Acta Astronautica 137 (2017) 145–156

Contents lists available at ScienceDirect

Acta Astronautica

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

Numerical study on dynamic characteristics for sharp opening procedure of boundary-layer suction slot

Yubao He, Hang Yin, Hongyan Huang, Daren Yu*

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Keywords:
Shock train
Boundary layer
Inlet unstart
Suction slot
Hypersonic inlet

ABSTRACT

Based on the sharp forward of shock train and taking the forthcoming unstart for a background, the dynamic characteristics for sharp opening procedure of boundary-layer suction slot are investigated numerically using the dynamic mesh technique. Results indicate that the climbing path of shock train with the complex background waves exhibits a sharp and slow forward state at different time. The compression waves in the primary shock sweep the trailing edge of the separation bubble, and the recirculation within the shock train is communicated with the separation bubble, which reveals that the flow is in a critical state and is about to be unstart at the subsequent time. Furthermore, the dynamic pattern for sharp opening procedure of boundary-layer suction slot can be classified into four distinct stages, namely, the formation of the jet plume without suction mass loss, the formation of the barrier shock with suction mass loss characterized by gradient increase and subsequent two oscillations, the evolution of the barrier shock and jet plume with suction mass loss that ramps up via a series of discrete step increases, and the formation of the stable structure accompanied by the linear suction mass loss.

1. Introduction

Space access is a critical area that must be developed further [1]. To achieve this goal, the Air Force Research Laboratory planed a “stair-step” approach that allows gradual maturation of hypersonic flight from ramjet to scramjet [2]. The dual-mode scramjet engine for a wide range of operating Mach numbers was proposed by Curran and Stull [3]. In the dual-mode engine, the inlet and isolator are the important aerodynamic components that provide the pre-combustion compression [4]. In general, the inlet is to provide homogeneous flow with the high total pressure recovery, while the isolator follows the inlet, thereby connecting it to the higher-pressure combustor of a dual-mode scramjet to reduce the sensitivity to the combustion backpressure [5,6]. However, in the ramjet mode of operation, due to the combustion release, the shock train/pseudo shock is formed and dominates flow. Hence, understanding the flow characteristics of the shock train/pseudo shock is of interest and necessary. The shock-train/pseudo-shock phenomenon has been investigated extensively in the experimental and numerical literatures. Typically, Waltrup and Billig [7] studied experimentally the shock structures in cylindrical ducts. Their results indicated that pressure distributions in the shock-train region present the similar shape and slope, which can be collapsed into a single empirical formula for an engineering design of the isolator model [8]. Recently, Smart [9] examined further the situation where the applied backpressure is more than that across the complete pseudo shock using the quasi one-dimensional method with variable area, friction, and heat transfer. The flow model of pseudo shock with “*X*-type” (proposed by Smart) can provide a good match with experimental data in both the interaction length and the pressure distribution above Mach 2.0. Significant computational efforts were also made to elucidate the characteristics of internal flow with the shock train/pseudo shock. As an example, Su et al. [10] investigated the effects of dynamic backpressure with different frequencies and amplitudes on the pseudo-shock oscillations. The results revealed that as the increase of frequency and amplitude, the effects of frequencies on the position of leading edge and the pressure fluctuation are weaken, while the amplitudes present noticeable impact. Huang et al. [11] investigated numerically the effects of divergent angle and backpressure on the shock-wave transition and the shock-train propagation. According to their report, with the divergent angle increased, the leading edge of primary shock goes through the change from the oblique to the normal shock, and then to the oblique shock; With the backpressure increased, the leading edge of shock train continues to relocate towards the isolator entrance until inducing the inlet unstart. Kamali et al. [12] investigated the parametric effect of wall temperature on the shock-train structure using large-eddy simulation, and reported that decreasing the wall temperature can control the shock-train behavior.

* Corresponding author.
E-mail address: yudaren@hit.edu.cn (D. Yu).

http://dx.doi.org/10.1016/j.actaastro.2017.04.019
Received 24 March 2017; Received in revised form 10 April 2017; Accepted 16 April 2017
Available online 18 April 2017

Nomenclature

C_p	constant pressure specific heat
D_s	width of the suction slot
e_t	total energy
h	enthalpy
h_{iso}	height of the isolator
I	turbulent intensity
k	turbulent kinetic energy
L_{cowl}	length of the internal compression on the cowl
L_{iso}	length of the isolator
L_s	length of the suction slot
M_w	molecular weight of the gas
M	Mach number
m	suction mass flow
P	pressure
R	universal gas constant
R_c	rounding radius of the shoulder
Re	Reynolds number
T	temperature
t	time
u	streamwise velocity
x	X-axis coordinate
x_{cowl}	X−coordinate of the cowl lip
y	Y-axis coordinate
y_{cowl}	Y−coordinate of the cowl lip
y_{iso}	Y−coordinate of the isolator
α	angle of attack
γ	ratio of specific heats
δ	ramp angle
θ	internal compression angle on the cowl
μ	dynamic viscosity
ρ	density
τ	viscous stress tensor
ω	specific dissipation rate

Subscripts

b	backpressure
i	inflow condition/related to direction i
j	related to direction j
o	stagnation condition
s	static condition
t	total condition
∞	freestream condition

Superscripts

$'$	fluctuations with respect to Reynolds average

Since the backpressure perturbations may lead to the inlet unstart [13], the established inlet-isolator shock system is disgorged out of the cowl lip, causing the transient pressure loads and a loss of engine thrust [5]. To control the multiple shock-waves/boundary-layer interactions and mitigate unstart, boundary-layer suction has been used to remove the low-momentum fluid near wall to increase the fluid robustness. Much recent work has been reported about the boundary-layer suction in supersonic and hypersonic inlets. For instance, Herrmann et al. [14] investigated the effectiveness of varied boundary-layer suction geometries, and suggested that the boundary-layer suction system needs to be adjusted flexibly according to the changes of specific flow topology. Soltani et al. [15] investigated the effects of suction position on the operation stability of a supersonic inlet. The results indicated that the suction slot is located in the place where the spilled normal shock stands, which can improve the stability margin. He et al. [16] investigated numerically the local resistance to backpressure with the boundary-layer suction, and revealed the local transformation of the shock-wave system and local evolution of the flowfield inside the suction slot.

However, for a real flight, to avoid the continuous loss of mass flow captured by inlet, the suction slot integrated with hypersonic inlet cannot open all the time during the operation. Besides, due to the time scale of the mechanical actuator motion in the real manipulation, the boundary-layer suction system cannot make an instantaneous response to the control system command triggered. Therefore, the paper explores a kind of opening mode and mimics sharp opening procedure based on the dynamic mesh technique, thereby investigating how the suction process to be built and the dynamic characteristics.

In current paper, an investigation of shock-train climbing path without suction control is first performed. Then, the dynamic characteristics for sharp opening procedure of suction slot are explored in detail. Lastly, the dynamic mass flow behavior for sharp opening procedure of suction slot is further obtained.

2. Methodology

2.1. Physical model

To examine the dynamic characteristics for the sharp opening procedure of the suction slot, a suction slot is integrated at the inlet-isolator model, which was tested by Tan et al. at the key laboratory of aerospace power system [17]. The geometric model used in current paper is a two-dimensional mixed-compression system. As presented in Fig. 1, it consists of a single external compression ramp with the inclination angle of δ=20°, an internal cowl with the flow turning angle of 11° and 9°, and a constant cross-sectional isolator where the length and height are 184 and 16 mm, respectively. A circular arc is attached between the ramp and the isolator with a radius of 40 mm.

The interaction between the cowl shock wave and ingested forebody boundary layer is controlled via the dynamic opening suction slot that is positioned directly at the cowl shock impingement point. The length and width of the suction slot are 16.589 and 0–5.863 mm, respectively. The detailed geometric dimensions are listed in Table 1. The back-pressure at the exit of the suction slot is specified as the freestream static pressure to simulate the plenum pressure that controls the suction mass flow rate. To avoid the effects of specific plenum size, the plenum is neglected to decrease the computational cost and mesh generation complexity.

2.2. Numerical methods

Numerical experiments in the paper are conducted by the density-based solver of the commercial software ANSYS FLUENT that overcomes the numerical stiffness with a technique called time-derivative preconditioning [18]. The effectiveness of the solver has been verified for multiple shock waves/boundary layer interaction in the inlet-

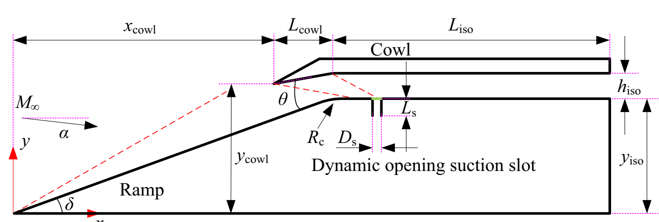

Fig. 1. Schematic diagram of the similar inlet model in [17].