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Experimental Study on Heat Transfer Performance of Combined Channel-film Flow Control for Critical Regions of Hypersonic Vehicles

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Abstract

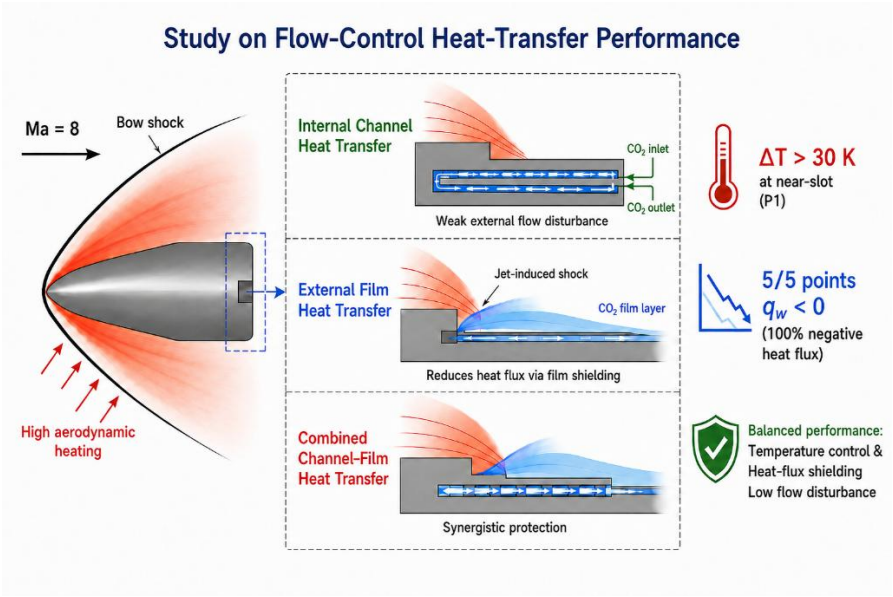
To address thermal protection of critical regions of hypersonic vehicle under strong shock waves, intense compression, and high heat-flux environments, this study employs supercritical pressure carbon dioxide as the heat-transfer medium and experimentally investigates three active thermal protection approaches: internal channel heat transfer, external film heat transfer, and combined channel-film heat transfer. Experiments are conducted in a 1.0 m diameter hypersonic wind tunnel at Mach number 8. The angles of attack are 0°, 10°, and 20°, and the carbon dioxide jet mass flow rate is approximately 120 g/s. Schlieren visualization is used to observe the bow shock, jet-induced shock, boundary-layer separation, and film coverage near the injection slot, while wall temperature-rise and heat-flux responses are analyzed. Results show that internal channel heat transfer causes weak disturbance to the external hypersonic mainstream and provides good overall wall heat-transfer capability, but has limited ability to suppress external aerodynamic heat input. External film heat transfer forms a low-temperature protective layer near the wall and effectively reduces wall heat flux, although its temperature-control effect attenuates downstream. Combined channel-film heat transfer integrates internal cooling and external film insulation, exhibiting superior comprehensive thermal protection in the near-slot region and sustained heat-flux suppression. Overall, this combined approach achieves a favorable balance among wall temperature control, heat-flux shielding, and external-flow disturbance control.

Keywords: Supercritical pressure carbon dioxide; Aerodynamic interference; heat transfer; Hypersonic flow.

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35 **Graphical Abstracts**



Graphical Abstracts

1. Introduction

Hypersonic vehicles ($Ma \geq 5$) have become an important development direction in the aerospace field owing to their rapid response capability and strong penetration performance. However, during reentry, cruise, and maneuvering flight, critical regions such as the nose, leading edges, control surfaces, inlet lips, and warhead walls are usually exposed to environments characterized by strong shock waves, intense compression, and high heat-flux density, resulting in severe aerodynamic heating problems (Li et al. 2020; Liu et al. 2022). In particular, under high Mach number conditions, shock compression and viscous dissipation are significantly intensified, leading to the formation of high-temperature boundary layers over the vehicle surface, with local heat-flux density reaching the MW/m² level (Zhu et al. 2018). Unlike aerodynamic heating over smooth walls, these critical regions are often accompanied by complex flow structures such as bow shocks, incident shocks, local steps, gaps, injection slots, and wall jets, which induce strong coupled interactions among the external freestream, shock system, and near-wall boundary layer. Previous studies have shown that hypersonic shock-wave/boundary-layer interactions can induce boundary-layer thickening, separation, and reattachment, while significantly increasing local pressure loads, heat-flux density, and unsteady fluctuations (Knight and Mortazavi 2018; Huang et al. 2020; Sabnis and Babinsky 2023). For thermally sensitive regions such as warhead walls, excessive wall temperature may not only cause thermal failure of materials but also degrade infrared detection performance and guidance accuracy. Therefore, aerodynamic interference effects and thermal protection issues in critical regions have become major bottlenecks limiting long-duration and highly maneuverable flight of hypersonic vehicles (Karthikraja et al. 2026).

With regard to hypersonic aerodynamic interference effects, extensive studies have first been conducted by researchers worldwide on typical shock-wave/boundary-layer interactions. Chang et al. (2022) investigated incident-shock impingement on a flat plate and found that shock impingement on the boundary layer can induce flow separation and significantly enhance wall pressure and thermal loads. Based on a compression-ramp configuration, Tang et al. (2024) further revealed the heat generation and transport mechanisms in the separation region, recirculation region, and reattachment region of hypersonic shock-wave/turbulent-boundary-layer interactions, indicating that boundary-layer compression and enhanced convective transport are important causes of the sharp increase in wall heat flux. Hypersonic wind-tunnel experiments conducted by Gülhan et al. (2021) showed that coupled shock/shock and shock-wave/boundary-layer interactions can significantly amplify local heat flux, with the heat-flux amplification factor reaching approximately 7 in some configurations. In addition, studies on typical configurations such as cone/flare models, double cones, and compression ramps have demonstrated that nose bluntness, compression angle, Reynolds number, and wall thermal boundary conditions all affect the separation length, peak reattachment heat flux, and level of unsteady loading (Volpiani et al. 2020; Youssefi and Knight 2017). These studies indicate that the aerothermal environment of critical regions in hypersonic vehicles is not determined solely by freestream parameters, but is also closely related to the local shock structure, boundary-layer state, and geometric discontinuities on the wall.

For the thermal protection of critical regions, thermal protection technologies for hypersonic vehicles mainly include passive thermal protection and active thermal protection (Li et al. 2021). Passive thermal protection relies on high-temperature-resistant materials, insulation coatings and heat dissipation structures to block and store heat. It has the advantages of simple structure and high reliability. However, the passive thermal protection method that solely relies on materials and structures for heat

storage/insulation still faces problems such as heat accumulation and structural thermal deformation under long-term high heat flux (Le et al. 2021). Active thermal protection actively removes heat through the flow of heat-transfer media, including internal channel heat transfer, film cooling, transpiration cooling, and other approaches. Owing to its strong controllability and high heat-transfer efficiency, active thermal protection has become a major research direction for thermal protection of warhead walls (Sun and Liu 2020; Kays et al. 2005).

Internal channel heat transfer is a commonly used approach in active thermal protection for hypersonic vehicles. Its basic principle is that the heat-transfer medium flows through internal channels within the wall and removes structural heat through convective heat transfer, thereby reducing the wall temperature. Tuckerman and Pease (1981) first demonstrated the high heat-transfer potential of microchannels, and Kandlikar (2005) and Morini (2004) further summarized the mechanisms of enhanced heat transfer in microchannels. In recent years, Wang et al. (2024) investigated supercritical carbon dioxide (S-CO₂) pin-fin channels and showed that pin-fin structures can reduce the peak wall temperature and improve heat-transfer efficiency. Sun et al. (2025) enhanced the heat-transfer efficiency in high-heat-flux regions through a variable-flow-rate cooling strategy. In general, internal channel heat transfer has the advantages of compact structure, high coolant utilization efficiency, and weak disturbance to the external flow field. However, it mainly acts on the heat-conduction path inside the wall and is therefore difficult to directly weaken the external aerodynamic heat input. Meanwhile, complex channel structures may increase flow resistance and pumping-power consumption (Zhang et al. 2026). Therefore, a single internal channel heat-transfer approach is difficult to meet the requirements of long-duration thermal protection for hypersonic vehicles. External film cooling injects low-temperature gas or fuel near the wall to form a low-temperature protective layer between the mainstream and the wall, thereby reducing the wall heat-flux density. Compared with internal channel heat transfer, film cooling can act directly on the near-wall boundary-layer region and thus has advantages in suppressing external aerodynamic heat input (Shen et al. 2022). Chen et al. found that transverse injection in a hypersonic boundary layer can generate complex shock-vortex structures, which in turn affect the film coverage and heat-transfer efficiency. Wei et al. (2026) pointed out that film cooling can effectively reduce the wall heat-flux density and, to some extent, weaken aerodynamic friction drag. However, the high-speed mainstream continuously washes and entrains the coolant film, causing it to become thinner and break up along the injection direction, which leads to a reduction in cooling efficiency. Simply increasing the injection mass flow rate may also introduce additional energy losses. Therefore, a single external film-cooling approach is likewise difficult to provide stable thermal protection under sustained high-heat-flux conditions.

Supercritical fluids exhibit strong heat-transfer potential under high-heat-flux-density conditions owing to their high density, low viscosity, and strong property variations near the critical point. Consequently, they have gradually become important heat-transfer media in thermal management and active thermal protection for hypersonic vehicles (Li et al. 2025). Among them, S-CO₂ has advantages such as moderate critical parameters, relatively high safety, excellent heat-transfer performance, and comparatively low system-integration complexity. It has been widely used in studies of regenerative cooling channels, microchannel cold plates, and heat transfer on walls subjected to high heat flux. Li et al. (2022) showed that S-CO₂ can significantly enhance convective heat transfer and reduce wall temperature in cooling channels. Liu et al. (2024) further verified the heat-transfer advantages of S-CO₂ under a high-speed mainstream thermal environment through experiments on parallel rectangular channels. Meanwhile, enhanced structures such as pin fins, microchannels, and rectangular channels can

strengthen near-wall disturbances and secondary-flow development, thereby further improving the heat-transfer efficiency of S-CO₂ (Wang et al. 2024; Cheng et al. 2026). However, existing studies on active cooling using S-CO₂ mainly focus on in-channel flow and heat transfer, cold-plate thermal management, and numerical simulations. Experimental investigations using S-CO₂ as the heat-transfer medium for active thermal protection of critical warhead regions under realistic hypersonic external-flow conditions remain very limited. In particular, for complex configurations involving bow shocks, injection-slot steps, boundary-layer separation, external film coverage, and internal channel heat transfer, the interference mechanism between the S-CO₂ jet and the hypersonic mainstream, as well as its influence on wall temperature rise and heat-flux suppression, remains unclear.

Based on the complementary characteristics of internal channel heat transfer and external film cooling, combined internal channel-external film heat transfer has received increasing attention in recent years. In this approach, the heat-transfer medium first absorbs structural heat in the internal channel and is then ejected through a surface injection slot to form an external film, thereby achieving a dual thermal protection effect of “first reducing wall temperature and then suppressing heat flux” (Han et al. 2013; Bunker 2005). The combined heat-transfer scheme integrating S-CO₂ internal channel cooling and fuel film cooling proposed by Zhou et al. (2024) indicates that combined heat transfer can simultaneously suppress wall heat-flux density and peak wall temperature, showing good thermal protection potential in both the near-slot and downstream regions. This approach is particularly suitable for critical regions such as warhead windows, where external heat flux is intense and internal space is limited. Related studies on gas-turbine blade cooling and thermal protection of reentry vehicles have also shown that hybrid heat-transfer approaches are generally superior to single heat-transfer methods and can alleviate local hot-spot problems (Fan et al. 2026). However, existing studies mainly focus on a single aerodynamic interference structure or a single heat-transfer method, while comparative investigations of internal channel heat transfer, external film cooling, and combined channel-film heat transfer under the same hypersonic mainstream condition remain insufficient. In particular, for critical regions such as warhead windows that simultaneously involve injection slots, steps, and near-wall boundary layers, the effects of different heat-transfer approaches on aerodynamic interference structures, wall temperature rise, and heat-flux suppression capability still need to be further clarified. Therefore, in this study, supercritical pressure carbon dioxide is employed as the heat-transfer medium, and comparative experiments are conducted on internal channel heat transfer, external film cooling, and combined channel-film heat transfer for critical regions of a warhead under Mach number 8 hypersonic wind-tunnel conditions. A schlieren system is used to analyze the bow shock, jet-induced shock, boundary-layer separation, and film-coverage characteristics near the injection slot. Combined with wall temperature-rise and heat-flux responses, the intrinsic relationship between aerodynamic interference effects and thermal protection performance under different flow and heat-transfer approaches is revealed.

2. Experimental Apparatus

2.1. Experimental Model

The flow-control heat-transfer performance of a vehicle warhead was investigated under the Ma 8 freestream condition in a 1.0 m diameter hypersonic wind tunnel. Three heat-transfer approaches were considered: internal channel heat transfer (H_{In}), external film heat transfer (H_{Out}) and combined channel-film heat transfer (H_{All}). Supercritical pressure carbon dioxide was used as the experimental jet working medium. The warhead model used in the experiments is shown in Fig. 1(b). The model has an overall length of approximately 340 mm, a tail width of approximately 271 mm, and a height of approximately 186 mm. A leveling platform was mounted on the model surface to ensure the accuracy of the model positioning angle. The model was installed in the wind-tunnel angle-of-attack mechanism through a rear-support sting, as shown in Fig. 1(c).

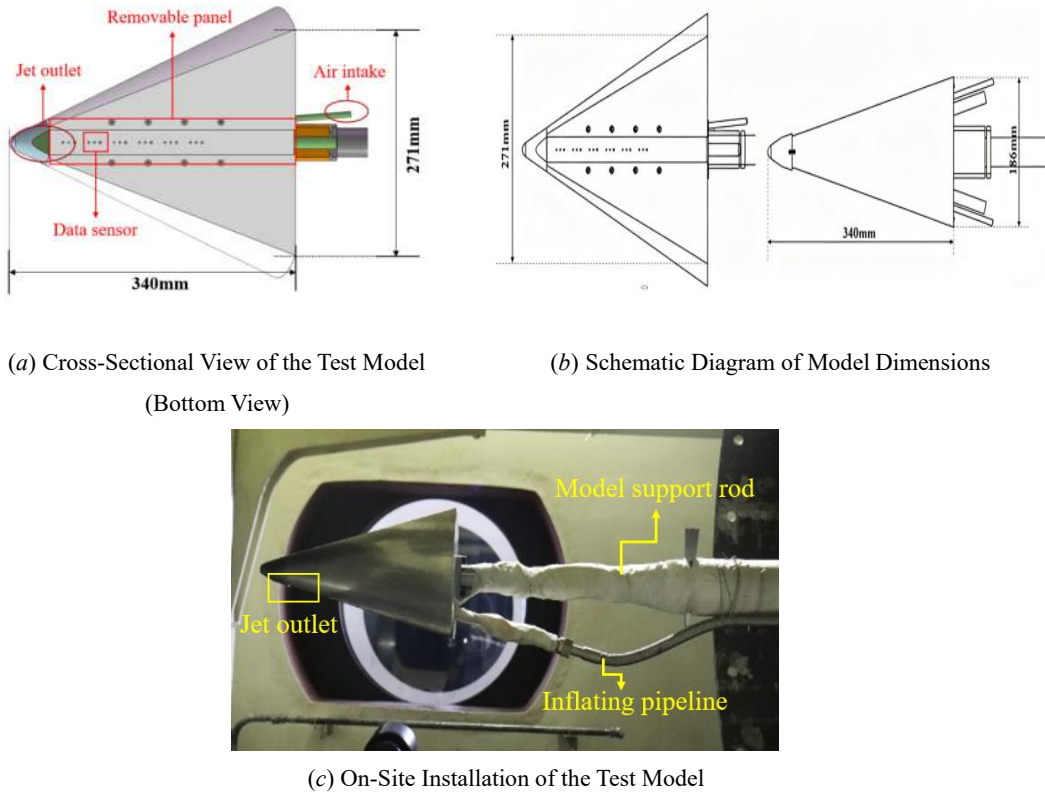


Fig. 1 Schematic Diagram of the Experimental Warhead Model

As shown in Fig. 2, a removable plate for controlling the heat-transfer mode was installed inside the warhead on the windward side. The removable plate consisted of a contoured Laval nozzle, internal heat-transfer channels, and wall measurement points. A through-flow channel was arranged inside the removable plate. CO₂ was injected from the rear inlet, underwent phase transition during the heat-absorption process along the flow path, and was transported upstream. It was then accelerated through the Laval nozzle and discharged from the nozzle exit, forming a supersonic film. To obtain the wall temperature and heat-flux response characteristics, six groups of measurement points (P_1 – P_6) were arranged along the length direction of the test article, from upstream to downstream. In each group, the pressure sensor, temperature sensor, and heat-flux sensor were arranged from left to right. The spacing

between sensors within the same group was 7.77 mm, and the spacing between adjacent measurement groups was 18.45 mm. The pressure sensor in the first measurement group was located 69.89 mm from the warhead stagnation point.

In the internal channel heat-transfer mode, as shown in Fig. 3(a), the gas flowed through the lattice channel into the plenum chamber and was then discharged through the lateral exhaust outlet, without forming a film in the external flow. In the external film heat-transfer mode, as shown in Fig. 3(b), the injected gas was supplied from an external high-pressure gas source and precisely regulated by a flow-control system before being delivered into the supply pipeline. It was then ejected from the tangential injection slot on the upper surface of the model to isolate the mainstream. In the combined heat-transfer mode, as shown in Fig. 3(c), the heat-transfer medium was first delivered from the supply system into the internal flow channel, where internal heat transfer was achieved. After exchanging heat with the optical window, the working medium passed through the chamber and was ejected from the tangential injection slot, forming a film over the optical window to reduce the heat load. As shown in Fig. 3(d), eight parallel rectangular channels were integrated inside the lattice channel. The cross-sectional size of each single channel was 1.6 mm, with a center-to-center spacing of 3 mm. This channel array served as the main flow passage for the CO₂ working medium and enabled efficient active heat transfer by increasing the internal heat-transfer area.

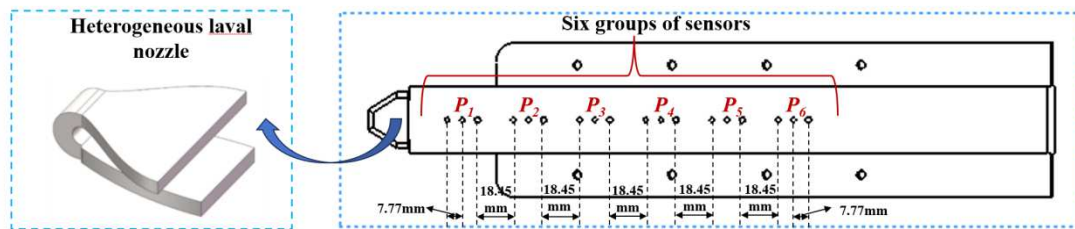


Fig. 2 Schematic Diagram of the Laval Nozzle and Wall Measurement-Point Layout of the Model

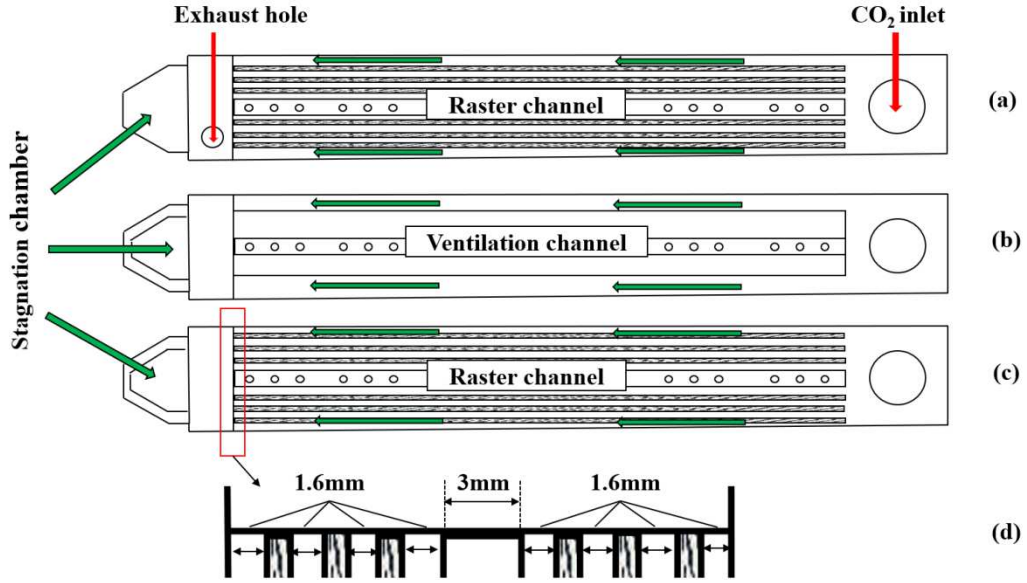


Fig. 3 Schematic Diagram of the Three Removable Plates

2.2. Carbon Dioxide Supply System

In the supply system for the heat-transfer medium, Supercritical pressure carbon dioxide was used as the active cooling working medium for the warhead. Fig. 4 shows a schematic diagram of the carbon dioxide supply system. In the experiment, pressurized storage tanks were used to supply CO₂ fluid. Controlled delivery and rapid start-stop operation of CO₂ to the test section were achieved through filtration, a mass flow meter, a Venturi tube, temperature and pressure measurements, and solenoid valves, thereby obtaining a stable and repeatable S-CO₂ flow rate.

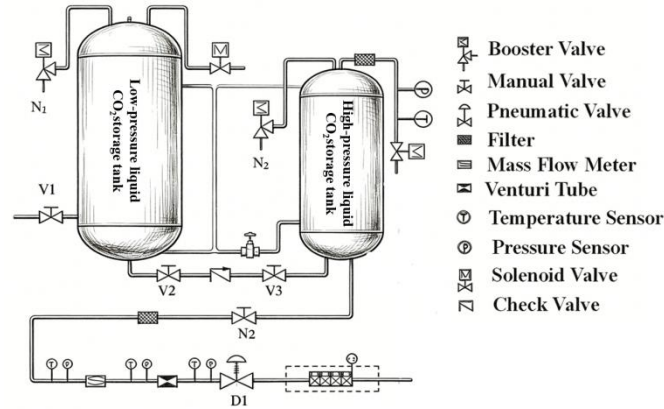


Fig. 4 Diagram of the carbon dioxide supply system

2.3. Experimental Procedure

The freestream conditions of the experiment were Mach number 8, a total temperature of 680 K, a total pressure of 0.4 MPa, and a unit Reynolds number of $1.03 \times 10^6/\text{m}$. The freestream parameters were kept constant for all test runs. The angles of attack (α) were set to 0°, 10°, and 20°. The detailed test conditions are listed in Table 1. In the table, F denotes the number of jet injections. An injection number

of 3 indicates that three jet injections were performed, namely, the supply of the heat-transfer medium was stopped after the first injection for a certain duration, followed by the second and third injections, with the same jet mass flow rate maintained for each injection. H denotes the heat-transfer mode for each test condition, and m_{jet} represents the CO₂ jet mass flow rate in each test run.

Table 1 Test task train number

Number	$\alpha(^{\circ})$	F	H	$m_{jet}(g/s)$
1	0	1	H_{In}	129
2	10	1	H_{In}	126
3	20	3	H_{In}	120
4	20	3	H_{In}	117
5	0	1	H_{Out}	128
6	10	1	H_{Out}	128
7	20	1	H_{Out}	126
8	0	1	H_{All}	124
9	10	1	H_{All}	129
10	20	1	H_{All}	127

Based on the thermocouple sensitivity coefficient of the sensor, the pressure difference can be converted into the wall temperature rise of the warhead, as expressed by the following equation:

$$\Delta T = T - T_0 \quad (0.1)$$

Where: ΔT denotes the wall temperature rise of the warhead. A positive value indicates that the wall temperature is higher than the ambient room temperature, whereas a negative value indicates that the wall temperature is lower than the ambient room temperature. T denotes the real-time wall temperature of the warhead, and T_0 denotes the ambient temperature at the test site, which was kept constant at

298.15 K.

According to Fourier's one-dimensional heat conduction law, when the heat flux (q) is applied to the outer surface of the sensor, the surface heat flux can be calculated from the temperature difference between the upper surface temperature (T_H) and the bottom surface temperature (T_C), as expressed by the following equation:

$$q = \frac{k}{d} (T_H - T_C) = \frac{k}{NdS_T} E \quad (0.2)$$

$$\frac{NdS_T}{k} = S_q \quad (0.3)$$

where k is the thermal conductivity of the thermal resistance layer, N is the number of thermocouple junction pairs, namely the number of turns, S_T is the Seebeck coefficient of the thermocouple, and E is the total potential difference output by the N thermocouple pairs. The sensitivity coefficient is denoted as S_q , which was obtained using the heat-flux calibration system. In the experiment, the heat-flux value under the corresponding condition could be obtained by dividing the measured voltage variation by the sensitivity coefficient.

3. Experimental Results and Analysis

This section analyzes the aerodynamic interference effects and flow heat-transfer characteristics of the critical regions of the warhead under hypersonic freestream conditions. Based on schlieren images, the bow-shock structure, near-wall boundary-layer development, and separation–reattachment phenomena induced by the injection-slot step under no-jet conditions at different angles of attack are first discussed, in order to clarify the coupled interference mechanism among the mainstream, shock waves, and boundary layer. Subsequently, the jet structure, film-coverage state, and external-flow disturbance range are compared among the three flow-control approaches, namely internal channel heat transfer, external film heat transfer, and combined channel-film heat transfer, to analyze the effects of different heat-transfer approaches on the near-wall flow field. On this basis, together with the temporal variations in wall temperature rise and heat flux, the wall heat-transfer capability and heat-flux suppression capability of different schemes are evaluated. The objective is to clarify the differences in heat-transfer performance and the corresponding mechanisms under different flow-control approaches, thereby providing experimental support for the design of active thermal protection schemes.

3.1. Aerodynamic Interference Analysis

The flow-field structures under no-jet conditions at different angles of attack are shown in Fig. 5. It can be observed that, under the Ma 8 hypersonic freestream, a distinct detached bow shock forms ahead of the warhead nose. After passing through the bow shock, the mainstream undergoes strong compression, resulting in a rapid increase in local pressure, temperature, and density. The post-shock flow then develops downstream along the model surface, forming a boundary layer in the near-wall region. Owing to the blunt-nosed configuration of the warhead, the region near the nose stagnation point experiences the strongest flow deceleration and compression, and is therefore subjected to intense aerodynamic loading. As the angle of attack increases from 0° to 10° and 20° , the symmetry of the flow field is gradually disrupted, and both the bow-shock shape and the shock stand-off distance change significantly. At an angle of attack of 0° , the flow structures over the upper and lower surfaces of the model are relatively symmetric, and the bow shock is distributed relatively uniformly ahead of the nose. With increasing angle of attack, the windward side is subjected to stronger freestream compression, causing the shock to move closer to the model surface. As a result, the local compression effect is enhanced and the thermal load near the wall increases. On the leeward side, the shock moves away from the wall and the shock-system intensity is weakened. Therefore, the variation in angle of attack directly changes the distribution of aerodynamic effects over different regions of the warhead surface.

The interference between the mainstream and the boundary layer is mainly manifested as the coupled process of “bow-shock compression–near-wall boundary-layer development–local separation and reattachment.” The hypersonic mainstream is first compressed by the bow shock, and the post-shock flow develops along the warhead wall, causing the boundary layer to thicken continuously. When the flow reaches the injection-slot step and its surrounding region, the local geometric discontinuity subjects the near-wall flow to an adverse pressure-gradient effect, which induces boundary-layer separation and forms a separated shear layer and a recirculation region downstream of the step. As the shear layer continues to develop downstream, the mainstream may reattach to the wall. The reattachment region is usually accompanied by strong momentum and energy exchange, which can easily lead to an increase in local heat flux. Therefore, even under no-jet conditions, the region near the injection slot is not a simple

smooth-wall boundary-layer flow, but rather a complex aerodynamic interference region involving multiple flow structures, including shock waves, boundary-layer separation, shear-layer development, and reattachment.

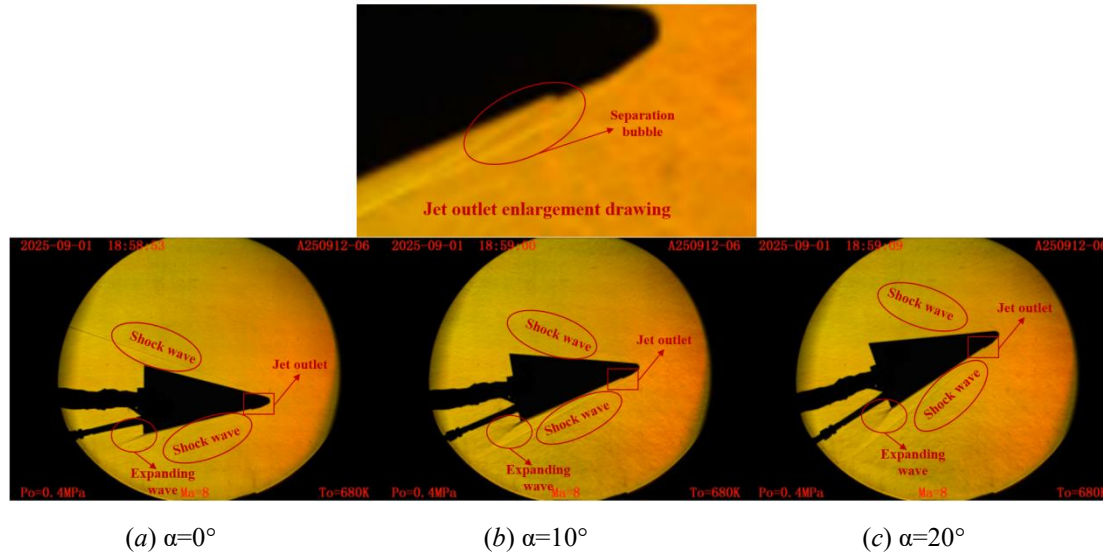


Fig. 5 Schematic diagram of the non-jet flow field structure

Under flow-control conditions, the flow characteristics near the injection slot are similar among the different approaches at the three freestream angles of attack. Therefore, only the flow-field structure at an angle of attack of 20° is presented here as an example, as shown in Fig. 6. For the internal channel heat-transfer approach, the heat-transfer medium mainly flows through the internal channels of the model and removes structural heat through internal convective heat transfer. Since this approach does not form an external jet within the mainstream boundary layer, its external flow-field structure is relatively close to that under the no-jet condition. The main bow shock and the near-wall boundary-layer morphology are not significantly altered, and only weak disturbances are observed near the outlet of the internal channel. This indicates that internal channel heat transfer causes relatively weak disturbance to the external hypersonic mainstream, which is beneficial for maintaining the stability of the external flow field. However, its direct effect on weakening the external aerodynamic heat input is relatively limited.

Different from the internal channel heat-transfer approach, in the external film heat-transfer mode, S-CO₂ is ejected from the wall injection slot and directly enters the hypersonic boundary layer, where it interacts strongly with the mainstream. After the jet penetrates the near-wall boundary layer, a distinct jet-induced shock structure forms in front of and around the injection slot, appearing in the schlieren image as an arc-shaped density-gradient region with clear bright–dark contrast. This structure indicates that the jet blocks and lifts the mainstream, forming a low-temperature protective layer of a certain thickness between the mainstream and the wall, thereby providing the capability to reduce wall heat-flux input. Meanwhile, strong shear mixing occurs between the jet and the mainstream. During downstream development, the film gradually becomes thinner and is entrained by the mainstream, so its protective effect exhibits an evident streamwise attenuation. From the perspective of the interference mechanism, after the external film jet is initiated, three main types of coupled interactions occur between the jet and the mainstream boundary layer. The first is film interference, in which the jet lifts the mainstream after entering the near-wall boundary layer and forms a low-temperature protective layer near the wall. The second is wave-system interference, in which the compression waves, expansion waves, and jet-induced shocks generated by the jet interact with the main bow shock and the near-wall boundary layer, thereby

modifying the local pressure distribution near the injection slot. The third is shear-mixing interference. Owing to the large velocity and temperature differences between the jet and the mainstream, a strong shear layer forms at their interface. As the flow develops downstream, mainstream entrainment is continuously enhanced, and the film-coverage capability gradually weakens.

For the combined channel-film heat-transfer approach, the heat-transfer medium first flows through the internal lattice channel and exchanges heat with the structural wall, and is then discharged through the injection slot to form a film over the external wall. Therefore, the external flow-field characteristics of this approach are similar to those of single film heat transfer to some extent. Both approaches form jet-induced shocks and film shear layers near the injection slot, indicating that combined heat transfer can also block mainstream heat input through the external film. The difference is that the heat-transfer medium in the combined heat-transfer mode has already participated in internal channel heat transfer before being ejected, so its energy distribution and temperature level are affected by the internal channel flow process. The schlieren results show that combined heat transfer does not induce a wider range of external-flow disturbance than single film heat transfer, indicating that while achieving the thermal shielding effect of the external film, it can still confine the main disturbance to the region near the injection slot.

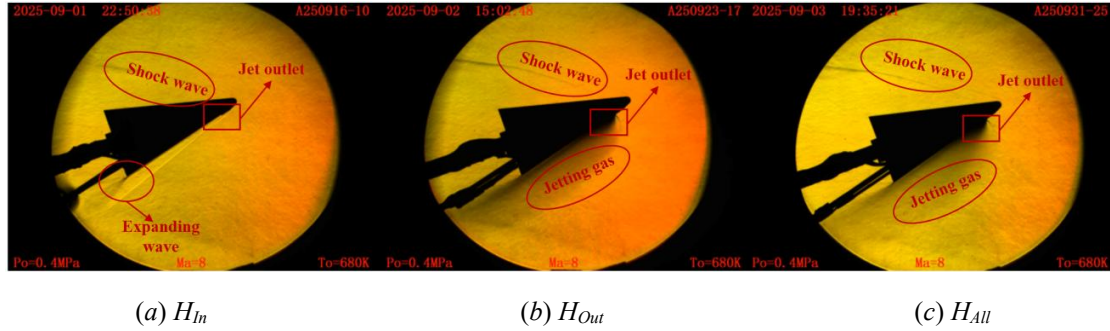


Fig. 6 Schematic diagram of the flow field structure of the jet at a 20° attack angle

Taken together, Fig. 5 and Fig. 6 indicate that the flow field around the hypersonic warhead is jointly affected by the angle of attack, the injection-slot geometry, and the ejection mode of the heat-transfer medium. Under no-jet conditions, the flow-field structure is mainly governed by the bow shock, the near-wall boundary layer, and the separation–reattachment process induced by the injection-slot step. The aerodynamic interference is primarily manifested in the establishment of the bow shock, the development of the boundary layer, and the adjustment of the local separation region near the injection slot. Internal channel heat transfer causes the weakest disturbance to the external flow field and mainly reduces the wall temperature through internal heat transfer. In contrast, external film heat transfer and combined channel-film heat transfer generate distinct jet-mainstream-boundary-layer interference structures near the injection slot. After jet initiation, the near-wall flow field is modified through jet blockage, mainstream lifting, shear mixing, and coupled wave-system interactions, while a low-temperature film isolation layer is formed near the wall, thereby weakening the direct aerodynamic action of the mainstream on the wall. These differences in flow-field structures provide the physical basis for the subsequent variations in wall temperature rise and heat flux: internal channel heat transfer is more favorable for overall wall heat transfer, whereas film cooling and combined heat transfer are more effective in directly suppressing external aerodynamic heat input.

3.2. Analysis of Flow and Heat-Transfer Characteristics

3.2.1. Single Flow-Control Heat-Transfer Approaches

The temporal variations in wall temperature and heat flux measured at the warhead surface under the internal channel heat-transfer mode and the film heat-transfer mode are shown in Fig. 7 and Fig. 8. The cases with angles of attack of 0° and 10° were selected for analysis. Since the sensor at measurement point 6 was damaged during the experiment, data from the remaining five measurement points were used to compare and analyze the heat-transfer performance of the single heat-transfer approaches. In the figures, solid lines represent the internal channel heat-transfer cases, while dashed lines represent the film heat-transfer cases. It can be seen that the temperature and heat-flux curves on the warhead wall during the experiment can be clearly divided into three characteristic stages. Stage I is the experimental preparation stage, during which the warhead position is fixed and the angle of attack is adjusted. At this stage, the flow field has not yet been started, and the sensor outputs remain basically stable, with both the temperature and heat-flux curves fluctuating slightly around zero. Stage II is the freestream start-up stage. As the mainstream is initiated, the warhead is subjected to the freestream, and the wall temperature begins to rise. Correspondingly, both the temperature and heat-flux curves show a significant upward trend. Stage III is the active heat-transfer stage. After the jet is initiated, heat exchange occurs between the working medium and the warhead. The temperature-rise and heat-flux curves corresponding to both internal channel heat transfer and film heat transfer decrease rapidly, gradually become negative, and finally reach a dynamic equilibrium. This indicates that both heat-transfer approaches can achieve effective wall heat transfer after jet initiation. Finally, the jet supply is stopped, the freestream is shut down, and the experiment is completed.

As shown in Fig. 7, after the S-CO₂ supply system is activated, the wall temperature-rise curves of both heat-transfer approaches exhibit a decreasing trend, but their response characteristics are different. Under the internal channel heat-transfer mode, the stable temperature reduction at each measurement point is concentrated within the range of 20–23 K. By comparing the temperature variations at different measurement points, it can be seen that the temperature decrease is more pronounced near the downstream region of the model close to the CO₂ inlet. The heat-transfer performance at sensor position 5 is significantly stronger than that at positions 1 and 3. The channel heat-transfer effect exhibits a clear streamwise distribution characterized by stronger cooling downstream and weaker cooling upstream, and no significant variation is observed with changes in the angle of attack. This is mainly because, as S-CO₂ flows through the lattice channel toward the plenum chamber, it removes heat through heat exchange with the wall, causing the temperature of the heat-transfer medium to increase. As the flow path becomes longer, the heat-transfer effect on the wall gradually weakens.

In contrast, the temperature reduction at different measurement points varies significantly under the external film heat-transfer mode. After jet initiation, the temperature reduction at measurement point 1 near the injection outlet is significantly greater than that at the other measurement points. Under the 0° angle-of-attack condition, the temperature reduction is approximately within the 10 K range, while under the 10° angle-of-attack condition, the wall temperature reduction can reach approximately 20 K. This region exhibits the best heat-transfer performance and is significantly superior to the downstream measurement points. This is because the angle of attack changes the shock structure and boundary-layer development state near the injection slot, enhancing the interaction among the jet expansion wave, jet-induced shock, and mainstream shock. To some extent, this pushes the mainstream away from the wall,

which is more favorable for film attachment and prolongs the residence time of the film, thereby enhancing the thermal insulation and heat-transfer effect in the near-slot region. For the other four measurement points, the temperature reduction under different angles of attack is concentrated within approximately 2.5 K, and the heat-transfer performance gradually deteriorates along the external jet flow direction. This is mainly because, as the heat-transfer medium is ejected and expands, the film coverage gradually decreases during downstream development, leading to a gradual weakening of the heat-transfer effect.

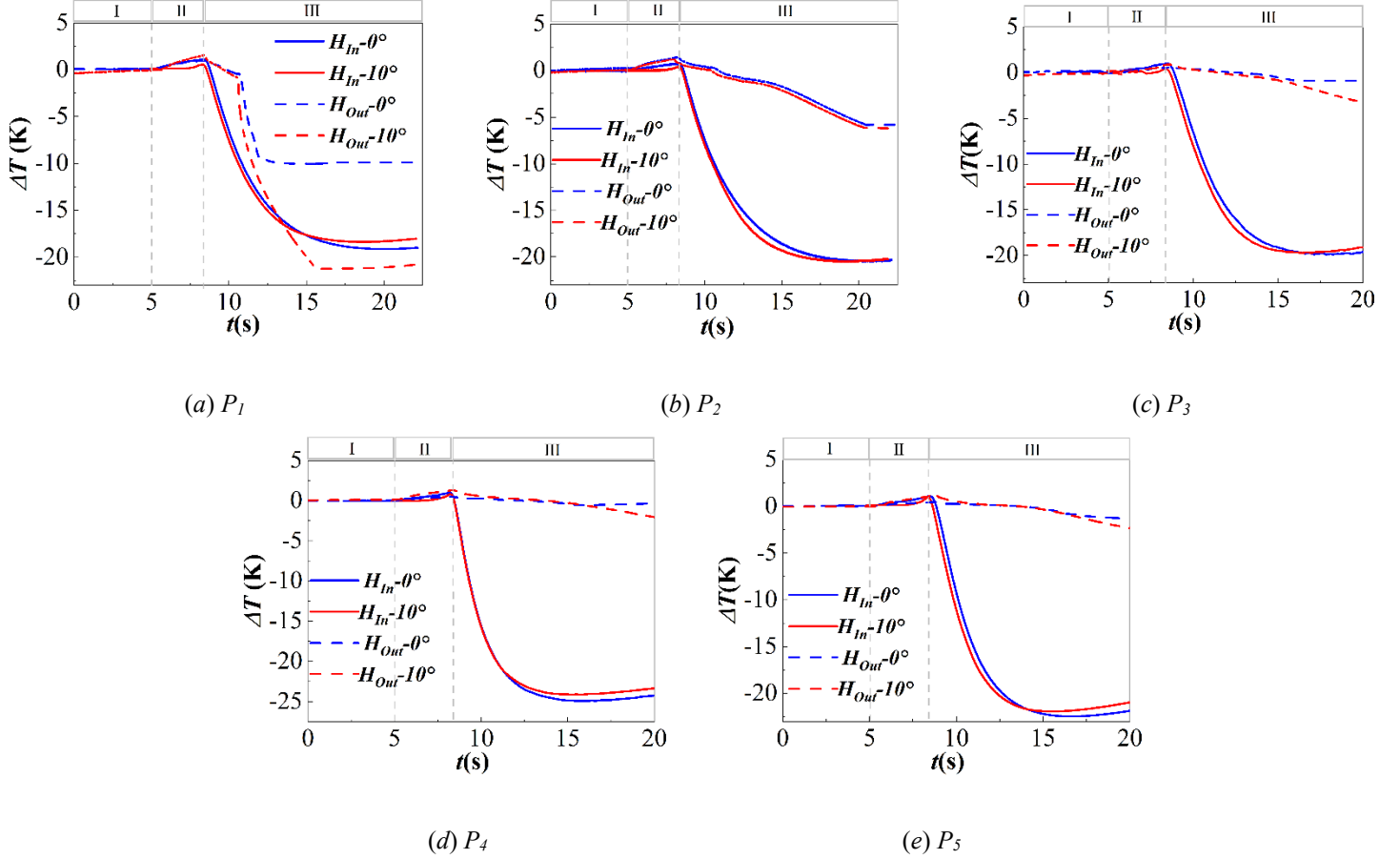


Fig. 7 Temperature rise variation at the measuring point under single-flow control heat exchange mode

The variations in wall heat flux on the warhead surface under the two heat-transfer approaches are shown in Fig. 8. For the internal channel heat-transfer case at an angle of attack of 10°, the shorter duration of Stage II is attributed to the shorter time interval between freestream initiation and jet initiation for this specific test condition. For the internal channel heat-transfer approach, after the supply of the heat-transfer medium is initiated, the heat-flux values at all measurement points decrease rapidly, and the heat flux at some measurement points becomes negative. This indicates that, at this moment, the heat-transfer effect of the jet working medium on the wall exceeds the aerodynamic heating effect of the mainstream on the wall. However, as the experiment proceeds, under the continuous aerodynamic heating of the mainstream, the wall heat flux of the model gradually increases and returns to positive values. This phenomenon is not contradictory to the negative wall temperature rise observed at the same measurement point and at the same time. The temperature rise reflects the variation in wall temperature relative to the initial ambient temperature, whereas the sign of the heat flux reflects the instantaneous direction of heat

transfer at the wall. When the internal channel heat-transfer effect is sufficiently strong, the wall temperature can be reduced below the ambient temperature, resulting in a negative temperature rise. However, since internal channel heat transfer does not form a film isolation layer on the external wall, the external hypersonic mainstream still continuously inputs aerodynamic heat into the wall, and the heat-flux sensor may therefore still measure a positive heat flux. This phenomenon indicates that internal channel heat transfer can effectively reduce the wall temperature, but its direct capability to suppress external aerodynamic heat input is limited. The wall remains in a heat-transfer state characterized by “external heating and internal heat removal.” Meanwhile, the heat-flux value increases monotonically with increasing angle of attack, indicating that a larger angle of attack further intensifies the wall thermal load and deteriorates the heat-transfer condition of the internal channel.

In sharp contrast, under the external film heat-transfer mode, after CO₂ is ejected, the heat-flux value on the warhead surface decreases rapidly and eventually stabilizes at a negative value. This indicates that this heat-transfer approach can continuously and effectively suppress wall heat flux and thus provides superior long-term thermal protection capability. It is worth noting that, under the film heat-transfer mode, the heat-flux values at the measurement points gradually increase along the jet flow direction. This trend clearly reflects that the suppression effect of the film on wall heat flux gradually weakens along the jet flow direction.

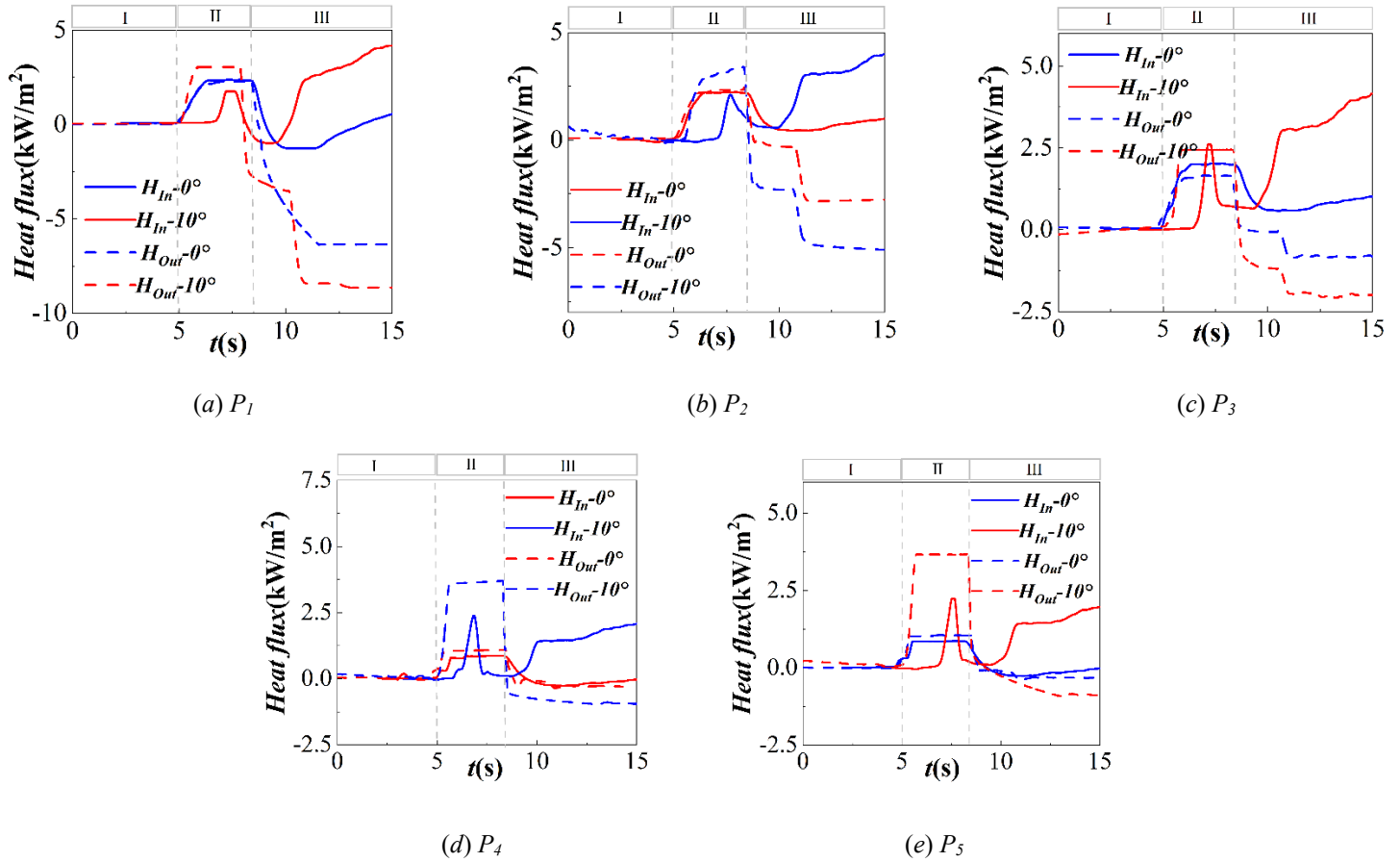


Fig. 8 Heat flux variation at the measurement point under single-flow control heat exchange mode

Based on the above experimental results, both internal channel heat transfer and external film heat

transfer can provide effective heat-transfer effects on the warhead wall, but they exhibit obvious differences in wall temperature-rise control and heat-flux suppression capability. In terms of wall temperature control, internal channel heat transfer shows a more prominent overall advantage, and its heat-transfer performance is significantly better than that of external film heat transfer. In the near-slot region, the temperature reduction achieved by internal channel heat transfer is approximately twice that achieved by external film heat transfer. In the middle and downstream regions of the warhead, the temperature reduction can reach up to about four times that of external film heat transfer. More importantly, the effectiveness of internal channel heat transfer is less affected by changes in the angle of attack, indicating good adaptability to different operating conditions.

However, in terms of wall heat-flux suppression, the two heat-transfer approaches exhibit opposite trends. Although internal channel heat transfer can temporarily reduce the wall heat flux during the initial stage after jet initiation, its heat-flux suppression capability gradually weakens as the experiment proceeds under continuous aerodynamic heating from the mainstream. Eventually, it almost loses its ability to reduce the external thermal-load input. In contrast, external film heat transfer can form a low-temperature isolation layer near the wall, continuously blocking the direct heat exchange between the mainstream and the wall. As a result, the wall heat flux remains at a relatively low level for a long duration, demonstrating superior sustained thermal protection capability. Meanwhile, its heat-flux suppression effect is also less affected by variations in the angle of attack, indicating that external film heat transfer maintains relatively stable heat-flux reduction capability under different freestream attitudes.

3.2.2. Combined Channel-film Flow-Control Heat-Transfer Approach

Under the combined flow-control heat-transfer approach, the temporal variations in wall temperature rise at different measurement points on the warhead surface under different angles of attack are shown in Fig. 9. In the figure, P_i denotes measurement points 1 to 5 arranged sequentially along the flow direction on the warhead wall. The three-stage evolution characteristics of the temperature curves under each condition are consistent with those shown previously in Fig. 7 and Fig. 8. In the first stage, when the flow field is not yet started, the temperature rise at each measurement point remains stable near 0 K without obvious temperature fluctuations, confirming the initial thermal-equilibrium state of the experimental system. In the second stage, after the mainstream is initiated, the temperature curves at all measurement points show a slow and slight upward trend under the action of the mainstream, indicating that heat begins to accumulate on the warhead wall. In the third stage, after the S-CO₂ supply is initiated, the temperature curves at all measurement points drop sharply, and the wall temperature decreases rapidly before gradually approaching a stable state.

As shown in the figure, under the 0° and 10° angle-of-attack conditions, the stable temperature reduction at measurement point1 near the injection slot exceeds 30 K, indicating the most significant heat-transfer enhancement. In contrast, the temperature reduction at the remaining middle and downstream measurement points decreases successively along the flow direction. The stable temperature reduction at measurement point2 is approximately 10 K, while that at the other measurement points is approximately 5 K. This distribution indicates that the combined flow-control heat-transfer approach provides strong heat-transfer capability in the near-slot region, but its heat-transfer effect attenuates markedly along the flow direction, resulting in relatively limited heat-transfer performance in the middle and downstream wall regions. Comparison with the single heat-transfer approaches shows that the combined heat-transfer approach exhibits significantly better heat-transfer performance in the near-slot region than either of the two single approaches. Compared with single external film heat transfer, the

temperature reduction at all measurement points is improved to varying degrees under the combined heat-transfer mode, demonstrating a clear advantage in overall heat-transfer performance. However, compared with single internal channel heat transfer, only the temperature reduction at measurement point1 near the injection slot is improved, whereas the temperature reductions at the middle and downstream measurement points, such as 3 and 5, decrease to different extents. Moreover, the streamwise decreasing distribution of temperature reduction is fundamentally different from that observed under single internal channel heat transfer. This may be attributed to the fact that, under the combined heat-transfer condition, the heat-transfer medium first exchanges heat in the internal lattice channel and is then ejected from the injection slot to form a film. A large amount of coolant is released and dissipated in the near-slot region, while the low-pressure entrainment effect induced by the high-speed jet significantly reduces the medium flow rate and residence time in the middle and downstream channels. In addition, mixing with the external hypersonic mainstream causes the film to attenuate rapidly along the flow direction, preventing sustained thermal insulation in the middle and downstream regions and weakening the stability of heat transfer there. Furthermore, the working medium undergoes secondary heating after absorbing heat internally before being ejected. The combined effects of these factors lead to lower heat-transfer efficiency at the middle and downstream measurement points than that under single internal channel heat transfer.

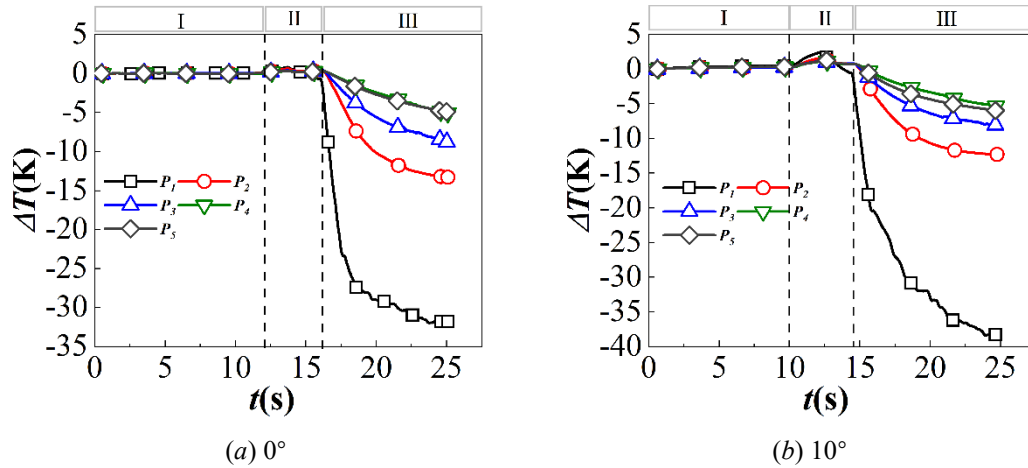


Fig. 9 Temperature rise variations of the measurement points on the surfaces of each attack angle under the combined heat exchange mode

Under the combined channel-film heat-transfer approach, the temporal variations in heat flux at different measurement points on the warhead wall under different angles of attack are shown in Fig. 10. The overall variation trend is in good agreement with the wall-temperature response characteristics. For the combined heat-transfer mode, after the S-CO₂ jet channel is activated, the heat-flux values at all measurement points exhibit an instantaneous sharp decrease, and the heat flux at all measurement points eventually becomes negative and remains stable. This phenomenon indicates that the convective heat-transfer effect of the jet working medium on the wall has fully covered and exceeded the heat input from the mainstream to the wall, thereby fundamentally weakening the aerodynamic heating effect imposed on the warhead wall.

Comparison with the single heat-transfer approaches shows that, relative to single internal channel heat transfer, the heat flux at all measurement points under the combined heat-transfer mode does not return to positive values throughout the process, and the absolute values in the stable stage are larger. This indicates that combined heat transfer can suppress wall heat-flux accumulation more persistently

and efficiently, significantly improving the sustained operating capability of the thermal protection system. Compared with single external film heat transfer, the heat-flux variation trends and stable heat-flux values at all measurement points under the combined heat-transfer mode are highly similar. This result clearly reveals that the wall heat-flux reduction effect of the combined heat-transfer approach mainly originates from the thermal insulation barrier formed by the film on the warhead surface. By establishing a low-temperature film isolation layer between the wall and the mainstream, direct heat exchange between the mainstream and the wall is blocked. This finding also corroborates the conclusion obtained from the previous temperature-field analysis that the near-slot region exhibits the best heat-transfer performance.

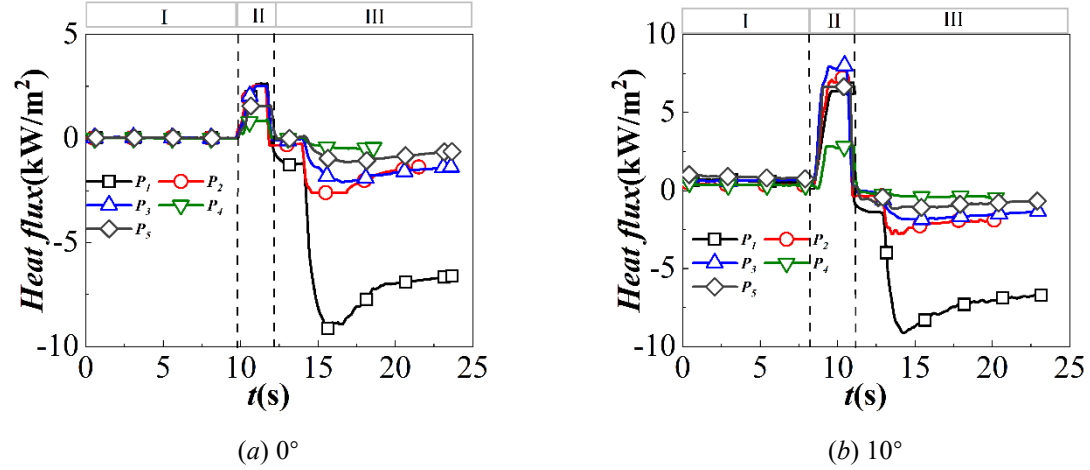


Fig. 10 Heat flux variations at the measurement points on the surfaces of various attack angles under the combined flow control heat transfer mode

Based on the comparative analysis of the wall temperature-rise distributions and heat-flux densities at different measurement points under the single and combined heat-transfer conditions, a clear conclusion can be drawn: the combined channel-film heat-transfer approach is significantly superior to single external film heat transfer in terms of overall wall heat-transfer effectiveness. The maximum wall temperature rise under the combined heat-transfer condition is markedly lower than that under the single film-cooling condition, indicating that the overall increase in wall temperature can be more effectively suppressed. However, compared with single internal channel heat transfer, the overall heat-transfer performance of the combined approach is still slightly inferior, mainly reflected in a certain gap in temperature-control capability in local wall regions. In terms of wall heat-flux reduction, however, the combined heat-transfer mode exhibits more prominent advantages. Its reduction in the peak wall heat flux is significantly greater than that achieved by single internal channel heat transfer, indicating that it can more effectively block heat transfer from the external flow to the wall. Meanwhile, its heat-flux reduction effect is basically comparable to that of single external film heat transfer, maintaining a similar level to film cooling in terms of the core thermal protection indicator. Overall, the combined channel-film heat-transfer approach integrates the advantages of internal channel heat transfer with the heat-flux shielding capability of external film cooling, achieving a favorable balance between thermal protection performance and heat-transfer medium consumption. Therefore, it is a hybrid thermal protection scheme with considerable engineering application potential.

4. Conclusion

This study addresses the thermal protection problem of critical regions of hypersonic vehicle subjected to severe aerodynamic heating. Supercritical pressure carbon dioxide was used as the heat-transfer medium, and comparative experimental investigations were conducted under Mach number 8 hypersonic wind-tunnel freestream conditions for three active thermal protection approaches: internal channel heat transfer, external film heat transfer, and combined channel-film heat transfer. The flow-field structures under different angles of attack and different heat-transfer approaches were observed using a schlieren system. Combined with wall temperature and heat-flux sensor data, the aerodynamic interference effects, wall heat-transfer capability, and heat-flux suppression characteristics of the critical warhead regions were analyzed. The main conclusions are as follows:

(1) The flow field around the critical regions of the hypersonic warhead is jointly affected by the angle of attack, the injection-slot geometry, and the ejection mode of the heat-transfer medium. Under no-jet conditions, a distinct detached bow shock forms ahead of the warhead nose, and the mainstream develops along the wall after shock compression, forming a near-wall boundary layer. As the angle of attack increases, the flow-field symmetry is disrupted, the shock on the windward side moves closer to the wall, the local compression effect is enhanced, and the wall thermal load increases accordingly. In addition, the injection-slot step induces boundary-layer separation, shear-layer development, and reattachment, making this region a complex aerodynamic interference zone governed by the coupled effects of shock waves, the boundary layer, and local geometric discontinuities.

(2) The three heat-transfer approaches exhibit distinct disturbance characteristics in the external flow field. Internal channel heat transfer mainly removes structural heat through convective heat transfer of the working medium within the internal channels. Since no obvious external jet is formed on the outer wall, its disturbance to the external hypersonic mainstream is relatively weak, and the main bow shock and near-wall boundary-layer structures remain generally stable. In contrast, external film heat transfer and combined channel-film heat transfer generate jet-induced shocks, expansion waves, and film shear layers near the injection slot. After the S-CO₂ jet enters the near-wall boundary layer, it lifts the mainstream and forms a low-temperature isolation layer of a certain thickness near the wall, thereby providing the capability to directly suppress external aerodynamic heat input.

(3) The single heat-transfer approaches show complementary advantages in wall-temperature control and heat-flux suppression. Internal channel heat transfer provides stronger overall wall-temperature reduction. After CO₂ injection, the stable temperature reduction at the measurement points is concentrated within 20-23 K. Compared with external film cooling, its temperature reduction is approximately doubled in the near-slot region, corresponding to an improvement of about 100%, and can be up to four times higher in the middle and downstream regions, corresponding to an improvement of about 300%. However, because no external film isolation layer is formed, the wall heat flux may return to positive values under continuous aerodynamic heating, indicating limited sustained heat-flux suppression capability. External film heat transfer shows weaker temperature-control capability, with a temperature reduction of about 10-20 K at P_1 and generally within 2.5 K at P_2 - P_5 , but it can maintain negative wall heat flux and therefore provides stronger sustained heat-flux shielding.

(4) Combined channel-film heat transfer exhibits the best comprehensive thermal protection performance in the near-slot region. Under the 0° and 10° angle-of-attack conditions, the stable temperature reduction at measurement point P1 exceeds 30 K. Compared with external film cooling, the combined heat-transfer mode improves the heat-transfer performance at P1 by more than 200% under

the 0° condition and by more than 50% under the 10° condition. Compared with internal channel heat transfer, the heat-transfer performance at P_1 is also improved by approximately 30%–50%. Along the streamwise direction, the heat-transfer performance of the combined mode gradually weakens, with the temperature reduction being approximately 10 K at P_2 and approximately 5 K at P_3 – P_5 , indicating that its heat-transfer capability is mainly concentrated near the injection slot. More importantly, after the S-CO₂ supply is initiated, the wall heat flux at all five valid measurement points rapidly changes from positive to negative and remains negative during the stable stage, meaning that 100% of the valid measurement points achieve sustained negative heat flux. Therefore, combined channel-film heat transfer integrates internal heat absorption and external film insulation, achieving a favorable balance between wall-temperature reduction and heat-flux suppression, and showing considerable engineering application potential for active thermal protection of critical regions of hypersonic vehicles.

In summary, internal channel heat transfer is more favorable for overall wall heat transfer, while external film heat transfer is more effective in continuously reducing external heat input. Combined channel-film heat transfer achieves a favorable synergistic effect between the two. This approach provides the strongest heat-transfer capability in the near-slot region, achieves wall heat-flux suppression comparable to that of single film heat transfer and clearly superior to that of internal channel heat transfer, and offers better overall heat-transfer performance than single film heat transfer. Therefore, combined channel-film heat transfer can achieve a favorable balance among wall temperature control, heat-flux shielding, and working-medium utilization, making it an efficient hybrid active thermal protection scheme suitable for critical regions of hypersonic vehicles.

Authors contribution

Yatian Zhao: Conceptualization, Methodology, Formal analysis, Writing - review & editing. Jia Wei: Investigation, Validation, Data curation, Formal analysis, Writing – original draft. Yang Xu: Project administration, Funding acquisition. Hongkang Liu: Resources, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Statements and Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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