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A novel method for trigger location control of the oblique detonation wave by a modified wedge

Qiongyao Qin, Xiaobing Zhang*

School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing 210094, PR China

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ABSTRACT

Reducing the scale of the oblique detonation wave engine is of great importance as the aircrafts are getting smaller and smaller. A key factor that determines the scale of the oblique detonation wave engine is the trigger location of the detonation wave. Motivated by a cavity stabilized micro combustion phenomenon, a novel wedge with a step added on the surface is proposed to control the trigger location of the oblique detonation wave. A numerical model based on two-dimensional compressible multi-species Euler equations is established to simulate the shock induced combustion phenomenon induced by the wedge. Detailed reaction kinetics mechanism is taken into consideration. An AUSM + scheme (Advection Upstream Splitting Method) is adopted to solve the model. Eleven cases considering different step locations, different Mach numbers of the incoming flow and different rear wedge angles are simulated. It is found that the novel wedge is capable to control the trigger location of the oblique detonation wave through a compression–expansion–compression process. The trigger location control can be accomplished through variations of the step location and the rear wedge angle. The trigger location is always following the step with a constant distance from the step as the step moves along the wedge surface. The trigger location moves towards the step as the rear wedge angle increases.

1. Introduction

The supersonic aircrafts have a tendency to become smaller and smaller, which makes the small-scaled engines an urgent demand. Engines utilizing detonation as the combustion mechanism are widely investigated, such as rotating detonation engine, pulsed detonation engine and oblique detonation wave engine [1–3]. The oblique detonation wave engine (ODWE), which utilizes the oblique detonation wave to generate thrust, is being greatly expected to bring aircrafts to high Mach numbers [4]. Thus, it is of great importance to reduce the scale of the oblique detonation wave engine. Figure 1 [3] is a schematic diagram of a typical ODWE. In the figure, an oblique detonation wave is stabilized in the engine by a surface, which can be regarded as a wedge corresponding to the incoming flow. Large-scaled engines run in the opposite direction of the smaller and smaller aircrafts. A key factor that determines the scale of the oblique detonation wave engine is the trigger location of the detonation. This investigation is motivated by the cavity stabilized micro combustion investigation [5]. In this investigation, Wan and Fan [5] experimentally investigated the flame stability in micro-tube. Results demonstrated that the cavity, acting as a flame holder, extended the operational ranges. This brings a question into our eyesight, that is, how to control the oblique detonation trigger location through structural modification. Due to the bright prospect of the ODWE, lots of studies have been conducted to investigate the oblique detonation wave dynamics, both numerically and experimentally.

An interesting experiment was conducted by Viguier et al. [6]. In the experiment, an oblique detonation wave was induced on a gaseous wedge. Two different mixtures, a driven mixture of a stoichiometric H_2–air and a driver mixture of $C_2H_2 + 2.5\ O_2$, were separated by a very thin Mylar film. A normal detonation wave was triggered in the driver mixture and a gaseous wedge was induced by the expansion of combustion products. An oblique detonation wave was triggered by the gaseous wedge. Besides, a calculation considering detailed chemical kinetic mechanisms was conducted and the overall structure was compared with the experimental one. Analogous experiments are available from other studies of Viguier et al. [7,8]. Desbordes et al. [9] carried out a similar experiment with those of Viguier et al. [6–8] and found that when thermal conditions behind the oblique shock wave (OSW) were lower, the flame initiated at the apex was stabilized as a turbulent oblique flame behind the OSW. Innovative experiments have been conducted to investigate the oblique detonation waves induced by solid surfaces [10–13]. Unlike the gaseous wedge induced detonation, Kudo et al. [10] conducted experiment concerning

* Corresponding author.
E-mail address: zhangxb680504@163.com (X. Zhang).

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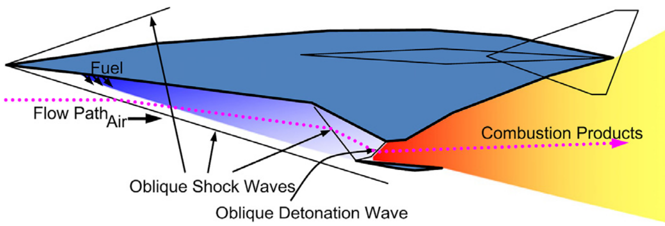

Fig. 1. Schematic of the supersonic combustion ramjets (scramjets) of a hypersonic plane [3].

the stabilization of oblique detonation waves in rectangular-cross-section bent tubes and concluded that the oblique detonation waves were stabilized under the conditions of high initial pressure and a large curvature radius of the inside wall of the rectangular-cross-section bent tube. Maeda et al. [11] adopted the schlieren technique and a high-speed camera to visualize the oblique detonation wave stabilized around a spherical projectile.

The oblique detonation wave is dominated by many parameters, including pressure, temperature, component and Mach number of incoming flow, wedge angle, etc. The effects of these parameters have been investigated numerically in many studies. Da Silva et al. [14] conducted a parametric numerical study to investigate a delayed oblique detonation wave (ODW) which resulted from an oblique shock wave (OSW) transition. Different temperatures and pressures of incoming flow as well as wedge angles were taken into consideration. The numerical results suggested control parameters for obtaining and stabilizing an ODW. A series of pioneering numerical studies have been conducted to investigate the oblique detonation wave [15–20]. Teng et al. [15] performed a parametric study to analyze the effect of inflow pressure and Mach number on the initiation structure and length. Fang et al. [16] numerically studied the oblique detonation formation in hydrogen–air mixtures with inhomogeneous equivalence ratio. A lateral linear distribution of the mixture equivalence ratio was imposed within the initiation region and results illustrated that the reaction surface was distorted in the cases of low mixture equivalence ratio. Iwata et al. [21] employed fuel concentration gradients described by the Gaussian function to deal with the incoming flow condition. In addition to the conditions of the incoming flow, configurations of the wedge also influence the formation of the detonation and much effort has been putted into this aspect. Papalexandris [22] considered two different geometrical configurations and phenomenon was observed that the leading shock curved smoothly until it reached a final angle for moderate wedge angles and the detonation became unstable for higher ones. Lu et al. [23] conducted important researches concerning detonation waves induced by special structure. Lu et al. [23] proposed a self-sustained normal detonation wave engine and the detonation waves induced by a confined wedge were simulated. Analogous research can be found in the study of Fan et al. [24]. Bhattrai and Tang [25] numerically studied the near-Chapman–Jouguet oblique detonation wave induced by a dual-angle ramp and conclusion was drawn that the dual-angle ramp was a simple and practical method for obtaining near-CJ ODWs. In addition to the instability of the detonation wave on the wedge surface, the detonation wave itself shows instability as well. Teng et al. [17] employed a numerical smoked foil records to reveal the unstable cellular structure of the oblique detonation and two kinds of cellular structure were studied. Similar investigation is available from other investigation of Teng et al. [18]. Verreault et al. [26] carried out full unsteady simulations and results showed that the spatial oscillations were transient in nature. Choi et al. [27] numerically studied the unsteady cell-like structures and several instability-driving mechanisms were conjectured from the highly refined results. The induction zone structures also influence the oblique detonation wave and this aspect was investigated by Teng et al. [19]. Choi et al. [28] studied the instability of the oblique detonation wave induced by a wedge of which the flow turning was greater than the maximum attach angle of the ODW. Wang et al. [20] simulated the initiation process of the oblique detonation wave, that is, the transition from oblique shock to the oblique detonation.

Although varieties of studies have been reported concerning the oblique detonation wave, from the perspectives of cell-like detonation wave, structure of the wave, stability of the wave, etc., there are few studies available about the trigger location control of the oblique detonation wave. Motivated by the research of Wan and Fan [5], in which a cavity is employed to hold the flame in a micro-tube, a novel wedge with a step added on the surface is proposed. The schematic of the novel wedge is shown in Fig. 2. Details of the wedge will be introduced in Section 2.2. A numerical model based on two-dimensional compressible multi-species Euler equations is established to simulate the shock induced combustion phenomenon. Detailed reaction kinetics model is taken into consideration. An AUSM + scheme (Advection Upstream Splitting Method) [29] is adopted to solve the equations. Eleven cases considering different step locations, different Mach numbers of incoming flow and different rear wedge angles are simulated to verify the feasibility of the novel wedge. The relationship between the trigger location and the step location is analyzed. A cold flow with chemical reactions suppressed is simulated to figure out the mechanism of the trigger location control. Besides, the performances of the novel wedge under different Mach numbers of incoming flow and different rear wedge angles are analyzed.

2. Computational details

2.1. Governing equations

The two-dimensional compressible multi-species Euler equations considering elementary reactions are adopted as the governing equations. The equations and the corresponding vectors are as follows:

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} = \mathbf{S} \tag{1}$$

$$\mathbf{Q} = [\rho_1, ..., \rho_N, \rho u, \rho v, \rho E]^{\mathrm{T}} \tag{2}$$

$$\mathbf{E} = \left[\rho_1 u, ..., \rho_N u, \rho u^2 + p, \rho u v, u(\rho E + p)\right]^{\mathrm{T}} \tag{3}$$

$$\mathbf{F} = \left[\rho_1 v, ..., \rho_N v, \rho u v, \rho v^2 + p, v(\rho E + p)\right]^{\mathrm{T}} \tag{4}$$

$$\mathbf{S} = [\dot{\omega}_1, ...\dot{\omega}_N, 0, 0, 0]^{\mathrm{T}} \tag{5}$$

where, all the governing equations, continuity, momentum and energy, are expressed in conservation form. **E** and **F** are flux terms. **U** is the solution vector. ρ is the density, u is the velocity in x-direction, v is the velocity in y-direction, p is the pressure, E is the total energy per unit mass. $\dot{\omega}_i$ is the net generation rate of species i from chemical reactions. For a multi-species system, the density and the total energy are given by:

$$\rho = \sum_{i=1}^{N} \rho_i \tag{6}$$

$$E = h - \frac{p}{\rho} + \frac{1}{2}(u^2 + v^2) \tag{7}$$