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Influence of incoming flow velocity and mixture equivalence ratio on oblique detonation characteristics

Hongbo Guo, Honglei Yang *, Ningbo Zhao, Shuying Li, Hongtao Zheng

College of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, China

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A B S T R A C T

In order to reveal the influence of incoming flow velocity and mixture equivalence ratio on the characteristics of oblique detonation, Euler equations coupled detailed chemical reaction model were used to numerically simulate the flow field of oblique detonation. We investigated the characteristic parameters and the morphology of oblique detonation with different wedge angles, velocities and mixture equivalence ratios of incoming flow. The results show that the variations of parameters for uniform inflow condition have obvious influence on the structure of the wave system and the internal stabilization of the oblique detonation flow field. With the increase of incoming flow velocity, the instability of oblique detonation flow field is suppressed. And the initiation position of the oblique detonation is advanced. Under the condition of high velocity inflow, the performance of oblique detonation propulsion is obviously improved. With the increase of the mixture equivalence ratio of inflow, the change law of oblique detonation initiation distance is U-shaped. The internal flow field of the oblique detonation becomes stabilized with the increase of excess oxygen. For the inflow equivalence ratio inhomogeneity, the deflagration front and oblique detonation front become distorted. In addition, the flow field properties of oblique detonation can be optimized by adjusting the inhomogeneity of equivalence ratio.

1. Introduction

In recent years, more and more attention has been paid to develop hypersonic aircraft. One of the engine concepts uses oblique detonation waves, which is considered as a feasible scheme to realize high efficiency propulsion [1–3]. The oblique detonation propulsion system not only has the advantages of Scramjet [4,5], but also realizes high thermal cycle efficiency based on the detonation combustion mode [6]. However, how to achieve the initiation and stabilization of oblique detonation in high speed combustible mixture gas is still the main problem facing the application of oblique detonation propulsion technology.

There has been a great progress in studying the fundamental characteristics of the oblique detonation initiation process. In early researches, the structure of oblique detonation wave (ODW) is approximately simplified as an oblique shock wave (OSW) coupled with an instantaneous post-shock heat release. Pratt et al. [7] theoretically solved the relationship between different inflow parameters and oblique shock or detonation properties, and obtained the analytical solutions between the angle of oblique shock/detonation wave and the inflow conditions. Li et al. [8] first numerically analyzed the formation of oblique detonation, and found that the ODW flow field is composed of a nonreactive oblique shock, an induction region followed by a reaction region, and an oblique detonation. The type of oblique shock-to-detonation transition is connected by a multi-wave point. Later studies show that there are two types of OSW-ODW transition structures in the initiation region of oblique detonation. Vlasenko et al. [9] obtained the smooth transition featured by the curved shock of oblique detonation through numerical simulation research. Ghorbanian et al. [10] theoretically analyzed the structural characteristics of oblique detonation wave and obtained the structural model of wave system in the flow field. Teng and Zhang et al. [11,12] thoroughly studied the initiation process and transition form of oblique detonation through numerical simulation. It is found that the initiation control mechanism of oblique detonation includes the aerodynamic mechanism and the chemical kinetic mechanism [11]. And the end of the induction region has a complex Mach reflection structure [12]. Recent research with the controlling parameters flight altitude and Mach number by Teng et al. [13], on wave systems morphology of ODW initiation region reveals that the existence of two special wave systems. Four ODWs with different wave system relations were discussed, and the morphology of ODWs is predicted by the geometric analysis of double Mach lines and the relation of Mach

* Corresponding author.
E-mail address: yanghonglei@hrbeu.edu.cn (H. Yang).

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numbers in the induction region. In addition, the formation mechanism of different wave systems is clarified. These results [11,14] indicate that the structure of oblique detonation wave system is more complicated than the two classical forms, so it is necessary to study their morphologic changes with incoming flow parameters.

On the other hand, how to realize stabilized oblique detonation in hypersonic is another attractive project. Verreault et al. [15] investigated the structure of oblique detonation waves stabilized on a hypersonic wedge via steady method of characteristics and unsteady simulations. It is found that there are spatial oscillations on the front of oblique detonation wave, which gradually evolve into transverse wave propagating downstream. Teng et al. [16], observed two types of cellular structure on oblique detonation surfaces from the simulations. It is found that a high degree of overdrive suppresses the formation of cellular structures, but does not eliminate it. The main influencing factors for achieving stable propagation of oblique detonation include the properties of combustible mixture [17,18] and incoming flow velocity [11,19]. In addition, in the actual situations the incoming reactive flow will unavoidably involve various types of flow inhomogeneity. Therefore, it is significance to understand the stability characteristics of oblique detonations under different inflow factors. Iwata et al. [20] simulated the flow field structure of oblique detonation in hydrogen-air inflow mixture with inhomogeneity of equivalence ratio. It is illustrated that the stabilization oblique detonation flow field has a distorted complex structure near the deflagration surface on the wedge. Fang et al. [21] studied the influence of a variable equivalence ratio in the inflow mixture on the formation and characteristic parameters of oblique detonation wave. It is pointed out that the oblique detonation wave can remain stable even under the condition of high concentration gradient equivalence ratio, and the characteristic parameters of the oblique detonation wave are determined by the forward flow fuel equivalence ratio. The latest studies [22,23] of ODW unsteadiness and thermal features explore by considering the ODW reflection on the upper wall before a corner. A series of complex wave systems or thermal choking happens due to the interaction between the oblique detonation wave and the wall resulting in the wave instability or the formation of fine flow structures.

Studies on oblique detonation mainly focus on the formation mechanism of typical structures in the initiation region or the instability feature of oblique detonation front. However, for practical application of oblique detonation propulsion system, it is necessary to predict the basic structure and characteristic position of oblique detonation wave qualitatively, so as to facilitate engineering design and control of the performance of oblique detonation engine. This study carries out a series of simulations and analyses of ODW characteristics. Based on the most widely used hydrogen fuel, the variation of the wave system structure in the oblique detonation initiation region with uniform flow velocity or equivalence ratio is qualitatively discussed, and the characteristic parameters of the flow field are analyzed. Building on this, the oblique detonation morphology and flow field characteristics under the effect of incoming flow inhomogeneity of equivalence ratio are studied. The flow conditions which are more suitable for the existence of stabilized oblique detonation and higher oblique detonation pressurization ratio are obtained.

2. Physical and mathematical models

A supersonic combustible gas mixture with an incoming flow velocity u_{in} reflects on the two-dimensional wedge with an angle of θ and generates an oblique shock wave (OSW), firstly. The OSW compresses the mixture, and triggers the chemical reaction exothermic. Under appropriate conditions, oblique detonation wave

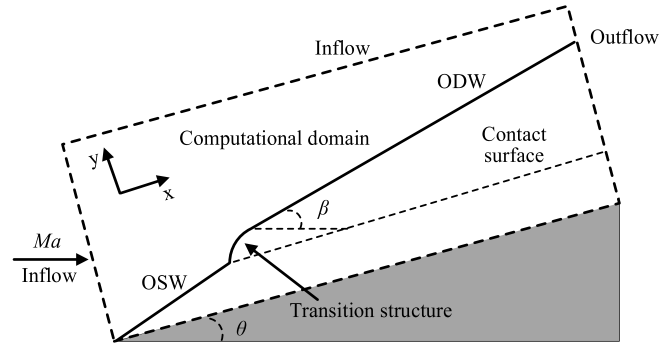


Fig. 1. Schematic of a typical ODW.

(ODW) with an angle of β is formed in the flow field finally, as shown in Fig. 1. The computational domain is represented by a region bounded by the dashed line, and the Cartesian grid is aligned with the wedge surface. The gray zone is the solid wedge, and its wall boundaries are given as solid-slipping reflective condition. The upper and left dashed lines represent the inflow conditions and the right dashed line represents the outlet condition.

The results of Li et al. [24] showed that the length of the initiation zone of ODW is usually on the scale of millimeter, hence the boundary layer has not fully developed yet, resulting in a thin boundary layer. Also, the boundary layer is far away from the main flow field of ODW and has little influence on the flow field structure or characteristic parameters. Besides, the detonation combustion heat release rate is fast. So, the influence of viscosity and diffusion on the overall structure of the oblique detonation can be ignored. Most of the successive results on the formation, stability, and structure of ODWs have neglected the effects of viscosity, mass diffusion and thermal conduction, e.g. [13–16,21–23,25–34]. Similar to these numerical investigations of ODW, this paper analysis is based on the two-dimensional multi-species unsteady reactive Euler equations, which can be written as follows:

$$U_t + [F(U)]_x + [G(U)]_y = S \tag{1}$$

$$\begin{pmatrix} U \\ F(U) \\ G(U) \\ S \end{pmatrix} = \begin{pmatrix} (\rho, & \rho u, & \rho v, & E, & \rho Y_1, & \cdots, & \rho Y_{N-1})^T \\ (\rho u, & \rho u^2 + p, & \rho v u, & (E+p)u, & \rho u Y_1, & \cdots, & \rho u Y_{N-1})^T \\ (\rho v, & \rho u v, & \rho v^2 + p, & (E+p)v, & \rho v Y_1, & \cdots, & \rho v Y_{N-1})^T \\ (0, & 0, & 0, & 0, & \bar{\omega}_1, & \cdots, & \bar{\omega}_{N-1})^T \end{pmatrix} \tag{2}$$

where, $\bar{\omega}_i$ is the ith species' specific mass production rate which is calculated by the Arrhenius law and chemical equilibrium conditions. Y_i is the mass fraction of ith species. ρ is the total density, and p is the pressure, with u and v denoting the velocity in the direction of x and y. E is the total energy which can be calculated by:

$$E = -p + \frac{\rho(u^2 + v^2)}{2} + \rho h \tag{3}$$

where, h is enthalpy per unit mass that can be written as $h = \sum_{i=1}^{N} \rho_i h_i / \rho$ with h_i calculated by the thermodynamic data of each species. Thermodynamic properties of the chemical species are evaluated using the nine-coefficient NASA polynomial representation [35]. All the gases involved are thermally perfect. As such the equation of state for perfect gas is used.

Considering the stiffness of the source terms, Strang splitting scheme [36] is used to divide the governing equations into the flow and the chemical reaction [37], which consists of solving two separate differential equations:

$$U_t + [F(U)]_x + [G(U)]_y = 0 \tag{4}$$

$$U_t = S \tag{5}$$

where, Eq. (4) is the 2D Euler equation for multi-species flow without chemical reaction process, the third order TVD Runge-Kutta method [38] and the fifth order WENO-LF scheme [39] are employed to discretize the temporal term and convection term, respectively. The flow equation is decoupled:

$$\frac{\partial U}{\partial t} + A(U)\frac{\partial U}{\partial x} + B(U)\frac{\partial U}{\partial y} = 0 \tag{6}$$

where $A(U)$ and $B(U)$ denote the Jacobian matrix in the x and y direction. The Roe average method is adopted to transform the governing equation (6) into a quasi-linear problem.

Eq. (5) is a purely chemical reaction equation. Hydrogen/Oxygen/Argon chemical reaction model which includes 9 species (H_2, O_2, O, H, OH, HO_2, H_2O_2, H_2O, Ar) and 19 chemical reactions [40], is selected from the widely used CHEMKIN package [41]. The stiff nature of the problem due to the chemical reaction calculation is solved by the DVODE package [42].

Default mixture is stoichiometric hydrogen-oxygen with highly diluted by 70% argon (H_2: O_2: Ar=2:1:7) with the temperature 300 K and the pressure 1.0 bar. This is ideal mixture so defined as the fuel-oxidizer equivalence ratio $\gamma = 1$, Changing the ratio of H_2 will vary the fuel-oxidizer equivalence ratio, such as H_2: O_2: Ar=1:1:7 corresponding $\gamma = 0.5$. The grid size 50×40 μm^2 including almost 10 grids in the half reaction length of the completely premixed ODW field, is employed in every case. As is indicted in previous studies conducted by Teng [16,43,44], this grid resolution is sufficient to capture not only the wave structure, but also the surface instability.

3. Numerical results and discussion

3.1. ODW influenced by the incoming flow velocity

The incoming flow velocity u_{in} of mixture with chemical equivalence ratio increases from 2400 m/s to 3000 m/s, the structures of the oblique detonation flow field are shown in Fig. 2 with the wedge angle θ is 25°, 30° and 35°, respectively. The upper part shows the flow field temperature, while the lower part shows the flow field pressure. It can be seen that the wave structure of oblique detonation flow field changes obviously with the variation of inflow velocity or wedge angle. The inflow velocity increased, the length of oblique shock wave at wedge tip shortened, and the OSW-ODW transition position moved upstream. In addition, when the inflow velocity is higher, the average temperature and pressure behind the oblique detonation wave is higher. It is because, under the condition of high-speed incoming flow, the combustible mixture kinetic energy increases resulting in the flow field internal energy increases after being compressed by wedge surface, and the temperature of flow field increases. Similarly, with the increase of wedge angle, the conversion amount of kinetic energy into internal energy though the compressed by wedge surface increases. The increase of inflow velocity or wedge angle makes the chemical reaction of combustible mixture intense, and the initiation position of oblique detonation advanced. Under the low-speed incoming flow condition, there is a transverse wave in the oblique detonation initiation region. With the increase of inflow velocity or wedge angle, the strength of the main transverse wave gradually decreases and finally disappears, and the type of transition zone changes from an abrupt structure to the smooth structure. It is because the difference of pressure between the oblique post-shock wave and the oblique post-detonation wave is large under the low-speed incoming flow condition. In order to match the flow field, a transverse wave is formed at the junction. With the increase of inflow velocity or wedge angle, the flow field compression behind the oblique shock wave enhances, while the combustion heat release behind the oblique detonation wave is fixed, resulting in the pressure difference at the junction of OSW and ODW flow field decreased, and the transverse wave intensity is weakened. With the flow development, the stationary oblique detonation surface has unstable left-running transverse wave structure [34], and the position that first appears corresponds to *LTW* point in figure. With the increase of the inflow velocity or wedge angle, the point *LTW* on the oblique detonation wave surface moves downstream, and the distance between adjacent transverse waves gradually decreases. Some transverse waves merge with each other and their morphology changes. It can be seen that with the increase of the inflow velocity or wedge angle, the left-running transverse waves appear hysterically on the oblique detonation wave surface, and the internal instability of the oblique detonation is suppressed. The fusion between two adjacent transverse waves is more likely to occur.

The influence of inflow velocity on the oblique detonation characteristics is further analyzed below. Length of induction region L_{ind} is defined as the distance from wedge tip along wedge surface to the beginning position of chemical reaction heat release. Length of initiation region L_{det} is defined as the distance from the wedge tip along the wedge surface to the position of initiation region. The end of induction region is the position where the temperature gradient reaches its maximum value. For the abrupt transition oblique detonation wave, the end of L_{det} is the projection of multi-wave point on the wedge surface. While for smooth transition oblique detonation wave, the end of L_{det} is the projection of the curved shock wave inflection point on the wedge surface. Fig. 3 shows the length variations of oblique detonation wave induction region and initiation region corresponding to the wedge angle 25°, 30° and 35° with the incoming flow velocity increases from 2400 m/s to 3600 m/s. It can be seen that these two characteristic lengths of oblique detonation wave decrease with the increase of inflow velocity or wedge angle. At low-speed degree, the inflow through the wedge surface has less compression, and the variation of inflow velocity or wedge angle has more obvious influence on the characteristic lengths. The characteristic values reflect the difficulty degree in initiation of oblique detonation. It can be seen that oblique detonation waves are more likely to form in the flow field when the high-speed inflow or big wedge angle. Fig. 4 shows the variation curve of oblique detonation angle β corresponding to the condition of Fig. 3. The oblique detonation wave angle decreases with the increase of incoming flow velocity or the decrease of wedge angle. The oblique detonation wave angle is larger, the combustion velocity post-detonation increases, and the compression degree of the combustion products decreases. Therefore, for the large wedge angle, the influence of inflow velocity or wedge angle variation on oblique detonation angle becomes more obvious, as shown in Fig. 4.

Fig. 5 and Fig. 6 respectively show the temperature variation curve and ratio of the total pressure P to the initial total pressure P_0 variation curve at the outlet boundary of the oblique detonation calculation domain, under the conditions of different inflow velocities with the wedge angle of 30°. As the inflow velocity increases, the oblique detonation height decreases. It can be seen from Fig. 5 that the change of inflow velocity has little influence on the temperature distribution of downstream flow field behind oblique detonation wave. This is because that the inflow composition is given and the heat release after combustion of the

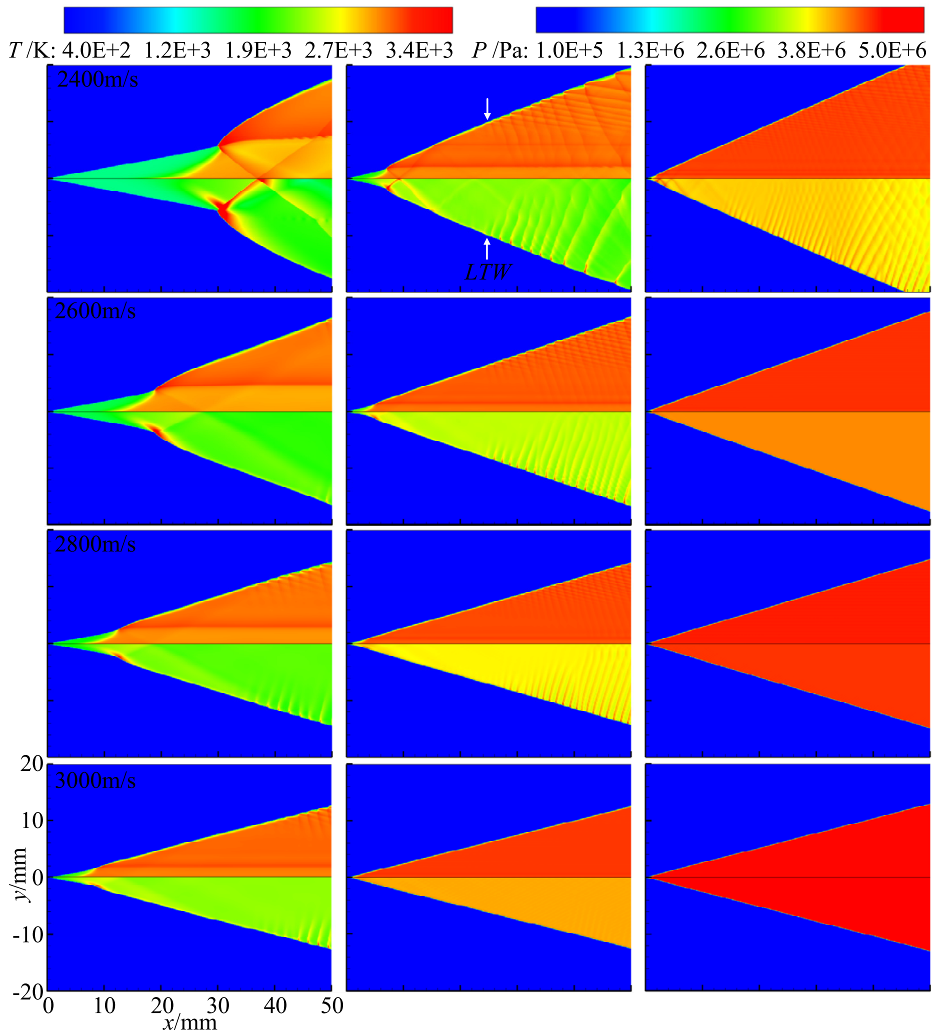


Fig. 2. Temperature (upper) and pressure (lower) with different incoming flow velocities and wedge angles. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

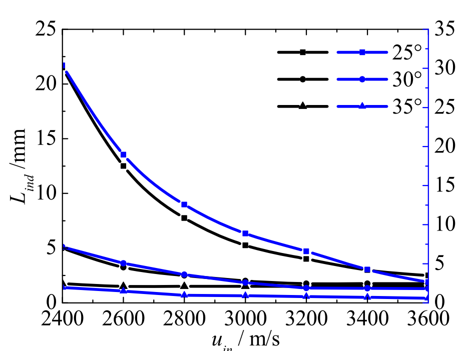


Fig. 3. Characteristic lengths with different incoming flow velocities and wedge angles.

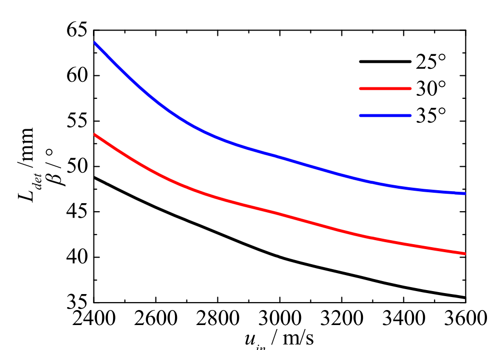


Fig. 4. Oblique detonation wave angles with different incoming flow velocities and wedge angles.

combustible mixture is fixed. As can be seen from Fig. 6, with the inflow velocity increases, the pressure oscillation amplitude behind the oblique detonation wave decreases, and the oblique detonation flow field becomes more stable. The greater the inflow velocity is, the more obvious the inhibition effect is on the internal instability of the oblique detonation flow field. Under the condition of high-speed incoming flow degree, the total pressurization ratio behind oblique detonation wave is relatively high, so the performance of oblique detonation propulsion increases obviously with the increase of incoming flow velocity.

3.2. ODW influenced by the equivalence ratio

The equivalence ratio γ of mixture with incoming flow velocity 2500 m/s increases from 0.8 to 1.6, the structures of the oblique detonation flow field are shown in Fig. 7 with the wedge

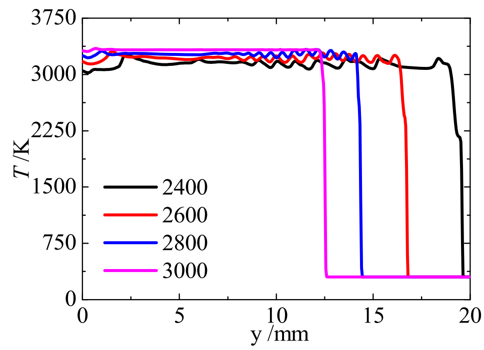


Fig. 5. The temperature on outlet boundary with different incoming flow velocities.

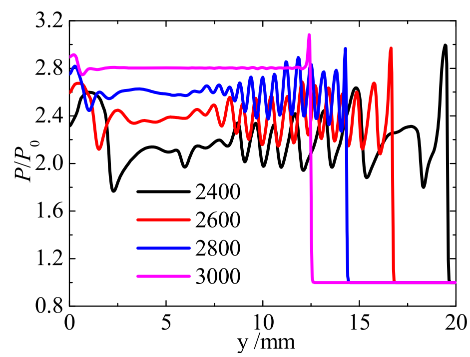


Fig. 6. The total pressurization ratio on outlet boundary with different incoming flow velocities.

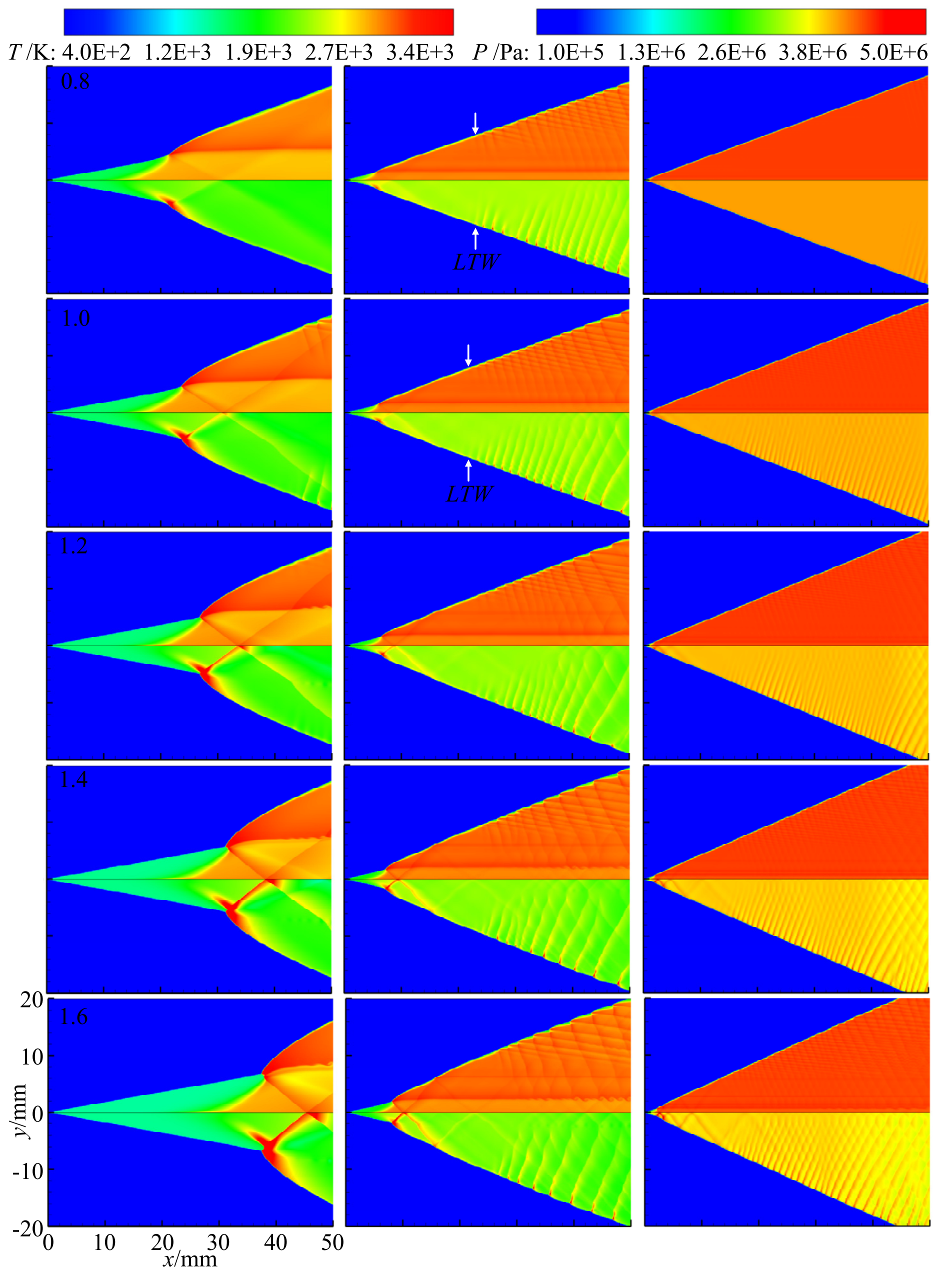
angle θ is 25°, 30° and 35°, respectively. The upper part shows the flow field temperature, while the lower part shows the flow field pressure. It can be seen that the wave structure of oblique detonation flow field changes obviously with the variation of inflow equivalence ratio or wedge angle. The inflow equivalence ratio increased, the length of oblique shock wave at wedge tip lengthened, and the OSW-ODW transition position moved downstream. This is because that the oxygen content in combustible mixture decreases with equivalence ratio increases, the exothermic process of chemical reaction weakens with less oxidizer, so the induction time of chemical reaction increases. The initiation process of oblique detonation is prolonged so that the initiation position moves downstream. In these cases, the structure characteristics of oblique detonation flow field under different wedge angles are mainly affected by the mixture internal energy after compression. In addition, the oblique detonation wave presents an abrupt transition structure within the scope of this study. With the increase of the mixture equivalence ratio, in the oblique detonation initiation region, the strength of the main transverse wave increases, and the Mach reflection becomes more enhancement. The variation of equivalence ratio changes the induction stage and the exothermic stage in the chemical reaction process, which affects the structure of the initiation region in the oblique detonation flow field. It can be seen that under different equivalence ratios, the position *LTW* where the left-running transverse wave first appears on the front of the oblique detonation wave is relatively close. With the increase of mixtures equivalence ratio, the distance between two adjacent transverse waves increases, and the structure of left-running transverse wave becomes clearer. This indicates that the internal instability of the oblique detonation increases with the increase of the combustible mixture equivalence ratio, in which the exothermic process of chemical reaction plays a major role. An intense exothermic process of chemical reaction has an inhibitory effect on the internal instability of the oblique detonation.

Fig. 8 shows the characteristic lengths of oblique detonation wave induction region and initiation region corresponding to the wedge angle is 25°, 30° and 35° with the equivalence ratio increases from 0.2 to 1.8. It can be seen that when the wedge angle is 25°, with the increase of equivalence ratio, the characteristic lengths of the oblique detonation wave first decrease and then increase, and the minimum value correspond to the mixture equivalence ratio around 0.8. The characteristic lengths curves of oblique detonation wave show the U-shaped change trend, which is consistent with the change law of detonation initiation energy or cell width with fuel-oxidant equivalence ratio [45]. The combustion mechanism of oil-rich region and oxygen-rich region is different. With the increase of wedge angle, the characteristic lengths of oblique detonation wave decrease. In the case of large wedge angle ($\theta = 30°$, $35°$), the variation of equivalence ratio has little influence on the characteristic lengths of oblique detonation, but the minimum value of characteristic lengths still appears around $\gamma = 0.8$. In conclusion, the exothermic process of chemical reaction is more intense and the oblique detonation is formed faster when the combustible mixture equivalence ratio is around 0.8. Fig. 9 shows the variation curves of oblique detonation angle β corresponding to the condition of Fig. 8. The oblique detonation wave angle increases with the increase of fuel-oxidant equivalence ratio or wedge angle. For the large wedge angle, the influence of equivalence ratio or wedge angle variation on oblique detonation angle becomes more obvious.

Fig. 10 and Fig. 11 respectively show the temperature variation curve and ratio of the total pressure P to the initial total pressure P_0 variation curve at the outlet boundary of the oblique detonation calculation domain, under the conditions of different equivalence ratio with the wedge angle of 30°. As the inflow equivalence ratio increases, the oblique detonation height increases. It can be seen that, within the study range shown in the Fig. 10, the change of inflow equivalence ratio has little influence on the temperature at the downstream outlet of the oblique detonation flow field. When the equivalence ratio is greater than 1, fuel cannot be consumed completely and the amount of heat released is limited by the oxygen content. So, the change of temperature at the outlet boundary is small. As can be seen from Fig. 11, with the inflow equivalence ratio increases, the total pressurization ratio behind the oblique detonation wave decreases. Under the condition of oil-rich, the oscillation amplitude of oblique detonation flow field downstream parameter is large and the post-wave total pressurization ratio is unstable.

3.3. Analysis of inhomogeneous equivalence ratios

The inhomogeneous incoming flow conditions of oblique detonation engines are mainly caused by the gradient of incoming flow velocity, which directly leads to the inhomogeneity of the mixture equivalence ratio of incoming flow. Next, the influence of the inflow equivalence ratio inhomogeneity on the morphology and feature of oblique detonation wave are studied. In order to approximately simulate the inhomogeneity of fuel-oxidant equivalence ratio in real conditions, the inflow γ inhomogeneity is introduced that covers the whole inflow in the calculated area. The representation of inflow γ inhomogeneity is also displayed in Fig. 12 (a). The equivalence ratio at the intersection of the left inflow boundary and the wedge surface is set as γ_b, and the equivalence ratio at the top of the outlet boundary is set as γ_a. For the convenience of calculation and analysis, the distribution function of equivalence ratio is given by linear interpolation method between γ_a and γ_b, to simulate the inhomogeneity of inflow. The change of equivalence ratio of inflow results in the change of flow field composition and sound velocity. Considering the flow characteristics of hypersonic, the constant incoming flow velocity $u_{in} = 2500$ m/s and wedge an-



(a) θ=25° (b) θ=30° (c) θ=35°

Fig. 7. Temperature (upper) and pressure (lower) with different equivalence ratios and wedge angles.

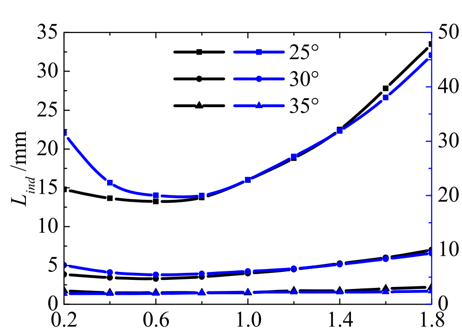


Fig. 8. Characteristic lengths with different equivalence ratios and wedge angles.

gle $\theta = 30°$ are selected in this paper. The initial temperature and pressure of the flow field are consistent with the previous cases. At the wedge tip, the equivalence ratio $\gamma_b = 0.2$, that is, H_2: O_2: Ar=0.2×2:1:7, and the maximum equivalence ratio is $\gamma_a = 1.8$, the parameters distribution of oblique detonation flow field is shown in Fig. 12. It can be seen from Fig. 12 (a) that the mass fraction of fuel H_2 decreases rapidly after combustion by oblique detonation wave. The mass fraction of H_2 behind the wave is approximately 0 and the fuel is all consumed near the tip of wedge. The outlet is an oil-rich condition with a relatively large equivalence ratio. H_2 is not completely consumed behind oblique detonation wave, corresponding to the high temperature and pressure in the flow field in this region, and the unstable left-running transverse wave structure appear on the oblique detonation wave surface, as shown in Fig. 12 (c) and Fig. 12 (d). Fig. 12 (b) shows the mass fraction of

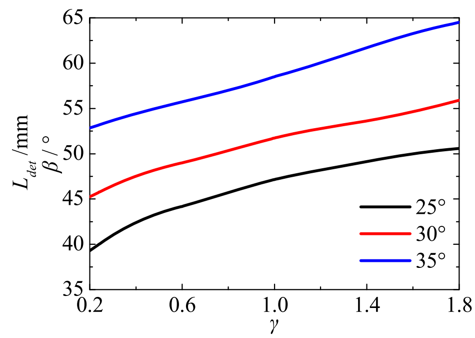


Fig. 9. Oblique detonation wave angles with different equivalence ratios and wedge angles.

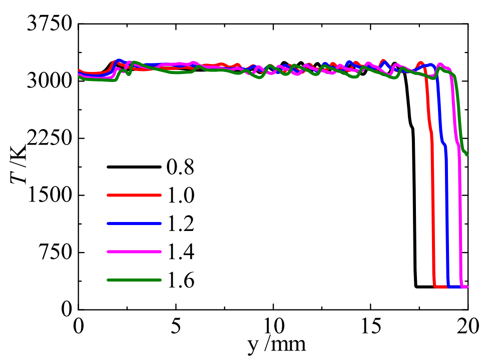


Fig. 10. The temperature on outlet boundary with different equivalence ratios.

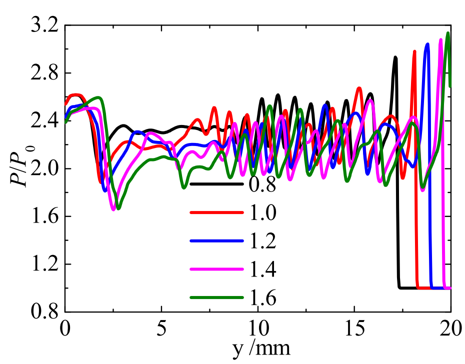


Fig. 11. The total pressurization ratio on outlet boundary with different equivalence ratios.

OH in the flow field, expressing the intensity degree of chemical reaction behind the oblique detonation wave. It can be seen that the chemical reaction process is most violent near the equivalence ratio of 1. The OH mass fraction is relatively small near the wedge tip and outlet boundary. According to Fig. 12 (c) of the flow field temperature, compared with the premix uniform incoming flow condition, the structure of the oblique detonation initiation region and oblique detonation wave surface appear obvious changes under the condition of non-uniform incoming flow equivalence ratio. The temperature of the flow field near the wedge is low, which is caused by the lack of fuel. Two temperature isolines (black lines) in the Fig. 12 (c) approximately represent the chemical reaction surface. Since the oblique shock wave front is a poor oil inflow condition and the heat release is slow, which causes the chemical reaction front to distort, presenting a V-shaped deflagration wave protruding upstream [20]. It can be seen from Fig. 12 (d) of the pressure distribution that, under the condition of inhomogeneity equivalence ratio of inflow, the surface of the oblique detonation wave bends towards the wedge, and the downstream unstable left-running transverse wave also bends. There is no main transverse wave structure in the initiation region, and it is a smooth transition type. In this case, the inflow fuel-oxidant equivalence ratio corresponding to the inflection point of curved shock wave is about $\gamma = 0.41$, and the initiation length is $L_{det} = 7.01$ mm. While, for the uniform inflow condition, the initiation length is 5.88 mm. The exothermic process of chemical reaction directly determines the oblique detonation wave characteristic. Under the inhomogeneity equivalence ratio of inflow, the exothermic process of combustion changes, leading to changes in the initiation process of oblique detonation, bending of the structure of the flow field wave system.

Next, the oblique detonation flow field is analyzed under the condition that the oil-rich inflow in the induced region. At the wedge tip, the equivalence ratio is $\gamma_b = 1.8$, and the top of outlet boundary reaches minimum equivalence ratio is $\gamma_a = 0.2$, the parameters distribution of oblique detonation flow field is shown in Fig. 13. It can be seen from Fig. 13 (a) that the H_2 mass fraction near the wedge is relatively large. This is because the equivalence ratio near the induction region is relatively large, and the unconsumed H_2 is propagated downstream. According to the OH mass fraction distribution Fig. 13 (b), the chemical reaction of the upstream oblique detonation flow field is the most intense, and the corresponding flow field temperature is higher, as shown in Fig. 13 (c). Under this inflow condition, the oblique detonation wave angle gradually decreases along the downstream direction, bending the oblique detonation wave surface is shown in Fig. 13 (d). There is a main transverse wave structure in the initiation region, and it is an abrupt transition type. In this case, the inflow fuel-oxidant equivalence ratio corresponding to the multi-wave point is about $\gamma = 1.56$, and the initiation length is $L_{det} = 8.87$ mm. While, for the uniform inflow condition, the initiation length is 8.06 mm.

To sum up, within the scope of this study, the initiation process of oblique detonation wave is significantly changed due to the inhomogeneity distribution of the inflow equivalence ratio. The initiation length increases and the detonation position moves downstream in the oblique detonation flow field under the action of inhomogeneity inflow equivalence ratio. The bending of the oblique detonation surface is directly related to the heat release process of incoming mixture.

Fig. 14 shows the total pressurization ratio fields and pressure contours corresponding to the above two cases of Fig. 12 and Fig. 13. It can be seen from the figure that there are significant differences in the main characteristics of the pressurization ratio in the flow field. When the inflow in front of the induction zone is oxygen-rich, as shown in Fig. 14 (a), there is a larger pressurization ratio near the wall surface. The pressurization in the induction region is realized by the deflagration process behind the oblique shock wave at the wedge tip. In this region, the flow field density is larger, and the velocity behind the oblique shock wave with low intensity is larger so that the total pressurization goes up significantly. For different equivalence ratio distribution in front of oblique detonation wave, the pressurization characteristics of downstream flow field are obviously different. As can be seen from Fig. 14 (b) with oxygen-rich inflow mixture ahead of the oblique detonation wave, the angle between the inflow velocity and the transverse wave on the oblique detonation wave surface is larger than that of Fig. 14 (a) with oil-rich incoming condition. When the intersection angle is large, the compression degree to the inflow is relatively large, so that the pressurization ratio is further improved. In conclusion, the oxygen-rich incoming flow in front of the oblique detonation wave can improve the overall pressurization performance of the oblique detonation propulsion system.

Regarding the wave system of the initiation region, the intensity of interaction between waves is different arise from the difference distribution of the inflow equivalence ratio ahead of the induction region. Fig. 15 shows the H_2 density fields and pressure contours

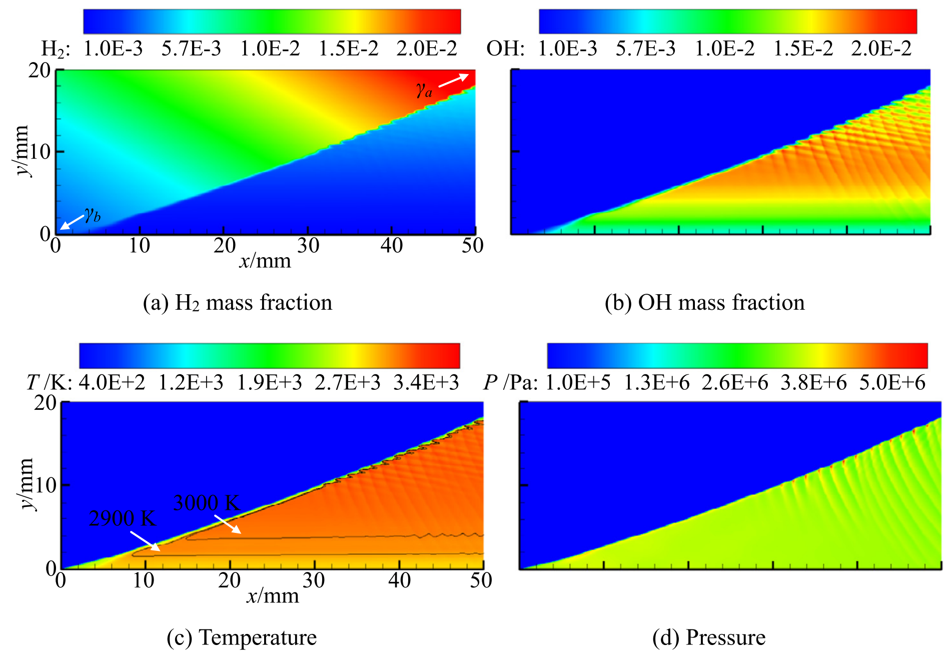


Fig. 12. H_2 mass fraction (a), OH mass fraction (b), temperature (c) and pressure (d) in the case of $\gamma_a = 1.8$, and $\gamma_b = 0.2$.

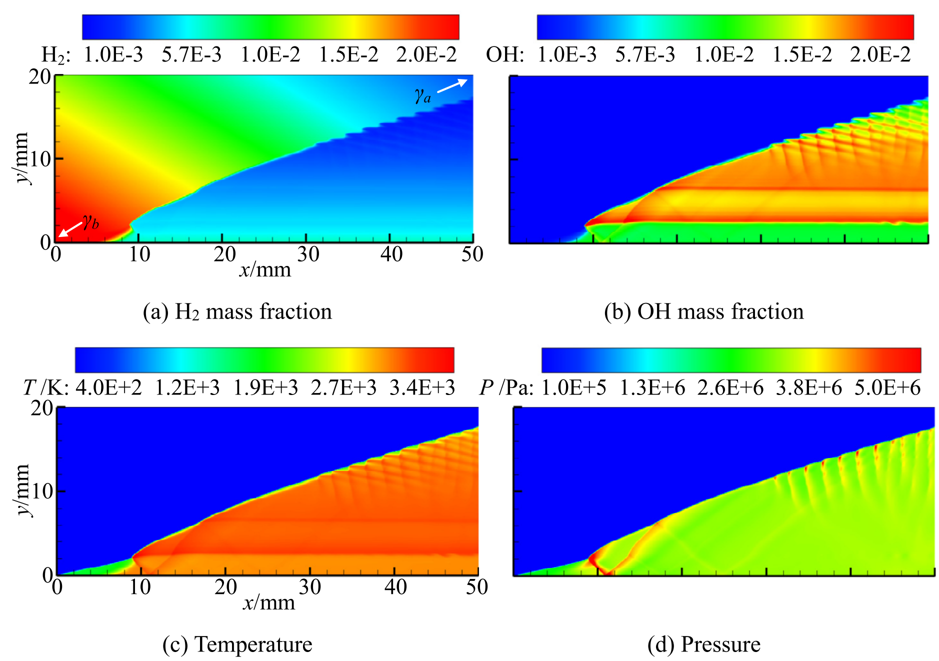


Fig. 13. H_2 mass fraction (a), OH mass fraction (b), temperature (c) and pressure (d) in the case of $\gamma_a = 0.2$, and $\gamma_b = 1.8$.

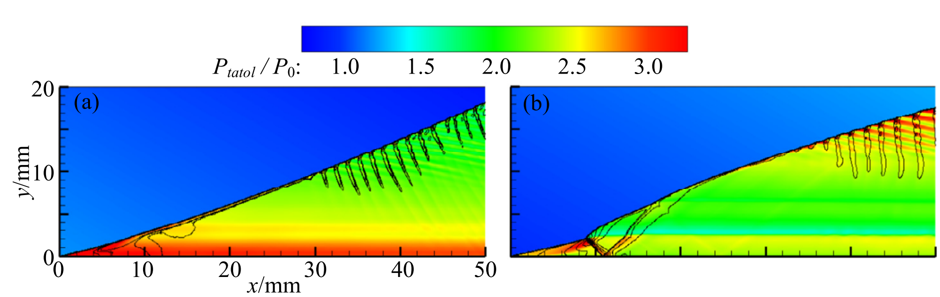


Fig. 14. Total pressurization rate fields overlapped with pressure contours (black): in cases of $\gamma_a = 1.8$, $\gamma_b = 0.2$ (a), $\gamma_a = 0.2$, $\gamma_b = 1.8$ (b).

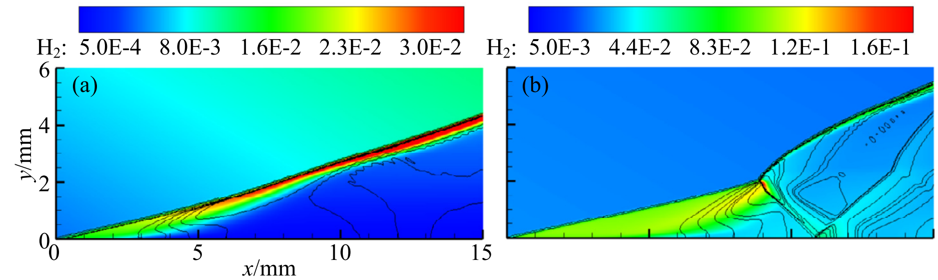


Fig. 15. H_2 density fields overlapped with pressure contours (black): in cases of $\gamma_a = 1.8$, $\gamma_b = 0.2$ (a), $\gamma_a = 0.2$, $\gamma_b = 1.8$ (b).

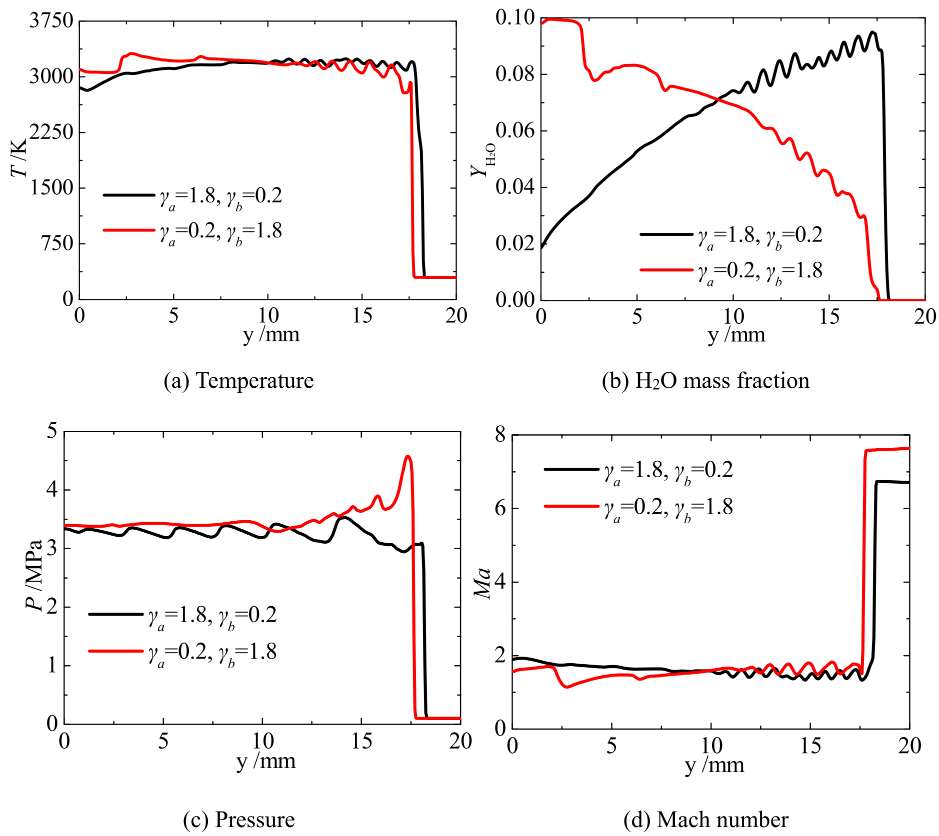


Fig. 16. Temperature (a), H_2O mass fraction (b), pressure (c) and Mach number (d) on outlet boundary with inhomogeneity inflow equivalence ratio.

in the oblique detonation initiation region. As can be seen from Fig. 15 (a), there is a post-shock region with high H_2 density, indicating that there are a series of compression waves in front of the heat release surface. Under the action of the compression wave, the chemical reaction begins to exothermic and weak ignition occurs [13]. This condition is considered to be slow initiation with a smooth transition in the initiation region. When the inflow parameter ahead of the induction region is oil-rich, the transition region from oblique shock wave to oblique detonation wave is observed in Fig. 15 (b), and the pressure contour gradually converges to a narrow space region with high H_2 density forming the main transverse wave. The convergence of compression waves couples with the heat release promoting the abrupt transition which is viewed as the fast initiation [13]. To sum up, the inhomogeneity of the equivalence ratio in front of the oblique detonation induction zone makes the oblique detonation wave have different initiation forms. The fast initiation of oblique detonation wave corresponding to oil-rich in front of the induction region.

According to the above analysis of the inhomogeneity of the inflow equivalence ratio ahead of the oblique detonation wave and the induction zone, it can be seen that the pressurization characteristic of the oblique detonation wave is improved for the oxygen-rich condition ahead of oblique detonation wave. And fast initiation can be achieved by increasing the hydrogen-oxygen equivalence ratio ahead of the induction zone. In addition, the height of oblique detonation wave can be adjusted by changing the equivalence ratio distribution to match the combustion chamber internal structure of the actual oblique detonation engine.

Fig. 16 shows the variation curves of the downstream outlet boundary parameters of oblique detonation under the incoming flow conditions as shown in Fig. 12 and Fig. 13. Fig. 16 (a) shows the variation of temperature at the outlet boundary. It can be seen that the inhomogeneity equivalence ratio of inflow mixture directly affects the temperature distribution in the downstream of the oblique detonation. The flow field temperature in the oxygen-poor region is higher than that in the oxygen-rich region, and the mass fraction of the production H_2O is larger, as shown in Fig. 16 (b). The height of the oblique detonation wave is determined by the equivalence ratio corresponding to the upstream flow field. The higher the equivalence ratio corresponding to the front of the oblique detonation wave is, the higher the oblique detonation wave height is. It can be seen from Fig. 16 (c) that the inhomogeneity equivalence ratio of the inflow has a great influence on the post-wave pressure distribution. When the upstream flow field is in the oxygen-rich region, the post-oblique detonation pressure is obviously higher. This is because that the oxygen-hydrogen mixture flow field density under the oxygen-rich condition is large, and the fuel is fully burned with a lot of heat release. Under the action of the above two factors, the pressure in the flow field increases obviously. Fig. 16 (d) corresponds to the Mach number distribution of the downstream outlet boundary of the oblique detonation flow field. It can be seen that the smaller the equivalence ratio of the front of oblique detonation wave is, the larger the post-wave Mach number is. So, the fuel is easy to be compressed, and the corresponding local pressure changes greatly resulting in the shock wave intensity is stronger.

4. Summary and conclusions

In this paper, the characteristic parameters and the morphology of oblique detonation flow field with different wedge angles, incoming flow velocities and fuel equivalence ratios are analyzed based on the numerical simulation method, and the following conclusions are obtained:

(1) Under the condition of uniform mixture equivalence ratio at ambient temperature and pressure, with the inflow velocity or wedge angle increases, the transition region structure of oblique detonation changes from abrupt type to smooth type. The distance between the left-running transverse waves on the oblique detonation surface becomes shorter and the flow field becomes more stable. For the condition of high-speed incoming flow or large wedge angle, the internal instability of detonation flow field is suppressed and the position of oblique detonation moves upstream. With the increase of incoming flow velocity, the total pressurization ratio behind oblique detonation wave increases, and the performance of oblique detonation propulsion improves obviously.

(2) Within the research scope of hydrogen-oxygen equivalence ratio in this paper, the structure of the oblique detonation initiation region under the condition of oil-rich is abrupt type. With the amount of oil richness increase, the transverse wave intensity below the multi-wave point is stronger, and the instability of oblique detonation flow field downstream is enhanced. The length of the oblique detonation induction region and the initiation region change with the inflow equivalence ratio into a U-shaped change trend. When the equivalence ratio is about 0.8, the characteristic lengths reach the minimum value. The equivalence ratio increases and the oblique detonation wave angle increases. The pressurization characteristic of oblique detonation wave is unstable under oil-rich condition.

(3) The inhomogeneous distribution of the equivalence ratio of incoming combustible gas has obvious influence on the initiation process and morphology of oblique detonation. In this research scope, the inhomogeneity equivalence ratio in front of the induced region makes the initiation length of oblique detonations increase, the initiation position moves downstream. The transition form of the initiation region is determined by the inflow condition ahead of induction region, and the morphology of the chemical reaction surface in the induced area is distorted. In addition, the inhomogeneous equivalence ratio of inflow leads to the difference in the heat release of the chemical reaction behind the oblique detonation wave making the oblique detonation wave surface with different curvatures at different positions. And the oblique detonation with fast initiation and high pressurization ratio can be obtained by adjusting the distribution of the inflow equivalence ratio.

Declaration of competing interest

We declare that we have no conflict of interest.

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References

[1] K. Kailasanath, Review of propulsion applications of detonation waves, AIAA J. 38 (9) (2000) 1698–1708.
[2] G.D. Roy, S.M. Frolov, A.A. Borisov, D.W. Netzer, Pulse detonation propulsion: challenges, current status, and future perspective, Prog. Energy Combust. Sci. 30 (6) (2004) 545–672.
[3] P. Wolanski, Detonative propulsion, Proc. Combust. Inst. 34 (1) (2013) 125–158.
[4] Z. Zhang, K. Ma, W. Zhang, X. Han, Y. Liu, Z. Jiang, Numerical investigation of a Mach 9 oblique detonation engine with fuel pre-injection, Aerosp. Sci. Technol. 105 (2020) 106054.
[5] J. Chan, J.P. Sislian, D. Alexander, Numerically simulated comparative performance of a Scramjet and Shcramjet at Mach 11, J. Propuls. Power 26 (5) (2010) 1125–1134.
[6] A. Hertzberg, A.P. Bruckner, D.W. Bogdanoff, Ram accelerator-a new chemical method for accelerating projectiles to ultrahigh velocities, AIAA J. 26 (2) (2015) 195–203.
[7] D.T. Pratt, J.W. Humphrey, D.E. Glenn, Morphology of standing oblique detonation waves, J. Propuls. Power 7 (5) (1991) 837–845.
[8] C. Li, K. Kailasanath, E.S. Oran, Detonation structures behind oblique shocks, Phys. Fluids 6 (4) (1994) 1600–1611.
[9] V.V. Vlasenko, V.A. Sabelnikov, Numerical simulation of inviscid flows with hydrogen combustion behind shock waves and in detonation waves, Combust. Explos. Shock Waves 31 (3) (1995) 376–389.
[10] K. Ghorbanian, J.D. Sterling, Influence of formation processes on oblique detonation wave stabilization, J. Propuls. Power 12 (3) (2015) 509–517.
[11] Y. Zhang, Y. Fang, H.D. Ng, H. Teng, Numerical investigation on the initiation of oblique detonation waves in stoichiometric acetylene-oxygen mixtures with high argon dilution, Combust. Flame 204 (6) (2019) 391–396.
[12] H. Teng, Y. Zhang, Z. Jiang, Numerical investigation on the induction zone structure of the oblique detonation waves, Comput. Fluids 95 (3) (2014) 127–131.
[13] H. Teng, C. Tian, Y. Zhang, L. Zhou, H.D. Ng, Morphology of oblique detonation waves in a stoichiometric hydrogen-air mixture, J. Fluid Mech. 913 (2021) A1.
[14] Y. Fang, Y. Zhang, X. Deng, H. Teng, Structure of wedge-induced oblique detonation in acetylene-oxygen-argon mixtures, Phys. Fluids 31 (2) (2019) 026108.
[15] J. Verreault, A.J. Higgins, R.A. Stowe, Formation of transverse waves in oblique detonation, Proc. Combust. Inst. 34 (1) (2013) 1913–1920.
[16] H. Teng, Z. Jiang, H.D. Ng, Numerical study on unstable surfaces of oblique detonations, J. Fluid Mech. 744 (2) (2014) 111–128.
[17] Z. Ren, B. Wang, Numerical study on stabilization of wedge-induced oblique detonation waves in premixing kerosene-air mixtures, Aerosp. Sci. Technol. 107 (2020) 106245.
[18] C. Tian, H. Teng, H.D. Ng, Numerical investigation of oblique detonation structure in hydrogen-oxygen mixtures with Ar dilution, Fuel 252 (9) (2019) 496–503.
[19] P. Yang, H. Teng, Z. Jiang, H.D. Ng, Effects of inflow Mach number on oblique detonation initiation with a two-step induction-reaction kinetic model, Combust. Flame 193 (7) (2018) 246–256.
[20] K. Iwata, S. Nakaya, M. Tsue, Wedge-stabilized oblique detonation in an inhomogeneous hydrogen-air mixture, Proc. Combust. Inst. 36 (2) (2017) 2761–2769.
[21] Y. Fang, Z. Hu, H. Teng, Z. Jiang, H.D. Ng, Numerical study of inflow equivalence ratio inhomogeneity on oblique detonation formation in hydrogen-air mixtures, Aerosp. Sci. Technol. 71 (12) (2017) 256–263.
[22] K. Wang, P. Yang, H. Teng, Steadiness of wave complex induced by oblique detonation wave reflection before an expansion corner, Aerosp. Sci. Technol. 112 (2021) 106592.
[23] J. Bian, L. Zhou, H. Teng, Structural and thermal analysis on oblique detonation influenced by different forebody compressions in hydrogen-air mixtures, Fuel 286 (2021) 119458.
[24] C. Li, K. Kailasanath, E.S. Oran, Effects of boundary layers on oblique-detonation structures, Aerosp. Sci. Meet. (2013) 450.
[25] M.V. Papalexandris, A numerical study of wedge-induced detonations, Combust. Flame 120 (4) (2000) 526–538.
[26] H. Teng, Z. Jiang, On the transition pattern of the oblique detonation structure, J. Fluid Mech. 713 (10) (2012) 659–669.
[27] J.Y. Choi, E.J.R. Shin, I.S. Jeung, Unstable combustion induced by oblique shock waves at the non-attaching condition of the oblique detonation wave, Proc. Combust. Inst. 32 (2) (2009) 2387–2396.

[28] Y. Liu, D. Wu, S. Yao, J. Wang, Analytical and numerical investigations of wedge-induced oblique detonation waves at low inflow Mach number, Combust. Sci. Technol. 187 (6) (2015) 843–856.
[29] Y. Liu, X. Han, S. Yao, J. Wang, A numerical investigation of the prompt oblique detonation wave sustained by a finite-length wedge, Shock Waves 26 (6) (2016) 729–739.
[30] S. Bhattrai, H. Tang, Formation of near-Chapman-Jouguet oblique detonation wave over a dual-angle ramp, Aerosp. Sci. Technol. 63 (12) (2017) 1–8.
[31] G. Li, G. Zhang, Y. Zhang, L. Ji, S. Gao, Influence of viscous boundary layer on initiation zone structure of two-dimensional oblique detonation wave, Aerosp. Sci. Technol. 104 (2020) 106019.
[32] M. Gui, B. Fan, G. Dong, Periodic oscillation and fine structure of wedge-induced oblique detonation waves, Acta Mech. Sin. 27 (6) (2011) 922–928.
[33] L. Yang, L. Yue, Q. Zhang, X. Zhang, Numerical study on the shock/combustion interaction of oblique detonation waves, Aerosp. Sci. Technol. 104 (2020) 105938.
[34] H. Teng, H.D. Ng, K. Li, C. Luo, Z. Jiang, Evolution of cellular structures on oblique detonation surfaces, Combust. Flame 162 (2) (2015) 470–477.
[35] M.W. Chase, JANAF Thermochemical Tables, Parts I and II, 3rd ed., J. Phys. Chem. Ref. Data, vol. 14, 1985.
[36] W.G. Strang, On the construction and comparison of difference schemes, SIAM J. Numer. Anal. 5 (3) (1968) 506–517.
[37] X. Hu, B.C. Khoo, D. Zhang, Z. Jiang, The cellular structure of a two-dimensional $H_2/O_2/Ar$ detonation wave, Combust. Theory Model. 8 (2) (2004) 339–359.
[38] C. Shu, S. Osher, Efficient implementation of essentially non-oscillatory shock-capturing schemes, J. Comput. Phys. 77 (2) (1988) 439–471.
[39] G. Jiang, C. Shu, Efficient implementation of weighted ENO schemes, J. Comput. Phys. 126 (1) (1996) 202–228.
[40] G.J. Wilson, R.W. MacCormack, Modeling supersonic combustion using a full-implicit numerical method, AIAA J. 30 (4) (1992) 1008–1015.
[41] R.J. Kee, F.M. Rupley, E. Meeks, J.A. Miller, CHEMKIN-III: A FORTRAN Chemical Kinetics Package for the Analysis of Gas-Phase Chemical and Plasma Kinetics, Sandia National Labs., Livermore, CA (United States), 1996.
[42] P.N. Brown, G.D. Byrne, A.C. Hindmarsh, VODE: a variable-coefficient ODE solver, SIAM J. Sci. Stat. Comput. 10 (5) (1989) 1038–1051.
[43] Y. Fang, Z. Hu, H. Teng, Numerical investigation of oblique detonations induced by a finite wedge in a stoichiometric hydrogen-air mixture, Fuel 234 (7) (2018) 502–507.
[44] T. Wang, Y. Zhang, H. Teng, Z. Jiang, H.D. Ng, Numerical study of oblique detonation wave initiation in a stoichiometric hydrogen-air mixture, Phys. Fluids 27 (9) (2015) 096101.
[45] B. Zhang, H.D. Ng, J.H.S. Lee, The critical tube diameter and critical energy for direct initiation of detonation in $C_2H_2/N_2O/Ar$ mixtures, Combust. Flame 159 (9) (2012) 2944–2953.