International Journal of Heat and Mass Transfer 127 (2018) 503–512

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Drag and heat flux reduction induced by the pulsed counterflowing jet with different periods on a blunt body in supersonic flows

Rui-rui Zhang [a], Wei Huang [a,*], Lang-quan Li [b], Li Yan [a], R. Moradi [c]

[a] Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha, Hunan 410073, People's Republic of China
[b] Hypervelocity Aerodynamics Institute, Chinese Aerodynamics Research and Development Center, Mianyang 621000, People's Republic of China
[c] Department of Chemical Engineering, School of Engineering & Applied Science, Khazar University, Baku, Azerbaijan

ARTICLE INFO

Article history:
Received 26 July 2018
Received in revised form 11 August 2018
Accepted 15 August 2018

Keywords:
Pulsed counterflowing jet
Period
Waveform
Drag reduction
Heat flux reduction
Supersonic flow

ABSTRACT

In the current study, three different kinds of pulsed jets with the period being 0.5 ms, 1.0 ms and 2.0 ms are established, and sinusoidal waveforms are used in all three pulsed jets. The pulsed counterflowing jets with the same amplitude but different periods on the nose of a blunt body in supersonic flows are investigated numerically, and an axisymmetric numerical simulation model of the counterflowing jet on the supersonic vehicle nose-tip is established. The obtained results show that the wall Stanton number and surface pressure change periodically with the pulsed jet, and the variations of the parameters show a strong hysteresis phenomenon. The hysteresis phenomenon becomes less significant as the period increases. At the same time, a better drag and heat flux reduction is obtained under larger period pulsed jet conditions. With the increase of the period of the pulsed jet, there is a significant decline in the maximum peak values of the wall Stanton number and surface pressure. Compared with the steady jet, the pulsed jet is more effective in heat flux reduction, but the drag reduction of the pulsed jet is less effective than the steady jet.

1. Introduction

The drag and heat flux relates to improve the speed and reliability of the aerospace vehicle, and the high pressure and severe aerodynamic heating induced by shock wave interactions will cause the damage on the nose of the aerospace vehicle. Moreover, the high pressure and severe aerodynamic heating could cause serious damage to the electronic hardware inside the aerospace vehicle. In addition, the great shock wave drag also restricts the flight speed of the aircraft. Therefore, the drag and heat flux reduction systems applied to aerospace vehicles have attracted an increasing attention due to the high pressure, severe aerodynamic heating and great shock wave drag. To solve these problems, many strategies have been proposed and investigated by the experimental test and numerical simulation according to whether the schemes are controllable, and the drag and heat flux reduction systems can be divided into two types, namely active and passive [1]. The passive drag and heat flux reduction system is to use heat-resistant material ablation to achieve thermal insulation, and its development mainly depends on the research and development of new ablative materials. However, the ablation of surface materials will inevitably affect the aerodynamic shape of the aircraft, and it can only protect the aircraft in a limited time but hard to sustain for long. The high temperature ablation on the surface of metal blunt body in a hypersonic flow was simulated numerically by Tahsini [2], and the drag coefficient was reduced by about 20%, but the increase in the heat flux from ablation is difficult to control. The active drag and heat flux reduction system is to add cooling medium to the high temperature area or design specific configuration, aiming at changing the flow field structures and realizing the purpose of drag and heat flux reduction. At present, there are several commonly used active drag and heat reduction systems, namely the forward-facing cavity [3,4], a retractable aerospike ahead of the blunt body [5–7], the concentrated energy deposition along the stagnation streamline, a counterflowing jet issued at the stagnation point [8–11] and their combinations [12–15]. The jet has been commonly employed in the scramjet engine to enhance the mixing process between the fuel and air as well [16–19], and Choubey and Pandey investigated the influence of its schemes on the flow field properties of a typical strut-based scramjet combustor numerically [20], as well as a typical double cavity scramjet combustor [21]. In this part, only active drag and heat flux reduction systems are introduced in detail.

The drag and heat flux reduction system of setting the counterflowing jet at the stagnation point of the aircraft was first proposed

---

* Corresponding author.
E-mail address: gladrain2001@163.com (W. Huang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.066
0017-9310/

in the 1950s, and it was proposed to solve the problem that the passive drag and heat flux reduction systems cannot be reused. The schematic diagram of the flow field with a counterflowing jet injected at the nose of a blunt body against the supersonic freestream is shown in Fig. 1. In this flow field, the counterflowing jet nozzle is usually arranged on the longitudinal axis of the nose cone, and the coolant medium spurts out from the jet nozzle at a high speed. The counterflowing jet forms a Mach disk in order to balance the pressure of the jet flow with the pressure of the flow behind the detached shock wave, and then the counterflowing jet contacts with the freestream. Accordingly, the contact surface is formed. The jet flow is pushed back by the freestream and reattached to the surface of the blunt body, and a recirculation region is formed around the exit of the nozzle. The recompression shock wave is formed near the reattachment of the jet layer. The high speed coolant medium can push shock waves off the surface of the aircraft and reduce the thermal load on the aircraft surface. In addition, the coolant medium could also reduce the temperature of the aircraft surface by heat transfer.

As one of the active drag and heat flux reduction techniques, the counterflowing jet has attracted an extensive attention. Hayashi et al. [22] gave an experiment on the opposing jet in the supersonic flow. In their experiment, a conventional blowdown-type supersonic wind tunnel was used, and a blunt body with the diameter being 50 mm was placed in the wind tunnel. The freestream Mach number is 3.98, the diameter of the sonic nozzle is 4 mm and the jet Mach number is 1.0. In their investigations, the obtained results show that a significant reduction of the surface heat flux was observed under the short penetration mode (SPM) with a higher total pressure ratio (PR), and the reduction of the heat flux caused by the counterflowing jet was quite effective at the nose of the blunt body. It was also found that no reduction of the surface heat flux was observed under the long penetration mode (LPM) with a lower total pressure ratio (PR). Under the long penetration mode, the heat flux is higher than that of the no-jet case. Based on this experiment, they carried out a numerical simulation on this configuration [23], they used the compressed air instead of nitrogen as a coolant medium, and the numerical results are in good agreement with the experimental results. Rong et al. [24–26] conducted an in-depth numerical simulation of the above configurations, and nitrogen was used as the coolant medium. The predicted results agree well with the experimental results. Lu et al. [27] gave a numerical investigation on properties of attack angle for an opposing jet thermal protection system with the above configurations, and the results show that the heat flux reduction effect has been lost under 10° of attack angle. In 2011, Venkatachari et al. [28] investigated the interaction of the counterflowing jet and the supersonic capsule flows numerically. In their study, a 2.6% subscale Apollo model with a supersonic nozzle at its center was established, and the diameter of the supersonic nozzle is 12.7 mm. The freestream Mach number is set to be 3.48. They observed the flow filed variations induced by changing the jet mass flow rate. At the same time, they found that both long and short penetration modes exist, and they both exhibit non-stationary behavior. By contrast, the long penetration mode is much more unstable than the short one. It was also found that the unstable long penetration mode only exists in a relatively small range of the jet mass flow rate. In 2011, Imoto et al. [29] carried out an experiment on a spherical cylinder with a diameter of 60 mm in a high enthalpy flow with a Mach number of 6.6, and the nitrogen and helium were both used as the coolant medium in the experiment. The total pressure ratio (PR) is between 0.0103 and 0.0432. They pointed out that nitrogen cools better than helium. In 2015, Huang [12] provided a detailed review on the reduction of drag and heat flux induced by the counterflowing jet and its combinations, and the combinations include the combination of the counterflowing jet and a forward-facing cavity, the combination of the counterflowing jet and an aerospike, and the combination of the counterflowing jet and energy deposition. Further, he and his co-workers investigated the drag and heat flux reduction mechanism induced by the combinational counterflowing jet and cavity concept numerically [30,31].

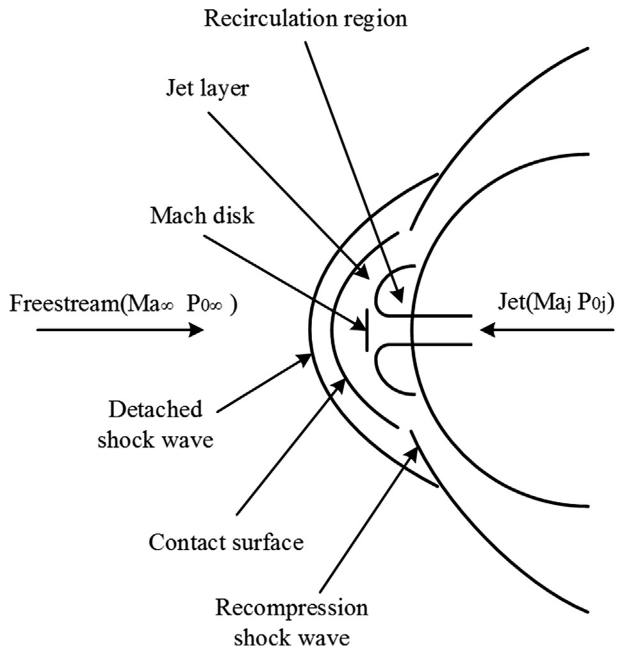

Fig. 1. Flow field of the counterflowing jet against the supersonic freestream.

In 2018, Zhang et al. [32] investigated the drag and heat flux reduction mechanism of the pulsed counterflowing jet on a blunt body in supersonic flows numerically, and the same physical model as in Hayashi's experiment [22] was employed in their study. A sine wave shape was chosen as the pulsation waveform to substitute the steady counterflowing jet, and it was employed in the scramjet combustor to enhance the mixing process as well [33]. The mean counterflowing jet static temperature and flow Mach number are equal to the counterparts described above for the steady jet, and the interval of the periodic variation of the total pressure ratio of the pulsed jet flow field is 0.2–1.0. The periodic time of the pulsed jet is $T = 0.001$ s, and one and a half periods are calculated in their study. The results show that the flow field structures in the instant of $PR = 0.2$ are very similar to those under the stable conditions. The structures of Mach disk, detached bow shock wave, contact surface and recompression shock wave are all clearly observed. Throughout the whole calculation cycle, the flow field presents a short penetration mode (SPM), and there is no appearance of the long penetration mode (LPM). The bow shock wave standoff distance, the peak values of the heat flux and the drag force all present a strong periodic variation as time goes on. The responses of the bow shock wave standoff distance, the peak value of the heat flux and the drag force caused by the pulsed jet have an obvious hysteresis phenomenon.

In the current study, three different kinds of pulsed jets with the period being 0.5 ms, 1.0 ms and 2.0 ms are established, and sinusoidal waveforms are used in all three pulsed jets. The pulsed counterflowing jets with the same amplitude but different periods on the nose of a blunt body in supersonic flows are investigated numerically.

2. Physical model

The diameter of the supersonic blunt body is set to be 50 mm, and the radius of the blunt body is 25 mm, namely $R = 25$ mm.