Applied Thermal Engineering 109 (2016) 238–250

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

An improvement of the base bleed unit on base drag reduction and heat energy addition as well as mass addition

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HIGHLIGHTS

- A 2D axisymmetric Navier-Stokes equation for a multi-component reactive system is solved.
- The coupling of the internal and wake flow field with secondary combustion is calculated.
- Detailed data with combined effects of boattailing and post-combustion are obtained.
- The mechanism of heat energy addition and thermodynamics performances is investigated.

ARTICLE INFO

Article history:
Received 6 June 2016
Revised 2 August 2016
Accepted 11 August 2016
Available online 12 August 2016

Keywords:
Heat energy addition
Drag reduction
Base-bleed
Post-combustion
H_2—CO system

ABSTRACT

Numerical simulations are carried out to investigate the base drag and energy characteristics of a base-bleed projectile with and without containing the effect of a post-combustion process for a boattailed afterbody in a supersonic flow, and then to analyze the key factor of drag reduction and pressure decreasing of base bleed projectile. Detailed chemistry models for H_2—CO combustion have been incorporated into a Navier-Stokes computer code and applied to flow field simulation in the base region of a base-bleed projectile. Detailed numerical results for the flow patterns and heat energy addition as well as mass addition for different conditions are presented and compared with existing experimental data. The results shows that, the post-combustion contributes to energy addition and base drag reduction up to 78% on account of that the heat energy released from the post-combustion using fuel-rich reaction products as the fuel in the wake region is much higher than for the corresponding cold bleed and hot bleed cases. In addition, the temperature distribution regularities are changed under post-combustion effect, presenting that the peak appears in a couple of recirculation regions. The fuel-rich bleed gas flows into the shear layer along the crack between these two recirculation regions and then those can readily burn when mixing with the freestream, thus causing component changes of H_2 and CO in the base flowfield.

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1. Introduction

Aerodynamic vehicles such as missiles, rockets, and projectiles undergo significant base drag due to flow separation at the base corner and the formation of a low-pressure, low-speed recirculation region near the base, especially, the drag in the base region has the most significant contribution to total dag. At transonic speed, for example, base drag constitutes a major portion up to 50% of the total drag for typical projectile at Mach 0.9 [1]. So, reducing the base drag is an efficient and practical way to reduce the total drag of the projectile. Two methods have been investigated and discussed in the literature. One method is to optimize the shape of the projectile, especially by using afterbody boattailing that can reduce the base surface area exposed to the afterbody expansion [2]. The other method consists of increasing the pressure and energy behind the projectile that can be accomplished with injection of a low velocity fluid in the recirculation region directly behind the base, known as base bleed [3,4]. The base bleed technology is particular effective for long range flights, where the integrated effect of the drag reduction is manifested. Such a capability is of significant current interest. Detailed understanding of the energy as well as mass addition and the fluid-dynamic interactions occurring around the projectile and especially the afterbody flow is a requirement before proposing solutions to reduce the drag.

Fig. 1 presents the schematic of the supersonic base flow with mass bleed [5]. The supersonic freestream flow expands at the base

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.072
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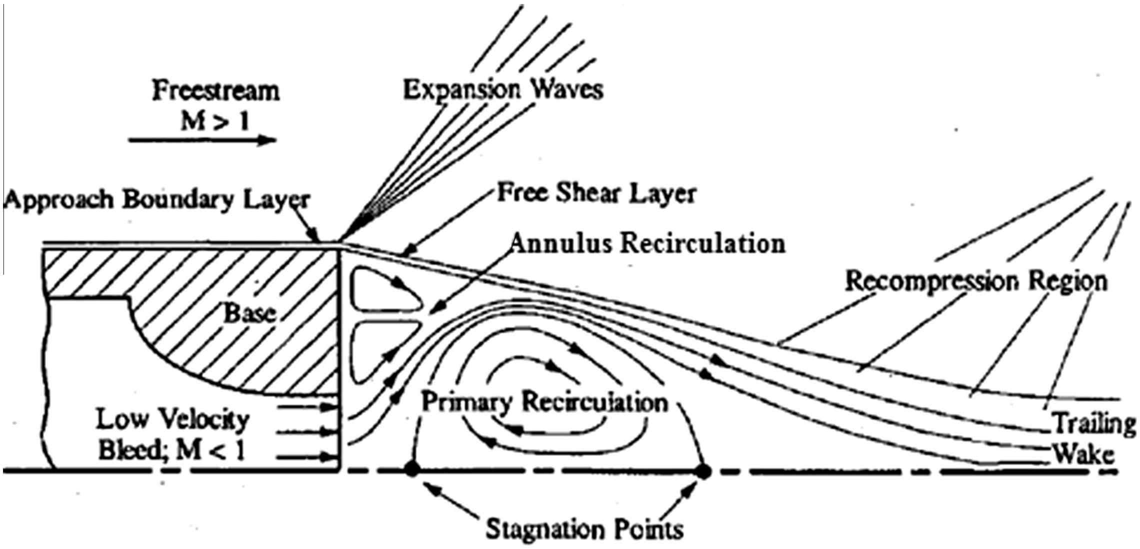

Fig. 1. Schematic of base flow with mass bleed.

corner and the turbulent boundary layer separates and forms a free shear layer that eventually undergoes recompression, realignment, and redevelopment in the wake of the afterbody. The primary recirculation region (PRR) is formed as the fluid from the region adjacent to the base is entrained and accelerated by the outer shear layer and subsequently returned to the base region by a recompression shock system. With base bleed, low-speed fluid is introduced into the base region causing a downstream displacement of the PRR and the appearance of a forward stagnation point whose location depends on the relative strengths of the bleed jet and the recirculating fluid [5]. Bleed gases escape from the bleed section between the PRR and the freestream and create a secondary recirculating region (labeled SRR) against the annulus surface of the base. The recirculation is now separated by a stream line starting and ending on the symmetry axis. There are two distinct mixing layers: the external mixing layer (between the PRR and the freestream), and the bleed jet mixing layer (between the bleed jet and the SRR, on the edge of the bleed jet) [6].

In actual system, the mass flow rate injected in the afterbody flow is provided by the combustion of the propellant and the base pressure of a projectile traveling at supersonic speed can be controlled by burning this fuel near the base region. Experiments performed by several researchers [7–10] to study the effect of bleed mass flow rate on the base pressure exhibit certain common characteristics and indicate three distinct operating regimes based on the quantity of bleed fluid injected. At low values of bleed mass flow rate (regime 1), the base pressure ratio increases fairly linearly with bleed rate. A peak in the base pressure ratio is observed at an intermediate value of bleed mass flow rate. Increases in base pressure ratio (relative to the no-bleed case) from 10 to 90% have been reported for the optimum bleed condition, which depends on factors such as the freestream Mach number and the size and geometry of the bleed orifice. Past the optimum value (regime 2), the base pressure ratio decreases with increasing bleed rate until it reaches a relative minimum. Further increase in the bleed flow leads to an increase in base pressure ratio (regime 3) due to the onset of power-on flow conditions.

From the combined above results, experiments using air, hydrogen, helium, argon, and nitrogen have shown that afterbody flows with base bleed can result in base drag reduction [11–14]. Significant increases in base pressure have also been observed using a heated bleed gas [15]. At low injection rates, the base pressure rise is nearly proportional to the enthalpy of the bleed gas. The peak base pressure is higher, and occurs at a lower of the bleed mass flow rate, than for the corresponding cold bleed case. Also, as reported by Bowman [15], the base pressure was measured as a function of the increase in enthalpy of the ejected gas for various flow rates when measurements of base pressure have been made on a cylindrical afterbody with the ejected gas heated by an arc heater that increased its enthalpy by up to 3000 J/g. since efficiency decreases with increasing base pressure, the application of pure base bleed seems to be limited to base drag reduction (i.e., to base pressures below the freestream pressure).

It is known that propellant of a base bleed unit (BBU) is made mainly of HTPB and AP (NH_4ClO_4) in which crystalline ammonium perchlorate (AP) serves as oxidizer and hydroxyl-terminated polybutadiene (HTPB) serves as fuel binder with AP and HTPB combined together physically in very fuel-rich composition [16]. Pre-burning of the BBU produces reactive gases with carbon-monoxide and hydrogen as major products (oxygen-negative gases), those can readily burn when mixed with air. Thus, the post-combustion will generate a significant amount of heat depending on the mixedness in the downstream of the secondary recirculation (Annulus recirculation) as shown in Fig. 1. Kaurinkoski and also Rose et al. [17,18] studied base bleed structure with special emphasis on the effect of chemical reaction between the bleed gases and the freestream. Bournot et al. [6] demonstrate that a possible way to obtain hot gases consisted of the addition of metal particles in the propellant and the energy released in the core flow or in the jet by the combustion of the metal particles that allowed a post-combustion benefit for base bleed can reduce the base drag, and also investigated that the combustion products temperature was a very important parameter in the base-bleed effect. However, it is very difficult to experimentally study the base bleed at supersonic flight condition under considering the post-combustion effect. so, most of the fine measurements were carried out only for non-reacting jets as above presentation and then were used for the validation data of numerical studies. Although the effectiveness of base bleed with a post-combustion as a drag-reducing technique has presented before us, the detail of the complex fluid dynamic characteristic and combustion behavior caused by base bleed and the freestream occurring in the base flowfield are not clearly understood. Gibeling and Buggeln [19] was the first computational study using detailed finite work chemistry model for the base bleed combustion. Also, Hubbartt [20] obtained that base burning with hydrogen resulted in even higher

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