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Initiation characteristics of wedge-induced oblique detonation waves in turbulence flows

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ABSTRACT

The initiation features of wedge-induced oblique detonation waves (ODWs) in supersonic turbulence flows are studied with numerical simulations based on the SST k-ω model. The results show that the ignition delays are smaller in turbulence flows which results in a decrease in the initiation lengths of ODWs, and the initiation length decreases with the increase of the turbulence intensity. The effects of turbulence on the initiation limits of ODWs are analyzed with the energetic limit and the kinetic limit. It is shown that the initiation limit is not affected by the energetic limit, but affected by the kinetic limit. Because the ignition delay decreases in a turbulence flow, the kinetic limit is more easily to be fulfilled. Therefore, the initiation limit decreases with the increase of the turbulence intensity, that is to say, ODWs in strongly turbulent flows are more easily to be initiated. Besides, the transition structures of ODWs are investigated and the results show that for the same inflow condition, transition structures of ODWs in strongly turbulent flows are smooth while it is abrupt in an inviscid or slightly turbulent flow, and the reasons are discussed.

1. Introduction

With deeper and deeper developments of traditional scramjet, breakthroughs have been achieved in many key technologies. However, limited by the inherent weakness of the combustion method, the thermodynamic efficiency is hard to be further improved, especially at Mach numbers larger than 10. Under the circumstances, propulsion devices based on detonation have attracted much attention for the higher thermodynamic efficiency and higher heat release rate [1–4]. The oblique detonation wave engine (ODWE) is a kind of propulsion device base on the oblique detonation wave (ODW), which is considered to be more applicable to hypersonic airbreathing flight. In the combustion chamber of an ODWE, the ODW is stabilized over a wedge, and chemical reaction just occurs next to the wave surface, which is beneficial to structure simplification and loss minimization of the engine. However, although it has been several decades since the concept of ODWE was proposed, it is far from engineering application compared with the pulse detonation engine (PDE) and the rotating detonation engine (RDE). Because of the rigorous requirements of the initiation and stabilization of ODWs on the inflow condition, it is extremely difficult to conduct effective experimental studies on ODWs in a supersonic channel. Most of previous studies on ODWs are carried out by shooting supersonic projectiles into a static combustible mixture, from which only instantaneous pictures can be achieved and the stability of ODWs cannot be studied. Therefore, investigations on ODWs are always based on numerical simulations, and focused on the initiation and the structure of ODWs.

An ODW is usually initiated by a supersonic projectile in a static mixture or by a fixed wedge in a supersonic inflow, both of them are treated as direct initiation, which requires prodigious amounts of energy. Studies on the initiation criterion have been conducted since 1940s, Zeldovich and Leipunsky [5] investigated shock-induced combustion and detonation, they found that the relation between the residence time of the combustible mixture and the characteristic time of the chemical reaction is a key factor that affects the experimental phenomenon. Soon afterwards, extensive investigations [6–8] on supersonic projectiles in static mixtures are carried out, but only shock-induced combustions are investigated. Until the middle of 1990s, Vasiljev [9] and Lee [10] proposed a theory on the initiation of ODWs independently, that is Vasiljev-Lee criterion or the energetic criterion. They argued that there is a critical energy, E_{cr}, in the initiation of cylindrical blast waves, and the energy that can be achieved from the supersonic projectile in unit length is equal to the drag on the projectile, F_d. When $F_d > E_{cr}$, direct initiation is possible for an ODW. Later, Higgins and Bruckner [11] carried out experimental studies on the initiation of ODWs. However, when they compared the experimental results with the energetic criterion, a deviation appeared at lower Mach numbers. They suggested that the energy cannot be absorbed

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instantaneously at lower Mach numbers which leads to the failure of direct initiation. Ju et al. [12] pointed out the limitation of the energetic criterion through numerical simulation and theoretical analysis, and the kinetic criterion based on the number of Damk**ö**hler was proposed. They argued that only when $Da_{ig} = \tau_{ig}/\tau_{tr} \leq 1$, the direct initiation of ODW is realizable. In the formula, τ_{ig} is the ignition delay, and τ_{tr} is the total time when the projectile moves in the combustible mixture. Verreault and Higgins [13] conducted experimental studies on the initiation of detonations by hypersonic conical projectiles launched into a combustible gas mixture. From analytic considerations of the flowfield, the energetic limit and the kinetic limit are proposed to predict the conditions required to initiate an ODW in the mixture. Five combustion regimes were observed about the projectile ranging from a prompt and delayed oblique detonation wave formation, combustion instability, a wave splitting, and an inert shock wave. The two limits provide a mean to interpret the observed flowfield regimes and are in satisfactory agreement with the experimental results.

Since then, the initiations of ODWs in supersonic flows have been investigated without cease, and great progress has been made in experimental and numerical studies. Han [14] studied the initiation limits of ODWs and the results showed that ODWs on a wedge with a larger angle is more easily to be initiated, but the effects of inflow Mach number is not certain. Meada et al. [15] investigated the oblique detonation waves and shock-induced combustions stabilized around the projectiles using the schlieren technique and they found that the stabilizing criticalities did not depend only on the ratio of the projectile diameter and the cell size of the mixture. Teng et al. [16] carried out numerical studies on the initiation characteristics of wedge-induced ODWs. The effects of inflow Mach number and pressure on the initiation structure and the initiation length were analyzed. The results showed that because of the increase in post-shock temperature, the initiation length decreases with the increase of inflow Mach number. For a given Mach number, the initiation length changes inversely with the increase of the inflow pressure. Besides, Teng et al. [17] conducted numerical studies on the initiation of ODWs induced by semi-infinite wedge and they found that the inflow Mach number and the wedge angle play an important role in the angle and the initiation length of ODW. In their study, the initiation length, L_{ini}, decreases monotonically with the increase of wedge angle θ, but the wave angle, β, has a minimum value, corresponding to $\theta = 29°$. When the inflow Mach number, M_{in}, decreases, both L_{ini} and β increase monotonically until M_{in} decreases below certain critical value. In the cases with high M_{in}, the oblique-shock induced self-ignition dominates and L_{ini} increases when M_{in} decreases. In the cases with low M_{in}, the interaction of ODW and SODW dominates, and L_{ini} decreases when M_{in} decreases.

The structure of ODW is another key point in the studies on ODWs. ODWs are considered abrupt or smooth based on the transition structure, and lots of studies on the transition structures have been conducted. Papalexandris [18] carried out numerical studies on the transition structures of wedge induced ODWs. They argued that when the wedge angle is small, a smooth transition occurs, and an abrupt transition appears at a large wedge angle. Silva and Dashaies [19] studied the initiation of wedge-induce ODWs in supersonic premixed mixtures and they introduced a time ratio t_i/t_r (where t_i and t_r are the induction time and the total reaction time, respectively) to estimate the transition structure. According to the criterion, an abrupt transition appears when $t_i/t_r \to 1$, and a smooth transition occurs when $t_i/t_r \to 0$. Wang et al. [20] investigated the existence of the transverse wave in the transition area with numerical method. A criterion associated to the ratio $\phi = U_2/U_{\mathrm{CJ}}$ (U_2 is the flow velocity behind the ODW and U_{CJ} is the CJ speed of the ODW) is proposed to predict the transition structure. When $\phi < 1$, a transverse shock wave forms, and an abrupt transition appears. When $\phi > 1$, the primary transverse wave does not occur, leading to a smooth transition. Teng et al. [21] carried out numerical simulations on the two kinds of transition structures and proposed a criterion based on the difference in the oblique shock angle and the detonation angle to predict the transition structures of ODWs. They suggested that a smooth transition occurs for a small angle difference while an abrupt transition appears for a large angle difference, and the smooth transition shifts to an abrupt transition when the angle difference is about 15°–18°. Besides, Teng et al. [22] simulated ODWs at different incident Mach numbers to study the induction zone structures. Three kinds of shock configurations, i.e., the λ-shaped shock, X-shaped shock, and Y-shaped shock, were observed at the end of the induction zone, which are all considered as abrupt transitions. Miao et al. [23] investigated the transition structure of ODW quantitatively, and they explained the formation mechanisms with a criterion $P_{\mathrm{d}}/P_{\mathrm{s}}$, where P_{d} is the equilibrium pressure behind the ODW and P_{s} is the pressure behind the induced shock wave. They argued that when the pressure ratio is large, an abrupt transition appears and when the pressure ratio is close to 1, a smooth transition occurs. The critical pressure ratio is about 1.3 in their paper. Besides, an empirical formula was summarized to predict the transition structure based on the inflow condition.

Previous studies on ODWs are mostly based on the two-dimensional Euler equations. However, the initiation of ODWs is a process that contains complex interaction between shock waves and combustions, it is strongly affected by nonequilibrium effect and turbulence flow. The investigations on turbulence detonations that have been reported are mostly focused on the influence of turbulence on deflagration to detonation transition (DDT) in static mixtures [24–36]. Fewer articles studied the interaction between normal detonation and turbulence flow [37–41] or the interaction between rotating detonation and turbulence flow [42,43]. However, the initiation and the stabilization of ODWs in supersonic combustible mixtures are quite different from DDT in a static mixture, and to the best of our knowledge, the initiation and stabilization of ODWs in supersonic turbulence flows have never been reported.

In the present study, two-dimensional numerical simulations are carried out to investigate the initiations and the structures of ODWs in turbulence flows. First, the numerical method is introduced and validated in Sections 2. Then, the numerical simulation results are discussed in Section 3, where the initiation length, the initiation limit and the transition structure are studied. Finally, the conclusions are summarized.

2. Details of the numerical simulations

2.1. Mathematical model

The two-dimensional simulations are conducted in a supersonic channel with a fixed wedge, which is shown in Fig. 1.

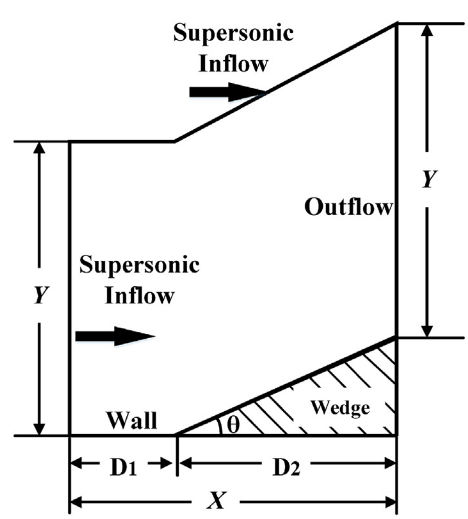

Fig. 1. Schematic of calculation domain.