Effects of fluctuating equivalence ratios on the formation of wedge-induced oblique detonations in pre-evaporated kerosene-air mixtures

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1 Introduction

The development of air-breathing hypersonic aircrafts has attracted increasing attention in recent years. To achieve a higher flight speed, the oblique detonation wave (ODW) can be formed in the reactive mixture flows past a solid wedge with a supersonic speed, and it has been studied as a potential power source for conceptual hypersonic propulsion technologies such as oblique detonation wave engine (ODWE) [1]. It has the advantages of detonation propulsion, mainly high thermal cycle efficiency with fast chemical reaction rates. Therefore, the ODWE has the potential to become the engines for future hypersonic aircrafts. However, considering the engineering applications, a comprehensive understanding of the initiation features and wave stabilization is required to develop reliable ODW-based propulsion systems.

Previous studies on the wedge-induced ODW mainly concerned the initiations [2], wave structures [3], and stabilities [4]. The shock-to-detonation transition through a triple point was confirmed as an abrupt transition. A smooth transition with a curved shock wave also exists. Beside the initiation wave structure, the surface instability features of ODW were also widely studied. The cellular ODW surfaces with triple points have been demonstrated and the combustible mixtures with the large activation energy are more susceptible to the transverse waves or triple point formation.

In practical situations the fuel-air mixtures of incoming flow will be unavoidable inhomogeneous. Therefore, it needs to understand the formation and stabilization features of ODW with various inflow features. Most of the previous research concerned the hydrogen fuel and analyzed the effects of inflow equivalence ratio [5-7]. The liquid hydrocarbon fuel holds the advantages in practices, because of easy storage, convenient application and service as engine coolant. Therefore, the present research considers the kerosene as the fuel

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with a pre-evaporation condition, and the effects of fluctuating equivalence ratios on the formation features of ODW are studied for the first time.

2 Physical Model and Geometrical Setup

The computational simulation is carried out in the dashed zone, as shown in figure 1, which extends in the transverse direction from 0 to L_y and in the streamwise direction from 0 to L_x. The characters x and y represent the streamwise and transverse directions, respectively. L_i is the initiation length of ODW. The wedge has a length of L_w and a height of H_w. For the computation domain, L_x is set to $3.5H_w$ and L_y is set to $1.75H_w$. The wedge starts from x = 0.013 m and the wedge angle θ_w equals to 20°. The streamwise length L_x is set as 0.06 m and the transverse length L_y is 0.03 m.

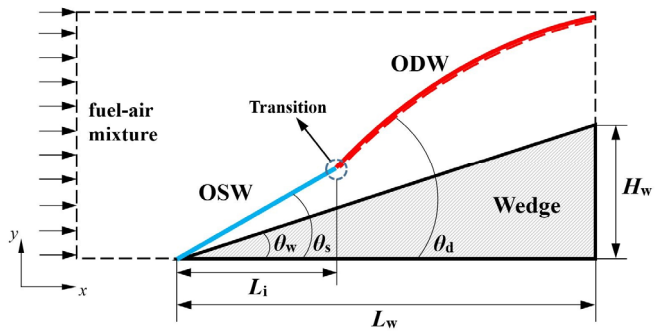


Figure 1. Schematic of wedge-induced oblique detonations in the reactive gaseous kerosene-air mixtures.

The two-dimensional Navier-Stokes equations, including the transport equations of six species are solved via utilizing our in-house numerical simulation codes [8, 9]. Thermodynamic properties are computed from the fifth-order polynomial, and the transport properties including viscosity, conductivity, and diffusion coefficient are obtained based on the kinetic theory. A finite difference approach is applied. An adaptive central-upwind sixth-order WENO (WENO-CU6) scheme [10] is used to simulate the turbulent fields with low dissipation and to achieve a good resolution the shock and detonation waves. A sixth-order symmetric compact difference scheme is applied for the viscous diffusion terms. An explicit third-order Runge-Kutta methodology is applied for time-integration. The chemical reaction of kerosene and oxygen is selected as a two-step reduced scheme [11]. The wedge configuration is constructed by the immersed boundary method. A slip and adiabatic wall boundary condition is used on the wedge surface. A supersonic inflow condition is set at x = 0. The other boundaries are set as zero-gradients, which are interpolated by assuming first-order derivatives of all the flow parameters.

Considering a high-altitude flight condition [8], the inflow streamwise velocity is U_0 = 3000 m/s, the static pressure is P_0 = 0.05 MPa and the static temperature is T_0 = 1000 K. The inflow Mach number, Ma_0, is 5.1 for a stoichiometric fuel-air mixture. These parameters are chosen as the inflow conditions. In the present study, we only disturb the inflow equivalence ratio with a sinusoid function to model a simplified but generic unsteady flow. The inflow equivalence ratio, Φ_t, varies with time as a sinusoidal function, $\Phi_t(t) = A \sin(\omega t) + \Phi_0$. Here, A is the fluctuating amplitude, ω is the frequency, and t is the time. Φ_0 equals to unity for a stoichiometric premixing condition. A derived parameter, N, is defined and used, which is the number of disturbance cycles in the streamwise length of the computation domain. We vary A and N to analyze the characteristics of ODW formation in the unsteady flow, and the simulation cases are summarized in Table 1.

$$\omega = \frac{2\pi U_0}{L_x} \cdot N \tag{1}$$

Table 1: Simulation cases.

Case #	A (fluctuating amplitude)	N (number of disturbance cycles)
V	/	/
V-A0.1-N1	0.1	1.0
V-A0.3-N1	0.3	1.0
V-A0.5-N1	0.5	1.0
V-A0.5-N2	0.5	2.0
V-A0.5-N4	0.5	4.0
V-A0.7-N1	0.7	1.0
V-A0.9-N1	0.9	1.0

3 Results and Discussion

The inflow conditions affected by the fluctuating equivalence ratios should be clarified before the following analysis. The variation in Φ_t changes the sound speed and the associated inflow Mach number owing to the effects from fuel mass addition with the the increase of inflow density, as shown in figure 2. As the inflow Mach number increases, the pressure and temperature of the reactive mixture after the oblique shock wave induced by the wedge become higher, which will accelerate the post-shock chemical reaction and promote the formation of ODW.

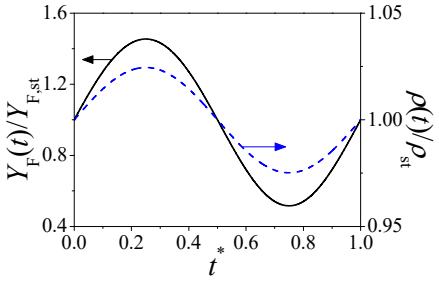


Figure 2. The variations of fuel mass fraction, Y_F, and density, ρ, of inflow mixture for Case V-A0.5-N1. Here, $Y_{F,st}$ and ρ_{st} are the values for a stoichiometric inflow mixture. $t^* = t/t_{flow}$ is the dimensionless time and t_{flow} is a characteristic time of the flow circle from the inflow to outflow boundaries.

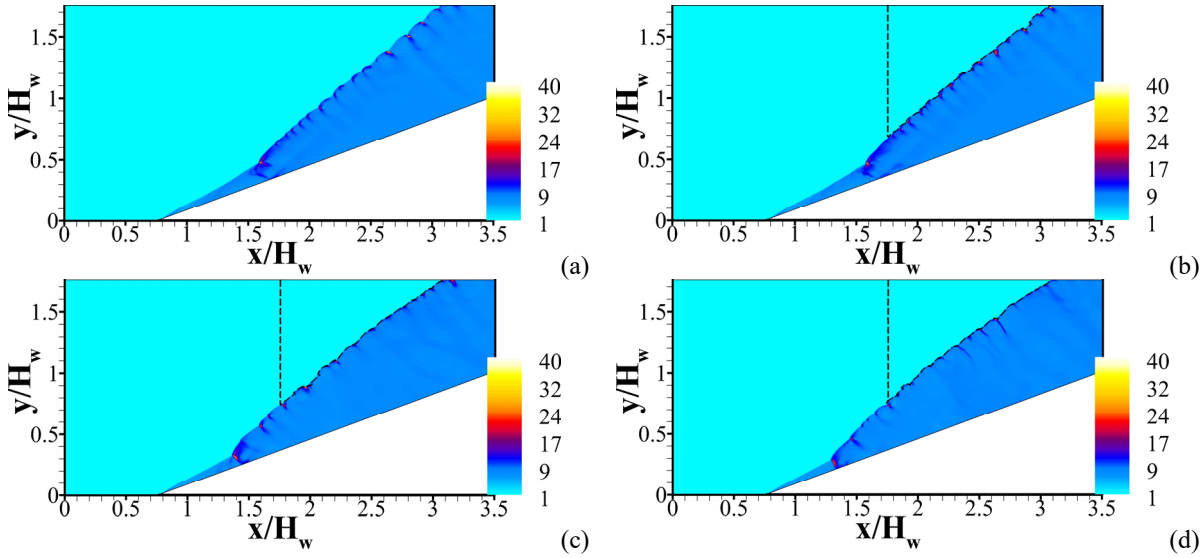
The ODW formed in the steady inflow mixture with $\Phi_t = 1.0$ is first simulated as the basic structure. Figure 3(a) shows the instantaneous pressure distributions for Case V, illustrating a typical structure with smooth initiation transition. The ODW initiation is featured by a curved shock occurred around $x/H_w = 1.6$, and the oblique angle of ODW increases obviously due to the chemical heat release. This structure was also observed in our previous studies [8].

To analyze the ODW formation in the unsteady inflow mixture, the structure is first disturbed with $N = 1.0$ and the fluctuating amplitude, A, is varied from 0.1 to 0.9. For a weak fluctuation ($A = 0.1$), the ODW almost keeps the same wave structure, e.g. the transition by curved shock and the cellular oblique detonation surface, but its initiation region moves upstream slightly due to the imposed disturbance, as shown in figure 3(b).

Because A is very low, the structure of ODW is quasi-steady without complicated phenomena. Furthermore, it is found that the ODW formation tends to be accelerated continually with the increase of A, as depicted from figures 3(b) to 3(d). The upstream movement of ODW formation location is mainly due to the increase of the equivalence ratio by the disturbance, i.e. $A \sin(\omega t) + \Phi_0$, in the first-half cycle, resulting an increase in the chemical reaction rate. In particular, the downstream region from the dashed line of $Y_{F,st}$ is fuel-rich and the upstream region is fuel-lean, as shown in figure 4(a). It is also found that the increase in A changes the transition pattern from OSW to ODW. As shown in figure 3(c) and 3(d), a multi-wave point with a much higher transition pressure is formed and the shock-to-detonation transition is observed to occur abruptly with a strong transverse wave. Although the evolution of ODW stabilization processes is unsteady and the location of ODW formation fluctuates due to the unsteady inflow mixture, the detonation structure can stabilize on the wedge after a dynamic process and is found to be resilient to the disturbances in the flow with a small fluctuating amplitude. More results and analysis for the evolution process of ODW formation will be given in the full-length paper.

The present simulation demonstrates that the increasing A from 0.5 to 0.7 results in the unstable stabilization processes of ODW. As shown in figure 3(e), the shock-induced deflagration results in the formation of ODW around $x/H_w = 1.3$. The transition from OSW to ODW is abrupt with a strong transverse wave, TW1. In the downstream region, the oblique detonation surface becomes unstable and a stronger transverse wave, TW2, is formed around $x/H_w = 2.4$. The distribution of fuel mass fraction shows that there are two reactive pockets in the downstream region of TW2. The TW2 consumes the fuel-rich pockets and propagates downstream. For Case V-A0.9-N1 with a higher fluctuating amplitude for Φ_t, the initiation of ODW moves downstream and the propagation of TW2 becomes more slowly with a weaker strength.

Figures 5(a)-5(h) depict the instantaneous pressure fields for illustrating the evolutions of TW2 for Case V-A0.7-N1. The transverse wave propagates to the fuel-rich reactive mixtures and induces a local explosion, and the shock wave couples with the chemical reaction to forms a transverse detonation wave, as shown in figure 5(b). The TW2 consumes the fuel-air mixtures and propagates downstream with a streamwise velocity higher than U_0. The detonation wave front is found to be curved during the propagation and this is mainly due to the inhomogeneous distribution of fuel-air mixtures in the downstream region. This inhomogeneity wrinkles the flame front and increases the flame area. This, in turn, increases the total fuel consumption rate and provides additional acceleration of the detonation wave.



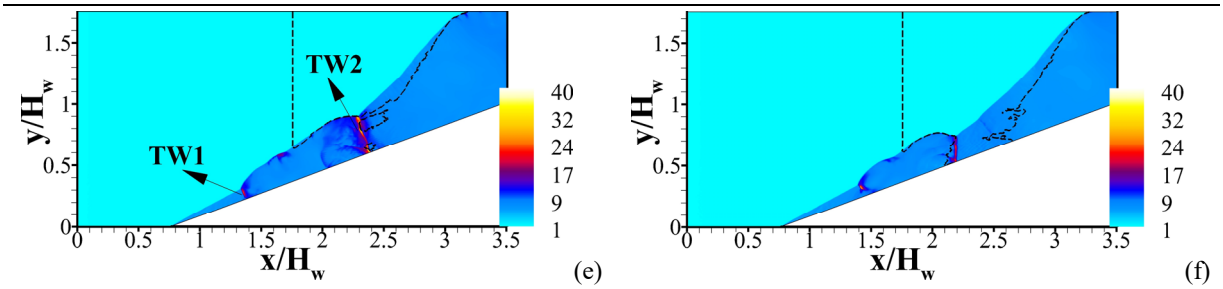


Figure 3. Distributions of dimensionless pressure P/P_0 at $t^* = 2.0$: (a) Case V, (b) Case V-A0.1-N1, (c) Case V-A0.3-N1, (d) Case V-A0.5-N1, (e) Case V-A0.7-N1 and (f) Case V-A0.9-N1. Here, the dashed lines refer to $Y_{F,st}$.

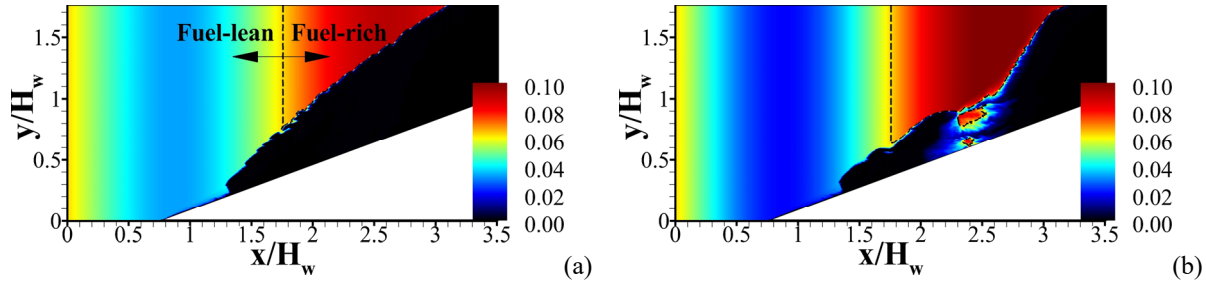


Figure 4. Distributions of fuel mass fraction, Y_F, at $t^* = 2.0$: (a) Case V-A0.5-N1 and (b) Case V-A0.7-N1.

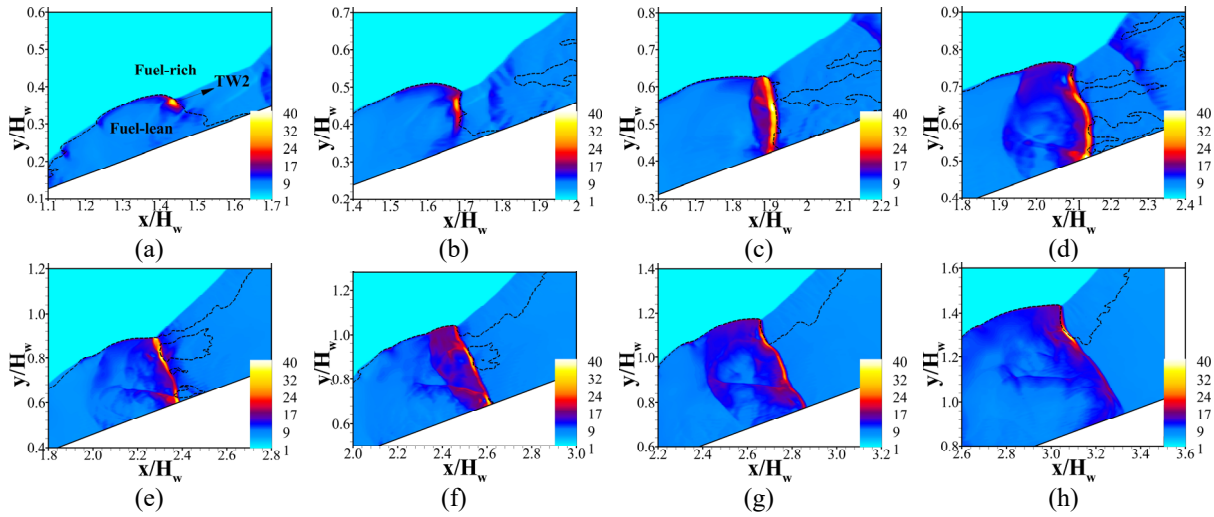


Figure 5. Evolutions of TW2 at times: (a) $t^* = 1.8$, (b) $t^* = 1.85$, (c) $t^* = 1.9$, (d) $t^* = 1.95$, (e) $t^* = 2.0$, (f) $t^* = 2.05$, (g) $t^* = 2.1$, and (h) $t^* = 2.2$. Here, the contours refer to dimensionless pressure P/P_0 and the dashed lines refer to $Y_{F,st}$.

The increasing wave number, N, accelerates the formation of oblique detonation and results in the unstable detonation surface. With $N = 2.0$, as shown in figure 6(a), the initiation structure for ODW forms in the fuel-rich regions and moves upstream, compared with that of Case V-A0.5-N1 in figure 3(d). This is due to the facts that more fuel-rich mixtures are supplied for the upstream chemical reaction and promote the couplings between the shock wave and heat release. A strong transverse wave forms downstream and the non-uniform

premixing inflow induces the periodic unstable detonation surface. For the fuel-lean regions, the detonation surface become more smother with less cellular structures. Further increasing N to 4.0 introduces more triple points and transverse waves are facing downstream. There are convex and concave surfaces connected by the triple points, appearing as cellular surface. Although the flow fields seem increasingly complicated, the ODW can stabilize on the wedge with a relatively stable state.

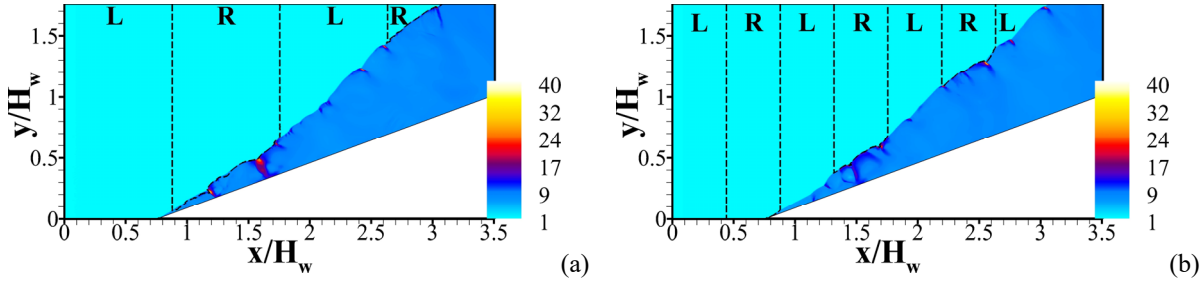


Figure 6. Distributions of dimensionless pressure P/P_0 at $t^* = 2.0$: (a) Case V-A0.5-N2 and (b) Case V-A0.5-N4. Here, the dashed lines refer to $Y_{F,st}$. The characters L and R refer to the fuel-lean and fuel-rich conditions.

4 Conclusions

Two-dimensional numerical simulations of wedge-induced oblique detonation in pre-evaporated kerosene-air mixtures are presented. The unsteady inflow is modeled by a continuous sinusoid equivalence ratio disturbance, and the effects of fluctuating amplitude and wave number on the formation of ODW are simulated and discussed. Based on a typical initiation structure with smooth transition with a curved shock, the increase of wave number makes the detonation surface more unstable with the cellular structures and the increasing fluctuating amplitude results in the unsteady dynamics for the ODW formation. The results indicate that for some conditions the ODW structure can re-adjust itself with local unstable features and tend to be resilient to the inflow disturbances.

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