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Numerical study of inflow equivalence ratio inhomogeneity on oblique detonation formation in hydrogen–air mixtures

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A B S T R A C T

In this study, numerical simulations using Euler equations with detailed chemistry are performed to investigate the effect of fuel–air composition inhomogeneity on the oblique detonation wave (ODW) initiation in hydrogen–air mixtures. This study aims for a better understanding of oblique detonation wave engine performance under practical operating conditions, among those is the inhomogeneous mixing of fuel and air giving rise to a variation of the equivalence ratio (ER) in the incoming combustible flow. This work focuses primarily on how a variable equivalence ratio in the inflow mixture affects both the formation and characteristic parameters of the oblique detonation wave. In this regard, the present simulation imposes initially a lateral linear distribution of the mixture equivalence ratio within the initiation region. The variation is either from fuel-lean or fuel-rich to the uniform stoichiometric mixture condition above the oblique shock wave. The obtained numerical results illustrate that the reaction surface is distorted in the cases of low mixture equivalence ratio. The so-called "V-shaped" flame is observed but differed from previous results that it is not coupled with any compression or shock wave. Analyzing the temperature and species density evolution also shows that the fuel-lean and fuel-rich inhomogeneity have different effects on the combustion features in the initiation region behind the oblique shock wave. Two characteristic quantities, namely the initiation length and the ODW surface position, are defined to describe quantitatively the effects of mixture equivalence ratio inhomogeneity. The results show that the initiation length is mainly determined by the mixture equivalence ratio in the initiation region. Additional computations are performed by reversing ER distribution, i.e., with the linear variation above the initiation region of uniform stoichiometric condition and results also demonstrate that the ODW position is effectively determined by the ER variation before the ODW, which has in turn only negligible effect on the initiation length.

1. Introduction

The development of air-breathing hypersonic aircrafts has attracted increasing attention in recent years. The oblique detonation wave (ODW) concept used in detonation-based engines [1] and Ram Accelerators [2] has long been considered as a viable option for achieving the required high efficient propulsion. This kind of aerospace propulsion system inherits the advantages of the Scramjet (Supersonic combustion ramjet), and furthermore achieves the high thermal cycle efficiency through the detonative combustion [3,4]. However, it remains challenging experimentally to initiate and subsequently stabilize steady oblique detonations in a high-speed flow of combustible mixture, and further systematic theoretical and numerical studies on the oblique detonation initiation and instability need to be performed for advancing the current engineering development of ODW-based propulsion systems.

The ODW phenomenon has been a subject of many theoretical, experimental and lately numerical investigations. Although the basic theoretical foundation for steady ODWs such as wave angles and steady configurations has been well established [5–8], there are still outstanding fundamental problems on the understanding and prediction of the ODW formation and unsteady structures, which are relevant to practical issues for stable operation of the ODW engine. There have been indeed continuous efforts in recent years to perform numerical simulation to describe these phenomena. Since the pioneering work of Li et al. [9] which first described the classical structure of oblique detonation wave composed of a non-reactive oblique shock, an induction region, a set of deflagration waves, and the oblique detonation surface all united at

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a multi-wave point, other types of initiation structure were also revealed from more recent numerical studies. These include the smooth transition from a curved oblique shock to ODW [10–12] and several more complex ODW formation of different wave configurations, for example, with the induction region observed to be ended by an internal Chapman–Jouguet (CJ) detonation wave for low inflow Mach number condition rather than a set of deflagration waves in the classical ODW structure [13–17].

Besides the complex formation structures, recent high resolution numerical simulations have also demonstrated clearly the inherent instability of the ODW. The fine scale, instability features on the oblique detonation surfaces with sets of transverse waves are typical of an unstable frontal structure of normal cellular detonations [18–22]. Furthermore, multi-mode detonation engines which combine the potential advantage of both ODW and the pulsed normal detonation [23,24] are proposed, and the ODW induced by a confined wedge is also analyzed numerically and theoretically [25,26].

For the application of oblique detonations for propulsion, their flow structures and locations need to be predicted to facilitate the engineering design and to control the engine performance. However, in practical situations the incoming reactive flow will unavoidably consist of various types of flow inhomogeneity. Hence, it is crucial to understand the oblique detonation structures with inflow perturbations [27–29]. In normal detonations, the initiation features and their correlation with other dynamic parameters such as cell width have been studied widely [30–33], but only few equivalent studies are performed on the ODW formation especially including inflow disturbance such as non-uniformity in the mixture equivalence ratio denoted in this paper by “ER”. Sislian et al. [34] described the effects of incomplete fuel/air mixing on two types of ramjets performance characteristics by assuming a Gaussian distribution of equivalence ratio in the combustible mixture flow, and the deflagration distortion is observed clearly. Zhang et al. [35] studied the formation of ODW with various ER and found that the initiation length as function of ER displays a classical “V-shaped” curve, similar to the relation between detonation cell size and initiation energy [36]. Iwata et al. [37] simulated the shock-induced combustion from a supersonic spherical projectile, illustrating several shock-flame configurations induced by inflow ER inhomogeneity. They also performed simulations on wedge-stabilized oblique detonations [38] with different Gaussian ER distributions, demonstrating that the near-wedge deflagration fronts are distorted into the complicated surface, generating the so-called “V-shaped” deflagration front and “V+Y” Mach stem.

Based on the previous studies on how the ER inhomogeneity influences ODW structures [35,37], the emphasis of this work is on how such inhomogeneity in the initiation region changes the characteristic parameters, such as the initiation length and ODW position, under practical operating conditions of ODW engines. Our previous study [39] demonstrates that considering the high flight altitude of ODW engines, the transition from OSW (oblique shock wave) to ODW is achieved by a curved shock, different from the abrupt transition structure studied widely [9]. This numerical study was performed using an ideal incoming well-premixed, combustible mixture with uniform ER. As part of our continuous effort to study the fundamental problem of ODW formation under practical flight conditions, the present numerical investigation addresses the effects of inflow ER inhomogeneity with similar flight characteristics. First, three cases with uniform ER values are simulated and a numerical mesh resolution study is performed. A lateral linear distribution of the mixture equivalence ratio within the initiation region is then introduced in the simulation and adjusted in several test cases, generating a variable fuel-lean or fuel-rich mixture in the initiation region before the oblique shock wave. Analysis is performed on the simulation results by defining two

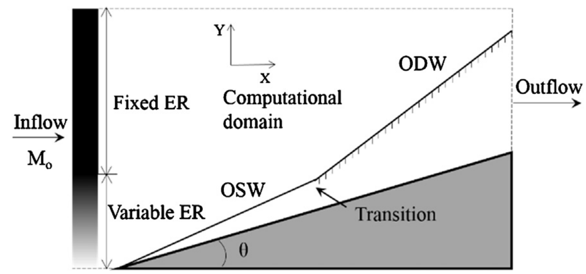

Fig. 1. Schematic of a typical oblique detonation wave.

characteristic length scales, namely, the initiation length and the ODW surface position, to assess the effects of ER inhomogeneity.

2. Physical and numerical models

A simple schematic of the oblique detonation wave induced by a semi-finite wedge from an inflowing combustible gas mixture is shown in Fig. 1. A supersonic combustible gas mixture with an incident Mach number M_o reflects on the two-dimensional wedge and generates first an OSW. The OSW will trigger combustion depending on M_o and incoming flow pressure and temperature (i.e., enthalpy), and under appropriate conditions will initiate the oblique detonation formation. Previous results [40] showed that the viscosity and boundary layer have little effects on this structure except changing the boundary layer thickness slightly, so most of the successive results use the inviscid calculation, e.g. [11–22]. Following this assumption, the governing equations are simplified as two-dimensional multi-species Euler equations and can be written as follows:

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

where:

$$\mathbf{U}=\left\{\begin{array}{c}\rho_1\\ \vdots\\ \rho_n\\ \rho u\\ \rho v\\ e\end{array}\right\},\quad \mathbf{E}=\left\{\begin{array}{c}\rho_1 u\\ \vdots\\ \rho_n u\\ \rho u^2+p\\ \rho u v\\ (e+p)u\end{array}\right\}$$

$$\mathbf{F}=\left\{\begin{array}{c}\rho_1 v\\ \vdots\\ \rho_n v\\ \rho u v\\ \rho v^2+p\\ (e+p)v\end{array}\right\},\quad \mathbf{S}=\left\{\begin{array}{c}\dot\omega_1\\ \vdots\\ \dot\omega_n\\ 0\\ 0\\ 0\end{array}\right\}. \tag{2}$$

In the above equations ρ_i $(i=1\ldots n)$ is the i-th species density and the total density is $\rho=\sum_{i=1}^{n}\rho_i$. u and v are the velocity in the x- and y-direction. Total specific energy e is calculated as

$$e=\rho h-p+\frac{1}{2}\rho\left(u^2+v^2\right) \tag{3}$$

where the specific enthalpy can be written as $h=\sum_{i=1}^{n}\rho_i h_i/\rho$ and the species specific enthalpy h_i can be obtained from the 9-coefficient NASA polynomial representation [41]. Equation of state is

$$p=\sum_{i=1}^{n}\rho_i R_i T \tag{4}$$

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