Acta Astronautica 133 (2017) 185–194

Contents lists available at ScienceDirect

Acta Astronautica

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

Effect of heat release on movement characteristics of shock train in an isolator

Chenlin Zhang[1], Juntao Chang*,[2], MengMeng Liu[3], Shuo Feng[4], Wen Shi[5], Wen Bao[6]

Harbin Institute of Technology, 150001 Heilongjiang, People's Republic of China

ARTICLE INFO

Keywords:
Shock train
Numerical simulation
Heat release
Supersonic combustion

ABSTRACT

In this paper, the effect of heat release on movement characteristics of shock train is numerically investigated in an isolator. It is found that the combustion heat release has a distinct effect on the shock train movement characteristics in the isolator. With increasing heat release, a shock train gradually forms and then propagates toward isolator entrance. In process of shock train formation, separation bubbles before injection ports entrain the high temperature burning gas into the boundary layer, which causes the shock train to shrink and stretch, and changes in configuration and number of shock waves. At the same time, the system force fluctuates. In addition, the shock train movement is divided into three stages, which have different wall pressure distribution. It is believed that these findings have a help the better understanding of the effect of heat release on the movement characteristics of shock train in an isolator.

1. Introduction

Dual-mode scramjet has attracted much attention from the research community because of its wide flight Mach number range. In a dual-mode scramjet, shock train is a unique internal flow phenomenon in an isolator. It results from by a complex interaction phenomenon between shock wave and boundary layer [1–6]. Along with heat release and flight Mach number variation, combustion-induced pressure and incoming flow lead to shock train change. Based on shock train movement characteristic, it could detect inlet unstart [7–9] and distinguish different combustion modes. It is of great significance to study the movement characteristics of shock train.

Much work has been done on shock train in recent years. For example, Mousavi et al. [10] studied the three dimensional shock train structure. Fischer et al. [11] investigated the effect of a wall temperature from 300 to 1000 K on the shock train in an isolator model and corrected the formula proposed by Waltrup and Billig. Geerts et al. [12] characterized the movement and dynamic behavior of shock train by the downstream pressure disturbance characteristics. Chen et al. [13] studied the transient behavior and three dimensional structures of shock train, illustrated the temporal evolution process of shock train, and revealed by wavelet decomposition the three states of shock train movement. In order to obtain a high backpressure to generate a shock train, a plug is often used in the combustor or at isolator exit in the experiment. Zhang et al. [14] and Tan et al. [15] investigated the shock train movement in the inlet unstart, and illustrated the dynamic mechanism for shock train oscillation by investigating the shock train dynamic characteristics with complex background waves [16]. In most of the numerical investigations, a preset high backpressure at isolator exit is used to replace the plug. Considering background flow structures and increase in backpressure, Xu et al. [17] found that the sharp forward movement of shock train can be predicted. Morgan et al. [18] employed large-eddy simulations to reveal the effect of regional flow blockage. To estimate the effects of combustion-induced backpressure, Su et al. [19] employed dynamic backpressure to study the movement characteristics of shock train. Different from setting backpressure to generate shock train, Larsson et al. [20] used combustion heat release to generate a stable shock train, but the shock train movement coupled with combustion has not been investigated.

At present, most of the shock train movement characteristics and

* Corresponding author.
E-mail addresses: 14B302007@hit.edu.cn (C. Zhang), changjuntao@hit.edu.cn (J. Chang), lmm_hit@163.com (M. Liu), luckyshuo@126.com (S. Feng), 14B302003@hit.edu.cn (W. Shi), baowen@hit.edu.cn (W. Bao).
[1] PhD Candidate, School of Energy Science and Engineering.
[2] Professor, Academy of Fundamental and Interdisciplinary Sciences.
[3] Graduate Student, School of Energy Science and Engineering.
[4] PhD Candidate, School of Energy Science and Engineering.
[5] PhD Candidate, School of Energy Science and Engineering.
[6] Professor, Academy of Fundamental and Interdisciplinary Sciences.

http://dx.doi.org/10.1016/j.actaastro.2017.01.031
Received 1 December 2016; Accepted 24 January 2017
Available online 25 January 2017
0094-5765/

Nomenclature

Ma	Mach number
F	system force
m	mass flow rate
p	pressure
v	flow velocity
A	cross section area
γ	ratio of specific heats
Ω	stagnation pressure loss rescaled
Φ	equivalence ratio
t	time
T	static temperature
p_r	pressure ratio
p_a	average pressure height
S	pressure integral along x axis
x_l	length of pressure increment
Re	Reynolds number based on boundary layer momentum thickness
H	height of isolator
L	length of isolator
θ	boundary layer momentum thickness for undisturbed flow
σ	*root mean square*
ε_r	*relative error*

Subscripts

1	entrance condition
2	exit condition
0	upstream stagnation value
2c	supersonic core flow with exit condition

motion path are obtained by adjusting the backpressure at isolator exit [13–17]. Not much articles investigate the effect of combustion on the shock train [20], and fews focus on the shock train movement characteristics. The strong influence of transverse injection and heat release should not be ignored in the whole process of shock train movement. Obtaining shock train movement of high temporal resolution requires smaller time steps and a larger amount of calculations. Therefore, the effect of heat release on shock train movement characteristics in an isolator is investigated using a flamelet model.

2. Physical model, computational fluid dynamics model and validation of numerical methods

2.1. Physical Model

A constant area duct is used to investigate the movement of the shock train because the interaction between shock wave and the boundary layer is extremely complicated. As shown in Fig. 1(a) and (b), two simplified isolators are 630 mm long. The airflow passes through the entrance of 40 mm high. Boundary conditions of backpressure variation and fuel variation are employed, respectively. Backpressure linearly increases at the exit of the isolator with time in the Fig. 1(a). In the Fig. 1(b), the equivalence ratio of fuel is increased with time by using the user-defined function. The fuel injection ports are located on the upper and lower walls, which are 400 mm away from the entrance. The flow conditions of the inlet and shown in Table 1.

Based on the order of the numerical scheme accuracy and grids, the different the structure grids, including 80×900, 160×1800 and 320×3600, is used as the error estimates of numerical calculation. And the 160×1800 grids are adopted as the calculation mesh at last. Most of grids are 2×10^{-4} m. In order to keep the typical value of y+ below 3 for cells near the wall, the first layer of grids near the wall surface is 1×10^{-5} m. And neighbor grid sizes increase by 1.2 times. The grids at the vicinity of injection ports are keeping appropriate orthogonal grids to improve the quality of grids. The method of error estimates refers to Smirnov [21]. The numerical calculation error estimates is shown in Table 2.

For all unsteady calculation cases, accuracy and convergence of numerical simulation are evaluated by some criteria. The residuals of the calculation variables are below the order of 10^{-3} in every time step. And the mass flow rate between inlet and outlet still keeps the balance in every time step.

2.2. Computational fluid dynamics model

2.2.1. Simulation methodology

Commercial computational fluid dynamics software Fluent was used to solve the 2-D compressible Reynolds-averaged Navier-Stokes equation with finite volume. And the associated boundary conditions were solved using a pressure-based, third-order MUSCL solver. The RANS approach is the efficient and rapid method to obtain the mean flow behaviors for the further mixing and combustion optimization in the supersonic flow. A two-equation shear stress transport (SST) $k-\omega$ turbulence model which was developed by Menter [22] was used to model the turbulence. The (SST) $k-\omega$ turbulence model is suitable to solve the flow fields with adverse pressure gradients, especially for the transverse injection flow field. And it is more accurately for predicting the wall pressure distribution of the transverse injection [23,24]. Considering the sensibility of turbulent Schmidt in simulation of the combustor peak pressures and isolator shock strengths, a turbulent Schmidt number of 1.3 was used for our present work to obtain the best pressure profile [25,26]. Viscosity and specific heat of the mixture were evaluated using the mass-weighted-mixing law. For individual fluids in the mixture, these properties were evaluated using the Sutherland's law and fifth-order polynomials in temperature, respectively.

Steady flamelet model was used as the combustion model for our present work [27–29]. The chemistry was pre-computed and tabulated as a series of laminar flamelet solutions for a given set of boundary conditions and background pressure. Based on the assumption that the chemistry is relatively faster than the mixing time scales, this approach can be accurately represented by a smaller number of scalar quantities. Considering chemistry reaction time, the time scale of hydrogen chemistry reaction is deemed to satisfy with the assumption [29,30]. To account for compressibility of gas and pressure varying of the system, density, temperature, species mass fraction and enthalpy in the PDF tables is updated after every flow interaction. Because the time

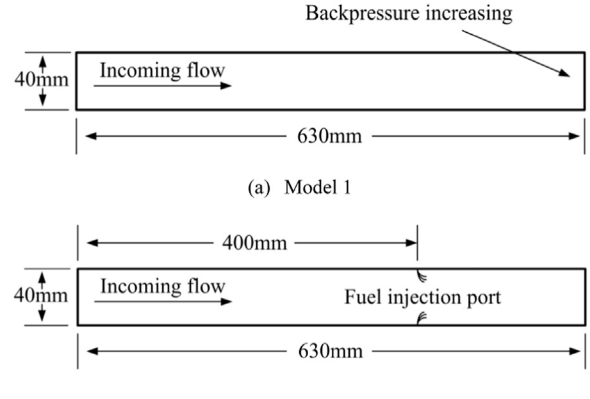

Fig. 1. Schematic diagram of simplified model.