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

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

A new design method of single expansion ramp nozzles under geometric constraints for scramjets

Zheng Lv [a], Jinglei Xu [a,*], Yang Yu [a], Jianwei Mo [b]

[a] College of Energy & Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, People's Republic of China
[b] Xi'an Aerospace Propulsion Institute, Xi'an, Shanxi 710100, People's Republic of China

ARTICLE INFO

Article history:
Received 4 November 2016
Received in revised form 21 January 2017
Accepted 9 March 2017
Available online xxxx

Keywords:
Scramjet
Maximum thrust theory
Single expansion ramp nozzle
Design directly
Geometric constraints
Method of characteristics

ABSTRACT

A new method based on maximum thrust theory to design a two-dimensional single expansion ramp nozzle with geometric constraints directly is presented in this paper. To generate the contour of the nozzle, the inviscid flowfield is calculated by using the method of characteristics and the reference temperature method is applied to correct the boundary layer thickness. The computational fluid dynamics approach is employed to obtain the aerodynamic performance of the nozzles. The results show that the initial arc radius slightly influences the axial thrust coefficient and that the variations in the length and initial expansion angle of the cowl significantly affect the axial thrust coefficient. The nozzle designed by truncating ideal nozzle is also investigated for comparison to verify the superiority of this new method. The nozzle designed by this proposed method shows increases in the axial thrust coefficient, lift, and pitching moment of 5.5%, 1098.2% and 20.3%, respectively, at the design point. Moreover, the proposed nozzle provided the positive lift with considerable increments in the axial thrust coefficient and in the pitching moment at off-design operations.

1. Introduction

Compared to common propulsion systems, a scramjet can provide a significant specific impulse at hypersonic speeds (Ma $>$ 5); hence, scramjets become a promising candidate for hypersonic flight vehicles [1]. A scramjet, which typically comprises an inlet, isolator, combustor, and nozzle, should be integrated with the airframe, as shown in Fig. 1. As an indispensable scramjet component, the nozzle controls the expansion of the exhaust gas from burner-exit static pressure to ambient pressure with the optimal performance throughout the operation of the vehicle. Airframe/propulsion integration requires that the nozzle should be always integrated with the after-body of the vehicle by using it as the upper expansion ramp. Besides, the wide range of flight Mach numbers has a detrimental effect on the operation of the nozzle. Therefore, the nozzle with single expansion ramp (SERN) is always employed in hypersonic propulsion systems for the geometric considerations and its certain self-adaptability at off-design operations.

The magnitude of the axial momentum on the exit section is identical to that on the entrance section in a scramjet, and therefore, the axial thrust of a nozzle considerably influences the acceleration of hypersonic vehicles; especially, the nozzle can produce 70 percent of the net thrust in the entire propulsion system, when the flight Mach number is greater than six [2]. Given that the expansion ramp of the nozzle is integrated with the after-body of the vehicle, the nozzle also stabilizes the vehicle by generating lift and strong nose-down pitching moment. Overall, the performance of a SERN is critical to the efficiency of the propulsion system and it should be designed carefully. Even though operating over a wide range of flight Mach numbers, the SERN is frequently designed at the cruise condition to obtain the optimal performance along the flight trajectory. At the same time, the off-design operation should be taken into account in designing the nozzle. Furthermore, the stringent geometric constraints also should be considered for the configuration and weight of the vehicle.

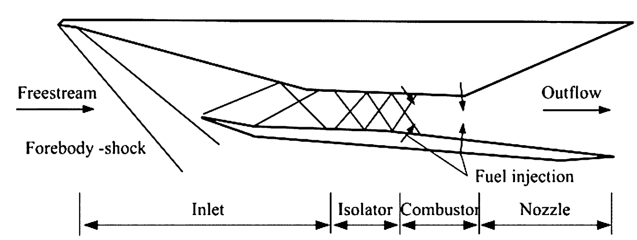

Fig. 1. Schematic of a typical scramjet engine.

* Corresponding author.
E-mail address: xujl@nuaa.edu.cn (J. Xu).

http://dx.doi.org/10.1016/j.ast.2017.03.013
1270-9638/© 2017 Elsevier Masson SAS. All rights reserved.

Nomenclature

A	area
a	speed of sound
C_{fx}	axial thrust
F	thrust
F_s	ideal thrust
G	asymmetry factor
H	flight height
h	height
I_m	impulse function at the nozzle entrance
L	lift
L_n	length of nozzle
L_c	length of cowl
L_{max}	maximum length of cowl
M	pitching moment
Ma	Mach number
$\dot{m}$	mass flow rate
N^*	term expressed as $(\frac{T^*}{T_{pri}})^{n-1}$
P	pressure
R	gas constant
R_{in}	initial arc radius
R_x	axial force by integrating the relative pressure on the nozzle internal wall
Re_x	local Reynolds number
T	temperature
T^*	reference temperature
V	velocity
X	nozzle performance parameters include C_{fx}, L and M
x	X direction coordinate
y	Y direction coordinate
α	Mach angle
δ	2D/axisymmetric switch
δ_1	boundary layer thickness
δ_L	initial expansion angle on the cowl
δ_U	initial expansion angle on the ramp
ΔX	augmentation of nozzle performance include ΔC_{fx}, ΔL and ΔM
γ	specific heat ratio
ρ	density
ϕ	slope angle
θ	flow angle
μ	viscosity
η	truncation ratio

Subscript

A	nozzle A
amb	ambient
aw	adiabatic wall
B	nozzle B
e	nozzle exit
in	nozzle entrance
pri	nozzle primary flow
t	flow parameter at total condition
w	wall
∞	freestream

In traditional nozzle designs, the uniform, parallel flow at the desired exit Mach number maximizes the resulting thrust by using the method of characteristics (MOC) [3,4]; however, the length of the nozzle exceeds the acceptable length for the propulsion system. To decrease the length of the ideal nozzle, previous studies developed some approaches, such as using a minimum length nozzle [5,6], or introducing an asymmetry factor to increase the expansion on the cowl [7]. Although these methods achieved the desirable results to some extent, the lengths of the ideal SERNs are still unacceptable for highly integrated hypersonic vehicles. Therefore, studies have been conducted to reduce the nozzle length by compressing or truncating perfect nozzles [8–13]. Hoffman [8] investigated the performance of linearly compressed perfect nozzles and found that an optimally compressed perfect nozzle was a good propulsive nozzle. Based on the method of linearly compressed perfect nozzle, Quan et al. [9] compressed only the rear part of an ideal nozzle, namely nonlinear compression, because it had very little contribution to the axial thrust. Nonlinearly compressed SERN performed more effectively at an off-design condition and the nozzle length was reduced by as much as 40 percent, but the optimal location of the initial compression was uncertain and required abundant time for computation. Compared to the compressed perfect nozzle, the truncated nozzle may be used more widely. Reference [10] showed that the ideal nozzle with 70% truncation had only a slight influence on the nozzle thrust performance at the design point, whereas it strongly deteriorated the performance under the off-design conditions. In reference [13], Zhao et al. introduced a new truncation method based on the balance of thrust and friction to reduce the length and weight of the nozzle by 25% and 34%, respectively. Besides, references [14–17] optimized the configurations of SERNs to match well with the geometric constraints.

In recent years, the three-dimensional asymmetric scramjet nozzle has been developed by using streamline tracing [18,19] and optimization design [20]. Compared to the two-dimensional SERN, the three-dimensional asymmetric nozzle may be superior in some aspects, but the complex contour induced problems to variable geometry, such as for the exhaust system of turbine based combined cycle (TBCC) engine with the wide range of flight Mach numbers, so the two-dimensional SERN is also attractive for hypersonic vehicles [21]. However, previous studies have yet to obtain the optimal contour of the two-dimensional SERNs. The methods of compressing and truncating perfect nozzles [8–13] only focused on trimming the ideal nozzle to satisfy the geometric constraints and were unable to consider the performance of the SERNs simultaneously. Although the optimization method [14–17] could obtain the optimal performance of the SERN under geometric constraints, it consequently required a long computational time. Therefore, a new method that can directly design an SERN with optimal performance while considering geometric constraints is necessary.

To increase the performance of the axisymmetric nozzle, Rao [22] developed the maximum thrust theory to obtain the optimal thrust of a rocket nozzle with a fixed length and mass flow rate. This solution has widely been used to design the rocket nozzles, and it can be used as a reference for the design of two-dimensional SERNs.

In this paper, the maximum thrust theory for a two-dimensional SERN is obtained by using the multiplier method in the Section 2, and the design process of the SERN under geometric constraints is presented in Section 3. The numerical solution, which is applied to obtain the detailed flowfield and performance of the designed SERNs, is introduced in Section 4. Section 5 displays the definition of performance parameters for the SERNS, and a SERN design case and the effects of the design parameters on the performance are studied in Section 6. In Section 7, a SERN designed by truncating ideal nozzle is also designed for comparing with the proposed SERN design method and the performance comparison between the two configurations is carried out to verify the superiority of

Please cite this article in press as: Z. Lv et al., A new design method of single expansion ramp nozzles under geometric constraints for scramjets, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.03.013