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A New Non-ablative TPS for Hypersonic Vehicles

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Abstract: In order to achieve effective wave drag reduction, a new concept of Non-ablative Thermal Protection System (NaTPS) for hypersonic vehicles was proposed. In the NaTPS, a spike-blunt body structure and lateral jets are combined together to realize the bow shock wave reconstruction. The spike acts to transform the bow shock into a conical shock, and the lateral jets works to push the conical shock wave away from the blunt body to avoid shock/shock interactions. Flow visualizations and pressure measurements were conducted in a hypersonic wind tunnel at Mach number 6 for demonstrating the concept. The peak pressure at the reattachment region is reduced by 65% even under a 4° attack angle by the lateral jet. This NaTPS concept is well demonstrated in this paper, and its engineering application appears to be quite promising.

Key words: Hypersonic flow, TPS, Shock wave, Drag reduction

0 Introduction

The shock-induced aerodynamic drag force and the severe heating are two major issues for the successful development of hypersonic vehicles [1]. The shock wave drag may occupy about two thirds of the total drag of cruising hypersonic vehicles, and one percentage of overall drag reduction will increase about 5-10% payloads [2]. Moreover, the shock-induced drag reduction will also result in the decrease of heat flux at the same time, which will benefit the design of thermal protect system (TPS). Therefore, the study of shock wave drag reduction for hypersonic vehicles is of significant importance.

So far, there have been several shock reconstruction methods or concepts proposed to reduce the shock wave drag. The most effective one of them is to install a physical spike on the nose of blunt bodies [3-15]. In these configurations, the physical spike changes the bow shock ahead of blunt bodies into a conical shock. Approximate 50% drag reduction was predicted under the condition of zero attack angle. However, the spike-blunt body structure becomes ineffective in shock drag reduction if the attack angle is not zero because the shock/shock interaction will

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take place on blunt bodies. This shock/shock interaction results in an extremely high pressure, being much higher than the stagnation pressure, at the interaction point [4]. Moreover, much severe aerodynamic heating occurs at both the spike tip and the shock/shock interaction point on blunt bodies. This difficult problem blocks the application of physical spike-blunt body concept to hypersonic vehicles.

The forward-facing jet injection was proposed to reduce the shock wave drag and stagnation heat flux [8-11]. Pressurized gases, liquids, or solid powders can be used for forward-facing injections. Approximate 50% drag reduction as well as a large percentage of heat flux reduction can be obtained at zero attack angle as well. However, in shock wave reattachment regions, the shock/shock interaction inevitably increases the local pressure and heat flux, which is similar to that of physical spike-blunt body. Moreover, there are two other important problems encountered in the application of the forward-facing jets. The first problem is that powerful jets are necessary to change bow shock waves into conical shock waves. The total pressure of forward-facing jet must be higher than the stagnation pressure, which will make higher requirements for TPS design. The second one is that the drag reduction depends strongly on the flight attack angle. Even the 2^0 attack angle will ruin its drag reduction performance. These two problems tend to limit its application to vehicles with extreme directional stability and very small attack angle variations over the flight range [11].

Another approach to shock drag reduction is to use focused energy depositions. Several energy deposition techniques were investigated, such as pulsed laser focusing, plasma arcs, microwaves, electron beams, pulsed detonations or explosions [16-21]. If the focused energy is deposited in the upstream region of a blunt body, the extremely hot gas is generated instantaneously to push its surrounding gas outward. The gas expansion leaves behind a core of low density and low pressure hot gases, which results in shock wave drag reduction when hypersonic vehicles fly within this core region. If the gas temperature inside the core is sufficiently high to make the gas flow around vehicles become subsonic, the bow shock wave is locally eliminated and the wave drag is further reduced significantly. It was reported that as much as 96% drag reduction was obtained [17]. The energy addition can also be produced by localized combustion [21]. Recent research progress indicates that this concept is more attractive [22, 23]. However, the power budget and the system complexity are highly prohibitive for using the energy deposition concept for hypersonic vehicles. In addition, the high temperature gas produced by local energy deposition probably imposes a heavier burden on the design of TPS.

In order to achieve effective shock drag reduction even under non-zero attack angles and avoid the severe aerothermodynamic heating problem, a new concept of Non-ablative Thermal Protection System (NaTPS) was proposed based on the idea of bow shock wave reconstruction and active cooling [24]. In this NaTPS concept, a spike-blunt body structure and lateral jets are combined together to develop a new shock-reconstructing system for hypersonic vehicles. The spike acts to recast the bow shock in front of the blunt body into a conical shock; meanwhile, the lateral jet works to protect the spike tip from overheating and push the conical shock away from the blunt body when a attack angle exists during flight. Both flow visualizations and pressure measurements were conducted in a hypersonic wind tunnel at Mach number 6 for conceptual demonstration. Numerical simulations were also carried out to examine the detailed complex flows around the NaTPS. Both experimental and numerical results demonstrate that the NaTPS works well for both shock drag reduction and thermal protection. The shock/shock interaction on shoulders of blunt bodies is avoided due to lateral jet injections; as a result, the peak pressure at the reattachment region is greatly reduced by 65% under a 4° attack angle. The lateral jet could be powered either by high-pressure gases stored in the vehicles or by evaporated coolants that absorb aerodynamic heat transferring from the hot surface of vehicles. Experimental data show that the gas pressure needed for producing lateral jets is much lower than that of forward-facing jets method. The NaTPS concept is well demonstrated and some important results are presented in this paper.

1 Experimental descriptions

The concept of NaTPS proposed for hypersonic vehicles is schematically shown in Fig.1. In the NaTPS, the coolant is stored inside blunt bodies used to absorb aerodynamic heats from the coming hypersonic flow. Gases generated from coolant evaporation move forward along the spike to actively cool its tip and then rush out laterally, as shown in Fig.1 (a). For an optimized configuration of NaTPS at a given flight Mach number, the spike-blunt body structure is able to recast the bow shock into a conical shock without any shock/shock interaction occurring at the shoulder of blunt bodies. The lateral jet becomes more effective in pushing away the conical shocks, especially, when flight attack angles become so large that shock/shock interaction points could approach the blunt body surface.

The shock/shock interaction becomes very severe for hypersonic vehicles because the angle of leading shock wave is very small in hypersonic region. The spike-blunt body structure has good performance in shock wave drag reduction in low Mach number region because the angle of shock wave is large at low Mach numbers. The shock wave angle is an important parameter. In this study, we first use lateral jets to enlarge the shock wave angle to avoid shock/shock interaction artificially. It will be demonstrated in the following part that this method produces good performance in shock wave drag reduction for hypersonic vehicles.

The test model consists of two parts: one part is a cylindrical body with a hemispherical nose, measured to be 240mm in length and D=80 mm in diameter; the other part is a spike having a cylindrical body of *L*=80mm in length and a hemispherical nose. The spike installed at the stagnation point is of a hollow structure with its outer diameter of *d*=12mm and the inner diameter of 6mm. There is a half-circular orifice with a width of 1mm on the spike body to produce lateral jets, which is very close to the spike tip. The blunt body and the spike all are made of the 30CrMnSiA alloy steel. For experiments, two rows of pressure transducers are distributed along the top and the bottom generatrix of the model and each row has 15 orifices, respectively. These orifices are 0.1mm in diameter.

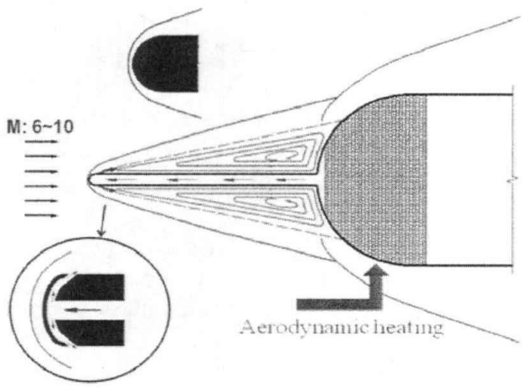


Fig.1 Schematic of NaTPS concept

Both flow visualizations and pressure measurements were conducted in the hypersonic wind tunnel of FD-07 in China Academy of Aerospace and Aerodynamics (CAAA), Beijing, China. The hypersonic wind tunnel has a nozzle of Φ500mm exit diameter and is calibrated at Mach number of Ma=5.9332. The total air pressure in the wind tunnel stagnation section was 20atm, which equals the total pressure of a flight at an altitude of 30km and a Mach number of 6. The lateral jet is air at 5atm total pressure and room temperature. A series of runs were completed in the present study for investigating the parameter effects of the total injection pressure of lateral jets, flight attack angles and shock/shock interaction structures. Flow pressures were measured by using 8400 electronic pressure scanners. Flow visualizations were carried out to study the shock/shock interaction structures around the NaTPS.

2 Results and discussion

There are four key issues that will be discussed in this section. The first issue is about the role of NaTPS in flow-field reconstruction in front of blunt bodies and the shock wave structures in the reconstructed flowfield. The second issue is to check whether the lateral gas injections are able to push the conical shock away from the blunt bodies where the shock/shock interaction takes place. The third one is about the recirculation region in front of the blunt body, which plays an important role in reforming the shock wave configuration. The last one is about the performance of NaTPS in drag and heat reduction for a given flight Mach number. These four issues are believed to comprise the main mechanisms underlying the shock-dominated flowfileds around NaTPS. There may be other issues that are also important to drag-reduction performance of NaTPS, such as the heat transfer between the incoming flow and coolants in the NaTPS, boundary layer development, and materials from which the NaTPS is made. These issues will be studied in the next step.

2.1 Role of NaTPS in flowfield reconstruction

Lateral jet injection is an important part of the proposed NaTPS concept. The first test case is to demonstrate the role of lateral jets on flowfield reconstruction. Two experiments were carried out at zero angle of attack at Mach number 6, one with jet injection and the other without it. The schlieren photos are presented in Fig.2.

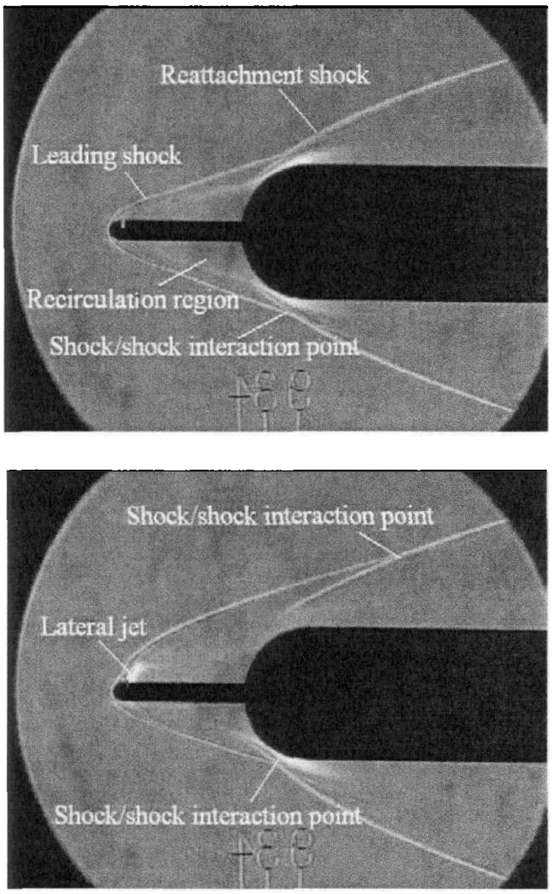


Fig.2 Flow visualization of the flowfiled around NaTPS test model at zero angle of attack

From Fig.2 (a) we can find that a conical shock wave is observable from the spike tip with a shock angle of about 34 degree. A curved reattachment shock wave develops at the shoulder of the blunt body. Shock/shock interactions between the conical shock wave and the reattachment shock wave appear near the surface of the blunt body shoulder. This is the typical flowfield of the spike-blunt body structure. The boundary layer separates from the spike tip and a low pressure recirculation region develops in front of the blunt. The size of the recirculation region depends on the NaTPS structure and the free stream Mach number. The schlieren photo of the second run with lateral jet injection is given in Fig.2 (b). The shock angle of the conical shock wave is increased up to 60 degree at injection position and then decreases finally to about 30 degree downstream. The conical shock wave in the upper flowfield is pushed away so that the shock/shock interaction point moves further away from the blunt body surface. This test case demonstrates that the lateral jet in conjunction with the aero-spike does work well in preventing shock/shock interactions on the shoulder of the blunt body.

2.2 Effects of lateral jet at f non-zero attack angles

Hypersonic vehicles sometimes fly at no designed flight conditions and shock/shock interactions may take place when the flight attack angle becomes larger. The second test case was conducted to investigate lateral injection effects on the reformed shock structure at non-zero attack angle. Two experiments were carried out for Mach number 6 at 4° attack angle, one with lateral jet injection and the other without it. Experimental schlieren photos are given in Fig.3.

Figure 3 (a) shows the result of the run without lateral injection on the windward side. It is observable that the conical shock wave impinges on the shoulder of the blunt body and interacts with the reattachment shock wave on the windward side. This result indicates that the shock/shock interaction cannot be avoided in the spike-blunt body structure that is designed to work for a certain flight condition. It is well understand that the shock/shock interaction will produce a very high peak pressure and peak heat flux at the reattachment point, which results in a severe problem for vehicle TPS system. Actually, the heat flux at shock/shock interaction point has been already demonstrated to be more than ten times higher than that at the stagnation point for decades [3]. And the peak heat transfer rate is related proportionally with the peak pressure [26, 27].

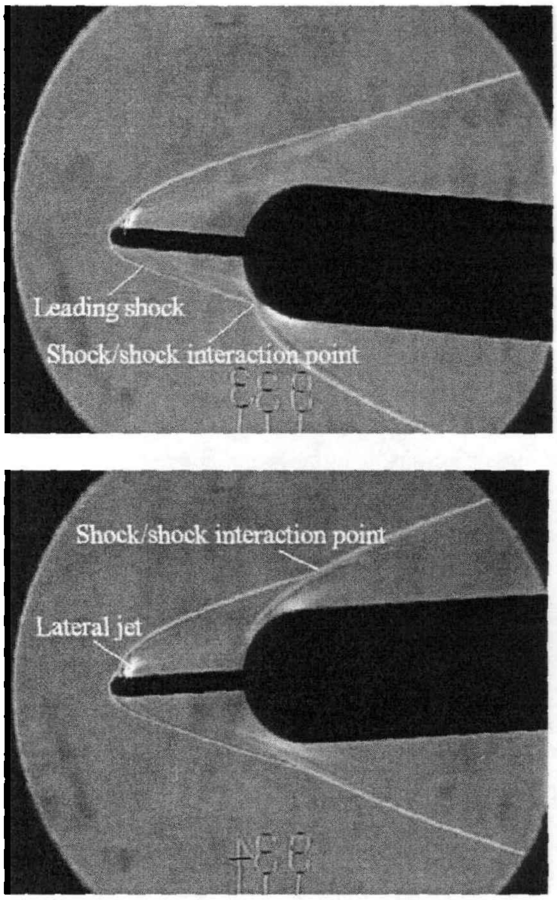


Fig.3 Flow visualization of NaTPS test model at 4° angle of attack

Pressure measurements were also carried out in experiments when visualizing shock structures in the above-mentioned test cases. Figure 4 depicts the measurement results showing comparisons of pressure distributions along the generatrix of windward side with and without lateral jet injection at 0 and 4° attack angles, respectively. The x-coordinate stands for the ratio of the arc length along the blunt body surface measured from the geometric stagnation point to the blunt body diameter. It is observable from test cases both with and without lateral jets that the peak pressure occurs at the reattachment region because of shock/shock interactions.

Figure 4 (a) shows that the peak pressure without lateral jets at zero attack angle is about 26kPa, while the peak pressure with lateral jets is about 9kPa. The peak pressure is reduced by 65% by the lateral jet injection. As a result, the shock wave drag reduction inferred from pressure measurements is 33%. This indicates that the lateral jet works not only for lowering heat transfer flux but also for reducing shock wave drag.

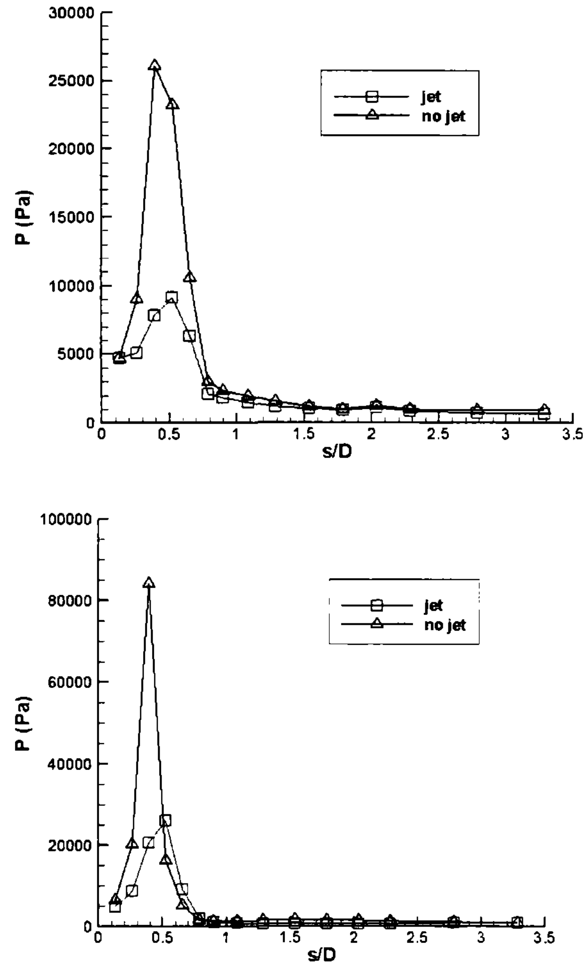
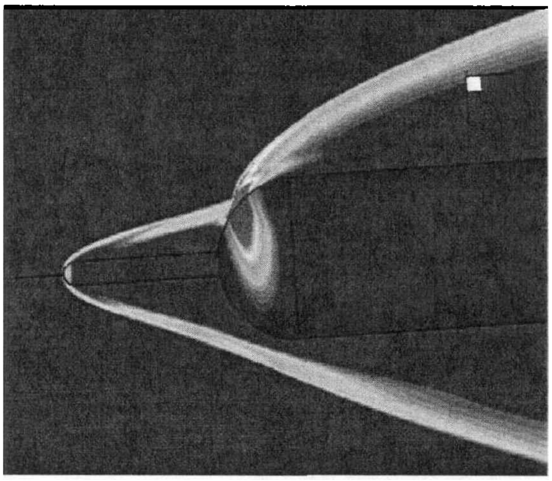


Fig.4 Comparisons of pressure profiles along the generatrix of NaTPS test model

Experimental results for the test cases at 4° attack angle are shown in Fig.4 (b). The peak pressure without lateral jet is about 82kPa, which is much higher than the stagnation pressure of 59.8kPa. When the lateral injection is applied, the peak pressure decreases to be about 26kPa, which is reduced by 65%. This peak pressure is higher than the one shown in Fig.4 (a), but still much lower than the stagnation pressure. The comparisons of pressure distributions quantitatively demonstrate that the lateral jet injection is significantly effective in modifying shock wave structures, mitigating shock/shock interactions, and further reducing both shock wave drags and heat transfer flux for the spike-blunt body TPS system.

2.3 Role of recirculation regions

In order to examine the role of recirculaition regions, three-dimensional numerical simulations with the same experimental conditions were conducted. The results of the cases at a 4° angle of attack both with and without lateral jets are presented in Figs.5 and 6, respectively.



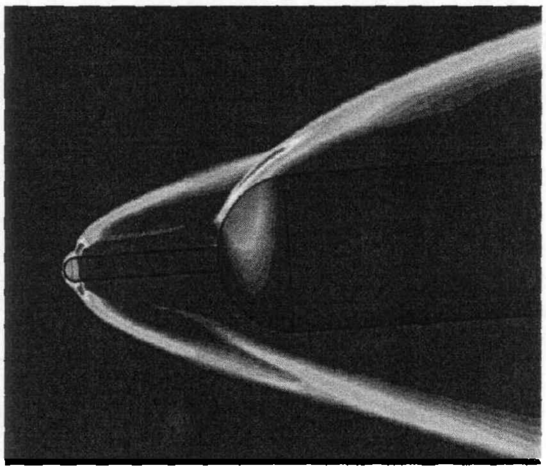


Fig.5 Density contours of test cases at 4° angle of attack with and without lateral jet

It is observable from density contours in Fig.5 (a) that for the case without lateral jet, the conical shock wave on the windward side impinges upon the blunt body surface and interacts with the reattachment shock wave, which results in a significantly high pressure and high temperature region around the shock/shock interaction point. This phenomenon occurs because a part of the gas on the windward side moves to the leeward side, which results in the shrinking of the corresponding recirculation region, as shown in Fig.6 (a). The smaller recirculation region leads to a smaller conical shock angle, so that the shock/shock interaction point approaches the blunt body shoulder. For the spike-blunt body structure, maintaining a big recirculation region on the windward side is the key issue for avoiding shock/shock interactions.

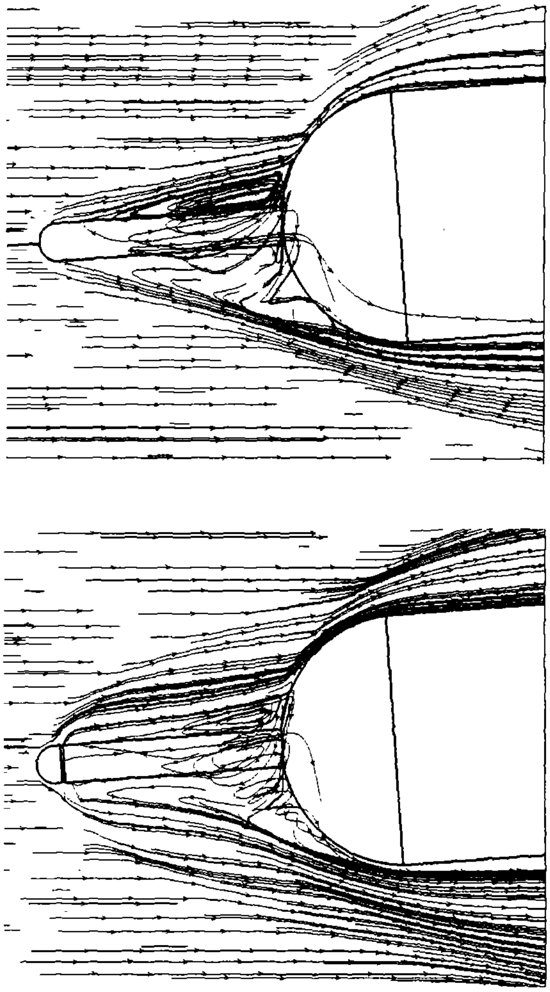


Fig.6 Streamlines of test cases at 4° angle of attack with and without lateral jet

Carefully examining the case with lateral jet injections, as shown in Fig.5 (b), we find that the lateral jet deflects the flow behind the conical shock wave effectively and pushes it away from the blunt body surface. The conical shock wave angle is enlarged so that the interaction of the conical shock wave with the reattachment shock wave could be avoided to occur on the shoulder of the blunt body. Figure 6 (b) shows the flow motion from windward side to the leeward side is weakened and a reasonable scale of recirculation regions is reserved. In this test case, the peak pressure and peak heat flux at the reattachment region are decreased significantly, and accordingly, both shock wave drag and aerodynamic heat addition to vehicles are also reduced significantly. In conclusion, keeping a reasonable size of recirculation regions to avoid shock/shock interactions on the blunt body is a fundamental issue for designing a NaTPS configuration.

3 Conclusions

A new concept of shock wave drag and heat transfer reduction was proposed for hypersonic vehicles, named as the Non-ablative Thermal Protection System (NaTPS). In the NaTPS, an aero-spike/blunt-body structure reforms the shock wave configuration in front of the blunt body. A coolant injecting laterally at the spike tip works effectively to increase the conical shock wave angle by pushing it away from the blunt body surface to mitigate the shock/shock interaction on the shoulder of the blunt body when the flight angle is not zero. As a result, both shock wave drags and the thermodynamic payloads on hypersonic vehicles are reduced significantly by the same TPS system.

Experimental Schlieren photos show that the conical shock wave generated at the spike tip is pushed away from the blunt body surface by the lateral jet and the shock/shock interaction on the shoulder is eliminated at the 4° attack angle. The peak pressure at the reattachment region is reduced by 65% and the shock wave drag inferred from the pressure measurements is reduced by 33%. For the case with zero attack angle, the peak heat flux reduction is about 56% and the peak pressure reduction is about 50%. Numerical results are in good agreement with experimental data. Further three-dimensional simulations reveal that the lateral injection deflects effectively the downstream flow, modifies shock wave configuration, and keeps recirculation regions in a reasonable scale to avoid shock/shock interactions. The very promising performance of the proposed NaTPS for shock wave drag reduction and thermal protection for hypersonic vehicles is well demonstrated and this new concept seems to be of potential importance for future engineering applications.

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