Acta Astronautica 121 (2016) 282–291

Contents lists available at ScienceDirect

Acta Astronautica

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

Non-reacting flow visualization of supersonic combustor based on cavity and cavity–strut flameholder

Zhao Yanhui *, Liang Jianhan *, Zhao Yuxin

Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha City, Hunan Province 410073, China

ARTICLE INFO

Article history:
Received 1 September 2015
Received in revised form
21 December 2015
Accepted 25 December 2015
Available online 7 January 2016

Keywords:
Supersonic combustor
Cavity flameholder
Central strut
Non-reacting flow field
Mass exchange between mainstream and cavity fluid

ABSTRACT

Nano-particle planer laser scattering and particle image velocimetry technology are employed to observe the flow field of scramjet combustors based on cavity and cavity–strut flameholder. Density field and velocity distribution inside combustors are obtained. Mainstream fluid enters into cavity nearby side wall in experimental observation because side wall shock waves interact with bottom wall boundary layer. Cavity fluid is entrained into mainstream in the middle of combustor meanwhile. Flow past cavity displays obvious three dimensional characteristics in both combustors. But cavity–strut combustor displays asymmetrical flow field because of strut configuration. Mass exchange between mainstream and cavity fluid is evaluated by statistic mass flow rate into cavity. Mass flow rate near side wall is raised to 6.62 times of the value in the middle of cavity combustor while it is 5.1 times in cavity–strut combustor. Further study is needed to injection strategies and realistic flow characteristics on condition of combustion.

1. Introduction

Scramjet engine becomes a highlight of hypersonic flight vehicle propulsion system with an excellent performance at high Mach number. However, the residence time of fuel injected into combustor remains only milliseconds because of supersonic incoming flow, which leads to insufficient mixing inside the combustor. Cavity is a kind of mixing enhancement device with flame stabilization performance as well [1]. Gruber et al. [2] studied flow characteristics on condition of several cavity configurations. It was revealed that cavity shear layer played a leading role on flow characteristics of supersonic combustor and related to cavity aft angle. Recirculation zone and vortices caused by cavity had great influence on mixing and combustion in supersonic combustor [3]. The interactions of jet with single cavity and dual cavity were detailed studied by Wang et al. via Large Eddy Simulation (LES) [4,5]. It is found that jet–cavity interactions remarkly enhanced the mass exchange between mainstream and cavity fluid. Jet location and injection pressure appeared to affect the interaction process. Cavity recirculation regions were extended and distorted by jet wake flow and a positive feedback loop was formed between the enhanced fuel–air mixing and heat release around the cavity. More information of the behavior of cavity optimal shape, fueling strategies, combustion stability, and interactions with disturbances in the main airflow has been ongoing provided by many researches [6–9].

In order to gain better mixing and combustion performance, Hsu et al. [10] studied flow characteristics of supersonic combustor based on cavity–strut flameholder. According to their results, strut injector improved ignition ability and flame stability effectively. LES was employed to study an experimental model based on cavity–strut flame holder by Ghodke et al. [11]. Reacting and non-reacting

* Corresponding authors.
E-mail addresses: mj311840@126.com (Y. Zhao), jhleon@vip.sina.com (J. Liang).

http://dx.doi.org/10.1016/j.actaastro.2015.12.040

Nomenclature

X	X coordinate
Y	Y coordinate
Z	Z coordinate
P_0	total pressure
P_s	static pressure
T_0	total temperature
T_s	static temperature
Ma	Mach number
Re_u	unit Reynolds number
ρ	density
D	cavity depth
L/D	cavity length to depth ratio
θ	cavity aft angle
m	total mass of cavity fluid
$\dot{m}$	mass flow rate from mainstream into cavity
τ	cavity resident time
v_y	velocity along y coordinate
A	area of cavity outer surface

flows in supersonic combustion were analyzed by means of compressible LES model. Non-reaction flow simulation agreed well with Hydroxyl Tagging Velocimetry (HTV) observation. As a result, multiple shear layers resulting from the strut provided a broad region for mixing, which was able to hold the flame by keeping local temperature. Low pressure area at the rear of strut increased mass transport between cavity and mainstream. Grady et al. [12] found installing upstream strut increased cavity recirculation along the centerline relative to the no-strut configuration. Cavity shear layer was observed to grow more quickly and impinged higher on the ramp wall by means of LES and Planar Laser-Induced Fluorescence (PLIF) of hydroxyl radical (OH). Zong et al. [13] worked on injection strategy. In their experiments, a larger bench thrust increment and a higher specific impulse have been obtained as more fuel was injected from the strut injectors. Because increasing the strut injection proportion made the combustion zone translate to the divergent segment downstream of the cavity, and led to the dominant flow changing from subsonic to supersonic in the minor fuel-rich condition.

Flow characteristics and combustion performance of cavity–strut flameholder have been studied by many studies. However, reported studies of the combination are limited by wall mounted strut. Combustion performance of central mounted strut has been experimental studied by Hu et al. [14] on condition of different injection strategies. It appeared that optimal fuel distribution existed in strut/wall injection, which suggested a potential combination of cavity and central strut.

This study is an exploration of flow visualization in supersonic combustor with cavity-central strut flameholder. Section 2 displays experimental equipments and combustor models. Two combustors are designed in order to provide a comparison. One is a combustor with single cavity while the other contains a combination of single cavity and central strut. Experimental observation is aiming at get detailed density flow field and velocity distribution of the combustor with cavity flameholder and cavity–strut falmeholder. Non-reacting flow field in combustors with cavity flameholder and cavity–strut flameholder are compared in Section 3. Flow field of cavity strut interaction is analyzed and influence of side wall shock wave is evaluated. Mass exchange statistics between mainstream and cavity is extracted from experimental data. Flow peculiarities of combustion are discussed based on non-reacting flow visualization.

2. Experimental equipments

2.1. Test wind tunnel and combustor models

The experiments are conducted in a supersonic low noise wind tunnel of the National University of Defense Technology (NUDT) as shown in Fig. 1. The wind tunnel is mainly composed of transition section, stability section, nozzle, experimental section and vacuum tank. The nozzle and experimental section are integrated, and optical windows are designed to be installed in the walls of experimental section. The dimensions of the experimental section are 200 mm $\times$ 200 mm with the length of 400 mm so as to get enough space for test models [15,16]. Incoming flow parameters of supersonic wind tunnel are listed in Table 1.

Both combustors are made by glass in order to provide sufficient transmittance and avoid the restrictions on observations caused by the complex structure of models. Configuration sketch of model combustors are displayed in Fig. 2. Cavity is located on the bottom wall of combustor. The depth of cavity (D) is 15 mm which is taken as the dimensionless unit in this paper. The cavity has an aft angle (θ) of 45° and its length-to-depth ratio (L/D) is 7. Cavity shape is same in the models. Central strut in 4 combustors is located above the cavity, and strut's aft wall flushes with the trailing edge of cavity. The strut has a wedge head with a 1 mm blunt body due to the processing technology. The strut is 5D away from the bottom wall of combustor. The models are glued to an installing plate with which they are designed to be placed inside wind tunnel experimental section. So that flow field inside combustor is able to be captured through glassy observing window.

2.2. Flow visualization methods

Nano-particle Planer Laser Scattering (NPLS) system is developed by Yi Shihe and Zhao Yuxin et al. [17–19]. Nano-particle is seeded in supersonic incoming flow to improve following behaviors of tracer particles so that density field is able to be analyzed via NPLS gray images [20,21]. Pictures with high spatial resolution are gained by using an interline transfer Charge-Coupled Device (CCD) equipped with 105 mm micro-lens. The number of CCD array is 4000 $\times$ 2096 pixels with 2048 grayscale grades. The shortest frame straddle time of this system is 200 ns which