Acta Astronautica 140 (2017) 351–361

Contents lists available at ScienceDirect

Acta Astronautica

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

Optimization design of energy deposition on single expansion ramp nozzle

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

Keywords:
Computational fluid dynamics
Scramjet nozzle
Hypersonic flow
Energy deposition
Optimization design

ABSTRACT

Optimization design has been widely used in the aerodynamic design process of scramjets. The single expansion ramp nozzle is an important component for scramjets to produces most of thrust force. A new concept of increasing the aerodynamics of the scramjet nozzle with energy deposition is presented. The essence of the method is to create a heated region in the inner flow field of the scramjet nozzle. In the current study, the two-dimensional coupled implicit compressible Reynolds Averaged Navier–Stokes and Menter's shear stress transport turbulence model have been applied to numerically simulate the flow fields of the single expansion ramp nozzle with and without energy deposition. The numerical results show that the proposal of energy deposition can be an effective method to increase force characteristics of the scramjet nozzle, the thrust coefficient C_T increase by 6.94% and lift coefficient C_N decrease by 26.89%. Further, the non-dominated sorting genetic algorithm coupled with the Radial Basis Function neural network surrogate model has been employed to determine optimum location and density of the energy deposition. The thrust coefficient C_T and lift coefficient C_N are selected as objective functions, and the sampling points are obtained numerically by using a Latin hypercube design method. The optimized thrust coefficient C_T further increase by 1.94%, meanwhile, the optimized lift coefficient C_N further decrease by 15.02% respectively. At the same time, the optimized performances are in good and reasonable agreement with the numerical predictions. The findings suggest that scramjet nozzle design and performance can benefit from the application of energy deposition.

1. Introduction

The scramjet is always integrated with air-breathing hypersonic vehicle, such as X-43 [1] and X-51 [2], and a scramjet generally consists of an inlet, an isolator, a combustor and a nozzle [3,4], as shown in Fig. 1. The single expansion ramp nozzle (SERN) has been employed as an important component of scramjet engines in which burned gas expands with high pressure and temperature, and generates required thrust and lift in order to achieve the propulsion performance [5].

Recently, with the rapid improvement of computer calculating ability and the advances of numerical calculation technique, computational fluid dynamics (CFD) analysis has been successfully applied to simulate the flowfield of SERN. Meiss and Meinke performed the performance of the single expansion ramp nozzle using Large-Eddy Simulations (LES) [6]. A series of numerical prediction of SERN performance was presented by Emblem using WIND code and the simulation results agreed well with the experimental data [7].

In addition, due to its short design period and low cost, optimization design technology has become an effective means to improve the aerodynamic performance and design efficiency of the SERN. It is undeniable that three-dimensional nozzle has more remarkable performance in some aspects compared to two-dimensional SERN, however, the complex configuration brings about problems in variable geometry, such as the exhaust system of turbine based combined cycle (TBCC) engine with the broader confines of flight Mach numbers. As a result, the two-dimensional SERN still has peculiar superiorities for hypersonic vehicles [8] [9]. The single- and multi-objective design optimization methods coupled with the Kriging surrogate model has been used by Huang et al. [10] to increase thrust and lift of two-dimensional SERN. In those study, the geometric parameters of horizontal length of the inner nozzle, the internal cowl expansion and the external expansion ramp has been as design variables, and effects of geometric parameters on nozzle performance have been investigated to improve the optimization efficiency.

In order to improve the performance of SERN, studies have been dedicated to flow control using the secondary flow injection. Gamble et al. [11] demonstrated the ability to use flow injection near the trailing edge of the cowl to control the resulting oblique shock angle and the

* Corresponding author.
E-mail address: yanchao@buaa.edu.cn (C. Yan).

http://dx.doi.org/10.1016/j.actaastro.2017.09.004
Received 3 August 2017; Received in revised form 30 August 2017; Accepted 3 September 2017
Available online 5 September 2017

Nomenclature

CFD	computational fluid dynamics
CFL	Courant-Friedrichs-Levy
C_N	lift coefficient
C_T	thrust coefficient
d	first grid heights in the direction normal
E	total energy
H	total enthalpy
H_e	height of energy deposition region
k	turbulent kinetic energy
L_e	length of energy deposition region
LES	Large-Eddy Simulations
LUSGS	Lower-Upper Symmetric Gauss-Seidel
m	the order of accuracy of numerical scheme
Ma	Mach number
MUSCL	Monotone Upstream-centred Schemes for Conservation Laws
n_{max}	the maximal allowable number of integration steps
NSGA II	non-dominated sorting genetic algorithm
P	pressure
P_0	stagnation pressure
P_k	production terms of the turbulent kinetic energy
P_{pitot}	pitot pressure
P_ω	production terms of the specific dissipation rate of turbulence
RBF	Radial Basis Function
Re	Reynolds number
Re_{grid}	grid Reynolds number
R_s	the ratio of maximal allowable number of integration steps
S_e	density of the energy deposition
SERN	single expansion ramp nozzle
S_{err}	the relative error of integration in all dimensions
S^{max}	the allowable value of total error
T	temperature
T_0	stagnation temperature
TBCC	turbine based combined cycle
T_w	wall temperature
u_i	velocity
X	stations along ramp
x_e, y_e	coordinates of the center of energy deposition region

Greek symbols

γ	the heat ratio
ΔL	the mean ratio of cell size
θ	angle of energy deposition region
μ_L	laminar viscosity
μ_T	turbulent viscosity
σ_k, σ_ω, β, β^*	closure coefficients in SST turbulence model
ω	dissipation per unit turbulence kinetic energy

Subscript

∞	freestream
w	wall
j	jet

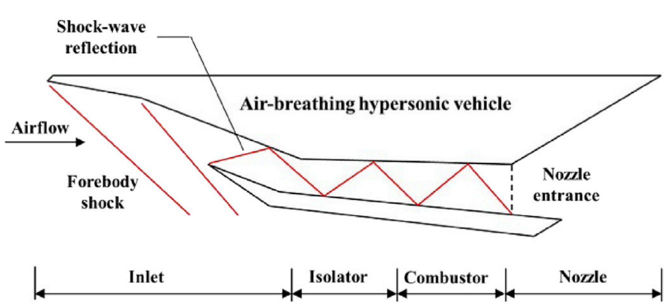

Fig. 1. Configuration of typical air-breathing hypersonic vehicle.

location of its impingement on the SERN ramp, However, the method of flow control by secondary flow injection makes structure more complex and it is difficult to apply to engineering.

In the recent years, energy deposition 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 [12]. The essence of the method is to create a heated region in the flowfield, for instance, the heat region can be generated by plasma, microwave, shooting combustible liquid and solid pellets [13,14]. Bracken and Myrabo et al. [15,16] performed the calculation and similarity theory of experiment simulating using a standard Euler equations including energy deposition source term. They found that the drag changed drastically with the energy deposition to supersonic flowfield in front of the body. Macheret, Shneider and Mile [17,18] created an energy deposition region to improve the performance of the scramjet inlet. The result showed that mass flow rate entering the inlet increased by more than 11%, without any loss of kinetic energy efficiency. Girgis et al. [19]. carried out a three-dimensional inviscid numerical simulation to determine the effect of energy deposition upstream of a cone on drag reduction and creation of steering force. The numerical results showed that the highest gain in lift-drag ratio is achieved, with the highest energy deposition density. However, lift-drag ratio gain does not grow linearly with the density of energy deposition.

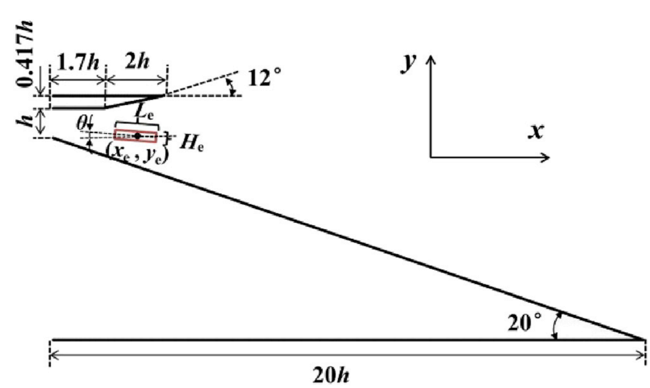

Fig. 2. Schematic of the scramjet nozzle configuration.

Table 1
Boundary conditions.

Contents		Unit	Value
Freestream Mach number	Ma_∞	–	6.0
Freestream static pressure	T_∞	K	58.29
Freestream static temperature	P_∞	Pa	1596.07
Jet Mach number	Ma_j	–	1.78
Jet total temperature	T_{0j}	K	475
Jet total pressure	p_{0j}	Pa	172,000

In the current study, the steady state energy is deposited to internal