Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Effect of energy addition parameters upon scramjet nozzle performances based on the variance analysis method

Shengjun Ju [a], Chao Yan [a], Xiaoyong Wang [a], Yupei Qin [a], Zhifei Ye [b]

[a] *National Key Laboratory of Computational Fluid Dynamics, Beihang University, Beijing 100191, China*
[b] *Chengdu Aircraft Design & Research Institute, Chengdu 610041, China*

ARTICLE INFO

Article history:
Received 11 July 2017
Received in revised form 6 August 2017
Accepted 28 August 2017
Available online xxxx

Keywords:
Computational fluid dynamics
Scramjet nozzle
Hypersonic flow
Energy addition
Variance analysis

ABSTRACT

As an important component, the nozzle produces most of thrust in scramjets. A new concept of increasing the aerodynamics of the scramjet nozzle with energy addition is presented. The essence of the method is to create a heated region in the inner flow field of the scramjet nozzle. In this paper, the two-dimensional coupled implicit compressible Reynolds Averaged Navier–Stokes (RANS) and Menter's shear stress transport (SST) turbulence model have been applied to numerically simulate the flow fields of the single expansion ramp nozzle (SERN) with and without energy addition. The variance analysis method coupled orthogonal experimental design has been introduced to investigate the effects of the energy addition parameters on the aerodynamics (i.e. thrust coefficient C_T, lift coefficient C_N and pitching moment coefficient C_M) of the scramjet nozzle. The numerical results show that the proposal of energy addition can be an effective method of increasing force characteristics of the scramjet nozzle, the thrust coefficient C_T, lift coefficient C_N and pitching moment coefficient C_M increase by 1.55%, 47.27% and 2.53% respectively. The effect of the energy addition density on the aerodynamics of the scramjet nozzle is substantial, and it must be foremost when considering the design of the scramjet nozzle. The findings suggest that scramjet nozzle design and performance can be benefitted from the application of energy addition.

1. Introduction

The scramjet is always integrated with air-breathing hypersonic vehicle and a scramjet generally consists of an inlet, an isolator, a combustor and a nozzle [1,2], as shown in Fig. 1. The single expansion ramp nozzle (SERN) is usually applied as an important component of scramjet engines in which burned gas expands with high pressure and temperature, and generates required thrust, lift and moment in order to achieve the propulsion performance [2,4].

Various significant researches have been dedicated to the numerical simulations, effects of geometric parameters and flow control of the scramjet nozzle.

The computational fluid dynamics (CFD) has been widely and successfully employed in the numerical simulations of scramjet nozzle. The numerical investigation of the flow field of a hypersonic single expansion ramp nozzle was presented by Meiss and Meinke using Large-Eddy Simulations (LES) [5]. Emblem performed a series of numerical prediction of SERN performance using WIND code and the simulation results agreed well with the experimental data [6].

The effects of geometric parameters on nozzle performance have been investigated in a few studies. Li and Song et al. [7] estimated the influences of geometric parameters upon scramjet nozzle performances by the way of numerical simulation and the sensibility coefficients of thrust coefficient, lift coefficient and pitching moment coefficient to geometric parameters, including divergent angles, nozzle total lengths, height ratios, and cowl angles, were obtained. Two-dimensional and three-dimensional simulations were conducted on a straight SERN configuration by Thiagarajan et al. [8], the variations of cowl lengths and side fence on the scramjet nozzle aerodynamic performances were found to be very significant.

In order to improve the performance of SERN, many studies have been dedicated to flow control using the secondary flow injection. The ability to use flow injection near the trailing edge of the cowl to control the resulting oblique shock angle and the impinging location was demonstrated by Gamble et al. [9,10]. However, the method of flow control by secondary flow injection complicates the structure and it is difficult to apply to engineering.

E-mail address: optju@buaa.edu.cn (S. Ju).

http://dx.doi.org/10.1016/j.ast.2017.08.033
1270-9638/© 2017 Elsevier Masson SAS. All rights reserved.

Please cite this article in press as: S. Ju et al., Effect of energy addition parameters upon scramjet nozzle performances based on the variance analysis method, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.08.033

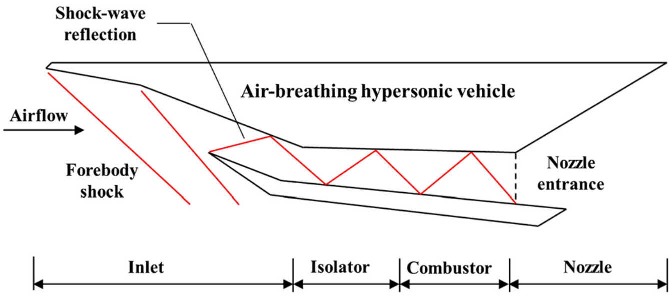

Fig. 1. Configuration of typical air-breathing hypersonic vehicle.

In the recent years, energy addition as a new flow control scenario for modification of the flow field is a very well-known technique and primarily has been studied and used to improve the performance of vehicle at supersonic/hypersonic speeds [11]. The calculation and similarity theory of experiment simulating were performed using a standard Euler equations including energy addition source term by Bracken and Myrabo et al. [12,13], and the result showed that the effects of energy addition to flow field could drastically change the drag on the body. Besides, energy addition was presented and used to improve the performance of the scramjet inlet by Macheret, Shneider and Mile [14,15]. They found that with the energy deposition of only the enthalpy flux into the inlet, the mass flow rate entering the inlet could increase by more than 11%, without any loss of kinetic energy efficiency. Therefore, the energy addition may be an effective measure to increase aerodynamic characteristics of the scramjet nozzle. A three-dimensional inviscid numerical simulation to determine the effect of energy addition upstream of a cone on drag reduction and creation of steering force were carried out by Girgis et al. [16]. The numerical results showed that the highest gain in lift-drag ratio was achieved, of course, with the highest power. However, lift-drag ratio gain did not grow linearly with the power of energy addition.

In this paper, numerical simulation of the single expansion ramp nozzle with and without energy addition by using computational fluid dynamics (CFD) method is performed to demonstrate and illuminate the characters and alterations of flow field. At the end of this paper, the effects of the energy addition parameters on the aerodynamic performance of the scramjet nozzle are investigated using the variance analysis method and the results of the variance analysis are verified.

2. Physical model and numerical method application

2.1. Physical model

In this paper, a general scramjet nozzle in hypersonic flow is investigated. The flow is two-dimensional in the (x, y) plane, where x is the freestream flow direction and y is the vertical flow direction, and the entrance point at the nozzle cowl be the Cartesian coordinate origin. Fig. 2 shows the schematic view of the scramjet nozzle configuration employed in the current study, and there are seven geometric parameters and six energy addition parameters. However, all of the geometric parameters have been set to be constant in the current study. The geometric parameters mainly include the height of nozzle inlet $H_1 = 200$ mm, the height of nozzle exit $H_2 = 730$ mm, the length of nozzle ramp $L_1 = 1600$ mm, the ramp of nozzle is described by a cubic curve, the inlet angle of nozzle ramp $\alpha = 30°$, the exit angle of nozzle ramp $\beta = 5°$, the cowl is described by a line, the length of nozzle cowl $L_2 = 480$ mm, the angle of nozzle cowl $\gamma = 3.6°$.

Cases both with and without energy addition are computed respectively. The energy addition profile is uniform distribution, the density of the energy addition, namely $S_e = 9$ kW·cm^{-3}. x_e and y_e are coordinates of the center of energy addition region ($x_e = 275$ mm, $y_e = 100$ mm), the length of energy addition region, namely $L_e = 75$ mm, the height of energy addition region in the current study, namely $H_e = 5$ mm, and the energy addition region may also be tilted at an angle θ with respect to the x axis ($\theta = 0°$).

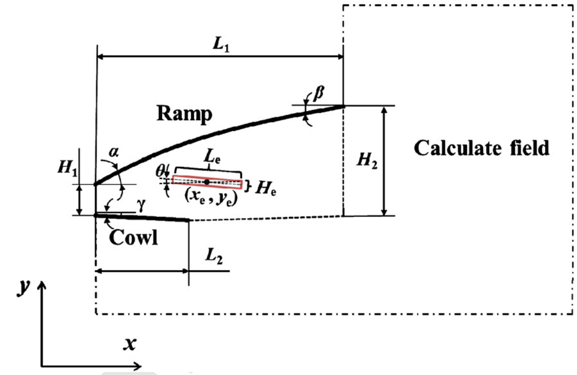

Fig. 2. Schematic of the scramjet nozzle configuration.

Table 1
Boundary conditions.

Contents		Unit	Value
Freestream Mach number	Ma_∞	–	6.5
Freestream static pressure	T_∞	K	223.536
Freestream static temperature	P_∞	Pa	1879.98
Jet Mach number	Ma_j	–	2.0
Jet static temperature	T_j	K	1309.525
Jet static pressure	p_j	Pa	41184.04

The hypersonic freestream flows with a flight speed of $Ma_\infty = 6.5$, the freestream values of static temperature and static pressure $T_\infty = 223.536$ K, $P_\infty = 1879.98$ Pa, respectively. The inflow parameters of the nozzle can be obtained from 1D calculation of combustor. The given inflow conditions are: Mach number $Ma_j = 2.0$, static temperature $T_j = 1309.525$ K, static pressure $p_j = 41184.04$ Pa. Table 1 depicts the corresponding freestream conditions and inflow conditions of the scramjet nozzle.

2.2. Numerical method and grid sensitivity analysis

2.2.1. Governing equations and turbulence model

The two-dimensional compressible Reynolds Averaged Navier–Stokes equations [17] coupled with Menter's k–ω shear stress transport (SST) model [18] are solved numerically to calculate the aerodynamics of scramjet nozzle. The flowfield of the nozzle is defined to be steady-state. The energy addition is added to the energy equation in the form of the source term. The governing equations are briefly described as follow [19–21]:

1) Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

2) Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

3) Energy equation:

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial(\rho u_j H)}{\partial x_j} = \frac{\partial(u_i \tau_{ij} - \dot{q}_j)}{\partial x_j} + S_e \tag{3}$$

Please cite this article in press as: S. Ju et al., Effect of energy addition parameters upon scramjet nozzle performances based on the variance analysis method, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.08.033