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Concept of Non-Ablative Thermal Protection System for Hypersonic Vehicles

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In order to reduce the shock-wave drag and aerodynamic heating of hypersonic vehicles effectively a new concept of non-ablative thermal protection system was proposed based on the idea of flowfield reconstruction. In this non-ablative thermal protection system a spike-blunt body structure and lateral jets are combined together to realize the flowfield modification. The spike transforms the bow shock into a conical shock, and the lateral jets increase the angle of conical shock wave and keep it away from the blunt body to avoid severe shock/shock interactions. Flow visualizations and pressure measurements were conducted in a hypersonic wind tunnel at Mach number 6 to demonstrate this concept. Numerical simulations were also carried out. Both experimental and numerical results demonstrate that the non-ablative thermal protection system works well for shock-wave drag reduction and thermal protection. The peak pressure at the reattachment region is reduced by 65% even under 4 deg attack angle by the lateral jet. Experimental data also show that the working pressure of lateral jets is much lower than that of forward-facing jets at the stagnation point. All the results show that the engineering application of non-ablative thermal protection system appears to be quite promising.

I. Introduction

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

The most common and useful method to reduce the shock-wave drag of hypersonic vehicles is to minimize the diameters of noses and the thickness of leading edges because conical shock waves induce less shock drag than normal shock waves. However, small diameters of vehicle nose and leading edge could increase the heat fluxes on vehicle surfaces dramatically, which will impose more severe problems upon TPS design. Therefore, exploring new concepts or methods that are able to reduce both the aerodynamic drag and the surface heat flux synchronously has been an attractive research topic for decades.

People proposed many new methods or concepts to reduce the shock-wave drag based on the idea of shock-wave reconstruction besides the modification of aerodynamic configuration. So far, the most effective one of them is to install a physical spike on the nose of blunt bodies [3–7]. In these methods, the physical spike changes the bow shock ahead of blunt bodies into a conical shock. Approximately 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 take place on blunt bodies. This shock/shock interaction results in an extremely high pressure at the interaction point, being much higher than the stagnation pressure. Moreover, much severe aerodynamic heating occurs at both the spike tip and the shock/shock interaction point on blunt bodies [8–10]. This difficulty blocks the application of this concept to hypersonic vehicles.

The method of forward-facing jet injection was then proposed to replace the aerospikes [11–15]. The main advantage of this method is that it can reduce the heat flux at the stagnation point significantly, or it can actively cool the nose of vehicles. Pressurized gases, liquids, or solid powders can be used as a jet. Approximatly 50% drag reduction, as well as a large percentage of heat flux reduction, was also obtained at zero attack angle. However, in shock-wave reattachment regions, the shock/shock interaction also produces local peak pressure and peak heat flux, which is similar to that of physical spike-blunt body. In addition, there are two other important problems encountered in the application of forward-facing jets. The first problem is that the total pressure of forward-facing jets must be higher than the stagnation pressure, which will make higher requirements for TPS design. The second is that the drag reduction depends strongly on the flight attack angle. Even the 2 deg 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].

A new concept to modify the flowfield by using focused energy depositions was proposed recently. Several energy-deposition techniques were investigated, such as pulsed laser focusing, plasma arcs, microwaves, electron beams, pulsed detonations or explosions, and localized combustion [16–22]. Its theory is a little different from that of aerospike or forward-facing jet. When 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. Recent research progress indicates that this concept is more attractive, and as much as 96% drag reduction was reported [19]. However, the power budget and the system complexity are highly prohibitive for using this 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,

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a new concept of non-ablative thermal protection system (NaTPS) was proposed based on the idea of bow shock-wave reconstruction and active cooling [23]. 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 recasts the bow shock in front of the blunt body into a conical shock; meanwhile, the lateral jets actively cool the spike tip from overheating and push the conical shock wave away from the blunt body when an 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. 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 4 deg 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. The NaTPS concept and some important results are presented in this paper.

II. Experimental and Numerical Descriptions

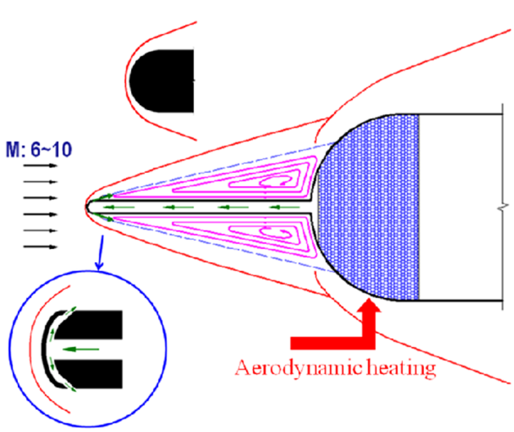
The NaTPS concept proposed for hypersonic vehicles is schematically shown in Fig. 1. In the NaTPS, the coolant stored in the blunt bodies is used to absorb the aerodynamic heats produced by the hypersonic flow. Gases generated by coolant evaporation move forward along the hollow spike to actively cool its tip and then rush out laterally, as shown in Fig. 1a. For an optimized configuration of NaTPS at a given flight Mach number it 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, 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. It produces peak pressure and peak heat flux, which is much higher than the values at stagnation point. The spike-blunt-body structure has good performance in shock-wave drag reduction in low Mach number regions because the angle of the shock wave is larger at low Mach numbers. Therefore, 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.

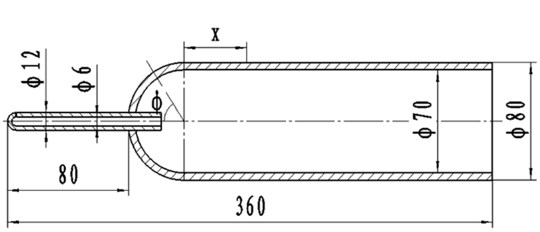
The test model simplified from the NaTPS concept is schematically shown Fig. 1b. The mode consists of two parts: the first part is a cylindrical body with a hemispherical nose, measured to be 240 mm in length and $D = 80$ mm in diameter; the second part is a spike having a cylindrical body of $L = 80$ mm in length and a hemispherical nose. The spike installed at the stagnation point is of a hollow structure with its outer diameter of $d = 12$ mm and inner diameter of 6 mm. There is a half-circular orifice with a width of 1 mm 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. Two rows of pressure transducers are distributed along the top and the bottom generatrix of the model. Each row has 15 orifices with a diameter of 0.1 mm, respectively.

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. The hypersonic wind tunnel has a nozzle of $\Phi 500$ mm exit diameter and is calibrated at Mach number of $Ma = 5.9332$. The total pressure in the wind-tunnel stagnation section is 20 atm, which equals the total pressure of a flight at an altitude of 30 km and a Mach number of 6. The total temperature of the wind tunnel is 465 K. The static pressure of the flowfield is 1357 Pa, and the Reynolds number is 2.0×10^7 1/m, respectively. The lateral jet is air with a total pressure of 5 atm and a total temperature of 298 K. The Mach number of the lateral jet is $Maj = 2.2$. The test model installed in the hypersonic wind tunnel is shown in Fig. 2. Flow pressures were measured by using 8400 electronic pressure scanners. Flow visualizations were carried out with Schlieren system to study the shock/shock interaction structures. A series of runs were completed to investigate the parametric effects of the total injection pressure of lateral jets, flight attack angles, and the shock/shock interaction structures.

Numerical simulations were also conducted to investigate the mechanisms underlying the NaTPS. Axisymmetric and three-dimensional compressible Navier-Stokes equations were accepted to be the governing equations. The Spalart-Allmaras one-equation turbulence model was applied to simulate turbulent effects on the boundary-layer and recirculation regions. The convective terms of governing equations were solved with the second-order scheme of finite difference method [24], and the viscous terms were calculated with the second-order central differencing. Steger-Warming flux splitting method was employed to account for the upwind effect. The temporal integration was performed using the three-order TVD Runge-Kutta method. The computational configuration was the same as the test model and freestream conditions were also taken to be the



a) Working principals of NaTPS for aerodynamic force and heat reduction



b) Dimensions and structure of the test model

Fig. 1 Schematic of NaTPS concept and its test-model dimensions.

Fig. 2 Test model installed in the hypersonic wind tunnel in CAAA.

same as the experiments. The wall boundary condition was assumed to be impermeable, non-slip, and isothermal surface of $T_w = 500$ K. Considering hypersonic flow natures, the outflow boundary was linearly extrapolated from the interior of the computational domain and the inflow quantities were taken to be freestream values of flight at 30 km altitude. The conditions of the lateral jet at the half-circular orifice were assumed to be a choked flow.

III. Results and Discussion

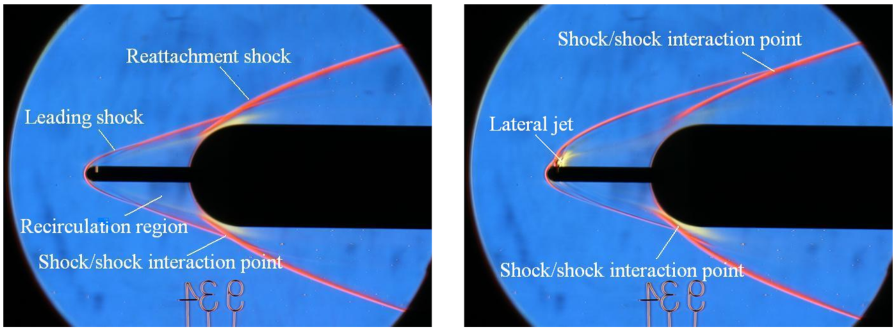
There are four key issues that will be discussed in this section. The first issue is about the role of NaTPS in flowfield reconstruction. The second issue is to check whether the lateral gas injections are able to push the conical shock away from the blunt bodies where the shock/shock interaction takes 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 to study the performance of NaTPS in shock-wave 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 shock-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.

A. Role of Non-Ablative Thermal Protection System in Flowfield Reconstruction

Lateral jet injection is an important part of the proposed NaTPS concept, which can increase the shock-wave angle without producing any drag force. 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. Two schlieren photographs showing the modified shock-wave structures are presented in Fig. 3. From Fig. 3a we can find that a conical shock wave forms at the spike tip with a half angle of about 34 deg. 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 body. The size of the recirculation region depends on the NaTPS structure and the freestream Mach number. The schlieren photographs of the second run with lateral jet injection is given in Fig. 3b. The half angle of the conical shock wave is increased up to 60 deg at the injection position and then decreases finally to about 30 deg downstream. The conical shock wave in the upper flowfield is pushed away by the lateral jet, and 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 aerospike does work well to prevent the shock/shock interactions from taking place on the shoulder of the blunt body.

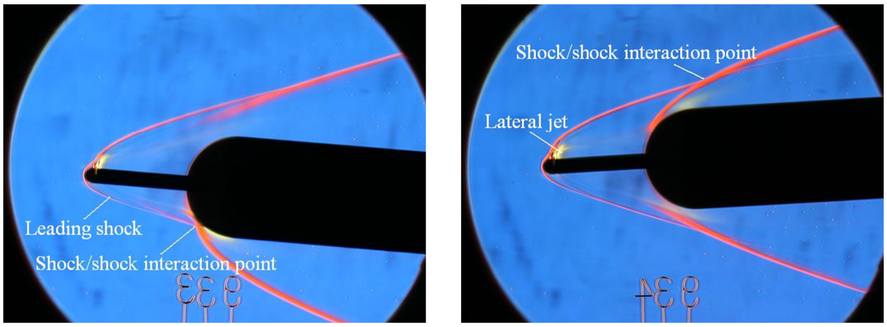
B. Effects of Lateral Jets at Non-Zero Attack Angles

Hypersonic vehicles sometimes fly at off-design conditions and shock/shock interactions become severe on the windward side when the attack angle becomes larger. The second test case was conducted to investigate the effects of lateral injection on the reformed shock structure at non-zero attack angle. Two experiments were carried out at 4 deg attack angle, one with lateral jet injection and the other without it. Experimental schlieren photographs are given in Fig. 4. We just discuss the flowfield on the windward side. Figure 4a 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 with stronger strength. This result indicates that the shock/shock interaction cannot be avoided in the spike-blunt-body structure when it is at a non-zero angle of incidence. It is well understand that the shock/shock interaction produces 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 demonstrated to be more than ten times higher than that at the stagnation point for decades. The peak heat transfer rate is related proportionally to the peak pressure [25–27]. This result reveals the main reason why the aerodynamic performance of aerospike becomes worse at non-zero attack angle.



a) Experiment without lateral jet b) Experiment with lateral jet

Fig. 3 Flow visualization of the flowfiled around NaTPS test model at zero angle of attack.



a) Experiment without lateral jet b) Experiment with lateral jets

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

The flow visualization of the second run with lateral injection applied on the windward side is shown in Fig. 4b. It is clearly seen that the lateral jet significantly increases the conical shock-wave angle and pushes it further away from the blunt body. The reattachment shock wave becomes weaker and the shock/shock interaction point is observed to be far away from the blunt-body surface. As a result, both the peak pressure and heat flux decrease significantly at the reattachment region. This result demonstrates well that the lateral jet works perfectly at non-zero attack angles and maintains the good performance of the spike-blunt body structure on reduction of both shock-wave drag and heat flux.

Pressure measurements were also carried out in experiments of the above-mentioned test cases. Figure 5 shows the comparisons of pressure distributions along the generatrix of windward side with and without lateral jet injection at 0 and 4 deg 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 5a shows that the peak pressure without lateral jets at zero attack angle is about 26 kPa, while the peak pressure with lateral jets is about 9 kPa. 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.

Experimental results for the test cases at 4 deg attack angle are shown in Fig. 5b. The peak pressure on the windward side without lateral jet is about 82 kPa, which is much higher than the stagnation pressure of 59.8 kPa. When the lateral injection is applied the peak pressure decreases to about 26 kPa, which is a reduction of 65%. This peak pressure is higher than the one shown in Fig. 5a, but still much lower than the stagnation pressure. These comparisons of pressure distributions quantitatively demonstrate that the lateral jet injection is very effective in modifying shock-wave structures, mitigating shock/shock interactions, and further reducing both shock-wave drag and heat transfer flux for the spike-blunt-body TPS system.

C. Characters of Recirculation Regions

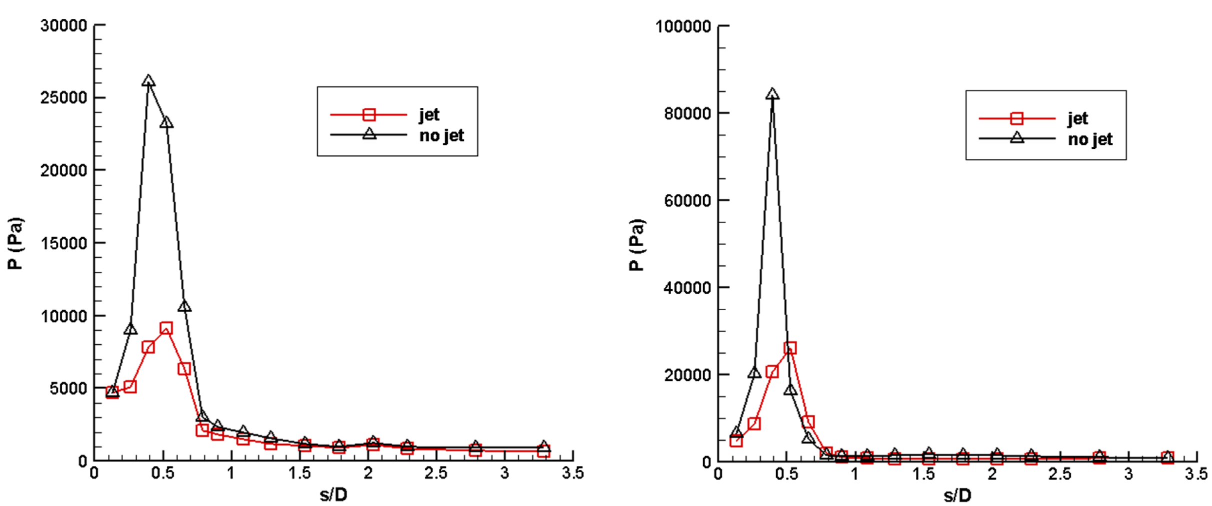
The recirculation region beside the spike and in front of the blunt body of the NaTPS has a close relationship with the conical shock angles; therefore, it is believed that the recirculation region plays an important role in reforming the bow shock-wave configurations. In order to further investigate the role of the recirculation region, numerical simulations were conduced to study mechanisms underlying the shock structure reformation. In order to demonstrate the reliability of numerical simulations, an axisymmetric case for the NaTPS was carried out and results were compared with the experiment at the same conditions. Figure 6a shows the reformed shock structure of the spike blunt body without lateral jet. The patterns of the reattachment shock and the shock/shock interaction look identical to the experimental photographs shown in Fig. 3a. The experimental and numerical pressure profiles are plotted together in Fig. 6b. The repeatability of experiments was conducted and the results are given in Fig. 6c. The maximum error at the attachment point between these two runs is 2.6%. It can be seen that very good agreement is achieved by the comparison. This validation not only verifies numerical results but also demonstrates that the key physical issues observed are reliable.

Three-dimensional numerical simulations with the same experimental conditions were conducted to explore the role of recirculation regions. The results of the cases at 4 deg angle of attack both with and without lateral jets are presented in Figs. 7 and 8, respectively. It is observable from density contours in Fig. 7a 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. 8a. The smaller recirculation region leads to a smaller conical shock angle so that the shock/shock interaction point approaches the blunt-body shoulder. Therefore, for the spike-blunt-body structure, maintaining a big recirculation region on the windward side is the key issue for avoiding shock/shock interactions and reducing shock drag and heat flux.

Carefully examining the case with lateral jet injections, as shown in Fig. 7b, 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 8b 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; accordingly, both the shock-wave drag and the total 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.

D. Reduction of Both Heat Flux and Shock Wave Drag

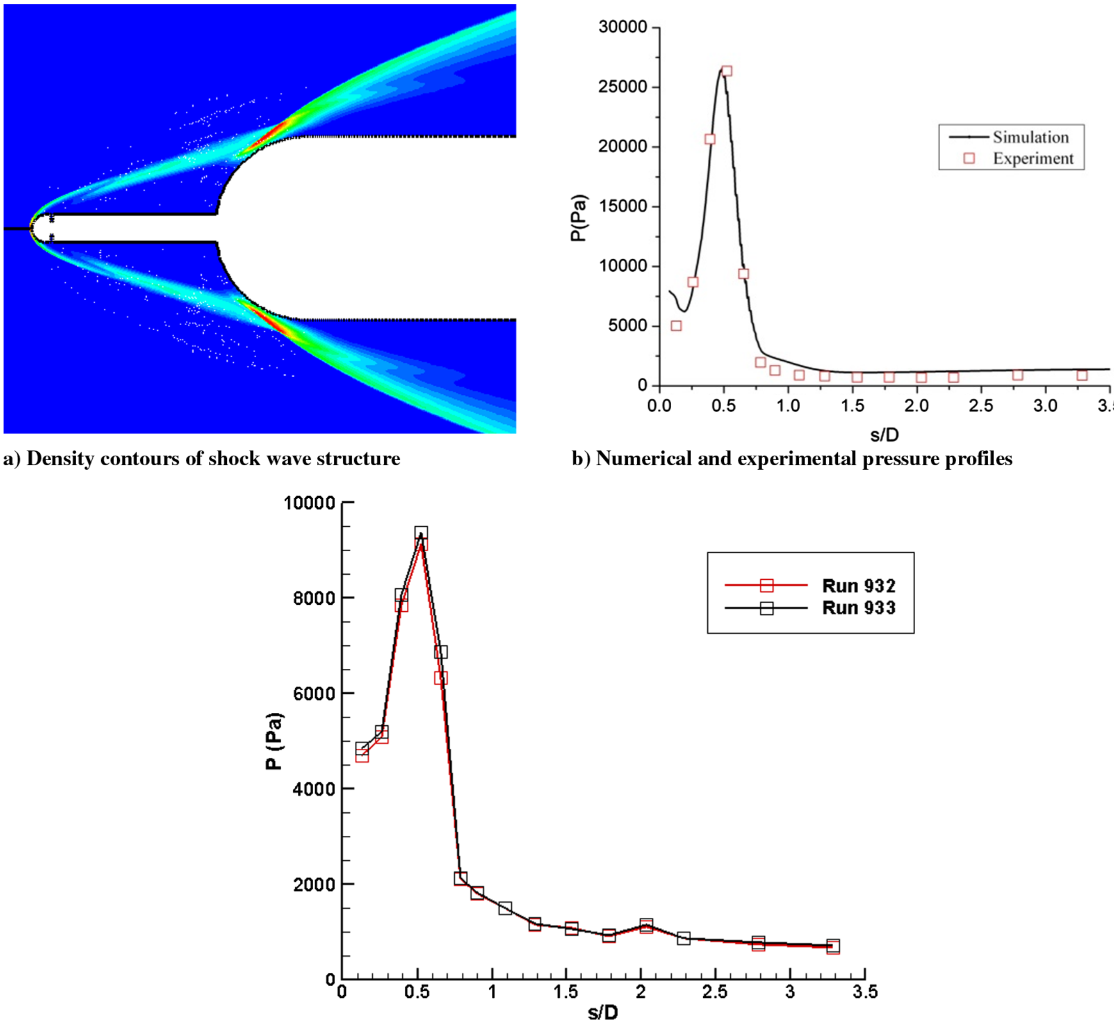
Axisymetric numerical simulations were conducted to study the heat flux of this configuration. Assuming that flight conditions are at



a) Pressure profiles at zero attack angle

b) Pressure profiles at 4° attack angle

Fig. 5 Comparisons of pressure profiles along the generatrix of NaTPS test model.



a) Density contours of shock wave structure

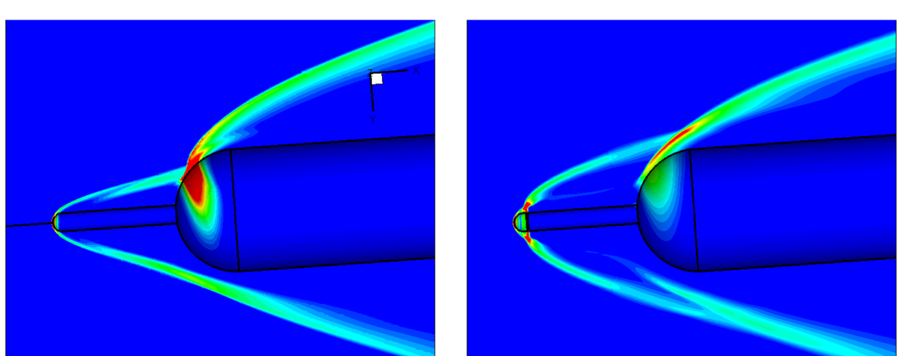
b) Numerical and experimental pressure profiles

c) Repeatability of experiments at 0 attack angle

Fig. 6 Validation of numerical results by experimental data.

an altitude of 30 km and a Mach number of 6, the performance of heat flux and wave drag reduction of NaTPS are carried out numerically and some numerical results are given here briefly. The heat flux on the test-model surface at zero attack angle was plotted in Fig. 9a for test cases both without and with lateral jets, and the corresponding pressure profiles were presented in Fig. 9b. It can be seen from Fig. 9 that the peak heat flux at the reattachment point is reduced from 625 $\mathrm{kW/m^2}$ to 350 $\mathrm{kW/m^2}$ by the lateral jet and the reduction rate is as high as about 56%. The peak pressure is reduced from 25,000 to 12,500 Pa and a 50% reduction in shock-wave drag is achieved. This reduction is on the base of the spike-blunt-body structure, so more than a 50% reduction becomes possible for pure blunt bodies. Therefore, the performance of the NaTPS is well demonstrated.

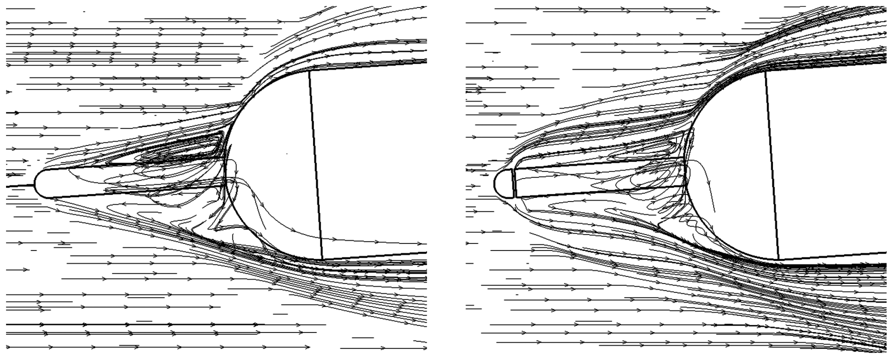
As is well known, the shock/shock interaction can induce severe peak pressure and peak heat flux that could be many times higher than that at the stagnation point. In the NaTPS concept, both the peak pressure and heat flux were reduced synchronously by the combination of lateral jets and the spike blunt body. Lateral jets work to push the shock/shock interaction point away from the body surface especially when a flight angle is not zero. If the injected flow flux is big enough it can actively cool the tip of the spike to prevent it from being overheated. The NaTPS is very promising for air-breathing



a) The case without lateral jet

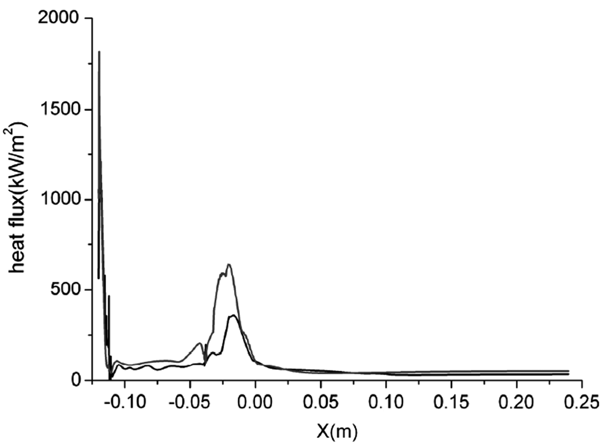
b) The case with lateral jets

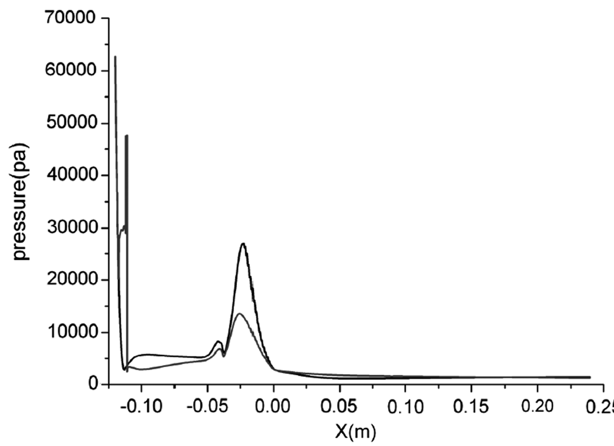
Fig. 7 Density contours of test cases at 4 deg angle of attack with and without lateral jet.



a) The case without lateral jet b) The case with lateral jet

Fig. 8 Streamlines of test cases at 4 deg angle of attack with and without lateral jet.





a) Heat flux for cases with and without jets b) Pressure profiles for cases with and without jets

Fig. 9 Comparisons of heat flux and pressure distribution of CFD results at zero attack angle.

hypersonic vehicles because the cross-section area of the spike is only 2.25% of blunt bodies; therefore, the NaTPS weight is not a critical issue for its engineering applications.

IV. Conclusions

In this paper, a new concept of shock-wave drag and heat-transfer reduction was proposed for advanced thermal protection system of hypersonic vehicles, named as the non-ablative thermal protection system (NaTPS). In the NaTPS, an aerospike/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 thermal protection system (TPS).

Both pressure measurements in hypersonic wind-tunnel and numerical simulations were conducted to verify this new concept. Experimental schlieren photographs 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 deg 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. Three-dimensional simulations further 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. All the results show that this new concept seems to be of potential importance for future engineering applications.

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