks are becoming more and more diversified. Under certain operating conditions, foreign objects (ice and snow on the ground, hailstone in the air, and ice flake shed from the inlet lip) may be drawn into the engine from the inlet, which could adversely affect the life, operational reliability, and efficiency of the engine. Therefore, it is important for helicopter inlets to have a good exclusion function [9].

At present, a large number of studies have been carried out on aerodynamics and the exclusion of helicopter inlets. For research on the aerodynamics of helicopter inlets, Kim et al. [10] conducted an experimental study of the interference between rotor wake and helicopter airframe. Misté et al. [11] analyzed the overall performance of the engine with helicopter pitot inlet by overall engine performance modeling. In addition, numerical studies of helicopter flow fields have been widely conducted, e.g., Wu et al. [12], Lakshminarayan et al. [13], Ramasamy et al. [14], Rovere et al. [15], and Tanabe et al. [16].

In the area of hailstone and ice flake impact dynamics, many studies have also been carried out by relevant units. On the study of the icing model, many scholars have conducted a wide variety of modeling studies of hailstone and ice flake in a range of fields. Kim et al. [17] developed the first numerical computational model of hailstone based on DYNA3D. Andy et al. [18] proposed a methodology for subscale iced-airfoil aerodynamic simulation. Bourgault et al. [19] developed a shallow-water icing model in FENSAP-ICE. In addition, Mi [20] and Wang et al. [21] built the hailstone and ice flake model based on the size of the engine inlet area combined with the requirements of airworthiness regulations. In the study of the hailstone and ice flake movement, in 2006, Papadakis et al. [22] investigated the motion of ice cubes in a three-dimensional flow field by means of the four-degrees-of-freedom (4-DOF) trajectory codes. In 2007, their team [23] presented a computational method to simulate the phenomenon of random ice shedding as well as a 6-degrees-of-freedom (6-DOF) trajectory codes for two simulated ice flakes (rectangular and glazed shattered corner ice flakes) shedding from the wing and fuselage of a commercial jet aircraft. In terms of experimental methods, Kim et al. [17] used a nitrogen gas cannon to investigate the threat of hailstone impact. In addition to this, ice simulation methods have been studied by Baruzzi et al. [24], Deschenes et al. [25], Mi [20], and Wang et al. [21]. Wang et al. [21] investigated the impact on engine performance during the process of foreign objects such as hailstone and ice flakes being sucked into the turboprop engine through numerical simulation. They simulated the collision problem in the exclusion process by combining it with the LS-DYNA software and obtained the numerical results of the movement process of foreign objects in the inlet. In summary, some numerical studies have been conducted on the motion characteristics of hailstone and ice flake in the helicopter fuselage/rotor/inlet coupled flow field. However, most of them are analyses of the correlations between a few coupling conditions. What's more, there are fewer systematic studies on ice exclusion characteristics under helicopter fuselage/rotor/inlet integration conditions for hailstone and ice flake, which are often present in the helicopter flight environment and pose a threat to flight safety.

In this paper, the influences of different parameters (foreign object properties, icing positions, and angle, the internal flow parameters) on the exclusion characteristics of hailstone and ice flake, and the influences of hailstone and ice flake on the aerodynamic performance of the inlet is studied by a synthetic numerical method. It reveals the motion characteristics of hailstone and ice flake under helicopter fuselage/rotor/inlet integration conditions. It analyzes the influence laws of helicopter working parameters on the motion characteristics of hailstone and ice flake and the aerodynamic performance of inlet in the integrated flow field. What's more, it provides the theoretical basis and technical support for the foreign object exclusion characteristics of the inlet in the flow field during a helicopter flight in an icing environment and provides some references for helicopter flight safety.

2. Model and Methodology

2.1. Computational Model

2.1.1. Helicopter Fuselage/Rotor/Inlet Integrated Model

UH-60 “Black Hawk” is one of the most representative helicopters in the world and has a lot of flight test data [26,27]. In this paper, the UH-60 is chosen as the research object, the details of which can be acquired from ref. [28]. The simplified geometric model of the UH-60 is given in Figure 1. The influence of the hub is ignored. Its basic parameters are shown in Table 1. Viewing direction from the nose to the tail, the left side is the left inlet and the right side is the right inlet.

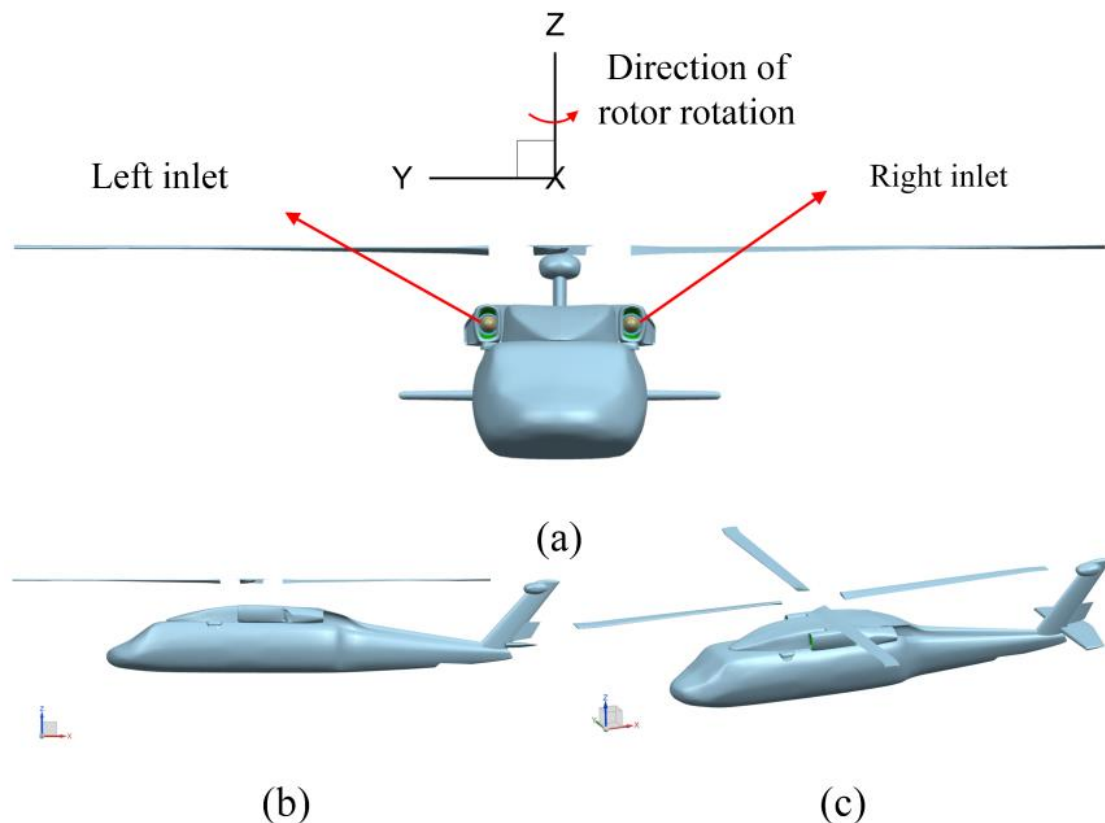


Figure 1. Geometric model of the UH-60 in (a) front view, (b) side view and (c) perspective view.

Table 1. Parameters of the helicopter geometric model.

Parameter	Parameter Unit	Parameter Value
Fuselage length	m	13.9
Fuselage width	m	2.6
Fuselage height	m	2.5
Rotor radius (R)	m	8.18
Number of blades (N)	/	4
Chord length (c)	m	0.53
Pitch angle (β)	$^{\circ}$	0

2.1.2. Hailstone and Ice Flake Model

The hailstones shall be ingested in a rapid sequence to simulate a hailstone encounter. The number and size of hailstones are determined according to the FAA-CFR [29]:

- (1) One 25 mm diameter hailstone shall be designated upstream of the entrance for engines with inlet areas of not more than 0.0645 m².

- (2) One 25 mm diameter hailstone and another 50 mm diameter hailstone shall be designated for each 0.0968 m^2 of inlet area, or fraction thereof, and for engines with inlet areas of more than 0.0645 m^2 .

The captured area of inlet for the model in this paper is 0.107 m^2 . As a result, two hailstones, including one of 25 mm diameter and another one of 50 mm diameter, were designated. The hailstone geometric models are shown in Figure 2a. The hailstone's position distributions are shown in Figure 2b. The geometric parameters of hailstone are shown in Table 2. The velocity of the hailstone is equal to the cruising speed of the aircraft. Its falling speed is calculated by the following equation.

$$v = \sqrt{\frac{2 \times W}{C_d \times \rho_0 \times A}} \quad (1)$$

where v is the falling speed of hailstone in m/s, W is the gravity of hailstone, C_d is the drag coefficient, ρ_0 is the atmospheric density in kg/m^3 , and A is the maximum cross-section. The C_d used in the calculation is 0.6.

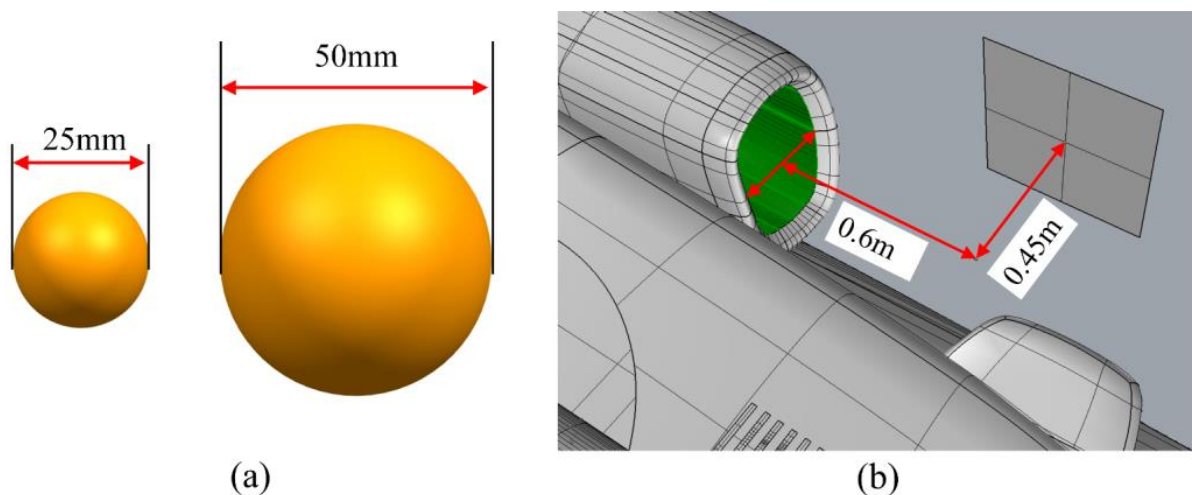


Figure 2. Hailstone geometric model and position distribution: (a) dimensions and (b) positions.

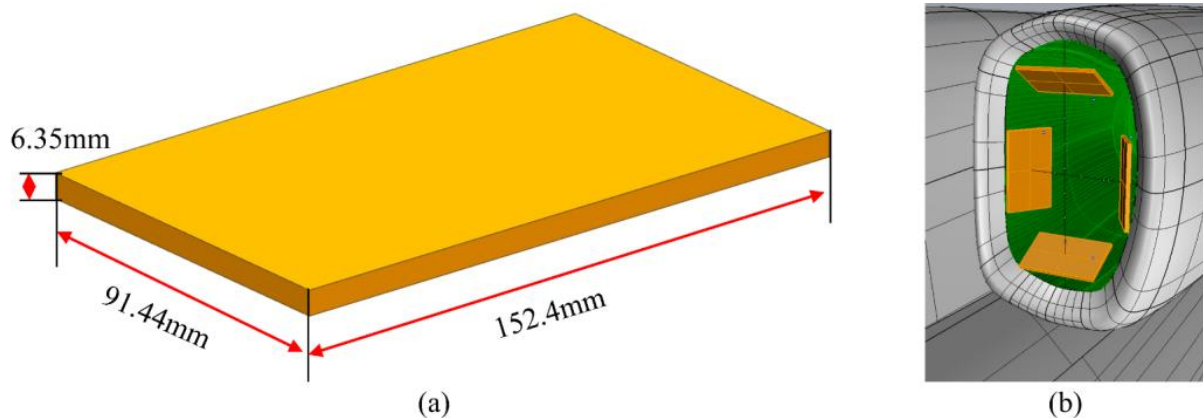
Table 2. Geometric parameters of hailstone and ice flake.

Type	Mass m/g	Moment of Inertia (I)
Hailstone 25 mm	7	$I = 4.346 \times 10^{-7}$
Hailstone 50 mm	59	$I = 1.39 \times 10^{-5}$
		$IXX = 1.46 \times 10^{-4}$
		$IYY = 5.3 \times 10^{-5}$
Ice flake	75	$IZZ = 1.98 \times 10^{-4}$

Currently, the dimensions of the ice flake are only set by the FAA, CFR [29]. According to the requirements specified of the ice flake dimensions in the CFR (Table 3), combined with the inlet area of the model in this paper, 75 g of ice flake is selected. Ice flake geometric model is shown in Figure 3a. Ice flake position distribution is shown in Figure 3b. The geometric parameters of ice flake are shown in Table 2.

Table 3. Minimum ice flake dimensions based on engine inlet size [29].

Engine Inlet Area (in ² /m ²)	Thickness (inch/mm)	Width (inch/mm)	Length (inch/mm)
0/0	0.25/6.35	0/0	3.6/91.44
80/0.0516	0.25/6.35	6/152.4	3.6/91.44
300/0.1935	0.25/6.35	12/304.8	3.6/91.44
700/0.4516	0.25/6.35	12/304.8	4.8/121.92

**Figure 3.** Ice flake geometric model and position distribution: (a) dimensions and (b) positions.

2.2. Numerical Method

A numerical CFD (Computational Fluid Dynamics) method combining dynamic mesh techniques with a 6-DOF motion model of the object was developed by the Aircraft Engine Environmental Adaptation (AEEA) group at Nanjing University of Aeronautics and Astronautics (NUAA).

2.2.1. Aerodynamic Method

The commercial Computational Fluid Dynamics (CFD) software ANSYS FLUENT was adopted to perform the calculation, which has been widely used for internal flow simulation [30,31]. In this paper, the software Fluent 2021R1 is used to simulate the flow field. The unsteady Reynolds-averaged Navier–Stokes (URANS) equation was solved by the pressure-based solver. The shear stress transport (SST) model was chosen to simulate the turbulence of the airflow field. The SIMPLE scheme was applied to solve the pressure-velocity coupling equation. The gradient term was discretized by the Least-Square-Cell-based scheme, as well as the pressure term by the second-order interpolation scheme and all the other spatial terms of the RANS and turbulence equations by the second-order upwind scheme. The transient formulation adopted the first-order implicit scheme.

The computational mesh includes four parts: helicopter/inlet/computational domain mesh, rotor mesh, ice flake, and hailstone mesh, all of which are unstructured mesh with γ -hexahedral mixing. The mesh was generated by Fluent Meshing and shown in Figure 4, the total mesh volume is about 20 million. In order to consider the accuracy of the flow field simulation and the computational efficiency, a rectangular space of $10R \times 10R \times 5R$ is selected as the fluid computational domain. The strategy of the interface is adopted for the rotor meshing, and the interface is used to connect the stationary fluid domain and the rotating domain. The sliding mesh method was adopted to simulate the rotation of the rotor part, which exchanges the flow information with the surrounding stationary part of the far field at the interface between the two parts. Figure 4a shows the fuselage mesh of the helicopter.

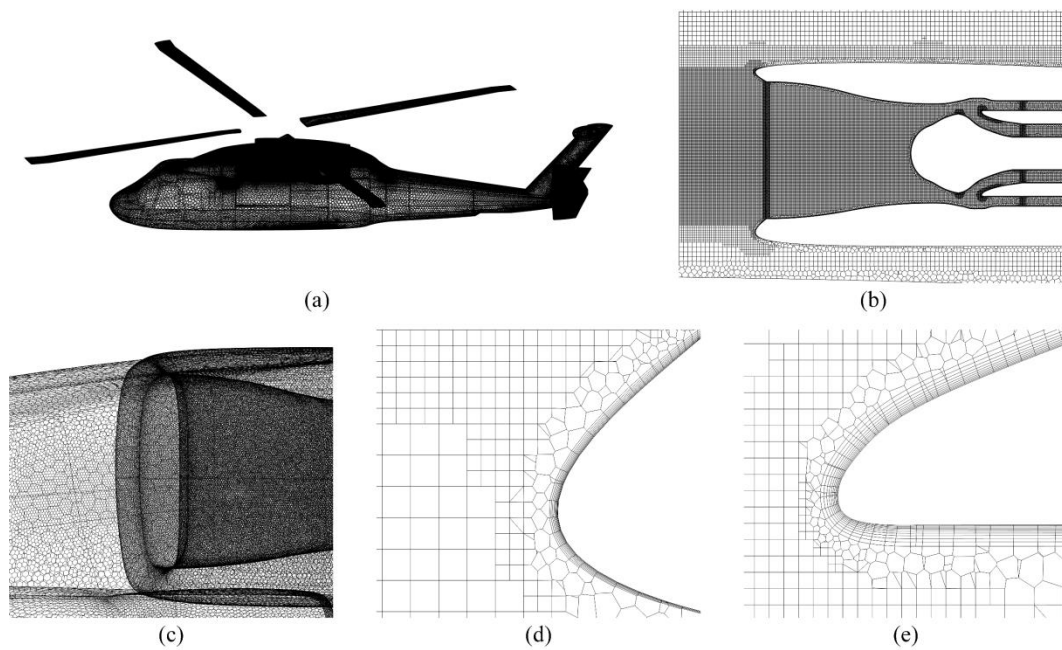


Figure 4. Computational mesh of the helicopter–inlet integration: (a) helicopter mesh, (b) inlet mesh, (c) inlet lip surface mesh, (d) lip boundary-layer mesh and (e) splitter boundary-layer mesh.

The IPS (Inlet Particle Separator) inlet is divided into two ducts that utilize inertial force to separate the foreign objects. The engine duct leads the clean airflow to the engine. The bypass duct exhausts the airflow carrying foreign objects into the atmosphere. The internal mesh of the inlet is shown in Figure 4b. Due to the complex internal structure of the inlet, the airflow flow is complex. Therefore, the mesh size is small compared to the external flow field. The presence of flow around the inlet lip has a great impact on the performance of the inlet, so the inlet lip surface mesh which is shown in Figure 4c is encrypted to make the surface smooth and continuous. Figure 4d,e shows the enlarged boundary layer mesh of the inlet lip and splitter locality, respectively. Hailstone and ice flake mesh are shown in Figure 5.

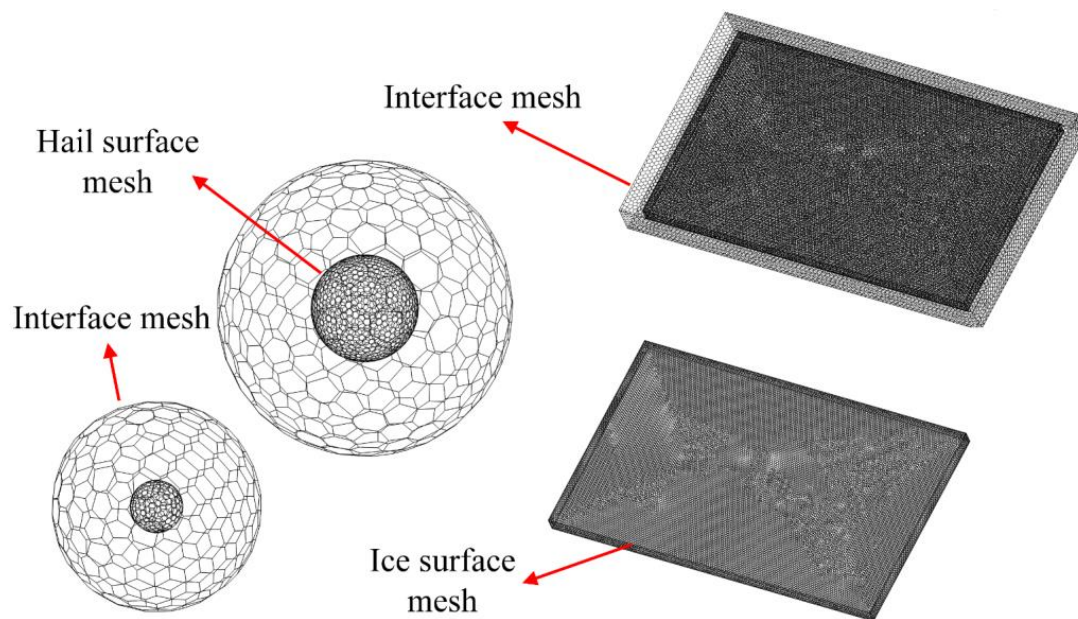


Figure 5. Computational mesh around the hailstone and ice flake.

2.2.2. 6-DOF Simulation Method

When the foreign object is under helicopter/inlet integration conditions, it will move dynamically with a coupled motion of translation and rotation. In this paper, the 6-DOF equations for the hailstone and ice flake were defined by using the built-in 6-DOF module in the Fluent software, including three rotational angular velocities of rotation around their own center of gravity and three translational velocities in three directions [32]. Note that the rotor effect was always included in the calculation of the motion of hailstones and ice flakes. The equation of the translational motion of the center of gravity in the inertial coordinate system:

$$\dot{\vec{v}}_G = \frac{1}{m} \sum \vec{f}_G, \quad (2)$$

where $\dot{\vec{v}}_G$ is rigid body center of gravity velocity vector, m is mass, and $\vec{f}_G$ is gravity vector. The equation for the rotational angular velocity of the object is

$$\dot{\vec{\omega}}_B = L^{-1}(\sum \vec{M}_B - \vec{\omega}_B \times L\vec{\omega}_B), \quad (3)$$

where L is inertia tensor, $\vec{M}_B$ is moment vector, and $\vec{\omega}_B$ is rigid body angular velocity vector.

$$\vec{M}_B = R\vec{M}_G, \quad (4)$$

where R is the transformation matrix.

$$\begin{vmatrix} C_\theta C_\psi & C_\theta S_\psi & -S_\theta \\ S_\phi S_\theta C_\psi - C_\phi S_\psi & S_\phi S_\theta S_\psi + C_\phi C_\psi & S_\phi C_\theta \\ C_\phi S_\theta C_\psi + S_\phi S_\psi & C_\phi S_\theta S_\psi - S_\phi C_\psi & C_\phi C_\theta \end{vmatrix} \quad (5)$$

where the shorthand notation $C_\chi = \cos(\chi)$ and $S_\chi = \sin(\chi)$ has been used, ϕ, θ, ψ is Euler roll, pitch, and yaw angle, respectively.

2.3. Numerical Simulation Method Validation and Mesh Independence Examination

2.3.1. Numerical Simulation Validation of Hailstone Motion Characteristics

The simulation method of hailstone in this paper is verified through experiment by measuring the positions data of 25 mm diameter hailstone during its motion. Figure 6 shows the hailstone meshing and the comparison between the experimental and simulated value of motion trajectory, where h/D is the positions of the hailstone in the vertical direction, x/D is the horizontal positions of the hailstone, and D is the diameter of the hailstone. From Figure 6, the hailstone moves in the x-direction for a long distance, and the hailstone also moves in the h-direction for a short distance due to the influence of gravity. Figure 6b shows that the hailstone moves in the channel as a parabolic motion affected by gravity. It can be seen that the experimental result matches with the simulation result. It confirms the reliability of the dynamic mesh and non-stationary method solution, which can be used in this paper to calculate and analyze the trajectory of the hailstone and ice flake in the inlet.

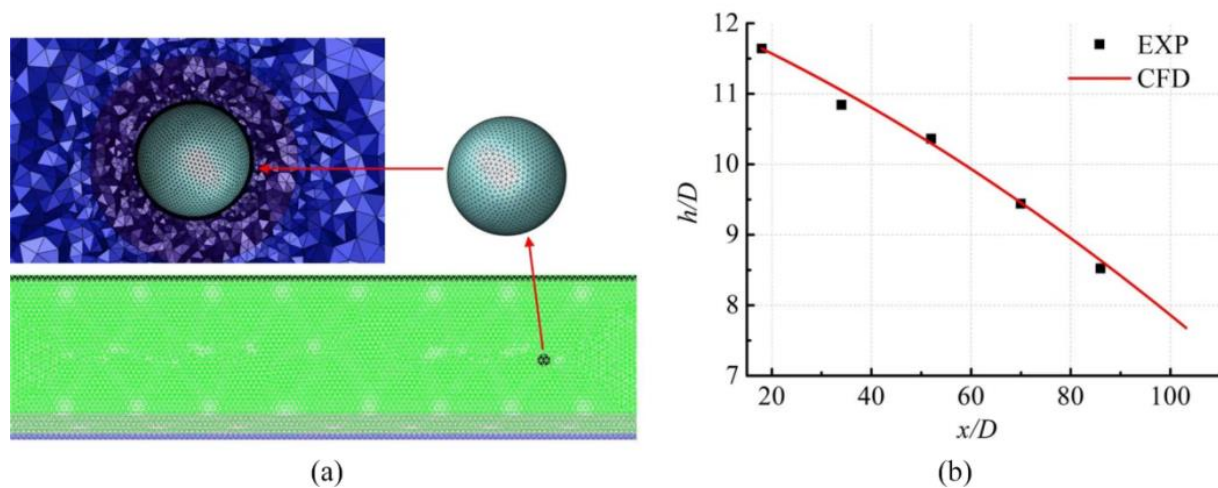


Figure 6. Hailstone trajectory validation results: (a) hailstone mesh details (b) comparison between CFD and experimental results.

2.3.2. Mesh Independence Examination

The NACA0012 model of the rotor with two blades was chosen to test the mesh sensitivity. For this model, three meshes of different volumes are constructed: 13 million, 25 million, and 32 million, respectively. Table 4 compares the tension coefficients obtained from the calculation of the above three meshes. It can be seen that there are some differences in the simulation results of the three meshes, but the difference is small in general. As a result, the effect of the mesh volume on the calculation results can be ignored.

Table 4. Variation of CT for different mesh volumes.

Mesh Volume	1300 w	2500 w	3200 w
C_T	0.003257	0.003297	0.003296

2.4. Physical Parameter Definition

The physical parameters used in this paper and their definitions are as follows:
Rotor tension coefficient formula:

$$C_T = \frac{T}{\rho \pi R^2 (\Omega R)^2}, \quad (6)$$

where T is the tensile force generated by the rotation of the rotor, ρ is the air density, R is the radius of the rotor, and Ω is the rotation angular velocity of the rotor.

The total pressure recovery σ is defined as

$$\sigma = \frac{p_2^*}{p_0^*}, \quad (7)$$

where p_0^* is the average total pressure at the AIP and p_2^* is the freestream total pressure.

The total pressure distortion $DC(60)$ is defined as

$$DC(60) = \frac{p_{av}^* - \bar{p}_{min60}^*}{q_{av}}, \quad (8)$$

where $\bar{p}_{min60}^*$ is the minimum total pressure in any sector region with the azimuthal angle of 60° , and q_{av} is the average dynamic pressure at AIP.

Ma_{AIP} (Mach number at the AIP section) is defined as

$$Ma_{AIP} = \sqrt{\frac{2}{k-1} \left[(p_{AIP}^*/p_{AIP})^{\frac{k-1}{k}} - 1 \right]}, \quad (9)$$

where p_{AIP}^* is the average AIP pressure and p_{AIP} is the static pressure in the AIP section, which is obtained by the static pressure measuring points of outlet, $k = 1.4$.

SCR (Scavenging ratio) is defined as

$$SCR = \frac{m_s}{m_c}, \quad (10)$$

where m_s is mass flow rate of the bypass duct and m_c is mass flow rate of the engine duct.

The formulas for the lift and drag coefficients for hailstone and ice flake are as follows:

$$C_L = \frac{L}{1/2\rho|V_\infty|^2l'}, \quad (11)$$

where l is the characteristic scale, L is the lift of the foreign object, which is vertical to the direction of the incoming flow, ρ is the air density, and V_∞ is the velocity of the incoming flow.

$$C_d = \frac{D}{1/2\rho|V_\infty|^2l'}, \quad (12)$$

where l is the characteristic scale and D is the drag of the foreign object, which is parallel to the direction of the incoming flow.

3. Results and Discussion

A multi-parameterized influence study of the exclusion characteristics of hailstones and ice flakes from the inlet of the helicopter during high-altitude flight is investigated. According to the open report [33], the maximum cruising airspeed is 135 sea miles per hour (i.e., about 69 m/s), as well as the maximum ceiling of 15,180 ft (i.e., about 4627 m). The rotational speed of the main rotor can reach 27 rad/s [34], i.e., about 258 rpm. By combining the fact that the AIP (i.e., the engine face) Mach number normally ranges around 0.5 ± 0.1 , it was considered that the flying conditions listed in Table 5 are rational and accessible, and thus were selected as the computational conditions to be used in this paper.

Table 5. Computational conditions.

Variable (Unit)	Value
Flight altitude (m)	1000
Flight speed (m/s)	60
Rotor speed (rpm)	250
AIP Mach number	0.45

3.1. Flow Field Characteristics of the Inlet under the Integrated Condition

The flow in the inlet under integrated conditions is so complex. Figure 7 shows the distribution of three-dimensional streamline velocity at the entrance and interior of the inlet. It can be seen that the flow tube at the entrance of the inlet expands, and the incoming flow decelerates and pressurizes at the entrance of the inlet. Therefore, the flow velocity is low at the entrance of the inlet, and the airflow is accelerated in the contraction section. When the airflow goes around the center body, the disturbance formed is strong due to the higher velocity and finally enters the engine duct. It is seen from Figure 8 that the flow field structure of the left and right inlet is similar. Figure 9 shows the total pressure recovery coefficient σ distribution of the AIP. There are more low total pressure areas in the left inlet, and the low total pressure areas in the left and right inlet are near the splitter side, which is caused by the separation of the high-speed airflow through the split area. Combined with

Table 6, it is observed that the difference between the total pressure recovery coefficient of the AIP of the left and right inlet is 0.0011, which is a relatively small difference.

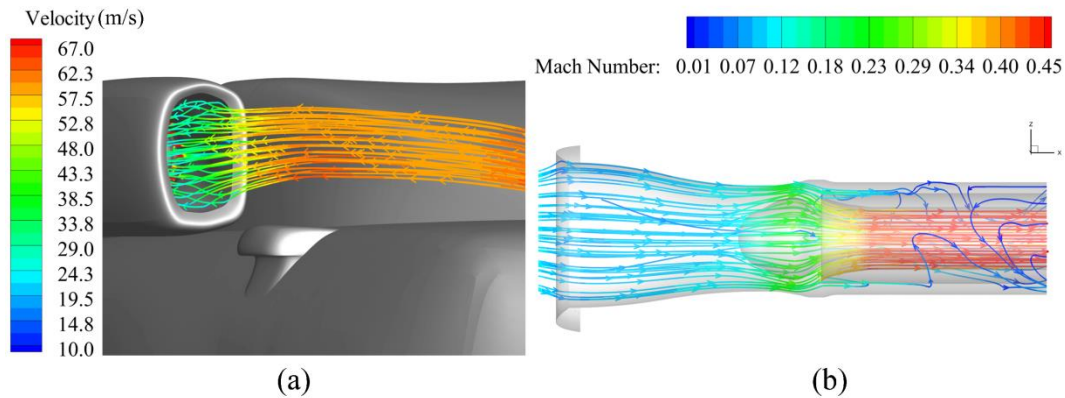


Figure 7. Distribution of three-dimensional streamline velocity (a) at the entrance and (b) in the interior of the inlet.

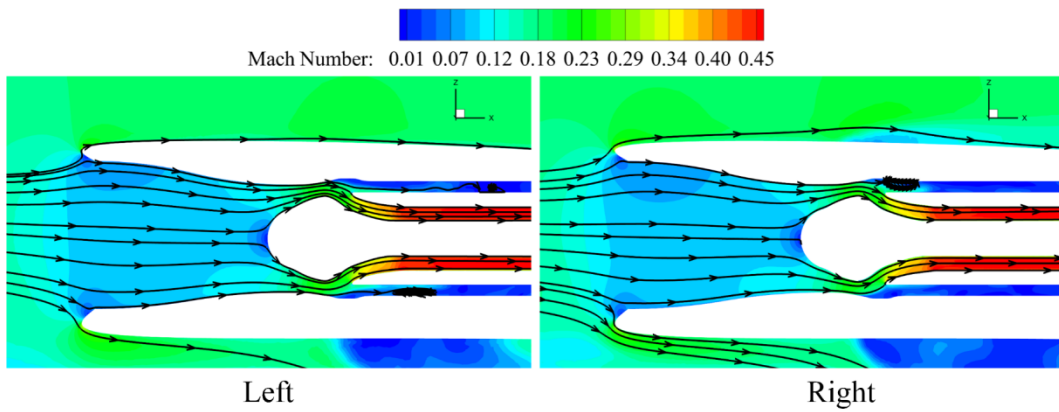


Figure 8. Distribution of velocity in the symmetry plane of the inlet.

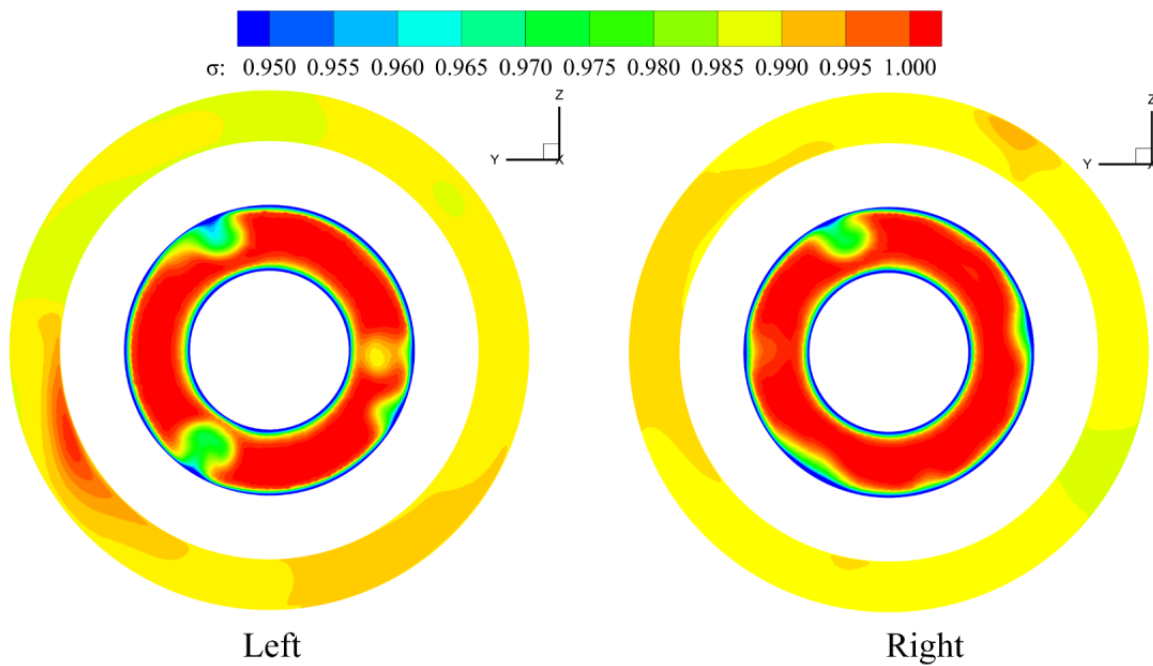


Figure 9. Total pressure recovery coefficient σ distribution of the AIP.

Table 6. Inlet performance.

Parameter	The Value of Parameter		Parameter
	L	R	
σ	0.9855	0.9866	
DC60	0.0292	0.0281	

3.2. Exclusion Characteristics of Hailstone

When the hailstone crosses the rotor and reaches the upstream of the entrance to the inlet, it could affect the performance of the inlet. The velocity of the hailstone in the calculation is equal to the incoming velocity of 60 m/s. The falling velocity is obtained according to Equation (1). The falling speed of a 25 mm diameter hailstone is 20 m/s and the falling speed of a 50 mm diameter hailstone is 28 m/s, and the parameters of the flow field are shown in Table 5.

The presence of hailstones has an impact on the structure of the flow field. Figure 10 shows the distribution of velocity in the symmetry plane of the left inlet at different moments. Figure 10a–c represents the velocity distribution at $T = 0$ s, $T = 0.005$ s, and $T = 0.009$ s, respectively (The time of foreign object movement is defined as T , and $T = 0$ s is the moment when the foreign object begins to move, the same below). At $T = 0$ s, the hailstones are located upstream of the entrance to the inlet, a low-velocity area appears near the hailstones and the velocity field becomes non-uniform. This indicates that inlet flow is already affected by the hailstones when they reach the upstream of the entrance to the inlet. At $T = 0.005$ s, the drag wake is formed on the back side of the hailstones and the airflow velocity field is separated at the entrance of the inlet. At $T = 0.009$ s, after the hailstones impact the lower wall surface of the front section of the inlet, the airflow at the entrance of the inlet is resumed. However, a larger area of separation is formed at the location where the hailstones impact. Moreover, it can be seen from the three-dimensional streamlines that the airflow will bypass when flowing through the hailstones.

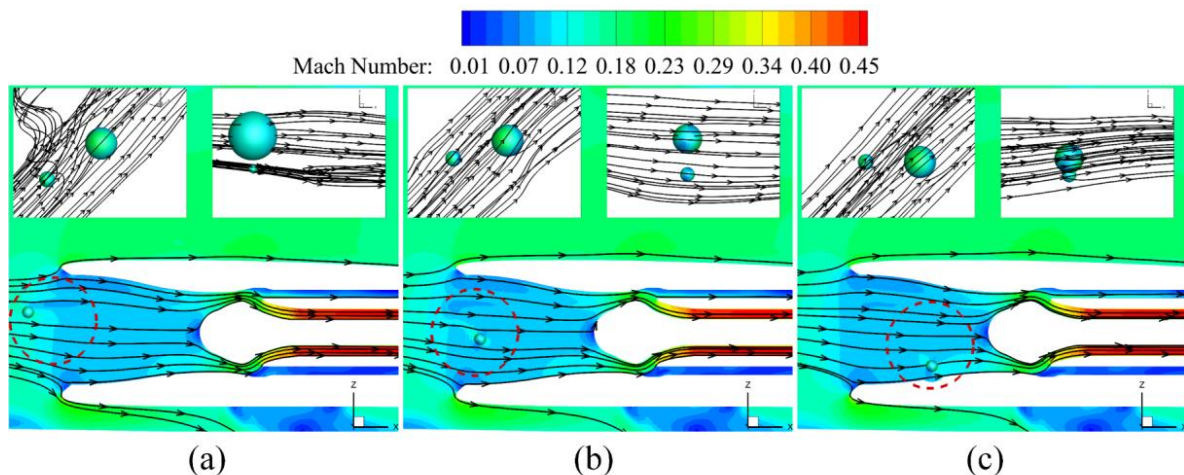


Figure 10. Distribution of velocity in the symmetry plane of the left inlet at (a) $T = 0$ s, (b) $T = 0.005$ s and (c) $T = 0.009$ s.

Besides, the presence of hailstones affects the performance of the inlet. Figure 11 shows the total pressure recovery coefficient distribution of the left inlet AIP at different moments. Figure 11a–c represents the total pressure recovery coefficient distribution at $T = 0$ s, $T = 0.005$ s, and $T = 0.009$ s, respectively. At $T = 0$ s, a small part of the inlet flow is blocked due to the presence of hailstones, which disturbs the flow at the entrance of the inlet and increases the swirling flow in the interior of the inlet. However, the circling flow at this time is favorable to the internal flow of the inlet as shown by the reduction of low total pressure area on the upper left side of the inlet AIP section (compared to the left inlet

in Figure 9. As a result of the hailstones, the large low-total-pressure area in the shape of the fan on the upper left side of the inlet is reduced. As the hailstones move to the interior of the inlet, the velocity of the hailstones is equal to the incoming velocity which is larger than the velocity of the airflow in the front part of the inlet. As a result, the disturbance of the flow field near the hailstones is reduced, as shown in the low-total-pressure area on the lower side of the AIP section gradually disappears and the total-pressure recovery coefficient is more uniformly distributed.

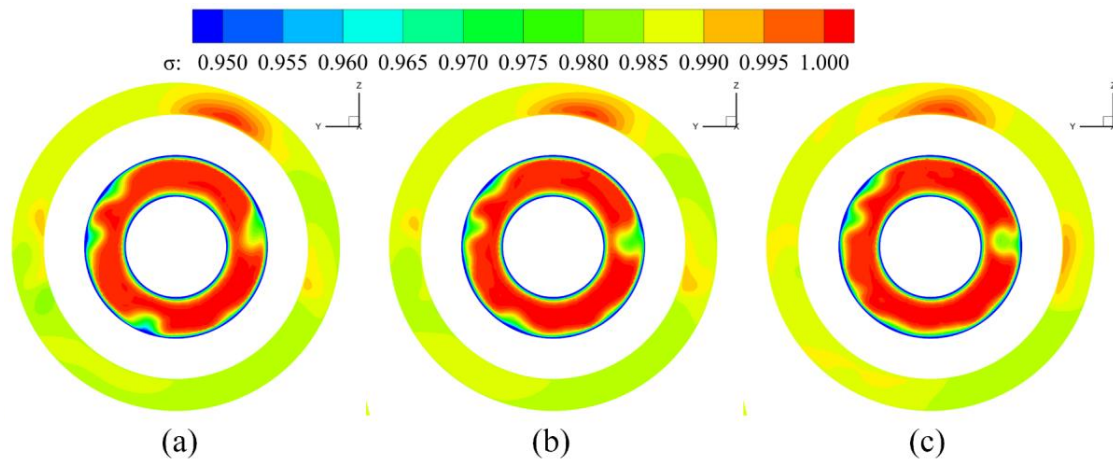


Figure 11. Total pressure recovery coefficient σ distribution of the left inlet AIP at (a) $T = 0$ s, (b) $T = 0.005$ s and (c) $T = 0.009$ s.

Table 7 shows the aerodynamic performance parameters of the left inlet at different moments. It can be seen that when the hailstones enter the inlet, they disturb the steady flow field and block a small part of the flow. However, the volume of hailstones is small relative to the entrance area of the inlet, which has essentially no effect on the total pressure recovery coefficient of the AIP section. And, the total pressure distortion of the AIP section is reduced due to the interaction of the bypass flow generated by the hailstones and the bypass flow generated by the splitter. As the hailstones enter the interior of the inlet, the flow at the entrance of the inlet is restored. Since the velocity of the hailstones is greater than the velocity of the inlet front section, the velocity of the surrounding airflow increases. As a result, the total pressure recovery coefficient increases. However, due to the continuous disturbance of the internal airflow by the hailstones after they enter the inlet, the swirling degree of the inlet interior is enhanced, and the distortion of the AIP section is increased.

Table 7. Left inlet performance at different moments.

Parameter	The Value of Parameter		
	T_0 s	$T_{0.005}$ s	$T_{0.009}$ s
σ	0.9855	0.9856	0.9857
DC60	0.022	0.0249	0.0279
σ	0.9810	0.9877	0.9885
DC60	0.0217	0.0201	0.0191

Figure 12 shows the characteristics of hailstone movement in the inlet and the variation of inlet performance parameters. For the trajectory of hailstones, the diameter l of the engine duct is used to be dimensionless. From Figure 12a, it can be seen that the trajectory of the hailstones is a straight line in the XZ plane. Since the falling speed of 50 mm hailstone is faster, it collides with the lower wall of the inlet more quickly. Figure 12b shows the change of hailstone velocity. The velocity of hailstones decreases when they enter the inlet from the upstream, and slowly increases after they enter the inlet. Figure 12c,d shows the change of lift coefficient and drag coefficient, respectively. Because of the role of gravity,

the contact surface of the hailstones and the airflow is small, and the lift of the hailstones is negative (foreign objects and airflow in the same direction as the positive value of drag, foreign objects, and airflow perpendicular to the direction of the right-hand rule for the positive value of lift). In Figure 12d, the drag force is negative for a period of time from the movement of the hailstones to the inlet. This indicates that at this time the hailstones are being resisted by the airflow from the interior of the inlet. As the flow direction develops the air velocity in the inlet gradually increases, and the aerodynamic force on the hailstones becomes positive on the x-axis, which pushes the hailstones to move forward so that the velocity of the hailstones also increases. Figure 12e shows the change in the total pressure recovery coefficient of the inlet. The total pressure recovery coefficient gradually increases as the hailstones go from lip to collision.

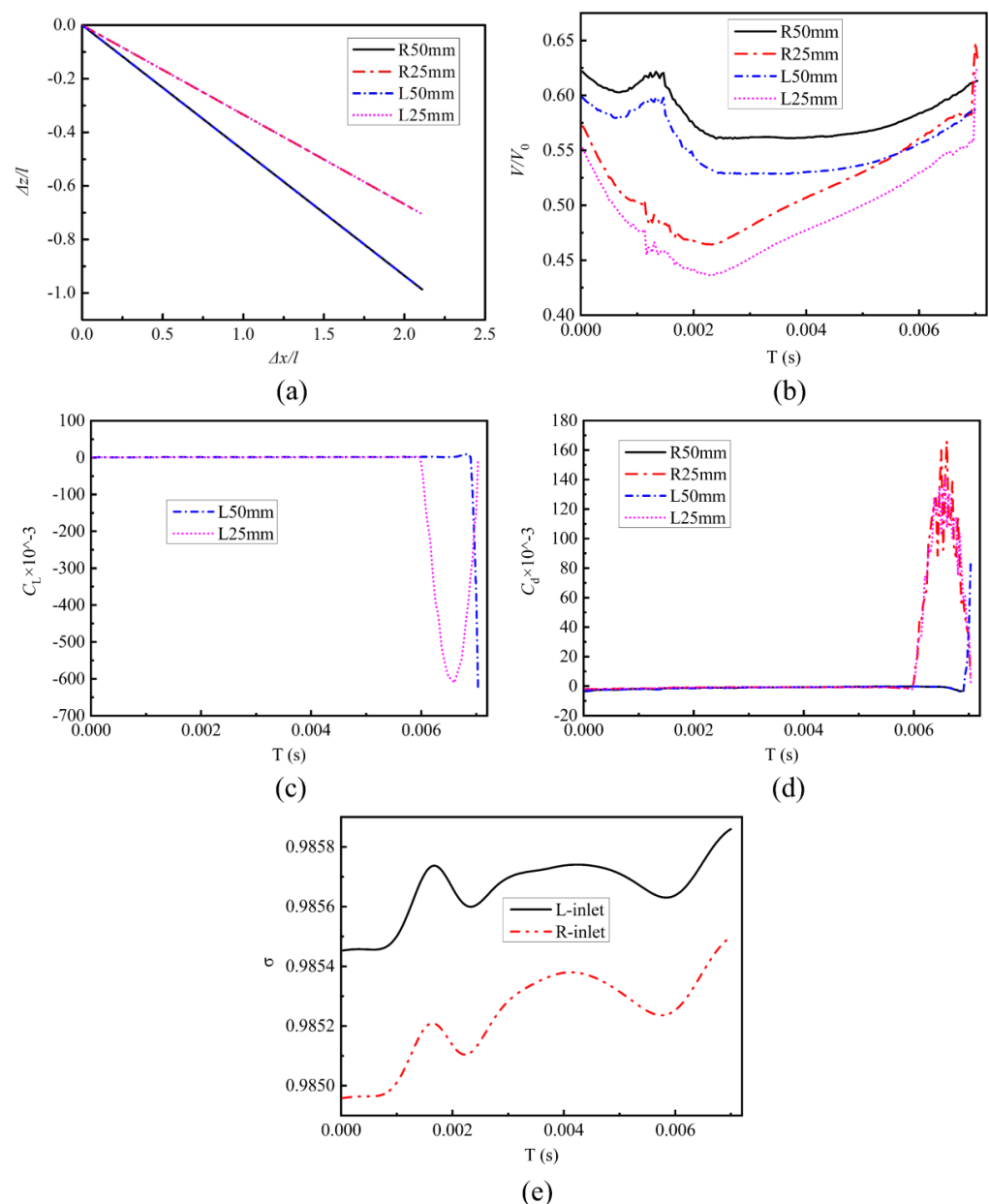


Figure 12. The movement characteristics of hailstone in the inlet and the variation of inlet performance: (a) the trajectory of hailstones in the XZ plane, (b) the variation in the velocity of hailstones during their movement, (c) the variation in the lift coefficient of hailstones during their movement, (d) the variation in the drag coefficient of hailstones during their movement and (e) the variation in the total pressure recovery coefficient during the movement of hailstones.

3.3. Exclusion Characteristics of Ice Flake

3.3.1. Exclusion Characteristics of Ice Flake under the Baseline Condition

The ice flake is studied when the ice flake is located at the upper lip of the inlet and at the angle of 30° (Angle of 30° to the direction of incoming flow), and the parameters of the flow field are shown in Table 5.

(1) Effect of ice flakes on the structure of the inlet flow field

The presence of ice flakes has an impact on the structure of the flow field. Figure 13 shows the distribution of three-dimensional streamline velocity at the entrance of the inlet with icing on the upper lip. It can be seen that the incoming flow is blocked by the ice flakes on the left and right lip. The airflow velocity near the ice flake decreases and the bypass flow increases. Figure 14a–c represent the distribution at $T = 0$ s, $T = 0.006$ s, and the moment of collision, respectively (Figures 15 and 16 are the same). It can also be seen in Figure 14a that a strong bypass flow is formed as the airflow flows through the ice flake at the upper lip, creating a large number of vortices that cause the streamline to flow downstream in the shape of the spiral.

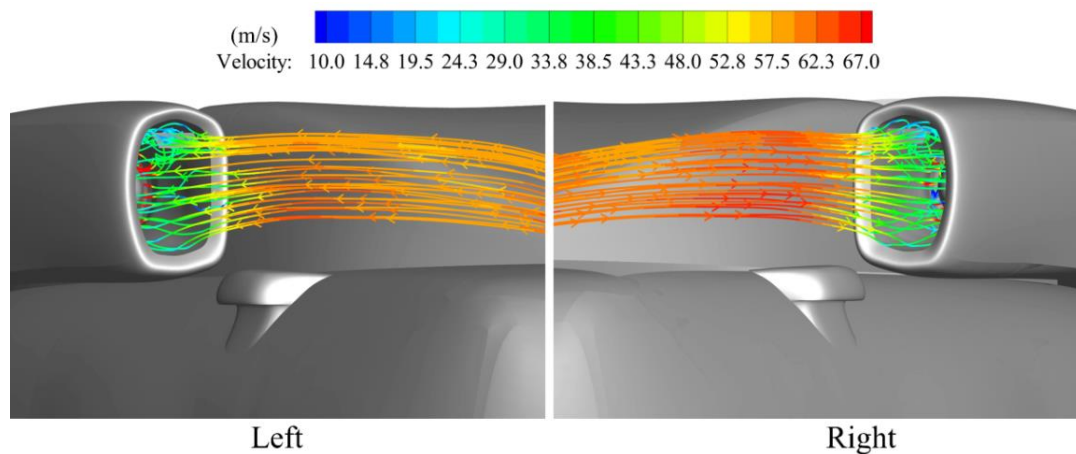


Figure 13. Distribution of three-dimensional streamline velocity at the entrance of the inlet with icing on the upper lip.

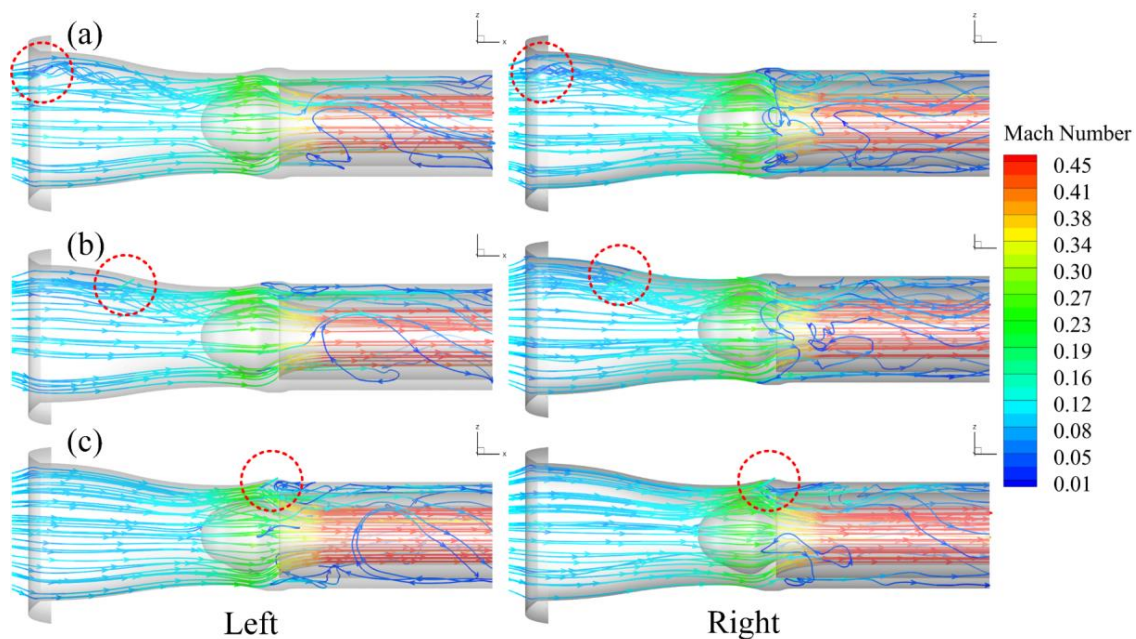


Figure 14. Distribution of three-dimensional streamline velocity at the interior of the inlet with icing on the upper lip at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

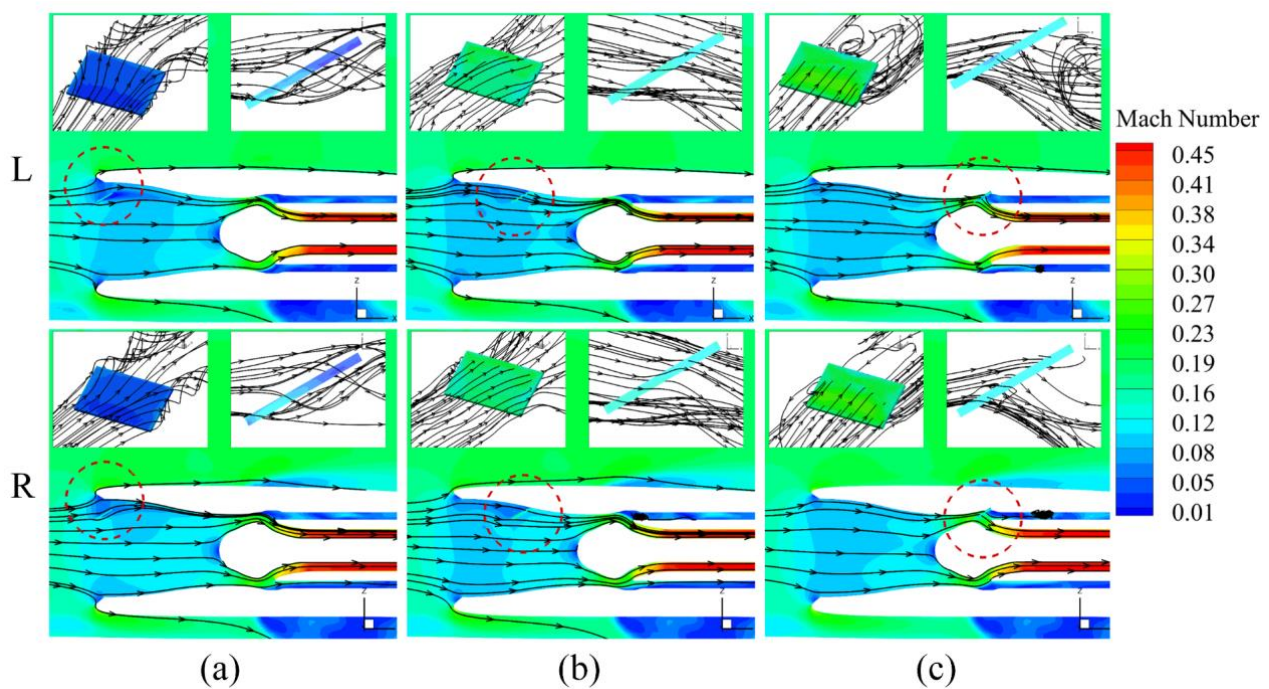


Figure 15. Distribution of velocity in the symmetry plane of the inlet with icing on the upper lip at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

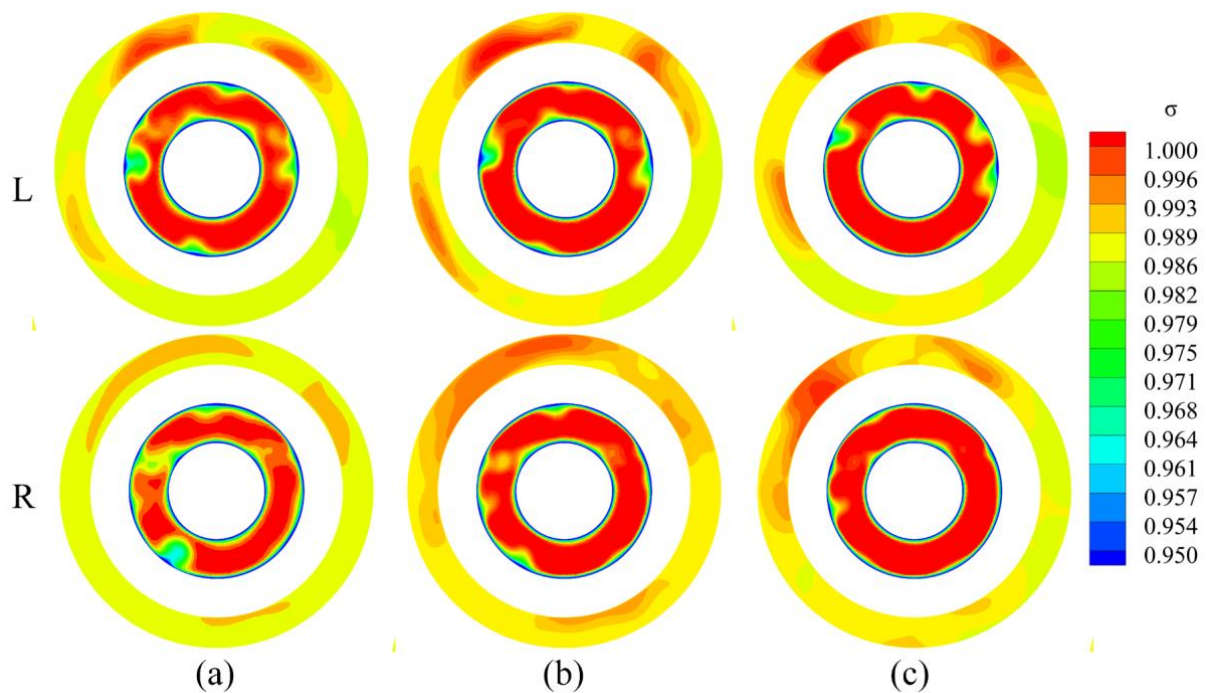


Figure 16. Total pressure recovery coefficient σ distribution of the inlet AIP at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

Figure 15a shows the distribution of velocity in the symmetry plane of the inlet with icing on the upper lip at $T = 0$ s. A large area of low velocity is formed in the inlet by the ice flake at the upper lip. The airflow is blocked by the windward side of the ice flake so that the airflow is separated here, and a low-pressure vortex area is formed on the leeward side of the ice flake so that the airflow is recombined far downstream of the ice flake. In addition to this, the flow state of the left and right inlet airflow was different when it flowed through

the ice flake. The curve curvature of the left inlet is small when it flows around the ice flake, and the low-pressure range of the ice flake's back side is large. The curve deflection is large when the airflow on the right inlet flows around the ice flake and the low-pressure range of the ice flake's back side is small.

From Table 8, it can be found that the total pressure recovery coefficient of the left AIP section at $T = 0$ s is higher, but the total pressure distortion is also large. This is because of the interference coupling of the down-wash of the rotor, incoming flow, and inlet suction flow, there is a difference in the distribution of airflow between the entrance of the left and right inlet. The flow field structure generated when the airflow is around the ice flake is different so that the low-pressure area on the leeward side of the ice flake on the left inlet is larger than that on the right inlet and the swirling flow generated in the interior of the inlet is large. Although the ice flake at the upper lip of the right inlet blocks the incoming flow, the swirling flow generated by it interferes with the disturbance formed by the splitter in the interior of the inlet so that the total pressure distortion of the right inlet is reduced by 0.0064.

Table 8. Inlet performance at different moments.

Case	Parameter	The Value of Parameter		
		$T_{0\text{ s}}$	$T_{0.006\text{ s}}$	$T_{\text{collision}}$
L	σ	0.9839	0.9875	0.9870
	DC60	0.0295	0.0271	0.0294
R	σ	0.9810	0.9877	0.9885
	DC60	0.0217	0.0201	0.0191

(2) Exclusion characteristics of ice flakes from the inlet

During exclusion, ice flake has obvious characteristics of movement and has a significant effect on the flow field and performance of the inlet. Figures 14 and 15 show the distribution of velocity at different moments. It is seen that as the ice flake moves downstream, the bypass flow on both sides of the ice flake decreases or even disappears, the low-pressure vortex area at the lip also disappears and the flow field in the inlet becomes uniform. Furthermore, at the collision between the ice flake and the wall, the airflow of the left inlet forms the separation vortex on the leeward side of the ice flake. The airflow of the right inlet does not separate, and the ice flake is eventually excluded from the bypass duct.

Figure 16 shows the total pressure recovery coefficient distribution of the inlet AIP at different moments. Combined with Table 8, it can be seen that the low-total-pressure area in the AIP section of the left inlet first decreases and then increases, the low-total-pressure area on the lower side disappears and the low-total-pressure area on the right side first becomes smaller and then larger. The total pressure recovery coefficient increases after the ice flake detaches from the wall. The vortex area is formed on the leeward side of the ice flake when the ice flake impacts the wall aggravating the flow distortion in the interior of the inlet, resulting in the total pressure recovery coefficient decreasing and the total pressure distortion increasing by 0.0023. The low-total-pressure area in the AIP section of the right inlet decreases, the lowest total pressure increases, the total pressure recovery coefficient of the inlet increases by 0.0075, and the total pressure distortion decreases by 0.0179. However, relative to the absence of ice flake (Table 6), the total pressure recovery coefficient of the AIP section in the left and right inlet increases, and the total pressure distortion of the AIP section in the left and right inlet decreases during the movement and collision of ice flake in the interior of the inlet. This is because of the larger velocity of the ice flakes, which accelerates the local airflow in the front section of the inlet. When colliding in the split section, the ice flake blocks the flow rate of the bypass duct and interferes with the splitter bypassing, which results in the flow rate of the engine duct increasing, and the separation loss of the splitter decreasing. Comparing Tables 6 and 8, the total pressure recovery coefficient of the AIP section in the right inlet increases by 0.002, and the total

pressure distortion decreases by 0.009. Overall, icing at the lip resulted in increasing the total pressure distortion of the inlet, decreasing the total pressure recovery coefficient, and ice flakes shed can cause damage to the internal structure of the inlet.

Figure 17 shows the characteristics of ice flake movement in the inlet with icing on the upper lip and the variation of inlet performance parameters. The trajectory of the ice flakes in the left and right inlet in Figure 17a overlap and move in the XZ plane in a similar parabolic motion. Because they have initial velocity in the X-direction and are influenced by gravity, their trajectories are close to a parabola. Figure 17b shows that the velocity of the ice flakes in the left and right inlet have the same trend, and the velocity of the ice flake in the right inlet is slightly larger than that in the left inlet. At the beginning of shedding, the velocity of the ice flake is equal to the velocity of the incoming flow. However, the velocity of the fluid around the ice flake is reduced by the deceleration and boosting at the entrance of the inlet, so that the velocity of the fluid around it is less than the velocity of the ice flake. Therefore, when the ice flake moves downstream, it is subject to the force in the negative direction of the X-axis of the airflow. As shown in Figure 17d at this time the drag force of the ice flake is negative. As it moves downstream, the velocity of the ice flake gradually increases. Before it enters the constriction section, the velocity of the ice flake has recovered to the velocity of the incoming flow. After entering the contraction section, the airflow in the contraction section is accelerated to a velocity greater than the velocity of the ice flake. Therefore, the airflow has a positive x-axis aerodynamic force on the ice flake. When the ice flake enters the split section, due to the expansion of the area here the velocity of the airflow decreases. However, at this time the velocity of the ice flake is the same as the velocity of the fluid in the constricted section. As a result of encountering the low-velocity airflow in the split section, the ice flake is subjected to negative aerodynamic force in the X-axis, and thus the velocity of the ice flake began to decrease again. Figure 17c,d shows that as the ice flake sheds, the lift and drag increase. When it enters the contraction section, the lift and drag begin to decrease. The positive value of the lift of the ice flake is in the Z-axis positive direction, and the positive value of the drag is in the X-axis positive direction. Figure 17e shows that the total pressure recovery coefficient of the AIP section is low when the ice flake is not shed and gradually increases after shedding.

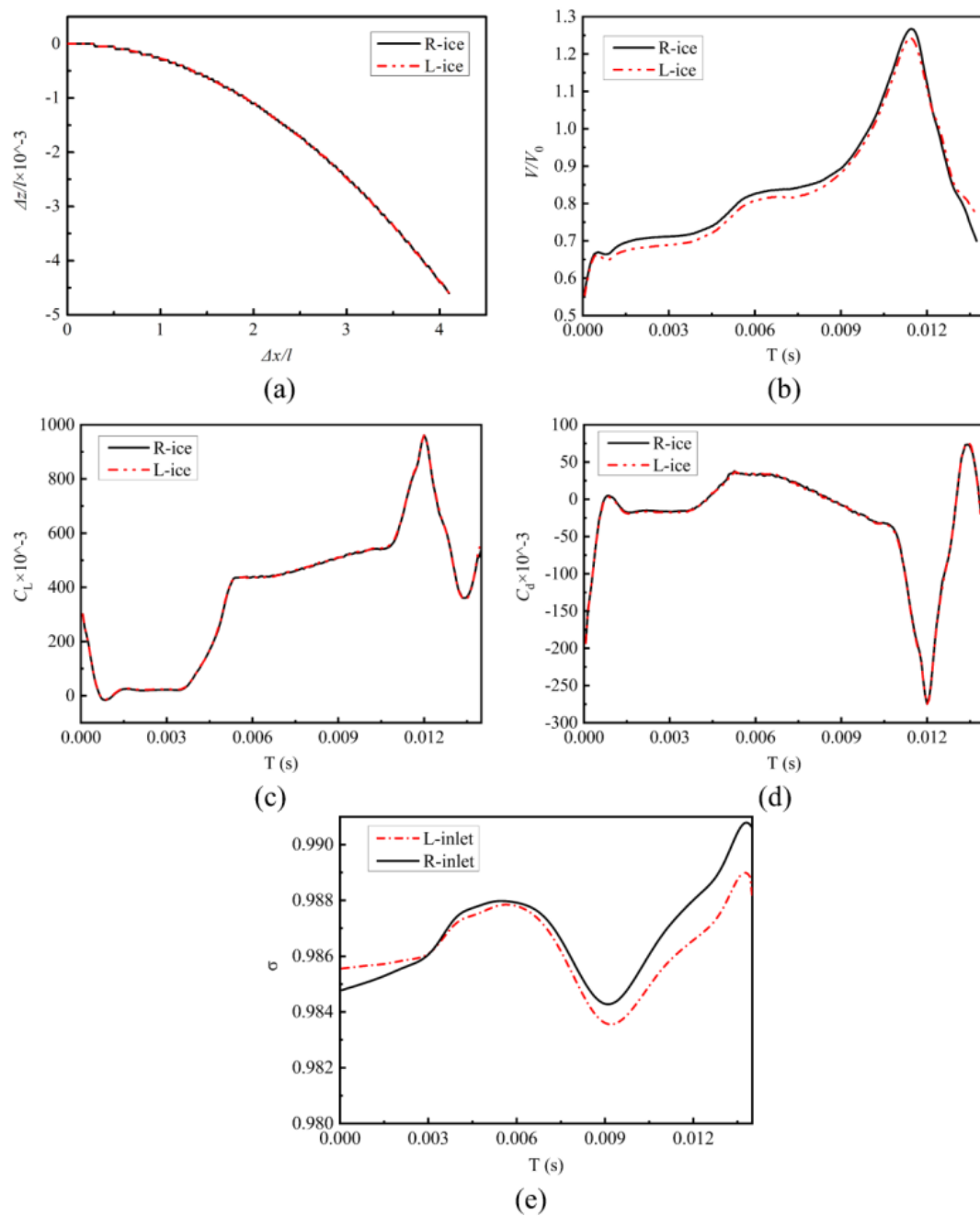


Figure 17. The movement characteristics of ice flake in the inlet and the variation of inlet performance: (a) the trajectory of ice flakes in the XZ plane, (b) the variation in the velocity of ice flakes during their movement, (c) the variation in the lift coefficient of ice flakes during their movement, (d) the variation in the drag coefficient of ice flakes during their movement and (e) the variation in the total pressure recovery coefficient during the movement of ice flakes.

3.3.2. Exclusion Characteristics of Ice Flake vs. Icing Positions

In order to study the effect of different icing positions on the exclusion characteristic of the ice flake, four icing positions were selected for the study in this paper, which were the upper, lower, inner, and outer lip positions of the inlet, and the angle between the ice flake and the lip wall was 30° , and the parameters of the flow field are shown in Table 5.

(1) Effect of different icing positions on the structure of the inlet flow field

Different icing positions have different effects on the flow field structure of the inlet. Figures 18 and 19a show the distribution of three-dimensional streamline velocity at the

entrance and interior of the left inlet for different positions of icing at $T = 0$ s, respectively. Figure 19a–c represent the distribution at $T = 0$ s, $T = 0.006$ s, and the moment of collision, respectively (Figures 20 and 21, are the same). It can be seen from Figures 18 and 19a that the ice flakes in all positions block the incoming flow. A large number of vortices are formed as the airflow passes through the ice flake. The streamlines spiral through the space and reattaches to the wall of the center body until the contraction section. And, then separation occurs again at the splitter and reattaches to the wall of the engine duct until it enters the engine duct again. The fluid flowing through the ice flake experiences the separation–reattachment–separation–reattachment process. As a result, the flow in the inlet becomes extremely complex due to the icing at the lip of the inlet.

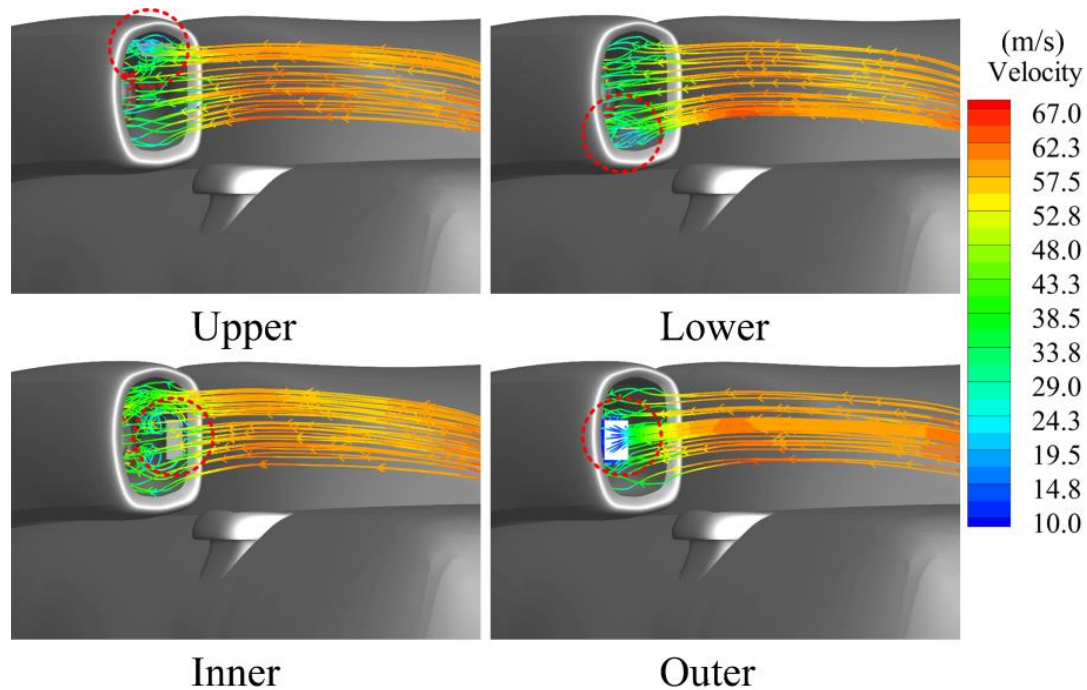


Figure 18. Distribution of three-dimensional streamlined velocity at the entrance of the left inlet for different positions of icing.

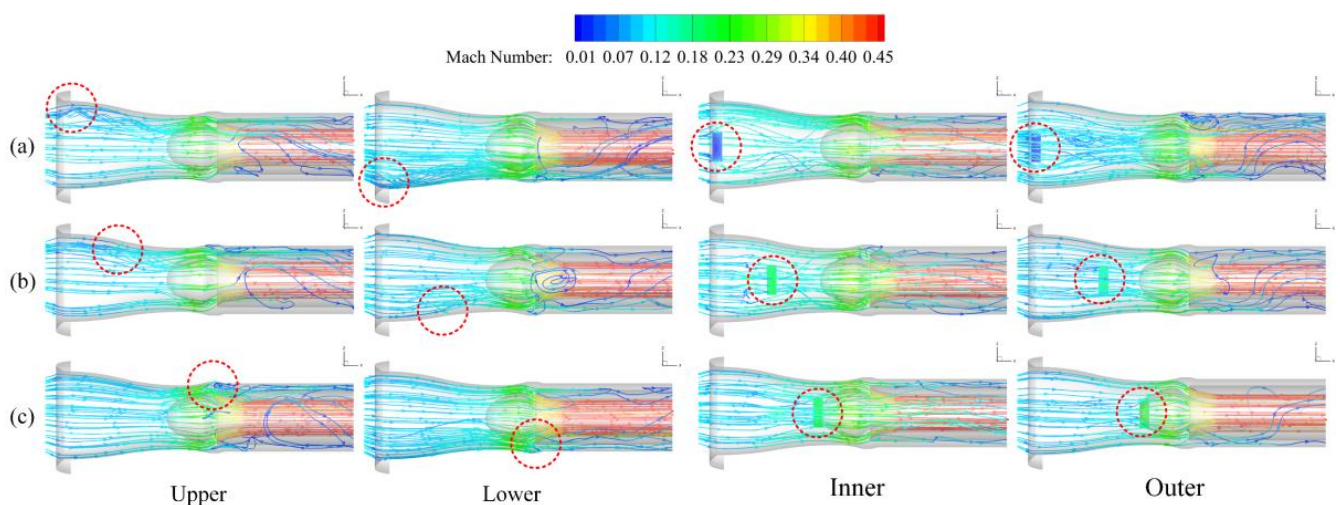


Figure 19. Distribution of three-dimensional streamline velocity at the interior of the left inlet for different positions of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

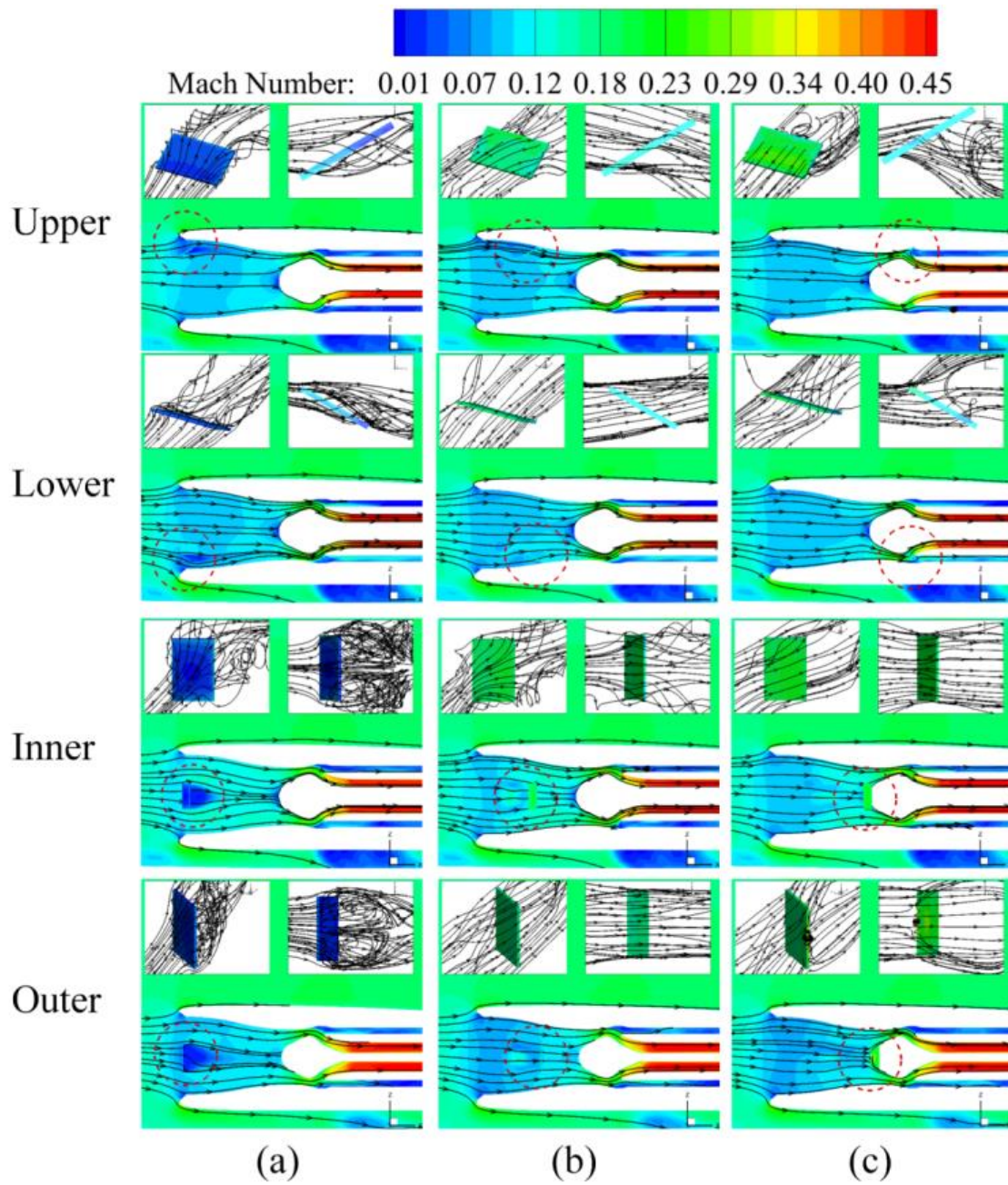


Figure 20. Distribution of velocity in the symmetry plane of the left inlet for different positions of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

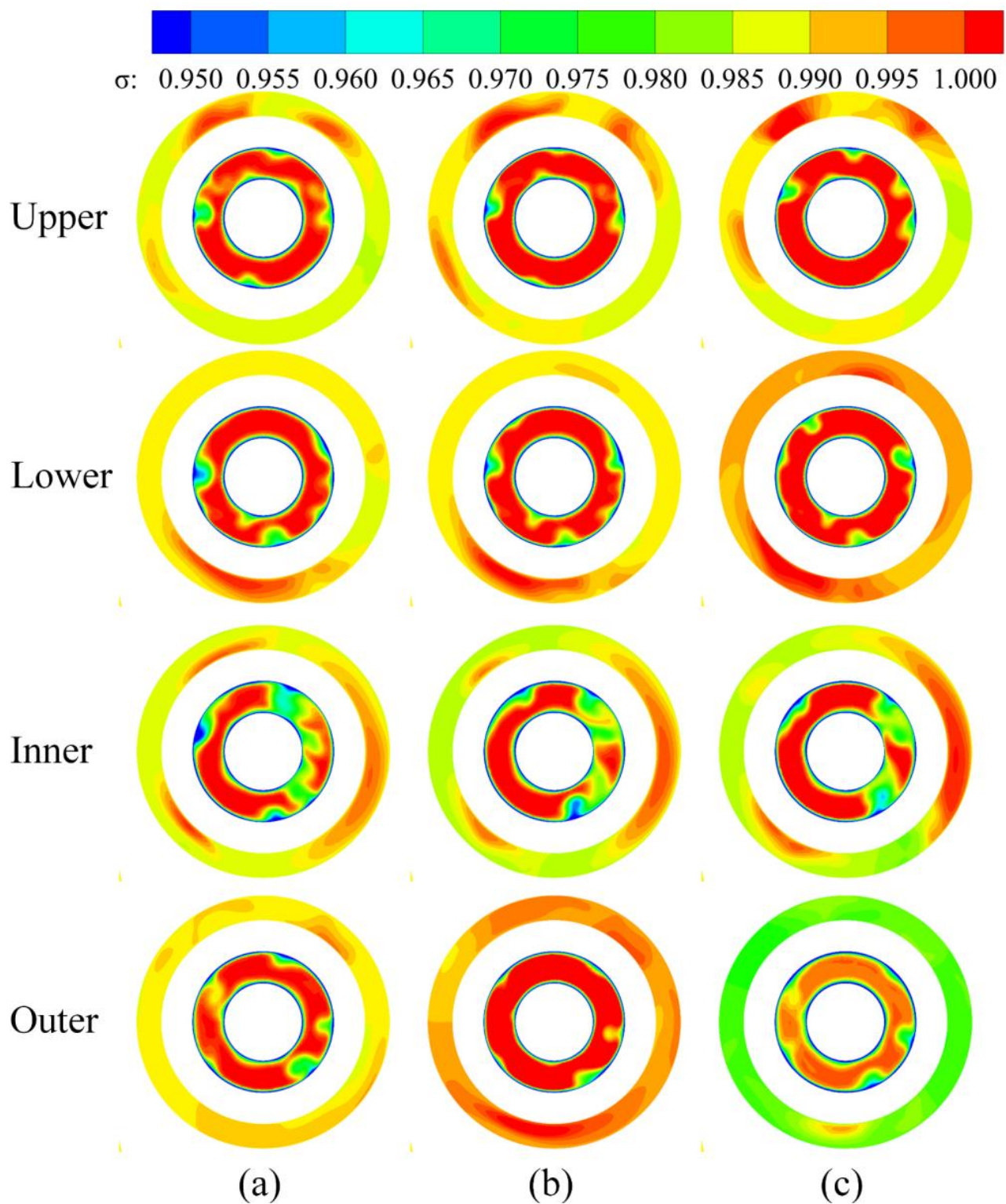


Figure 21. Total pressure recovery coefficient σ distribution of the left inlet AIP for different positions of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

Figure 20a shows the distribution of velocity in the symmetry plane of the inlet for different positions of icing at $T = 0$ s. Ice flakes in all four positions form low-pressure vortex regions on their leeward sides. The difference is that in the inner and outer walls, the low-pressure region is larger, and the velocity of flow is lower. However, the upper and lower walls with the lip form a triangle on the windward side, which forms a large

stagnation of the incoming velocity, so that a large stagnation zone of the airflow appears on the windward side. It is seen from the streamlines flowing through the ice flake that the vortices on both sides of the ice flake on the upper and lower wall are two spirals going downstream. And, a pair of large vortices on the leeward side are formed by the three-dimensional streamlines of the ice flakes on the inner and outer walls, resulting in a greatly enhanced swirl in the flow field.

Figure 21a and Table 9 show the distribution of the total pressure recovery coefficient and aerodynamic performance parameter of the inlet AIP section for different positions of icing at $T = 0$ s, respectively. Large areas of low total pressure are observed under all four positions, with the inner wall icing being the most severe. It can also be found in Table 9 that the total pressure recovery coefficient in the inner wall at $T = 0$ s is the lowest, and the total pressure distortion in the inner wall at $T = 0$ s is the largest. It indicates that the icing on the inner wall of the inlet causes severe flow loss and separation in the inlet. The icing on the outer wall of the inlet has the least effect on its aerodynamic performance, with the difference in total pressure recovery coefficient of 0.006 and total pressure distortion of 0.0652 between it and the worst inner wall icing. Consequently, it can be seen that icing at different positions has the greatest effect on the interior swirl structure of the inlet.

Table 9. Left Inlet performance for different positions of icing at different moments.

Case	Parameter	The Value of Parameter		
		$T_{0\text{ s}}$	$T_{0.006\text{ s}}$	$T_{\text{collision}}$
Upper	σ	0.9839	0.9875	0.9870
	DC60	0.0295	0.0271	0.0294
Lower	σ	0.9836	0.9862	0.9868
	DC60	0.0377	0.0257	0.0264
Inner	σ	0.9785	0.9798	0.9869
	DC60	0.0903	0.0631	0.0561
Outer	σ	0.9845	0.9862	0.9848
	DC60	0.0251	0.0210	0.0141

(2) Effect of different icing positions on the exclusion characteristics of the ice flake

Icing at different positions also has a significant effect on the exclusion characteristics of the ice flakes. Figure 19 shows the distribution of three-dimensional streamline velocity at the interior of the left inlet for different positions of icing at different moments. It can be seen that as the ice flakes are shed, the ice flakes on the upper and lower walls collide and shatter with the wall surface of the outer cover in the split section, and eventually most of them flow into the bypass duct to be excluded. The ice flakes on the inner and outer walls collide with the center body and break up, and part of the broken ice flakes go into the engine duct and part into the bypass duct. It is also seen from Figure 20 that as the ice flakes enter the downstream of the inlet, the flow field structure at the lip of the inlet is restored. The ice flakes interact with the airflow during their movement in the flow field of the inlet, the degree of deflection of the streamlines reduces and the bypassing flow reduces. However, the ice flake on the inner wall still has airflow bypassing on both sides of the ice flake during the process of shedding, forming a three-dimensional vortex structure spreading downstream. Furthermore, when the ice flake collides with the wall, the ice flakes of different positions form the vortex with different scales downstream of the ice flakes. Since the collision position and separation position of the upper and lower wall ice flakes are at the bypass duct, they are able to share part of the loss of the engine duct. The collision position and separation position of the inner and outer wall ice flakes are at the engine duct, which causes greater performance loss and structural damage to the engine duct.

Figure 21 shows the total pressure recovery coefficient σ distribution of the left inlet AIP for different positions of icing at different moments. It can be seen that the total pressure

recovery coefficients at all moments are poor, and there is a large low total pressure area. However, as the flow rate at the entrance of the inlet increases after the ice flake sheds, the total pressure recovery coefficient of the AIP section increases, and the low total pressure area decreases. When the ice flakes on the outer wall collide with the wall, the airflow distortion generated by the collision results in the overall decrease in the total pressure recovery coefficient of the inlet AIP. As can be seen in Table 9, the total pressure recovery coefficient of the AIP section in the inlet increases by 0.0031 and 0.0084 as the ice flakes shed on the lower and inner walls, respectively. The total pressure recovery coefficient of the AIP section in the inlet increases and then decreases as the ice flakes shed on the upper and outer walls. The total pressure distortion of the AIP section in the inlet decreases and then increases as the ice flakes shed on the upper and lower walls. The total pressure distortion of the AIP section in the inlet decreases by 0.0342 as the inner ice flake goes from shedding to collision. The total pressure distortion of the AIP section in the inlet decreases by 0.0342 and 0.011 as the inner and outer ice flakes go from shedding to collision, respectively.

Figure 22 shows the characteristics of ice flake movement in the inlet for different positions of icing and the variation of inlet performance parameters. From Figure 22a, it can be seen that the trajectories of the ice flakes at the four positions are still in the shape of a parabola, only the final impact positions are different. In a comparison of the velocity of the ice flake in Figure 22b, it can be seen that the velocity characteristics of the ice flake on the upper and lower wall are basically the same, and the velocity of the ice flake on the inner wall is the same as the velocity trend of the ice flake on the upper and lower wall. The difference is that the ice flakes on the upper and lower walls have greater velocity during their movement and impact earlier on the wall of the center body. The reason for their greater velocity is that they are located in the center of the inlet vertical position, where there is no low-speed bypass area of the upper or lower lip, and the airflow velocity is slightly greater than that at the upper or lower lip, thus resulting in faster velocity recovery and greater velocity during the movement. From Figure 22c, the variation in the lift of the ice flakes on the inner and outer walls is small, while the variation in lift on the upper and lower walls is large. This is because the contact area between the ice flakes on the upper and lower wall surfaces and the airflow in the vertical direction is large, and thus the ice flakes are subjected to the greater force in the direction of the lift. In Figure 22d, due to the earlier collision of the ice flake on the inner wall, it is basically the same as the drag curve of the ice flake on the outer wall, as seen through its drag change. Ice flake on the inner wall is subject to the drag of the airflow in the front section of the inlet and is pushed by the high-speed airflow when it enters the contraction section. Ice flakes on the upper and lower walls are subject to basically the same drag from the airflow in the front section of the inlet. After they enter the contraction section they are pushed by the airflow, and as they enter the split section the pushing force starts to decrease. Figure 22e the total pressure recovery coefficient of the inlet increases after the ice flakes are shed.

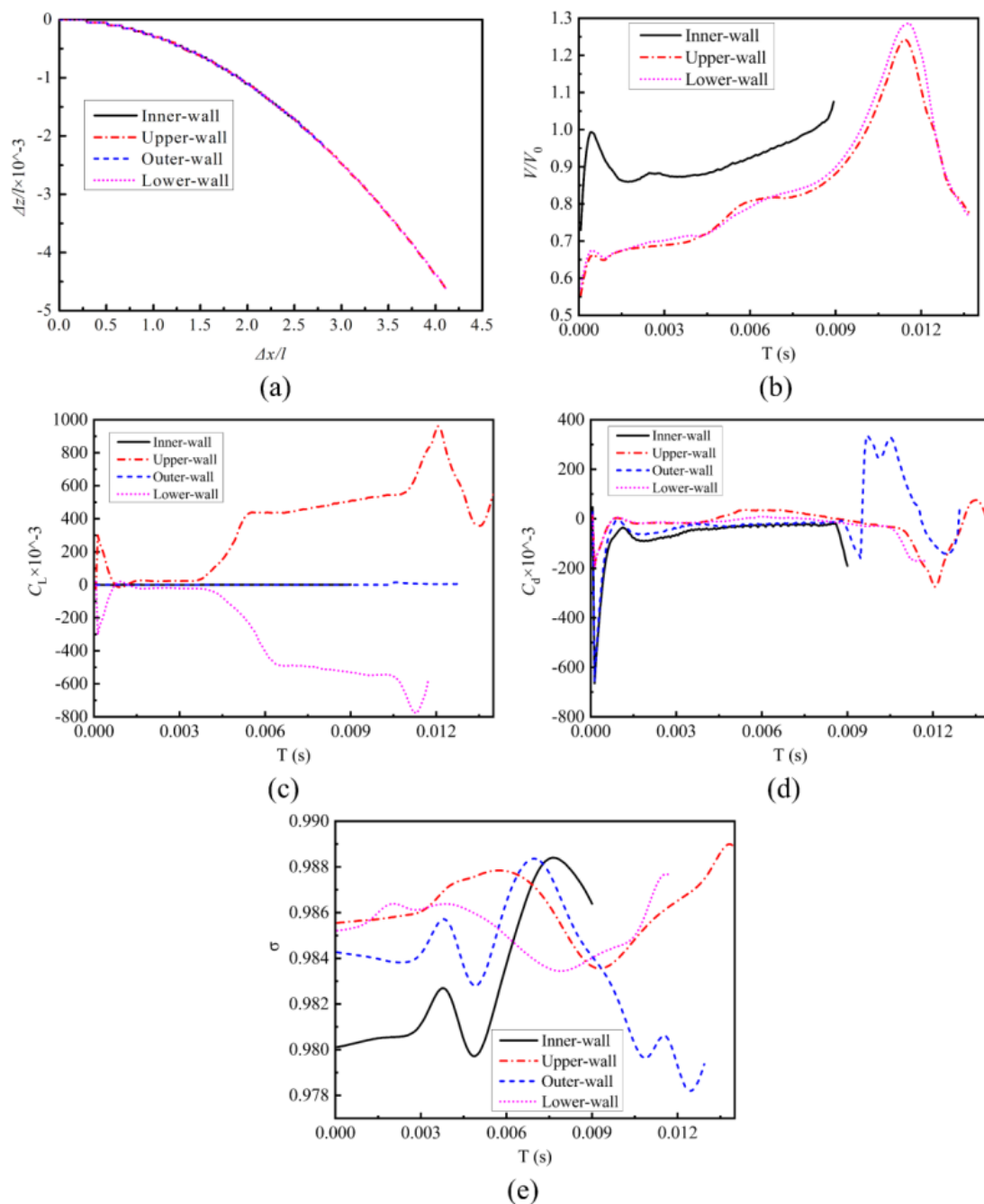


Figure 22. The movement characteristics of ice flake at different icing position in the left inlet and the variation of inlet performance: (a) the trajectory of ice flakes in the XZ plane, (b) the variation in the velocity of ice flakes during their movement, (c) the variation in the lift coefficient of ice flakes during their movement, (d) the variation in the drag coefficient of ice flakes during their movement and (e) the variation in the total pressure recovery coefficient during the movement of ice flakes.

3.3.3. Exclusion Characteristics of Ice Flake vs. Icing Angle

Due to the different angles of icing at the lip of the inlet, it will affect the airflow distribution at the entrance of the inlet. Therefore, the effect of different angles of icing on the lower wall of the inlet on the exclusion characteristics of ice flake in the inlet is investigated in this paper. The angle between the ice flake and the incoming flow is 30° and 150° , respectively, and the parameters of the flow field are shown in Table 5.

(1) Effect of different icing angles on the structure of the inlet flow field

Different icing angles have different effects on the flow field structure of the inlet. Figure 23 shows the distribution of three-dimensional streamline velocity at the entrance of the inlet for different angles of icing. Figure 24a–c represent the distribution at $T = 0$ s, $T = 0.006$ s, and the moment of collision, respectively (Figures 25 and 26, are the same). It can be seen that the ice flake with an angle of 30° forms a large amount of low-velocity fluid on the lower side of the ice flake, the ice flake with an angle of 150° forms a large amount of low-velocity fluid on the upper side of the ice flake. This is because the incoming flow impacts the ice flake and the velocity of the flow stagnates, creating a high-pressure area. It is also seen from Figure 24a that when the angle of the ice flake is 30° , the vortex of the airflow on the lower wall of the inlet is greater, and the streamlines spiraling downstream have already affected the flow in the constriction section. When the angle of the ice flake is 150° , the degree of disturbance to the airflow on the lower wall is smaller, and its disturbance of the wake has begun to disappear in the constriction section.

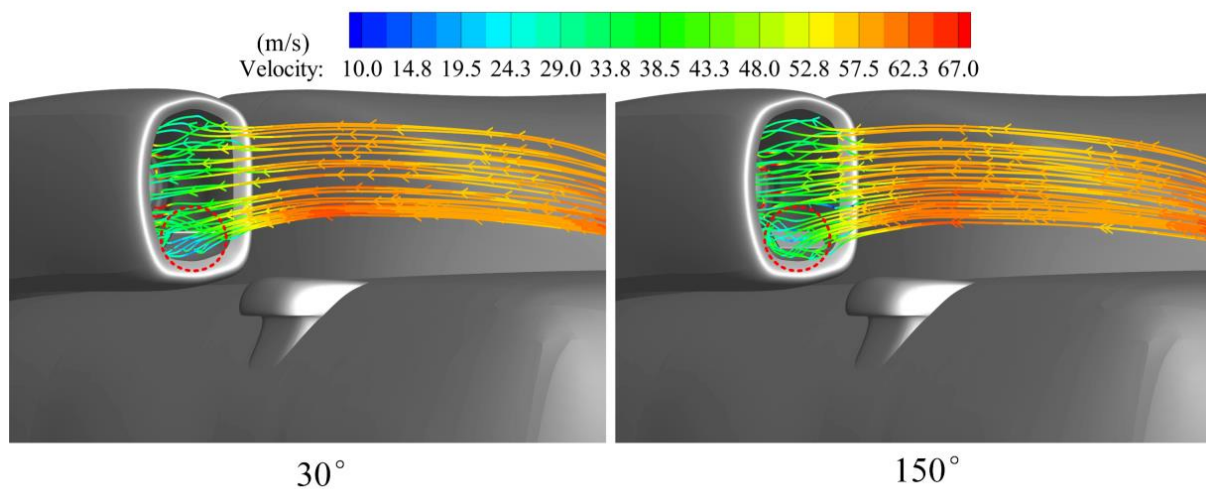


Figure 23. Distribution of three-dimensional streamline velocity at the entrance of the left inlet for different angles of icing.

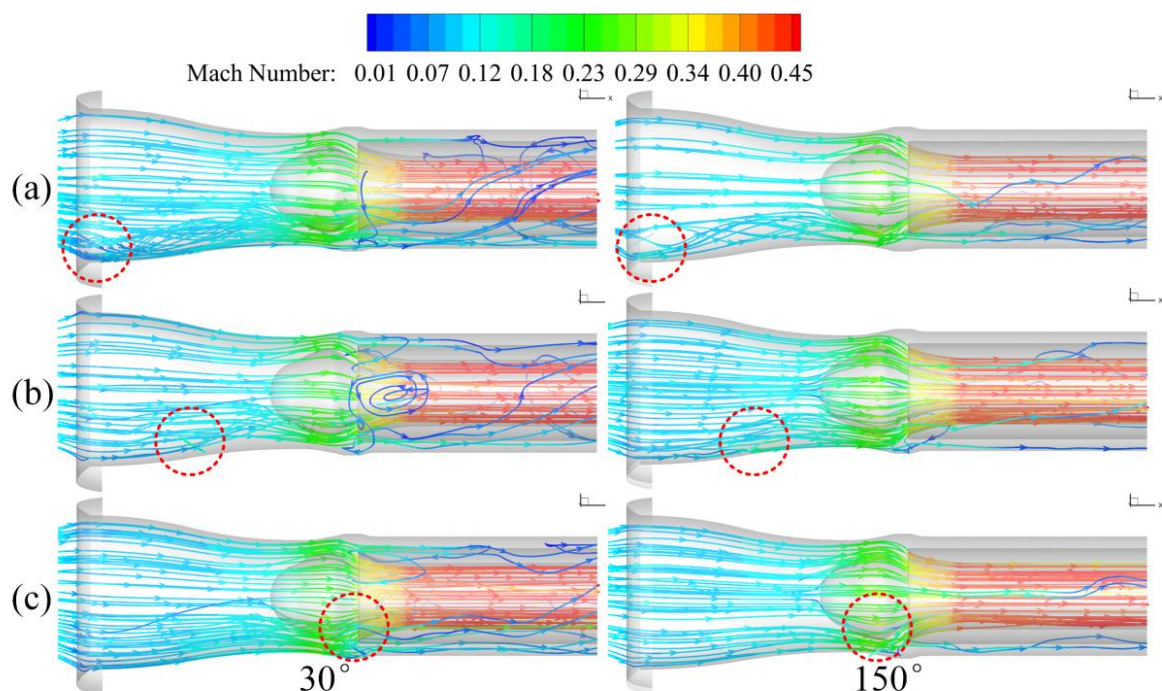


Figure 24. Distribution of three-dimensional streamline velocity at the interior of the left inlet for different angles of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

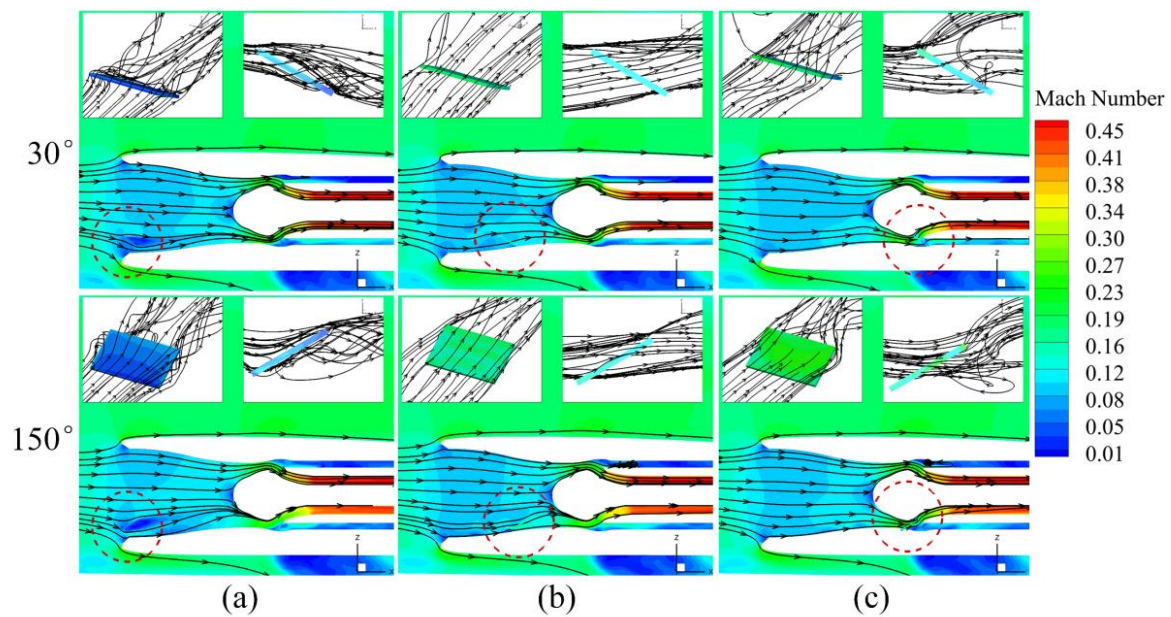


Figure 25. Distribution of velocity in the symmetry plane of the left inlet for different angles of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

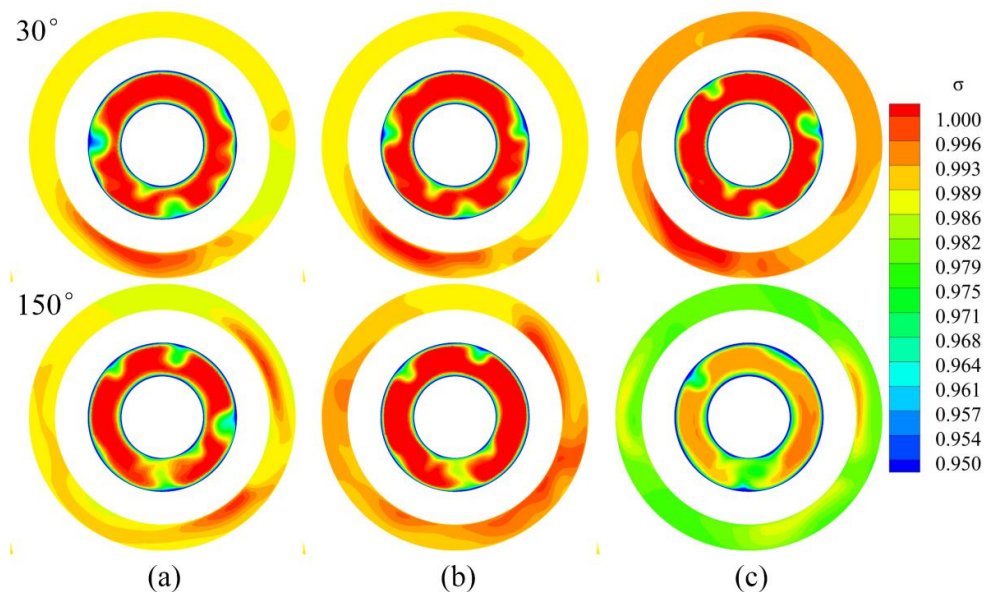


Figure 26. Total pressure recovery coefficient σ distribution of the left inlet AIP for different angles of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

Figure 25a shows the distribution of velocity in the symmetry plane of the left inlet for different angles of icing at $T = 0$ s. When the angle of the ice flake is 30° , the incoming flow forms a triangular stagnation area between the ice flake and the lower lip. When the angle of the ice flake is 150° , the low-pressure area formed on the front side of the ice flake is smaller, but a larger low-energy vortex area is formed on the back of the ice flake. It can be seen from the streamlines that when the angle of the ice flake is 30° the fluid separates at the ice flake and flows along the lower wall into the split section and finally into the engine duct, and when the angle of the ice flake is 150° the fluid separates at the ice flake and the flow has a larger angle to reattach to the wall of the center body at the beginning of the constriction section.

Figure 26a shows the total pressure recovery coefficient σ distribution of the left inlet AIP for different angles of icing at $T = 0$ s. It can be found that a large number of low total pressure areas are present in both cases, whereas a large area of lowest total pressure is formed

on the left side of the AIP section when the angle of the ice flake is 30° . As shown in Table 10, when the angle of the ice flake is 30° at $T = 0$ s the total pressure recovery coefficient of the AIP section is low, and the total pressure distortion is large. This is caused by the increase of low-energy fluid on the windward side when the angle of the ice flake is 30° and the direct spreading of its bypass disturbance into the engine duct.

Table 10. Left inlet performance for different angles of icing at different moments.

Case	Parameter	The Value of Parameter		
		T_0 s	$T_{0.006}$ s	$T_{\text{collision}}$
30°	σ	0.9836	0.9862	0.9868
	DC60	0.0377	0.0257	0.0264
150°	σ	0.9851	0.9872	0.9828
	DC60	0.0223	0.0254	0.0262

(2) Effect of different icing angles on the exclusion characteristics of the ice flake

Icing at different angles also has a significant effect on the exclusion characteristics of the ice flakes. Figure 24 shows the Distribution of three-dimensional streamline velocity at the interior of the left inlet for different angles of icing at different moments. As the ice flake shedding moves downstream, the flow field at the entrance of the inlet gradually recovers and the ice flake bypassing flow decreases. Eventually, it collides with the wall at the split section. When the angle of the ice flake is 30° , ice collides on the split section near the side of the bypass duct. Most of it enters the scavenging runner after breaking, which is less threatening to the engine. When the angle of the ice flake is 150° , the ice flake collides on the split section in the position direction parallel to the flow direction of the engine duct in the inlet. After colliding and breaking on the splitter, a large amount of ice flake debris enters the engine duct, threatening the engine's operation. It can be seen from Figure 25 that the flow field is different at different moments of the movement that the ice flakes with different icing angles shed in the flow field of the inlet. It is mainly reflected in the following: at first, when the angle of the ice flake is 30° at $T = 0.006$ s, the airflow forms the separation at the lower wall of the inlet and the streamlines are deflected to flow towards the wall of the center body to reattach. What's more, when the angle of the ice flake is 150° , the ice flake collides on the side of the bypass duct, creating a vortex in the bypass duct. The streamlines flowing into the engine duct on the leeward side of the ice flake do not bend, but the ice flake forms the block to both sides of the ducts. When the angle of the ice flake is 30° , the ice flake collides on the interface between the engine duct and the split section. It forms a large area blocking the flow rate of the engine duct. And, the back side of the ice flake forms a vortex, and finally, this part of the streamline goes into the engine duct.

Figure 26 shows the total pressure recovery coefficient σ distribution of the left inlet AIP for different angles of icing at different moments. It is seen that the lowest total pressure of the AIP section with a 30° angle of the ice flake increases with the ice flake shedding, and the low total pressure area decreases. The low total pressure area of the AIP section with 150° angle of the ice flake decreases with the ice flake shedding from 0 s to 0.006 s, the overall total pressure of the AIP section decreases at the moment of collision and the inlet performance is greatly decreased. Furthermore, from Table 10, the total pressure recovery coefficient of the AIP section from shedding to collision increases by 0.0032 for a 30° angle of ice flakes, the total pressure distortion first decreases and then increases by 0.012, with a maximum difference of 0.012. The total pressure recovery coefficient of the AIP section from shedding to collision increases by 0.0021 and then decreases by 0.0044 for a 30° angle of ice flakes, and the total pressure distortion increases by 0.0039. This difference is caused by the different collision positions of the ice flakes in the interior of the inlet. In summary, when the icing on the lower lip of the inlet at 150° does not shed, it has a small impact on inlet performance. But as the ice flake shed, it produces a greater threat to the safety of the engine operation downstream.

Figure 27 shows the characteristics of ice flake movement in the inlet for different angles of icing and the variation of inlet performance parameters. From Figure 27a, the trajectories

of the two different angles of ice flake shedding are parabolic, while the 30° ice flake moves a longer distance in the x-direction and enters into the bypass duct to collide and break up. Figure 27b shows that the trend of velocity variation is consistent for both, the velocity recovery of the 150° angle of the ice flake is faster and the velocity is larger. This is because the angle between the ice flake in the front part of the inlet and the low-speed airflow in the inlet in the direction of flow is the acute angle. Thus, it is subjected to low drag, and velocity recovery is fast. Figure 27c,d show that the lift and drag of the 150° ice flake are higher and its lift variation is slightly slower in the interior of the inlet. Figure 27e illustrates the variation of the total pressure recovery coefficient of the AIP section, which first decreases and then increases for the 30° ice flake, first increases and then decreases for the 150° ice flake.

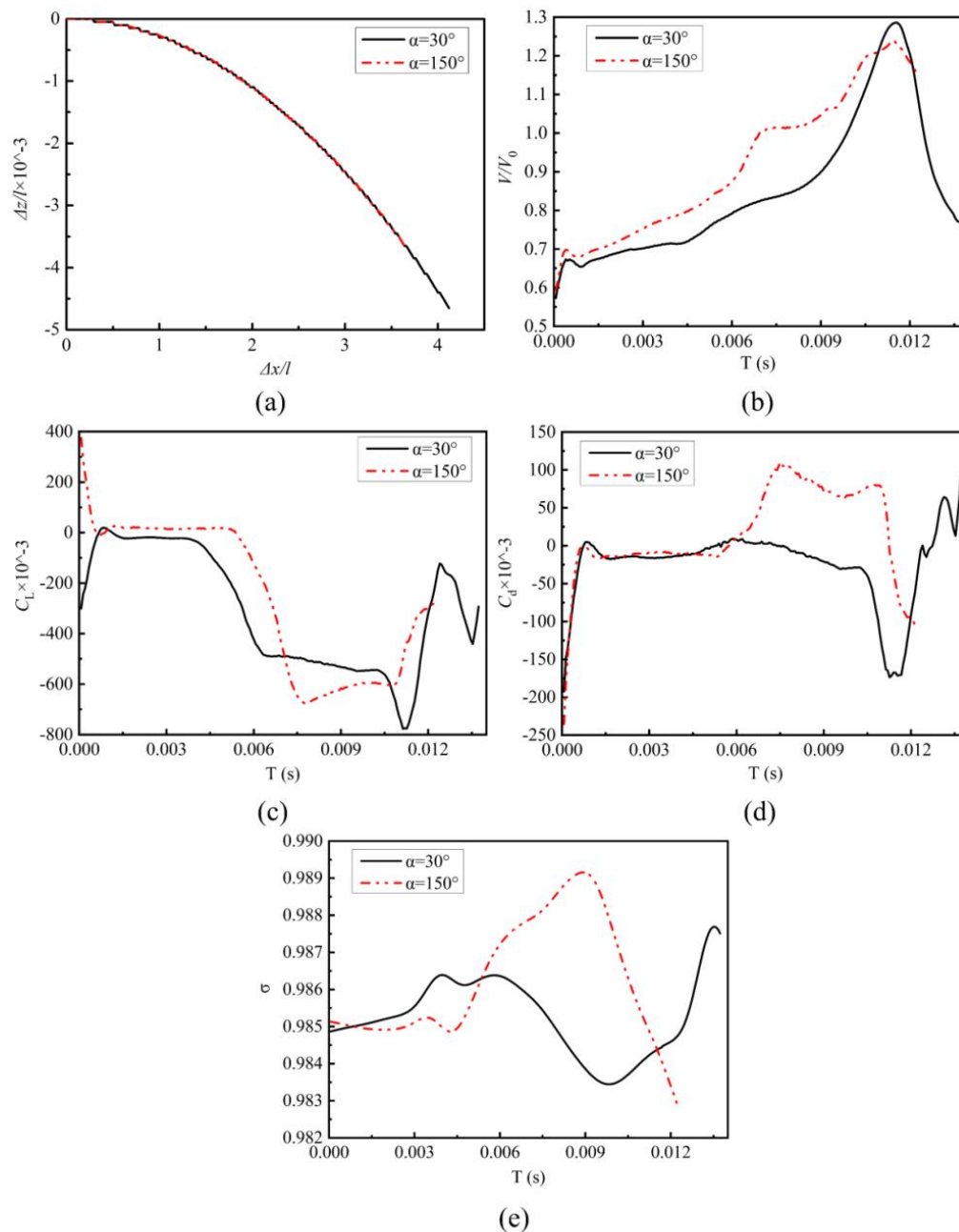


Figure 27. The movement characteristics of ice flake at different icing angles in the left inlet and the variation of inlet performance: (a) the trajectory of ice flakes in the XZ plane, (b) the variation in the velocity of ice flakes during their movement, (c) the variation in the lift coefficient of ice flakes during their movement, (d) the variation in the drag coefficient of ice flakes during their movement and (e) the variation in the total pressure recovery coefficient during the movement of ice flakes.

3.3.4. Exclusion Characteristics of Ice Flake vs. AIP Mach Number

Under the premise of other flow parameters being unchanged, the outlet back pressure of the engine duct is reduced to study the exclusion characteristics of the ice flakes on the upper lip under the three conditions of the engine duct outlet Mach number ($Ma = 0.3, 0.45$, and 0.6).

(1) Effect of different AIP Mach numbers on the structure of the inlet flow field

Different AIP Mach numbers have different effects on the flow field structure of the inlet. Figure 28a–c represent the distribution at $T = 0$ s, $T = 0.006$ s, and the moment of collision, respectively (Figure 29a–c are the same). Figure 28a shows the distribution of velocity in the symmetry plane of the left inlet for different AIP Mach numbers at $T = 0$ s. It can be seen that as the AIP Mach number increases, the low-pressure vortex area on the leeward side of the ice flake increases, the turn of the airflow on the ice flake becomes steeper, and the spiraling streamlines on both sides of the ice flake extend downstream. In addition, at 0.3 Ma, the separation area on the leeward side of the ice flake is large, and the airflow velocity is low. The streamlines separate at the upper and lower walls of the ice flake, only to converge downstream. Figure 29a shows the total pressure recovery coefficient σ distribution of the left inlet AIP for different AIP Mach numbers at $T = 0$ s. It is seen that as the AIP Mach number increases, the low total pressure area of the AIP section increases, and the minimum total pressure decreases. Combined with Table 11, when the ice flake is at $T = 0$ s, with the increasing of Mach number, the total pressure recovery coefficient decreases, and the total pressure distortion first decreases and then increases. At 0.6 Ma, the total pressure recovery coefficient decreases by 0.0181 , and the total pressure distortion increases by 0.018 .

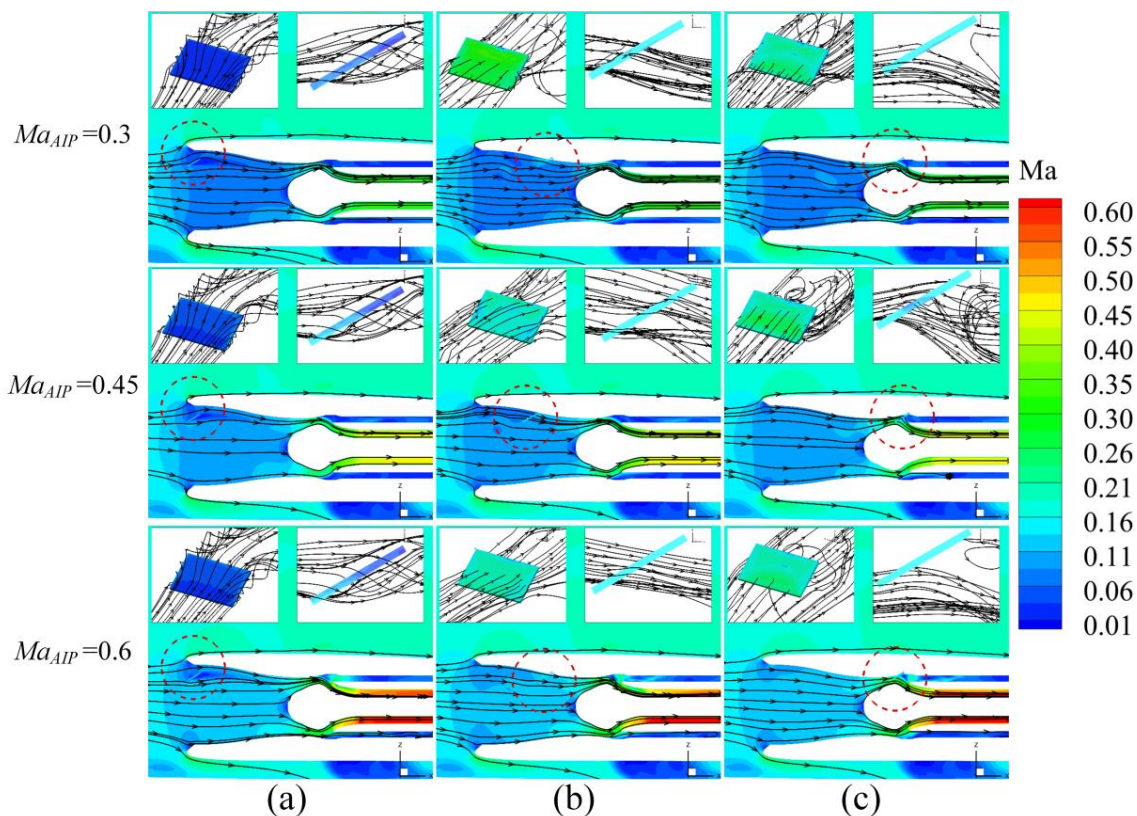
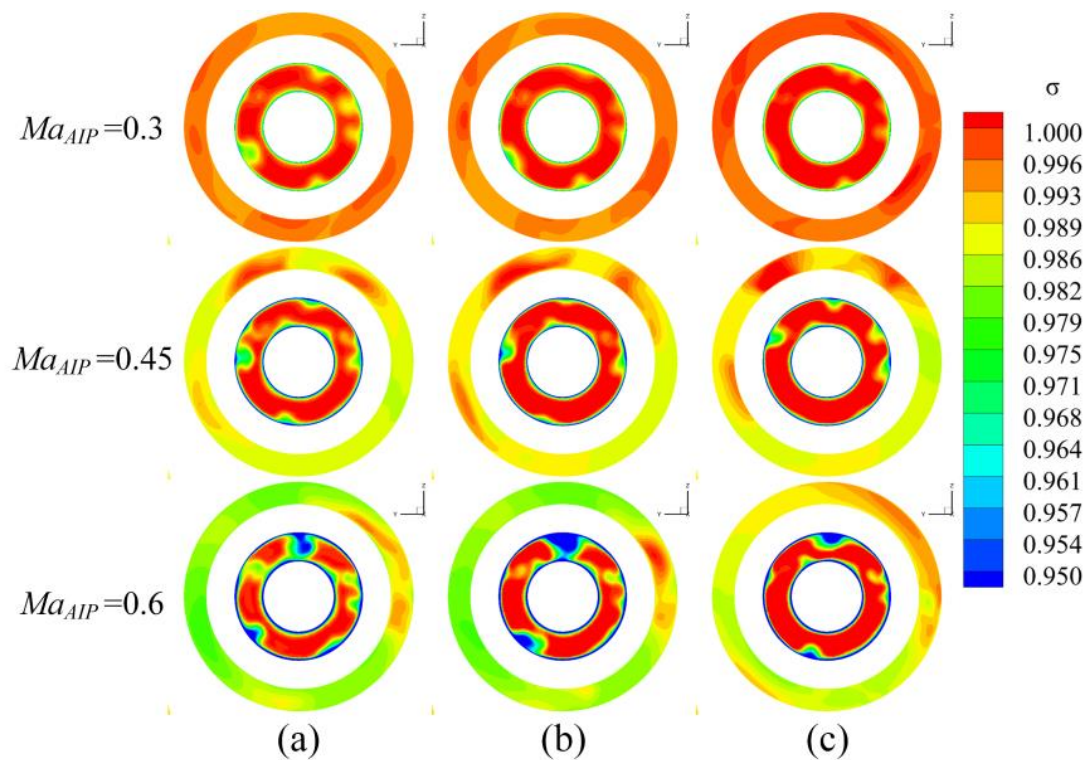


Figure 28. Distribution of velocity in the symmetry plane of the left inlet for different AIP Mach numbers of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

Table 11. Left Inlet performance for different AIP Mach numbers of icing at different moments.

Case	Parameter	The VALUE of Parameter		
		T_0 s	$T_{0.006}$ s	$T_{\text{collision}}$
$M_{\text{exi}} = 0.3$	σ	0.9918	0.9933	0.9924
	DC60	0.0424	0.0246	0.0256
$M_{\text{exi}} = 0.45$	σ	0.9839	0.9875	0.9870
	DC60	0.0295	0.0271	0.0294
$M_{\text{exi}} = 0.6$	σ	0.9737	0.9739	0.9771
	DC60	0.0475	0.0910	0.1546

**Figure 29.** Total pressure recovery coefficient σ distribution of the left inlet AIP for different AIP Mach numbers of icing at (a) $T = 0$ s, (b) $T = 0.006$ s and (c) the moment of collision.

(2) Effect of different AIP Mach numbers on the exclusion characteristics of the ice flake

Different AIP Mach number also has a significant effect on the exclusion characteristics of the ice flakes. Figure 28 shows the distribution of velocity in the symmetry plane of the left inlet for different AIP Mach numbers at different moments. As the ice flake shedding moves downstream, the separated flow field at the entrance of the inlet is gradually recovered. However, the recovery of the flow field at the inlet of the 0.6 Ma condition is slower. This is due to the increase of flow velocity at the outlet of the engine duct, the velocity at the entrance surface of the inlet also increases, and the low-energy fluid formed in the low-pressure vortex area of the ice flake has a larger difference in velocity with respect to the fluid in the surrounding flow field. Therefore, the low-pressure area is slower to recover after the ice flakes shed. The ice flake moves in a parabolic motion along the upper wall of the inlet and eventually collides with the outer wall at the split section. The collision position of the ice flake blocks the airflow into the engine duct and a large vortex could be seen to form on the leeward side of the ice flake as the airflow moves. Combined Figure 29 and Table 11, it can be seen that during the downstream movement of ice flakes, the total pressure recovery coefficient for the 0.3 Ma condition first increases by 0.15% and then decreases by 0.09%, and the total pressure distortion first decreases by 0.0178 and then increases by 0.001. The total pressure recovery coefficient for the 0.45 Ma condition increases by 0.37% and then decreases by 0.05%, and the

total pressure distortion decreases by 0.0024 and then increases by 0.0023. The total pressure recovery coefficient for the 0.6 Ma condition increases by 0.35% and the total pressure distortion increases by 0.1071. It indicates that the airflow distortion at a high AIP Mach number is most affected by the movement of the ice flakes in the interior of the inlet. In other words, the degree of airflow disturbance in the high-velocity flow inlet increases, and the airflow circumferential pulsation increases. Figure 30 shows the characteristics of ice flake movement in the inlet for different AIP Mach numbers and the variation of inlet performance parameters. It can be seen that the trajectory of the ice flake is less affected by the AIP Mach number. As the AIP Mach number increases, the velocity of the airflow in the interior of the inlet increases, the ice flakes move with greater velocity in the interior of the inlet, and the lift of the ice flakes decreases (force in the z-direction), and the drag increases (force in the x-direction).

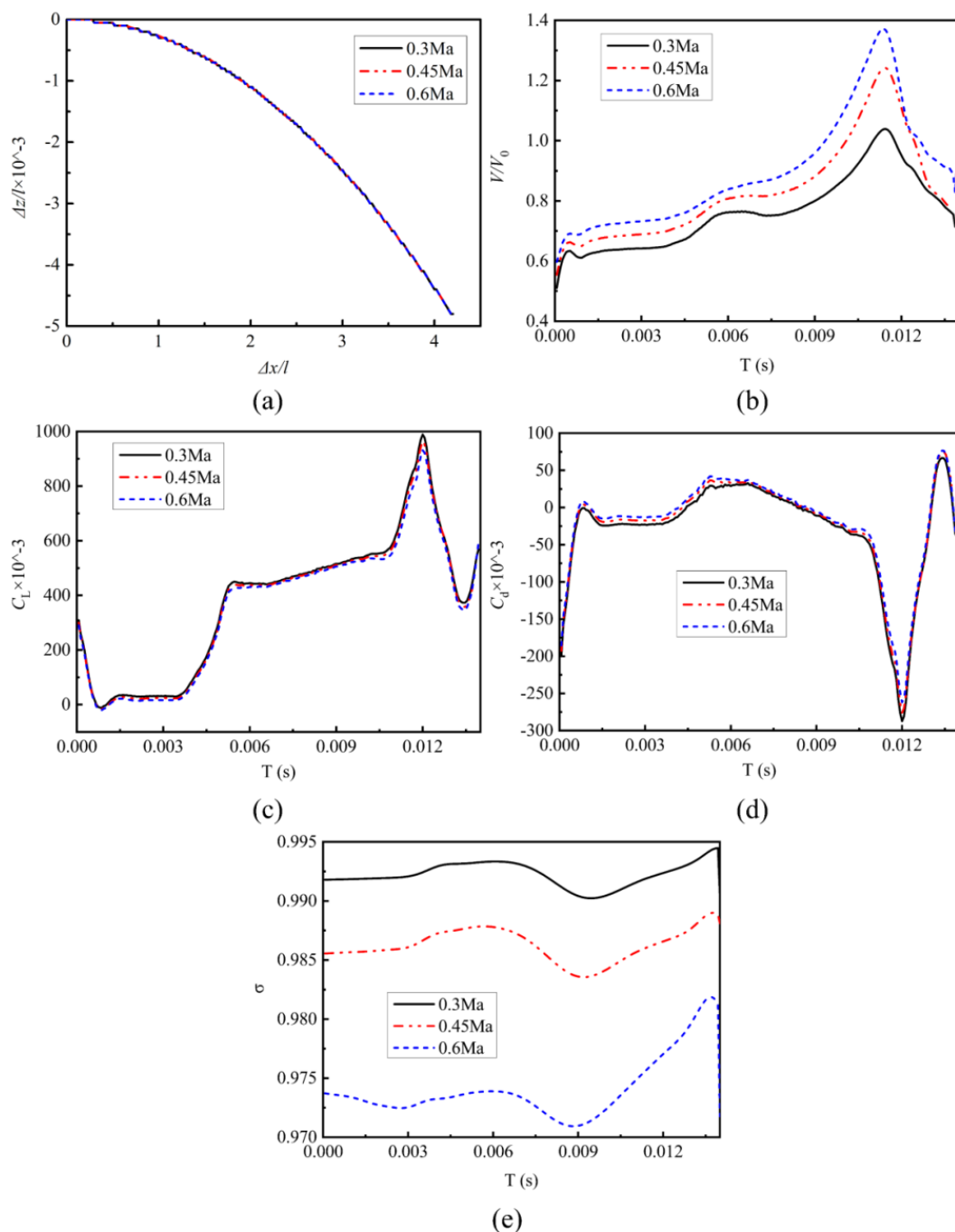


Figure 30. The movement characteristics of ice flake at different AIP Mach number in the left inlet and the variation of inlet performance: (a) the trajectory of ice flakes in the XZ plane, (b) the variation

in the velocity of ice flakes during their movement, (c) the variation in the lift coefficient of ice flakes during their movement, (d) the variation in the drag coefficient of ice flakes during their movement and (e) the variation in the total pressure recovery coefficient during the movement of ice flakes.

4. Conclusions

In this paper, the influences of different parameters on the exclusion characteristics of hailstone and ice flake, as well as the influences of hailstone and ice flake on the aerodynamic performance of the inlet, are investigated by numerical simulation. The inlet aerodynamic performance of the total pressure recovery coefficient and total pressure distortion index are concerned. The effects of various factors, including icing position, icing angle, and AIP Mach number, have been carefully investigated. The following conclusions can be drawn from the above results.

- (1) After entering the inlet, the hailstones eventually impacted the lower wall and broke up. Inhalation of hailstone in the inlet decreases total pressure distortion by about 20%, and the total pressure recovery coefficient is essentially unchanged.
- (2) When icing on the upper lip, the total pressure distortion of the inlet is decreased by about 22%, and the total pressure recovery coefficient is decreased by about 0.6%. After the ice flake sheds, it impacts the outer wall in the split section breaks up, and is eventually excluded from the bypass duct. The total pressure recovery coefficient of the inlet increases, and the distortion index decreases during the movement of the ice flakes.
- (3) Icing on the outer lip has the least impact on the performance of the inlet, and the performance of the inlet is worse when icing on the inner lip. Compared to icing on the inner lip, the total pressure recovery coefficient is 0.006 higher and the total pressure distortion index is 0.0652 lower when icing on the outer lip. The ice flakes shedding from the inner and outer lip impacted the center body and broke which will cause damage to the engine duct. The ice flakes shedding from the upper and lower lip eventually excluded from the bypass duct.
- (4) The lower lip icing angle of 30° has a greater effect on the aerodynamic performance of the inlet than 150° , with the total pressure recovery coefficient decreasing by 0.15% and the total pressure distortion index increasing by 70%. As the ice flake shed, ice flake at an angle of 150° to the lower lip can result in a large amount of ice flake debris entering the engine duct, threatening the performance and structure of the engine in the rear. Ice flake at an angle of 30° to the lower lip shedding from the lip eventually excluded from the bypass duct.
- (5) As the AIP Mach number increases, the total pressure recovery coefficient decreases, the velocity of the airflow in the interior of the inlet increases, the ice flakes move with greater velocity in the interior of the inlet, and the lift of the ice flakes decreases and the drag increases. In addition, the airflow distortion at a high AIP Mach number is most affected by the movement of the ice flakes in the interior of the inlet.

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