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Drag reduction of supersonic blunt bodies using opposing jet and nozzle geometric variations

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ABSTRACT

Passive and active flow control methods are used to manipulate flow fields to reduce acoustic signature, aerodynamic drag and heating experienced by blunt bodies flying at supersonic and hypersonic speeds. This paper investigate the use of active opposing jet concept in combination with geometric variations of the opposing jet nozzle to alleviate high wave drag formation. A numerical study is conducted to observe the effects of simple jet as well as jet emanating from a divergent nozzle located at the nose of a blunt hemispherical body. An initial discussion is presented of the complex shock wave pattern flow physics occurring when opposing jet ejected from a nozzle under various operating conditions interacts with the free stream flow. The complex flow physics that include long penetration and short penetration mode is studied in conjunction with effect on drag. The numerical setup consists of supersonic free stream flow interacting with an opposing sonic jet under varying pressure ratios. Initial computational results are validated by identifying prominent flow features as well as comparing available experimental data of surface pressure distributions. Preliminary validation is followed by the introduction of a divergent nozzle in the blunt body nose region. A series of numerical iterations are performed by varying nozzle geometric parameters that include nozzle divergent angle and nozzle length for a certain jet pressure ratio. Long penetration mode, short penetration mode as well as flow separations are captured accurately during the analysis. The results show a considerable reduction in drag by the use of a divergent nozzle. Specifically, 46% and 56% reduction in drag coefficient is achieved at pressure ratio of 0.6 and 0.8 respectively in the divergent nozzle cases as compared to the simple blunt body without any nozzle.

1. Introduction

Although blunt profiles in high speed help in reducing heat transfer to the body, they also increase overall drag experienced by the body. This high value of drag can be useful in re-entry applications where it actually helps to reduce the velocity during re-entry. However, for supersonic transport applications, where greater velocities are advantageous, the blunt body profile produces unnecessary drag. Efforts to reduce drag have been under study since the very inception of high speed vehicles. In this regard the opposing jet concept has gained the most interest in the research community due to its reusability and relatively economic implementation as compared to other methods. Series of research efforts over the years have showed a marked decrease in both heat and drag experienced by blunt profiles using an opposing jet issuing from the fore body region. All applications whether supersonic, hypersonic can achieve more efficient flight missions by the use of counter flowing forebody jets. The high speed application band encompasses fighter jets, transport jets, reconnaissance systems, supersonic cruise missiles and Inter-Continental Ballistic Missiles. Advancement in the study of the active flow control system can prove to be quite helpful in progressing research activities for the new space technologies such as Reusable Launch Vehicles, Orbital Transfer Vehicles, and the more commercial application of space tourism. The opposing jet can play a key role in overcoming the challenges of the severe flight conditions experienced in these rapidly advancing technologies.

1.1. Related work

By the end of World War II supersonic flight gained great importance in the form of high speed rockets. The development of Inter-Continental Ballistic Missiles (ICBM) started in 1953 [1]. From here began an era of supersonic vehicles which through further advancement have evolved into hypersonic travelers including jet aircrafts, missiles, space shuttles and re-entry vehicles. All these

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Nomenclature

L	Length of divergent nozzle	PR	Pressure Ratio
α	Angle of divergent nozzle	P_∞	Free stream static pressure
θ	Location on surface of body	P_e	Nozzle exit pressure
M_∞	Free stream Mach number	D	Diameter of blunt body
M_J	Jet Mach number	d_J	Diameter of jet
$P_{0\infty}$	Free stream stagnation pressure	SPM	Short Penetration Mode
P_{0J}	Jet stagnation pressure	LPM	Long Penetration Mode

missions must combat a common feature of high drag, high temperature environment and high acoustic signature. Therefore, with the development of supersonic travelers in the early 1950's; efforts to combat their severe aerodynamic environments were also initiated alongside.

Studies on the use of opposing jet to manipulate flow fields began since early 1950's [2]. Early research in the area was concerned mainly on understanding flow physics of the opposing jet phenomena [3,4]. The earliest work on heat transfer effects was made by Inouye [5] in which it was concluded that at low flow rates heat transfer to body decreases by the use of opposing jet. A similar conclusion was made by Warren [6] where nitrogen and helium gases were used as opposing jets. It was inferred that as long as the jet flow remains small enough to not penetrate the free stream, heat reduction over body will occur. However, Finley [7] pointed out that Warren's study included very low pressure ratios. Hence, larger pressure ratios beyond the unstable region actually help to reduce heating. This conclusion was also made in the work of Rashis [8].

In 1960s and 1970s, attention was directed towards the heat and drag reduction effects of opposing jets. Advancement in the research of opposing jet technology lead to the study of various other aspects such as effect of different jet ejection materials, effect of flow variation and geometric parameters. Warren [6] studied the effect of nitrogen and helium gas on heat transfer rates. Barber [9] studied the effects of hydrogen, helium and nitrogen jets and found the results to significantly vary with jet mass flow rates. From research it has been concluded that the flow field of an opposing jet from a blunt body in supersonic flow mainly depends upon factors such as jet to body diameter ratio, jet to free stream pressure ratio, jet and free stream Mach numbers. Initially, Finley [7] studied effect of jet Mach no, effect of jet to body diameter ratios, and pressure ratios. Riggins [10] studied the effect of varying exit Mach number and exit diameter of jet. His results showed a decrease in drag with decrease in exit Mach number and increase in jet exit diameter.

Hayashi [11,12] experimentally and numerically studied the effect of change in jet exit diameter, temperature, Mach number and pressure ratio. He found a decrease in heat loads with increase in pressure ratio, Daso et al. [2] carried out extensive experimental tests on jet ejection from the nose of blunt reentry body. Effect of changing angle of attack on heat and drag reduction was also catered. In his study, he varied alpha to 9° and found that in this range of alpha variation there was not much significant change in flow as compared to alpha 0° case.

Efforts to understand the opposing jet flow phenomena have leaded many researchers to identify specific regions of flow [2, 13–15]. Jarvinen and Adams [13] studied different jet penetration modes namely Long Penetration Mode (LPM) and Short Penetration Mode (SPM). They found that LPM occurred at low thrust rates whereas SPM occurred at high thrust rates. Moreover transition from LPM to SPM occurred at a fixed pressure ratio called as the 'critical pressure ratio'. A similar discussion can be found in the works of Hayashi and Zheng [14,15]. Three different regions were identified based on pressure ratio. At small pressure ratios oscillation of shockwave may occur. The shockwave is dispersed and may have long standoff distances from the body. Flow may exhibit diamond shaped patterns. This is known as unstable region. At higher pressure ratios no oscillations of shockwave occur and shock stand-off distances are lesser. A distinct bow shock and terminal shock can be observed. There exists a free stagnation point at which both the flows come to rest, and the jet flow reverses its direction towards the body creating a recirculation region. This is known as stable region. There also exists a transition region during which flow changes from unstable to stable region. This region is difficult to capture.

Alongside experimental work, many efforts are also being carried out to numerically simulate the opposing jet phenomena computationally [11,16,17]. Hayashi [11] not only validated results with experimentations but also carried out a series of iterations varying jet exit Mach number and temperatures to gain results which would otherwise be difficult and time consuming to obtain through experiments. Through his study he showed that decrease in jet temperature decreases the heat flux. Nair et al. [16] validated numerical code by applying it to a number of different configurations of opposing jet. Shah [17] numerically captured the shock standoff distance and also studied the transition mode from LPM to SPM.

Different jet ejection schemes have also been considered. Multiple jet ejection as opposed to single jet emanating from nose of body is one of the earliest concepts considered. One of the most initial experimental works done in this regard is that of Jarvinen [18]. It is an extensive report studying different configurations, jet nozzles, Mach numbers as well as effect of angle of attack. The multiple jet scheme is very promising not only for heat reduction but also finds its application in Retro propulsion phenomenon for re-entry phase of space modules. There is however limited literature of this concept due to its difficulty in implementation experimentally, and high computational cost numerically. Cordell [19] studied numerically the works of Jarvinen [18]. Sriram [20] carried out experimental work on multiple microjets.

One of the most recent advancements in active flow control technologies is the use of combinational strategies. In these methods, the jet is combined with other techniques such as forward cavities or aero spikes to achieve better control over flow. The works of Tamada [21] show very promising results. He showed that by the use of jet-spike combination i.e. ejection of jet from an aero spike; better drag reduction can be achieved at much lower pressure ratios. His results show that the use of an aero spike reduces drag coefficient to almost half of the baseline case of Ogive body with no jet. Morimoto [22] also studied the jet-spike configuration and found a considerable reduction in heat flux.

Another combination strategy is the use of forward facing jet cavity [23,24]. According to the works of Haibo [23], the addition of a cavity in the flow path allows the jet to develop properly and aids to reduce initial instabilities experienced during jet free stream interaction. The present study is inspired by the jet combination strategy concept. It is suggested to use a divergent nozzle

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