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Detailed parametric investigations on drag and heat flux reduction induced by a combinational spike and opposing jet concept in hypersonic flows

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ABSTRACT

In the current study, the flow field behavior induced by a novel combinational opposing jet and spike concept has been investigated numerically. A comprehensive analysis on the selections of the turbulence model and the height of the first grid point off the wall (Δx) has been conducted firstly. Then, this paper mainly focuses on the influences of the nozzle diameter (d_0), the length-to-diameter ratio of the aerospike (L/D) and the jet pressure ratio (PR) on the flow field structures, the aerodynamic drag and heat properties. The results show that when d_0 is 2 mm, adding the opposing jet to the single spiked blunt body has no help in modifying the high drag and heat environment. However, the combinatorial thermal protection system has a great contribution to reduce the drag and heat when d_0 is 4 mm, with 45% and 38% drop on the wall Stanton number (St) and drag coefficient (Cd) respectively. The values of the wall heat flux, the static pressure and the drag coefficient decrease apparently when L/D increases from 1.0 to 1.5, while the drop rates of these indexes seem not so obvious when L/D rises from 1.5 to 2.0. Meanwhile, the introduction of the opposing jet creates a recirculation zone upstream the spike head, and there is a recirculation zone emerges downstream the aerodisk as well when L/D increases to 2.0. Both of the recirculation zones have alleviated the high temperature the aerodisk sustained significantly.

1. Introduction

The aircraft that cruises for long hours in hypersonic conditions is called a hypersonic vehicle, and it has the advantages of high flight speed, short response time and strong breakout ability [1]. The huge economic and performance advantages make it as one of the most promising technologies in the future aerospace industry [2]. However, due to the aerodynamic drag and heat problem caused by the high-speed flight [3,4], the operational performance of hypersonic vehicles has dropped dramatically, and the aircraft will face serious challenges in the practical application [5]. Therefore, the study on the thermal protection system of hypersonic vehicles is extremely urgent, as well as its control problem [6–10].

The thermal protection technology is usually divided into two kinds, namely passive and active thermal protections [5]. The passive thermal protection technology mainly uses heat insulating or ablative materials to protect the aircraft surface from thermal effects [11], whereas the active thermal protection principally takes the advantage of jetting cooling medium, designing special configuration or installing drag diminish equipment. The effect of the passive thermal protection technology depends on the characteristics of the protective material. As the wall heat flux of the aircraft heats up, the thicker the material required on the surface, resulting in an increase on the overall aircraft mass, and this is detrimental to the maneuverability. Meanwhile, due to the difficulty in controlling the additional heat flow caused by the ablation of the surface material and the truth that many thermal insulation materials cannot be reused, the effect of the passive thermal protection technology cannot last for a long time. The active thermal protection techniques include forward-facing cavity [12], opposing jet [13,14], energy deposition [15], installation of aerospike [16] and their combinations [17]. A number of research teams around the world have carried out experiments or numerical simulations on active thermal protection systems for hypersonic vehicles, and this section will briefly introduce the research progress on the opposing jet, the aerospike and the counterflowing jet-aerospike combinational thermal protection system.

The aerospike has the ability of pushing the strong bow shock wave off the wall of the aircraft head effectively, and a weak cone

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shock wave formed from rod head which can reduce the pressure and temperature of the flowfield after the shock wave. At the same time, the additional spike has the function of separating the upstream flowfield of the blunt body, and the shear layer caused by the separation flow attaches to the aircraft surface forming a recirculation zone in the flowfield near the head of the aircraft. Under the combined action of the conical shock wave and the recirculation zone, the drag and heat to the aircraft wall will be greatly reduced. After decades of investigation, installing an aerospike on the head of a hypersonic vehicle has been proved to be a simple, reliable and effective way to reduce the aerodynamic drag and heat [18].

The effects of the spike length, the aerodisk shape and size on the flowfield structure and aerodynamic phenomena around the blunt body have aroused wide concern in recent years. Ahmed and Qin [19] made a very detailed discussion on the research progress of aerospike. They listed 77 articles about the wind tunnel tests and numerical simulations done by researchers in the appendix A of their paper. From this paper, a comprehensive summary of the experimental research shows that the length-to-diameter ratio of the aerospike (L/D) is a significant geometric parameter of the thermal protection system. A large number of scholars have carried out extensive and profound experiments [20–24] and numerical simulations [25–31] on the aerospike configuration (spike length, the aerodisk configuration, the number of the disk, etc.). In addition, in order to improve the performance of the aerospike system [20,32,33] when there is a flow angle of attack [34–37], a self-aligning spike approach has been proposed, and various experiment tests and numerical simulations have been carried out. The obtained results show that even at high angles of attack, the adaptive aerospike system still has the ability of well aligned with the incoming flow direction, and this can make the total drag of the blunt body decline within a wide range of angle of attack. Khurana and Suzuki [38] originally carried out a wind tunnel experiment on the drag and heat reduction effect on the aerospike system of a lifting body, and the physical model is 0.004 times scale down X-33 aircraft with the freestream Mach number being 7.0. In their experiments, the effect of spike configuration on the flowfield structure and the aerodynamic performance was studied, and the ultimate practicability of these configurations on the lifting body was evaluated as well. Deng et al. [39] conducted a three-dimensional numerical simulation on the drag decrease system of a lifting body, and the freestream Mach number is 8.0. Results show that installing an aerospike at a certain angle not only plays an important role in reducing the drag and improving the lift-to-drag ratio, but also helps in maintaining the effect of the thermal protection system in the case of an angle of attack.

The opposing jet scheme was proposed to solve the problem that some thermal protection systems cannot be reused and cannot provide a long-term protection for hypersonic vehicles [40], and the transverse injection strategy has been widely applied in the airbreathing propulsion system [41]. In the early research period, a large number of scholars [42–45] have conducted in-depth mechanism study on the opposing jet, and its mechanism can be described as follows. The working medium (gas [46], liquid [47], solid [48] or plasma [49]) which jets reversely from the head of a blunt body pushes the shock wave away from the surface, changing the pressure distribution on the wall of the blunt body and cutting down the wall load successfully. Under the combined effect of the incoming and jet flows, a recirculation zone is formed which can dramatically weaken the heat flux around the head of the blunt body. The research hotspots in the opposing jet include the long/short penetration modes, the nozzle configuration, and the jet medium and so on. Both the experimental and numerical investigations on the counterflowing thermal protection system were reviewed in detail by Huang [5] and Wang et al. [50].

The wind tunnel experiment [51,52] and numerical simulation [53] carried out by Hayashi et al. clearly revealed the flow field structures in front of the blunt body with different jet pressure ratios (PR), and the results of their studies are regarded as the criterion for numerical approach verification by many researchers. There are many research groups conducted careful studies on the counterflowing system installed on the blunt body, slender body or lift body. They mainly focus on the flow field structures of the long/short penetration modes, the oscillation phenomenon of the shock wave, the critical PR of the two penetration modes and so on [54–57]. Daso et al. [58] conducted a three-sonic wind tunnel experiment and numerical simulation on a 2.6% scale-down Apollo aircraft model under the hypersonic condition, and the obtained results show that the long-penetration mode appears at low injection rates (0.05, $0.1 lb_m/s$) and the short-penetration mode appears at higher jet rates ($>0.1\ lb_m/s$). The opposing jet has the benefit of decreasing the heat fluxes around the head of the aircraft significantly. Moreover, the flow can even absorb wall heat fluxes in the short penetration mode, making the wall aerodynamic heat decline. The same conclusion was achieved by Gerdroodbary et al. [59]. Shen et al. [48] introduced a new type of gas supply device to the opposing jet thermal protection system and employed the solid fuel (azodicarbonamide (ADC) and basic cupricnitrate (BCN)) as the cooling medium. Their research shows that the effect of the high temperature solid fuel with a total temperature of 900 K on the drag and heat reduction is as good as gas. In addition, Bibi et al. [60] carried out a numerical simulation which aimed to study the influence of the expansion nozzle. Li et al. investigated the impacts of the opposing jet nozzle configuration [61,62] and the freestream flow conditions [63] on the drag and heat reduction with a counterflowing system by using three-dimensional numerical simulation.

Although the aerospike system has the benefits of simple structure and obvious effect, it cannot offer a long-term effective protection for aircrafts due to the head of the spike being in a severe aerodynamic heating environment and needs frequent replacement. At the same time, it is necessary to attach a complicated jet device when the opposing jet technology is implemented on an aircraft, which will increase the aircraft load greatly and it has been proved to be not conducive to the maneuverability of the aircraft. Therefore, although a single scheme has great value to look into, it will bring new benefits to the drag-diminish and heat-proof for reentry vehicles in hypersonic flows vitality by associating two or more thermal protection technologies. As a combined thermal protection system has the capability of reinforcing complementary advantages of each single technique, it has a crucial development and application prospect.

Gerdroodbary et al. [64] studied the combination of an aerospike and an opposing jet at the Mach number of 5.75, in which the cooling gas was ejected from the top of the blunt body. The results of the study demonstrate the enormous benefits of a combined thermal protection system for the drag reduction and thermal relaxation of the blunt body. The total heat of the blunt body wall drops obviously with the increase of PR, and the down trending of the total heat is even more noticeable by using He as the cooling gas when compared with CO_2. Eghlima et al. [65,66] depicted the numerical simulation of the drag force variation and the heat flow transformation around a spherical head cylinder when a combinatorial thermal protection system was installed, and the jet gas was air. Huang et al. [67] conducted a numerical simulation on the aerospike and opposing jet combinational system in the hypersonic flow with a Mach number of 3.98, and the jet gas in their research was nitrogen. In both studies, the cooling medium was ejected from the spike head. Jiang et al. [68] carried out a wind tunnel experiment on the hemispherical-cylindrical blunt body, and their aim was to study the effect of the aerospike