Combustion and Flame 162 (2015) 470–477

Contents lists available at ScienceDirect

Combustion and Flame

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

Evolution of cellular structures on oblique detonation surfaces

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ARTICLE INFO

Article history:
Received 6 March 2014
Received in revised form 13 June 2014
Accepted 21 July 2014
Available online 7 August 2014

Keywords:
Detonation
Instability
Cellular structure
Transverse wave
Numerical simulations

ABSTRACT

In this study, numerical simulations using the inviscid Euler equations with one-step Arrhenius chemistry model are carried out to investigate the effects of activation energy and wedge angle on the stability of oblique detonation surfaces. Two kinds of cellular structure are studied, one is featured by a single group of transverse waves traveling upstream, referred to as LRTW (left-running transverse waves), and the other is featured by additional RRTW (right-running transverse waves). The present computational simulation reveals the formation of un-reacted gas pockets behind the cellular oblique detonation. Numerical smoked foil records are produced to show the emergence of the two types of transverse waves and the evolution of the unstable cellular structure of the oblique detonation. The transverse wave dynamics, including the colliding, emerging and splitting types, are found to be similar to the normal detonation propagation, demonstrating the instability mechanism is originated from the inherent instability of cellular detonations. Statistical analysis on the cellular structure is carried out to observe quantitatively the influences of activation energy and wedge angle. Results from the parametric study show that high activation energy and low wedge angle are favorable to the LRTW formation. However, the condition for the RRTW formation is more complex. In the case of low activation energy, small wedge angle is beneficial to the RRTW formation, as to the LRTW formation. In contrary, for high activation energy, there appears one moderate wedge angle favoring the RRTW formation and giving the shortest length between the onset of both LR and RR transverse waves. For quantitative comparison, we analyze the variation of two distances with the wedge angle, one is between the detonation initiation and LRTW formation points, and the other between LRTW and RRTW formation points. Results show the latter is relatively less pronounced than the former, indicating the RRTW formation depends mainly on the activation energy and the generation of LRTW.

1. Introduction

The phenomenon of oblique detonation induced by a supersonic combustible flow over an inclined wall has long attracted interest because of its potential application to detonation-based hypersonic propulsion systems for high propulsive efficiency [1,2]. Examples of the application of oblique detonation are the development of continuous detonation wave engines and ram accelerators [3].

In the literature a wealth of research studies on oblique detonations can be found. For instance, the simplified structure in most pioneering analysis is modeled as an oblique shock wave followed by an instantaneous post-shock heat release. Using numerical simulation Li et al. [4] revealed that the multi-dimensional oblique detonation structure consists of a non-reactive oblique shock, an induction region, a set of deflagration waves, and an oblique detonation surface. In this description the oblique shock-oblique detonation transition occurs abruptly giving a λ-like structure in the vicinity of the leading edge of the wedge. Such structure was verified from experiments [5], and is often considered as the standard model of oblique detonations, e.g., [6,7]. Nevertheless, later studies had revealed other type of transition structures due to various complicated unsteady processes. For example, Vlasenko and Sabel'nikov [8] showed that the shock-to-detonation transition may occur smoothly by an arc shock, rather than occurring in a multi-wave interaction point. A number of parametric studies were carried out numerically to investigate the dependence of the transition type on various initial conditions and flow parameters such as the incoming flow Mach number, wedge angle and the reactivity of the mixture [7,9,10]. It is noteworthy that most early numerical studies focused primarily on the stable structure of ODW and the transition from oblique shock to detonation, i.e., how the oblique detonation is established. On the other hand,

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http://dx.doi.org/10.1016/j.combustflame.2014.07.021
0010-2180/

the detailed characteristics of the oblique detonation surface, i.e., how the cellular oblique detonation structures form and evolve, have not yet been fully understood.

Another fundamental characteristic of ODW is the instability of the formed detonation. Indeed from both experiments [5] and numerical simulations [9–14], it was observed that the oblique detonation surface can be unstable with the generation of triple points and fine scale cellular unstable structures very similar to normal cellular detonation. Numerically, it was found by Choi et al. [11] using mixtures of different activation energies that these unstable oblique detonation structures cannot be captured without sufficient numerical resolution. In the numerical results of unstable ODW front obtained by Choi et al. [11], the structure is featured mainly by a single group of transverse waves traveling upstream, referred to as LRTW (left-running transverse waves). This is different from normal detonations with one pair of triple points traveling in opposite direction. By using higher order numerical schemes and extending the computational domain allowing the instability to further develop, recent numerical simulations [12,13] indeed reveals the existence of RRTW (right-running transverse waves) in ODW.

Although these two kinds of cellular structures are observed, i.e., structure featured either by a single-sided triple point or dual-headed triple point, their origin and formation mechanism are still not clear. These characteristics are significant to understand the ODW dynamics and performance of the oblique detonation propulsion system. Recently, Teng et al. [14] demonstrated that the LRTW derives from small perturbation upstream, induced by the interior instability unconditionally. Gui et al. [12] noticed that with variation in activation energy of the combustible mixture, the surface disturbance becomes more and more significant, which induces the LRTW and RRTW successively. Verreault et al. [13] observed more closely that the formation of RRTW derives from the compression wave, which may be amplified along the oblique detonation surface. Despite these aforementioned studies and observations by different researchers, the formation of both transverse waves, especially RRTW, has not been studied systematically with different parameters. As for the simulations of normal cellular detonations, the difficulty in investigating this problem is due to the numerical requirement of a wide computational domain covered with a sufficient level of numerical resolution so to reveal correctly the final transverse wave structure of ODW. In this study, the oblique detonations with various activation energies and wedge angles are simulated. To ensure convergence of the numerical results, numerical resolution study is also performed. The instability characteristics of the ODW structure are then analyzed by examining the resolved flow fields. A quantitative study on the transverse waves is also performed by using a statistic method.

2. Numerical methods

The numerical method follows closely our early work on oblique detonation [10,14]. A schematic of the oblique detonation wave induced by the wedge in a combustible gas mixture is shown in Fig. 1. An oblique shock wave forms first at the wedge front, and if the post-shock temperature is sufficiently high, an exothermic chemical reaction begins and induces an oblique detonation. For convenience, the coordinate is rotated to the direction along the wedge surface, and the computational domain is shown in region enclosed by the dashed line. Hence, the Cartesian grid in the rectangular domain is aligned with the wedge surface. Similar to previous numerical studies on oblique detonations [9–15], the present analysis is based on the inviscid, reactive two-dimensional Euler equations. The non-dimensional governing equations with a single-step, irreversible chemical reaction are of the form:

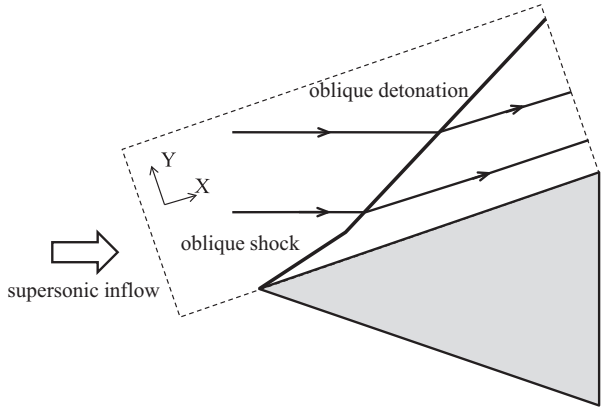

Fig. 1. A schematic of the oblique detonation wave induced by the wedge in the combustible gas mixtures.

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2+p)}{\partial x}+\frac{\partial(\rho u v)}{\partial y}=0 \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho u v)}{\partial x}+\frac{\partial(\rho v^2+p)}{\partial y}=0 \tag{3}$$

$$\frac{\partial \rho e}{\partial t}+\frac{\partial[\rho u(e+p)]}{\partial x}+\frac{\partial[\rho v(e+p)]}{\partial y}=0 \tag{4}$$

$$\frac{\partial \rho \lambda}{\partial t}+\frac{\partial(\rho u \lambda)}{\partial x}+\frac{\partial(\rho v \lambda)}{\partial y}=\rho \dot{\omega} \tag{5}$$

with

$$e=\frac{p}{(\gamma-1)\rho}+\frac{1}{2}(u^2+v^2)-\lambda q \tag{6}$$

$$p=\rho T \tag{7}$$

$$\dot{\omega}=k(1-\lambda)\exp\left(-\frac{E_a}{T}\right) \tag{8}$$

where ρ, u, v, p, e denote the density, velocity in x- and y-direction, pressure and the total energy, respectively. All the flow variables have been made dimensionless by reference to the uniform unburned state (with subscript o). For the chemical reaction, λ is the reaction progress variable which varies between 0 (for unburned reactant) and 1 (for product), and q is the amount of heat release non-dimensionalized by RT_o. The reaction is controlled by the activation energy E_a (also non-dimensionalized by RT_o) and the pre-exponential factor k. The latter is chosen to define the spatial and temporal scales. The mixture is assumed to be ideal and calorically perfect. In this study, we fix the dimensionless parameters with the values $q = 50$ and $\gamma = 1.2$. The governing equations are discretized on Cartesian uniform grids and solved with the MUSCL-Hancock scheme with Strang's splitting. The MUSCL-Hancock scheme is formally a second-order extension to the Godunov's first order upwind method by constructing the Riemann problem on the inter-cell boundary [16]. The scheme is made total variation diminishing (TVD) with the use of slope limiter MINBEE, and the HLLC solver is used for the Riemann problem. If not specified, a numerical resolution of 32 points per half reaction length $l_{1/2}$ of a CJ detonation is used in all simulation cases. This equivalently provides approximately 10 pts/$l_{1/2}$ of an overdriven ODW (along its normal direction) in flow conditions considered in this work.