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Effects of dynamic backpressure on shock train motions in straight isolator

Jianhua Cai *, Jin Zhou, Shijie Liu, Zhiyong Lin

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

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ABSTRACT

A numerical study of an oscillating shock train under different types of sinusoidal backpressure in a straight isolator is conducted. In comparison, the shock train location and structure under steady backpressure are explored at first. The results reveal that the shock train moves upstream in a nonlinear way with the increasing backpressure and it keeps nearly the same structure in the process of moving upstream under a certain range of backpressure. Secondly, the typical characteristic of shock train motions under dynamic backpressure is investigated from many aspects. When subjected to sinusoidal backpressure, the shock train undergoes a consistent and repeatable periodic motion, which is similar to the simple harmonic motion. Moreover, the impacts of frequency, amplitude and the average of dynamic backpressure on shock train motions are discussed systematically in this paper. It is found that the average backpressure has a great influence on the location of shock train oscillating region, which moves upstream as the average backpressure is increased. The amplitude of dynamic backpressure has a noticeable effect on the size of shock train oscillating region, which is positively correlated with the amplitude. The frequency affects both the location and size of shock train oscillating region. As the frequency increases, the oscillating region becomes smaller and closer to the exit of the isolator.

1. Introduction

With the successful flight test of the X-43A and the X-51A, the hypersonic airbreathing propulsion techniques have drawn more attention of researchers worldwide. As a critical component of the scramjet engine, the isolator plays a key role in stabilizing the precombustion shock and isolating it from the inlet, which can avoid an inlet unstart and a significant loss in thrust over a broad range of adverse pressure gradients [1]. In the isolator, shock waves and boundary layer interact with each other to form the shock train and accomplish the pressure matching between the inlet and the combustor [2]. According to previous studies, combustion instabilities were observed in the scramjet [3,4]. Studies about pulse detonation engine also show that there are high frequency pressure oscillations existing in this type of engine [5–8]. These pressure disturbances can propagate forward to affect the flowfield of the isolator and even unstart the inlet because of the large enough pressure blockage [9]. Therefore, studying the effect of pressure disturbances on shock train motions is of great importance to engine performance and even flight success.

The nature of the isolator flow is the interaction between shock waves and the boundary layer and it has been studied by many researchers during the past few decades [10–13]. Matsuo et al. [14] and Gnani et al. [15] summarized the previous research results and elaborated the shock train phenomena in internal gas flows systematically. They pointed out that the backpressure is one of the most important factors influencing the characteristic of shock train and it can be divided into steady backpressure and dynamic backpressure.

On the study of steady backpressure, Waltrup and Billig [16] conducted a lot of parametric experiments in cylindrical ducts under different backpressures and introduced a classic empirical relation to estimate the length of shock train. After that many researchers developed the relation and made it adapted to more conditions [17–19]. Paek [20] studied the shock train location affected by different backpressures produced by symmetric ramps, and Hutzel et al. [21] created several models to predict these locations. Su et al. [22] investigated the effect of backpressure on the unsteadiness of flow, the pseudoshock oscillation, and the velocity of the unstart shock wave in the hypersonic inlet-isolator. Kawatsu et al. [23] observed the structure of the pseudoshock in straight and diverging ducts with rectangular cross section numerically and experimentally.

On the study of dynamic backpressure, Su et al. [24] investigated the impact of dynamic backpressure on the pseudoshock oscillation in scramjet inlet-isolator. However, more details about the pseudoshock motions were not included in Su's investigation. Geerts et al. [25]

* Corresponding author.
E-mail addresses: caijianhua.1993@163.com (J. Cai), zj706@vip.sina.com (J. Zhou).

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Nomenclature

A	average backpressure ratio
B	amplitude of backpressure ratio
D	diameter of isolator (mm)
F	frequency of dynamic backpressure (Hz)
H	height of isolator (mm)
Ma	Mach number
P	static pressure (kPa) Re Reynolds number
Re^*	unit Reynolds number (m^{-1})
T	static temperature (K)
t	physical time (s)
$\hat{t}$	dimensionless time
v	freestream velocity (m/s)
X	streamwise position (mm)
X	distance downstream from leading edge (mm)
γ	ratio of specific heats
δ	boundary layer thickness (mm)
θ	boundary layer momentum thickness (mm)
ρ	density (kg/m^3)
Subscripts	
B	exit condition
I	entrance condition
Ref	reference value
0	stagnation value
1	upstream of normal shock
2	downstream of normal shock

characterized the quasi-steady shock train in a rectangular isolator under slowly varying backpressure conditions. The results may have difference from these under a high varying frequency. Bruce et al. [26–29] studied the effect of disturbance frequency on the oscillating normal shock wave in a parallel-walled duct, but other disturbance parameters were not investigated.

Although a significant amount of work has been aimed at investigating the shock train location or structure under steady backpressure, very little was known about the unsteady shock train dynamics under downstream pressure perturbations. The present study focuses on the typical characteristic of shock train motion under dynamic backpressure, which is based on the first shock location. As it is known, the formation of shock train is essentially a three-dimensional phenomenon. However, according to Haberle's study [30], the results of 2D simulation agree fairly well with that of 3D simulation, especially in the highly viscous dominated throat region of the inlet. Jang's study [31] also reveals that even though there are some differences in shock train structures between 2-D and 3-D simulations, the displacement of the first shock is hard to notice. All of these findings mean that the 2-D simulation can also predict the first shock location accurately, so the 2-D simulation is chosen to carry out this work. The relations between backpressure parameters and shock train motion are also discussed systematically in this paper. This will help to improve current understanding of unsteady shock train motions and provide references for optimizing isolator design.

2. Numerical methods

2.1. Governing equations and solution methods

The governing equations of continuum fluid mechanics are Navier-Stokes equations, including continuity equation, momentum equation and energy equation. In order to obtain an averaged form of these equations, the density weighted time average decomposition of u_i and e_0, and the standard time average decomposition of ρ and p are introduced. So the Favre-averaged Navier-Stokes equations are given as:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{u}_j\right)=0 \quad (1)$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\tilde{u}_i\right)+\frac{\partial}{\partial x_j}\left[\bar{\rho}\tilde{u}_i\tilde{u}_j+\bar{p}\delta_{ij}-\left(\tilde{\tau}^l_{ij}+\tilde{\tau}^t_{ij}\right)\right]=0 \quad (2)$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\tilde{e}_0\right)+\frac{\partial}{\partial x_j}\left[\bar{\rho}\tilde{u}_j\tilde{e}_0+\tilde{u}_j\bar{p}+\left(\tilde{q}^l_{ij}+\tilde{q}^t_{ij}\right)-\tilde{u}_j\left(\tilde{\tau}^l_{ij}+\tilde{\tau}^t_{ij}\right)\right]=0 \quad (3)$$

To close these equations, it needs to specify an equation of gas state. Assuming a calorically perfect gas is also necessary. The density averaged total energy $\tilde{e}_0$, stress tensors $\tilde{\tau}_{ij}$ and heat flux $\tilde{q}_{ij}$ are defined by:

$$\tilde{e}_0=\tilde{e}+\frac{1}{2}\tilde{u}_k\tilde{u}_k+k \quad (4)$$

$$\tilde{\tau}^l_{ij}=\mu_l\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}-\frac{2}{3}\frac{\partial\tilde{u}_k}{\partial x_k}\delta_{ij}\right);\tilde{\tau}^t_{ij}\approx\mu_t\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}-\frac{2}{3}\frac{\partial\tilde{u}_k}{\partial x_k}\delta_{ij}\right)-\frac{2}{3}\bar{\rho}k\delta_{ij} \quad (5)$$

$$\tilde{q}^l_{ij}\approx-c_p\frac{\mu_l}{Pr_l}\frac{\partial\tilde{T}}{\partial x_j};\tilde{q}^t_{ij}\approx-c_p\frac{\mu_t}{Pr_t}\frac{\partial\tilde{T}}{\partial x_j}\tilde{q}^t_{ij}\approx-c_p\frac{\mu_t}{Pr_t}\frac{\partial\tilde{T}}{\partial x_j} \quad (6)$$

where k is the turbulence kinetic energy, the laminar Prandtl number Pr_l is given by $\frac{c_p\mu}{\lambda}$, and the turbulent Prandtl number Pr_t is a constant which equals 0.9. The laminar viscosity coefficient μ_l is calculated by Sutherland's law, and the turbulent viscosity coefficient μ_t is obtained from Menter's shear-stress-transport (*SST*) $k-\omega$ two-equation model presented as the following:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho k u_j\right)}{\partial x_j}=\tilde{P}_k-\beta^*\rho\omega k+\frac{\partial}{\partial x_j}\left[\left(\mu_l+\sigma_k\mu_t\right)\frac{\partial k}{\partial x_j}\right] \quad (7)$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial\left(\rho\omega u_j\right)}{\partial x_j}=\alpha\frac{1}{\nu_t}\tilde{P}_k-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu_l+\sigma_\omega\mu_t\right)\frac{\partial\omega}{\partial x_j}\right]+2(1-F_1)\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} \quad (8)$$

$$\nu_t=\frac{a_1k}{\max(a_1\omega,SF_2)};S=\sqrt{2S_{ij}S_{ij}};P_k=\mu_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad (9)$$

In these equations, F_1 and F_2 are blending functions which are equal to zero away from the surface ($k-\varepsilon$ *model*), and switches over to one inside the boundary layer ($k-\omega$ *model*). The constants for this model can be refer to Ref. [32] and all these constants are computed by a blend from the corresponding constants of the $k-\varepsilon$ and $k-\omega$ model via $\alpha=\alpha_1F_1+\alpha_2(1-F_1)$, etc.

The inviscid flux vectors of governing equations are discretized with the fifth-order WENO scheme, while the viscous flux vectors are solved with the Roe-averaged central-difference scheme which is second-order accurate. The third-order Runge-Kutta method is employed for the time advancement. The CFL number used in this study is fixed to be 0.5, corresponding to a physical time step of the order of 1×10^{-8}s, which makes the difference scheme with TVD property.

2.2. Code validation

This code is developed from Sun's hybrid RANS/LES approach, which has been widely used in studying flow problems [33–35], and it's shown