Acta Astronautica 133 (2017) 233–243

Contents lists available at ScienceDirect

Acta Astronautica

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

Research paper

Numerical investigation of improving the performance of a single expansion ramp nozzle at off-design conditions by secondary injection

Zheng Lv[a], Jinglei Xu[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

Keywords:
Single expansion ramp nozzle
Poor performance
Over-expanded condition
Improve
Secondary injection

ABSTRACT

The performance of a single expansion ramp nozzle (SERN) is poor due to over-expansion at off-design conditions. The present study focuses on improving the SERN performance by secondary injection on the cowl and is carried out by using the $k-\varepsilon$ RNG turbulence model. The incidence shock wave resulting from the secondary injection impinges on the expansion ramp, resulting in separation and the increase of the pressure distribution along the ramp. The performance of the SERN can be improved significantly, and the augmentation of the thrust coefficient, lift and pitch moment can be as high as 3.16%, 29.43% and 41.67%, respectively, when the nozzle pressure ratio (NPR) is 10. The location of the injection has a considerable effect on the lift and pitching moment, and the direction of the pitch moment can be changed from nose-up to nose-down when the injection is on the tail of the cowl. The effect of the injection on the axial thrust coefficient is much more apparent, if the operation NPR is far from the design point, and however, the results for the lift and pitching moment are opposite. The increases of injection total pressure and injection width have positive impacts on the SERN performance. And if the parameter φ maintains constant, the axial thrust coefficient would increase when the injection total pressure decreases, so low energy flow can also be used as the secondary injection without decreasing the lift and pitching moment. The mass flow rate of the injection can be decreased by applying the higher total temperature flow without reducing the performance of the SERN.

1. Introduction

With the development of hypersonic flight and propulsion technologies, the vehicle that can take off horizontally and fly up to a top speed of Mach 5+ will become a reality. As the most promising propulsion systems for hypersonic flight vehicles , the airbreathing engine does not need to carry any oxidizer on board, so it can provide a significant specific impulse, compared to the conventional transportation system such as rockets. One common feature of the propulsion system is that it should operate over a wide range of the flight Mach numbers [1].

Thus, the single expansion ramp nozzle (SERN) integrated with the after-body airframe, which is the indispensable component of the airbreathing propulsion system, also undergoes the Mach numbers from subsonic to hypersonic, so the nozzle pressure ratio (NPR, i.e., the ratio of internal total pressure at the nozzle entrance to the ambient static pressure) of the SERN ranges from 2 to 600 or even higher at hypersonic speeds depending on the inlet recovery [2]. In addition, the SERN acts as the major thrust producing part of the engine and it produces 70% of the net thrust in the entire propulsion system, when the flight Mach number is great than six [3], so the performance of the SERN has a significant influence on the efficiency of the whole propulsion system and the SERN is always expected to obtain the optimal performance over the wide flight trajectory. Unfortunately, it is designed on the certain operation point, usually at the cruise condition [4,5], resulting in the great in the expansion area ratio. As a result, when operating at the off-design conditions, the SERN would be strongly over-expanded, which leads to the low pressure acting on the expansion ramp [6]. The sub-ambient pressure distribution along the ramp tends to increase drag and reduce performance with low thrust and strong nose-up pitching moment, which seriously affects the acceleration and stability of the vehicle [12,25].

In order to avoid detrimental over-expansion losses and improve the performance of the SERN under a highly over-expanded condition, previous studies have put forward to some approaches such as variable geometry [7,8], external burning [13,14], passive cavity concept [15,16] and secondary air injection [9–11]. The expansion area ratio can match fairly well with the NPR by means of variable geometry over the wide flight Mach numbers, and as shown in Fig. 1 [8], a rotatable

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

http://dx.doi.org/10.1016/j.actaastro.2017.01.013
Received 21 September 2016; Received in revised form 4 January 2017; Accepted 9 January 2017
Available online 14 January 2017
0094-5765/

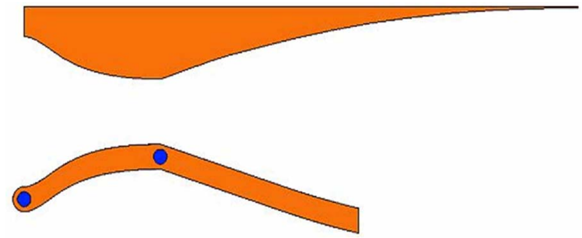

Fig. 1. Schematic of variable geometry [8].

Nomenclature

NPR	Nozzle pressure ratio
RANS	Reynolds-averaged Navier-stokes
SERN	Single expansion ramp nozzle

Variables

A	Area of nozzle entrance or exit
b	Width of secondary injection
C_{fx}	Axial thrust coefficient
F_x	Axial thrust
F_s	Ideal thrust
H_e	Height of nozzle exit
H_t	Height of nozzle throat
h_s	Height of the injection-plume terminal shock
L	Lift
L_C	Length of cowl
L_R	Length of ramp
L_{Sec}	Distance from secondary injection to nozzle throat
M	Pitching moment
$\dot{m}$	Mass flow rate
Ma_∞	Flight Mach number
$\vec{n}$	Direction of the nozzle entrance or exit plane
P	Static pressure
P_b	Back pressure of the secondary injection
P_t	Total pressure
R	Gas constant
R_x	Axial force by integrating the relative pressure on the nozzle internal wall
T_t	Total temperature
$\vec{V}$	Velocity
V_x	Axial velocity
X	Nozzle performance parameters include C_{fx} , L and M
x	Streamwise coordinate
ΔX	Augmentation of nozzle performance include ΔC_{fx},ΔL and ΔM
α	Angle of secondary injection
ρ	Gas density
θ	Slope angle of the nozzle exit
γ	Specific heat ratio
φ	Non-dimensional parameter defined as $\frac{NPR_{Sec}b}{H_t}$

Subscript

amb	Ambient
AB	Nozzle entrance plane
CD	Nozzle exit plane
no	Without secondary injection
P	Nozzle primary flow
Sec	Secondary injection
with	With secondary injection

cowl is applied to change the nozzle exit area for different operations. Even though the nozzle performance can be improved considerably, the adjustment mechanism is complicated with unacceptable weight, limiting its application in highly integrated propulsion system. Youngster et al. [13] studied the effects of the external burning on the performance of the SERN operating at transonic speeds. The fuel was injected into the external flow and was subsequently mixed and burned, and then increased static pressure acts on the entire expansion ramp and cowl trailing edge, as shown in Fig. 2. The results indicated that external burning can be superior to other forms of thrust augmentation methods at transonic speeds. However, a large base drag created by the external burning can offset the augmentation of the nozzle thrust and much more fuel should be carried on board. Reference [15,16] investigated a passive cavity concept for improving the off-design performance of fixed-geometry exhaust nozzles. The passive cavity added the ability to control the off-design nozzle by either encouraging or alleviating the separation appearing in it. Encouraging stable separation offered significant improvements at low NPRs by improving off-design thrust efficiency as much as 2.8%, while separation alleviation had the potential to reduce off-design static thrust efficiency as much as 3.2% at forward flight speeds. Therefore, the passive cavity may have completely opposite effects on the nozzle performance at different flight Mach numbers. In reference [9], a secondary injection on the expansion ramp that filled out the large after-body exit area was employed to avoid the non-matched nozzle state, giving rise to favorable gross thrust angles and improve thrust efficiency in the flight direction. Nevertheless, the complicated adjustment mechanism was also required to turn the injection flap upwards to close the injection air duct. At the same time, the optimal expansion ramp contour might be changed, which was unfavorable to the performance at the cruise condition.

As mentioned earlier, the sub-ambient pressure acting on the ramp is the main reason for the poor performance of the nozzle at off-design flight conditions. One possible solution to raise the pressure distribution along the ramp is to induce the separation of the over-expanded flow. Consequently, Gamble et al. [10,17] introduced an oblique shock generated by the interaction between primary flow and sonic injection on the lower cowl (Fig. 3) to separate the over-expanded flow on the ramp. Compared to the injection on the ramp, this method requires only simple adjustment mechanism without changing the contour of the expansion ramp.

The interaction between a sonic jet and a supersonic cross flow has been the subject of interest in aerospace engineering [18–20], and it is mostly employed to the thrust vectoring nozzle in prior investigation [21,22], and the studies of its application on over-expanded nozzle are very few [10,17]. In Ref. [10], a performance analysis based on the turbojet cycle resulted in a net thrust increase of 3% and thrust specific fuel consumption improvement of 1% with the fluidic injection, validating the feasibility of the design. Reference [17] studied the effects of the injection pressure and flow on the performance of the over-expanded nozzle, but the resulting performance decreased as flow

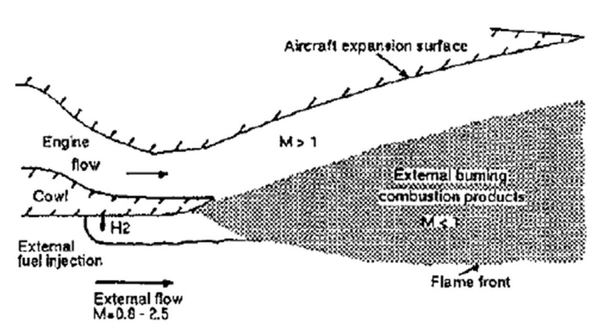

Fig. 2. Schematic of external burning [13].