International Journal of Heat and Mass Transfer 121 (2018) 84–96

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Parametric study on the heat transfer of a blunt body with counterflowing jets in hypersonic flows

Jinghui Guo [a], Guiping Lin [a], Xueqin Bu [a,*], Lizhan Bai [a], Yanmeng Chao [b]

[a] *Laboratory of Fundamental Science on Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China*
[b] *Beijing Institute of Electronic System Engineering, Beijing 100034, China*

ARTICLE INFO

Article history:
Received 16 October 2017
Received in revised form 15 December 2017
Accepted 22 December 2017

Keywords:
Parametric study
Counterflowing jet
Heat transfer
Hypersonic
Point-collocation NIPC

ABSTRACT

A quantified parametric study for the heat transfer acting on a hypersonic blunt body with counterflowing jets is presented. Three-dimensional turbulent Navier-Stokes equations are solved to simulate freestream-jet interactive flowfields. The freestream and jet controlling parameters are treated as input sources of variation, and a point-collocation non-intrusive polynomial chaos (NIPC) method is utilized to quantify the variations in the output surface heat flux and total surface heat load acting on the blunt body by identifying the maximum and minimum of surrogate response values predicted by the NIPC. All of the sample cases are confirmed to form steady jet structures. Furthermore, through a global sensitivity analysis, Sobol indices evaluated by the NIPC, are used to rank the contributions of each input parameter to the variation in output quantities of interest. It is found that the designed upstream injection of baseline case effectively reduces the heat transfer to body surface compared with the no-jet case. The variations of input parameters induce remarkable variations of output heat flux and total heat load. The sensitivity analysis indicates that the jet-to-freestream total-pressure ratio is the top contributor to variations in heat flux, followed by the freestream Mach number. The jet total temperature is mainly important on the front part of forebody, while the contributions of jet Mach number and freestream temperature slightly increase downstream. The freestream density has the smallest effect. The sensitivity of total heat load to input parameters coincides with that of heat flux. This parametric study is expected to illustrate the significance of flow-controlling parameters to the heat transfer over blunt body and provide insight for aerothermal management by using counterflowing jets in hypersonic flows.

1. Introduction

A hypersonic flying vehicle suffers from considerable aerothermal loads, as strong shock waves formed around the body yield much loss of its kinetic energy which renders substantial increase of local temperature [1]. Such high levels of shock-induced aeroheating can produce undesirable effect on the vehicle performance. Excessive heating enhances the likelihood of material ablation or failure [2] and may lead to the malfunction of onboard electronic devices [3], which presents a challenge in the design and requirement of thermal protection system (TPS). Therefore, effective reduction of aerodynamic heating is of great importance for hypersonic vehicles.

As is known, at hypersonic speeds, the blunt shape of vehicle helps attenuate aeroheating yet causes higher wave drag [1]. The usability of passive TPS can only attain limited promotion in thermal protective capability primarily by elevating the ultimate temperature or thickness of materials. In view of the contradiction in altering vehicle shape and the dilemma in passive TPS methods, a variety of active flow-controlling concepts and techniques have been explored to alleviate the aerothermal environment in high-speed flows [4,5]. Out of these approaches, a few simple and efficient means, based on the instructive idea of modifying the flowfield in front of vehicles, have been found out, including a protruding physical aerospike attached at the fore-end of nose [6–8], a counterflowing jet issuing in the stagnation zone of the body [9,10], a forward-facing cavity mounted at the nose [11,12], and their combinations [13–18]. Previous work has ascertained that using a counterflowing jet is capable to accomplish efficient surface heating reduction [19], therefore the counterflowing jet is focused in the current study.

Preceding studies have generally verified that there exists a jet bifurcation phenomenon and the corresponding critical point is governed by the jet-to-freestream total-pressure ratio [9,20]. The bifurcation divides the jet flow into two motion modes. With the

* Corresponding author.
E-mail address: buxueqin@buaa.edu.cn (X. Bu).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.115
0017-9310/

total-pressure ratio below the critical value, the unsteady multi-cell jet flow emerges with oscillation motions [9,20]. Unfavorable aerodynamic heating effects occur ascribed to widely varied and even increased heat flux caused by the perturbed flow within thin jet layers, thus the cooling performance of jet is impaired [9,21–24]. As the total-pressure ratio exceeds the critical value, the flow is nearly steady and the jet column containing only one cell terminates by the Mach disk [9]. The coolant gas of steady mode forms stable recirculation region and thick jet layer, inducing low and even negative surface heat flux, thus presenting efficient cooling effects [22–24]. Therefore, a steady jet configuration is designated by the current study considering the available stable flow properties along with appreciable capacity in aeroheating reduction required for hypersonic flight.

A number of investigations have been conducted to examine and identify the key factors that determine the flow structure, aerodynamics and aerothermodynamics of high-speed vehicles with opposing jets. Thereby, the underlying controlling mechanism for effects of counterflowing jet on aeroheating reduction can be revealed and suitable values of flow-controlling parameters can be assigned. Grenich and Woods [25] designed a supersonic jet protection for a hypersonic ballute aerobraking concept. The influence of jet Mach number and jet flow rate on shock pattern and temperature distribution associated with flow steadiness was examined. Romeo and Sterrett [26] and Tolle [27] discovered two different flow types, which included a steady blunt-body flow type transiting to an unsteady spike-like flow type by raising the total-pressure ratio or momentum ratio of jet to freestream. Considering the drag penalty resulted from high jet thrust of spike-like flow, Meyer et al. [28] employed the injection of steady blunt-body type to reduce drag and heat transfer of a blunt vehicle flying with Mach 6.5 at 30 km altitude. With the jet total pressure and total temperature fixed, the jet conditions were altered by changing jet Mach number for each ratio of body diameter to jet diameter, and the jet thrust was derived inversely related to jet Mach number. The wave drag, heat transfer rate and skin-friction drag were mainly controlled by the shock stand-off distance, which was greatly affected by jet thrust. It was concluded that the drag and thermal loads can be substantially reduced by properly selecting jet conditions.

The experimental and numerical investigations conducted by Hayashi et al. [24,29] and Imoto et al. [30] exhibited that in the stable jet flow state, the aeroheating diminution was appreciable. As the total-pressure ratio increased, the heat flux and total heat load decreased over the whole surface. Daso et al. [22] experimentally and numerically studied the flow physics of counterflowing jets from a 2.6%-scale Apollo test article. They designed a rich set of test runs incorporating different freestream Mach numbers, jet nozzles with distinct jet Mach numbers and nozzle diameters, various jet mass flow rates as well as angles of attack, all of which were elaborately matched. The jet flow rate was highly focused on, and the variations of flow pattern, drag and heat flux with varying flow rates were reported. Gerdroodbary et al. [10,23] detailed the flow scenarios of counterflowing jets over highly blunted cone using different coolants. The effectiveness of total-pressure ratio for various Mach numbers, total temperatures, molecular weights and diffusivity of jets on aeroheating reduction was assessed. Li et al. [31] used counterflowing jets to modify the flowfield around a blunt waverider in hypersonic flow, and identified an optimum total-pressure ratio for enhancement of aerodynamic and aerothermal performance of the waverider. Regarding better drag and heat reduction, Li et al. [32–34] also amended circular injection orifice as polygon shapes and performed analysis of aerodynamic and aerothermal characteristics at various angles of attack, sideslip and jet flow.

From aforementioned literature, it is concluded that the controlling mechanism of heat transfer for jet from blunt body against high-speed flow is very complicated. Therefore, in-depth analysis coupled with effective methodology is necessary for shedding light on the consequent varied heat transfer characteristics due to the variations of flow-controlling parameters. Focusing on effects of flow-controlling factors on aerodynamic and aerothermal characteristics of vehicle, which is generally referred to as a parametric study [35–37], preceding researches have broadly adopted a somewhat Variable-Controlling Method (VCM). That is to say, only investigate the effect of an individual parameter each time. Specifically, first alter the investigated parameter and fix other parameters unchanged, then evaluate the influence of variation in this parameter on the vehicle performance. Afterwards, change to concentrate on next parameters required to be studied in the same way. Nevertheless, for the VCM, the varying values of each parameter depend primarily on artificial selections from researchers and the number of illustrated computations is usually quite limited.

Consequently, we cast the parametric study of counterflowing jets from a blunt body in hypersonic airflows into a stochastic model problem. In recent years, the point-collocation non-intrusive polynomial chaos (NIPC) technique has successfully been applied for the uncertainty quantification in numerical modeling predictions associated with fluid dynamics [38–41]. The NIPC enables to construct accurate surrogate model based on the spectral representation of uncertainty and requires no modification of the deterministic CFD code, computationally efficient compared to traditional methods such as Monte Carlo sampling [42,43]. Through this methodology, the input uncertainty from modeling parameters is propagated to output quantities of interest and the uncertainty in the output is quantified. Followed by a global nonlinear sensitivity analysis, the important uncertain parameters that contribute to the output uncertainty are also identified through relatively ranking the contributions of uncertainty sources.

It can be further explored by the theory and features of NIPC that the NIPC is not merely confined in the application of uncertainty assessment, but also provides a powerful tool for the parametric study subject to variations of input flow-controlling parameters. The variations of input parameters are considered simultaneously, and the variations of output quantities of interest associated with flowfield and vehicle performance can be calculated by the stochastic response surface. The significance of each input parameter to the variation of output quantities is evaluated by the sensitivity analysis. For efficient propagation of input variation, utilizing stochastic expansions based on the NIPC to construct surrogate model is expected to be more representative and to save more computational expense compared to direct CFD deterministic evaluations.

Accordingly in this paper, a conception that treats parametric study as stochastic problem is introduced and addressed in the sense that construction of surrogate model is effective and computationally efficient to propagate the variations in flow-controlling parameters and evaluate their influence on flow characters. For the present work, a quantified parametric study of the heat transfer over a blunt body with counterflowing jets in hypersonic flows is performed based on the point-collocation NIPC technique. The freestream and jet controlling parameters are treated as input sources of variation, and the variations of output surface heating are evaluated by identifying the maximum and minimum of the response values predicted by surrogate models. The relative contributions of each input parameter to the total variation in output quantities of interest are derived by a global sensitivity analysis using Sobol indices [44], which allows a direct expression for the effects of flow-controlling parameters on output quantities. Thereby, the key factors that govern freestream-jet flow can be