# Effects of Finite Length Wedge on the Initiation Structure of Oblique Detonation Waves in Combustor

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**Abstract:** The oblique detonation engine (ODE) uses the oblique detonation wave (ODW) generated by a wedge in supersonic combustible mixtures to achieve fast and efficient combustion, which is more applicable to air-breathing hypersonic aircraft with higher flight Mach numbers than a conventional scramjet. Prior to the practical application of ODE, it is first necessary to clarify the initiation structure characteristics of ODWs in the combustor under flight conditions. However, previous studies usually used the infinite length wedge hypothesis which cannot really reflect the flow and combustion characteristics of finite length induced ODW in the actual combustor. Two key design parameters, i.e., the wedge length and end inclination angle, are used to investigate the effects of finite length wedge on the initiation structure of ODW in an ODE at different flight Mach numbers. Results show that there is a critical wedge length for different ODW initiation structures corresponding to different flight conditions. Only when the wedge length is shortened to the critical length, the ODW initiation structure will change significantly. When the wedge length is equal to or less than this critical length, both the wedge length and end inclination angle will affect the structure. On the contrary, the expansion wave generated at the end of the wedge cannot affect the heat release and compression wave convergence on the wedge, so it will not affect the ODW initiation process and structure. By analyzing the heat release process on the wedge, a theoretical method for predicting the critical wedge length is proposed to contribute to the combustor design. The calculated results under different flight conditions are in good agreement with the simulation results.

**Key words:** oblique detonation; initiation type; finite length wedge; theoretical criterion

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## 0 Introduction

Hypersonic vehicle based on air-breathing power has become the frontier and hotspot in the aerospace field, because of its broad military and civilian application prospects[1]. The oblique detonation engine (ODE), which uses oblique detonation wave (ODW) as the main combustion organization form, has the advantages of short combustor and high specific impulse, and has great application potential in the field of higher Mach number air-breathing propulsion[2-5]. The key to the ODE development is to achieve efficient and stable ODW combustion in the combustor. Therefore, it is necessary to conduct an in-depth study on the ODW initiation mechanism.

Previous studies by numerical simulations[6] and experiments[7] have found that ODW structure consists of a non-reactive oblique shock wave (OSW), an oblique detonation wave and a series of compression waves (CWs). Further research shows that complex wave system structures will also be formed during the transition from the OSW to ODW, which can be seen as the initiation process of ODW, and the transition zone is the ODW initiation zone[8]. According to the connection between

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OSW and ODW in the ODW initiation zone, the initiation type can be divided into abrupt initiation and smooth initiation. In the abrupt initiation, the OSW and the ODW are connected by multi-wave point, while the smooth initiation is connected by a curved shock wave[9]. Later, it is found that there were differences in total pressure loss of combustion and stability between the two initiation types[10]. Therefore, some researchers carried out many research on the differences and prediction criterion between them[11-12]. However, the recent research[13] found that the ODW structure is more complex in high-altitude flight conditions, and the wave system structure in the initiation zone will change significantly under different flight conditions. In addition to the traditional smooth initiation and abrupt initiation, there are secondary ODWs, normal detonation waves (NDWs) and other complex flow and combustion phenomena in the initiation zone. And a theoretical prediction criterion for detonation types from the perspective of CW convergence has been proposed[14], which further deepens the understanding of the structure of ODW initiation zone. However, the above researches on ODW usually adopt the hypothesis of infinite wedge. In practical applications, the stable ODW combustion needs to be realized in the limited space of the ODE combustor. Under the influence of the geometric boundary of the combustor such as the finite length wedge, the ODW will produce more complex initiation characteristics and structures. Thus, it is necessary to study the flow and combustion characteristics of finite length induced ODW in the actual combustor.

For the ODE combustor, the wedge length is the most critical geometric parameter. Early research[15] found that when the wedge length is not long enough, the ODW will quench. Further research[16-17] found that under the influence of the expansion wave at the end of a finite length wedge, the ODW after the initiation of a large angle wedge would attenuate to a near-CJ (Chapman-Jouguet) ODW with a wave angle close to the CJ ODW angle in the downstream. Besides, the expansion wave generated at the end of the finite length wedge will not only have an impact on the initiation and angle of the ODW, but also have an important impact on the initiation structure[18]. Recently, some researchers have studied the change of ODW structure when the wedge length gradually shortens, focusing on the impact on ODW initiation characteristics, and found that the quenching process of ODW is different for the smooth and abrupt initiation[19-20]. Based on the fitting of simulation results, the prediction criterion of the shortest wedge length for ODW initiation of smooth initiation is established[21]. In addition to the limited length of the wedge, the combustor and nozzle in the ODE are closely coupled, and the ODW combustion products must enter the nozzle to expand to generate thrust. Therefore, it is also necessary to pay attention to the influence of the rear inclined angle of the finite length wedge on the ODW. It has been found that when the wedge length is the same, the rear inclined angle of the finite length wedge may also cause the ODW fail to initiate[22]. To sum up, the current research on the impact of finite length wedge on ODWs mainly focuses on the abrupt and smooth initiation found in earlier research. For ODWs with more complex structures in the initiation zone in high-altitude flight conditions, the initiation characteristics and evolution in finite length wedge are still unclear, and there is a lack of universal prediction criterion independent of simulation results for initiation length. From the perspective of ODW practical application in real engine combustor, the study of ODW initiation characteristics and structure with the finite length wedge and high-altitude flight conditions needs more in-depth study, which can not only deepen the understanding of ODW initiation physical mechanism, but also facilize the practical design of ODE.

Based on the above background, this paper establishes a calculation model of finite length wedge according to the characteristics of internal flow of ODE, and studies the structural evolution of ODW initiation under the influence of finite length wedge in high-altitude flight conditions. At the same time, considering the requirements of wide range flight, effects of finite length wedge on ODW initiation characteristics and structure in different flight conditions are further explored. And the shortest wedge length prediction criterion for wide range flight conditions independent of simulation results is proposed from the perspective of detonation initiation mechanism, providing theoretical support for realization and regulation of efficient and stable ODW combustion in ODEs.

## 1 Physical Model and Computational Method

To study the ODW characteristics in high-altitude flight conditions, the integrated configuration of aircraft and engine should be considered first, so as to obtain the appropriate inlet parameters of ODE combustor. The ODE generally works at high speed in high altitude. The high-altitude low density and temperature inflow must be compressed by the engine inlet before entering the combustor, in order to increase the temperature and pressure, facilitating trigger of the ODW.

Fig.1 shows the schematic of an ODE and the finite length wedge-induced ODW computation domain. The ODE inlet adopts two equally strong shock waves to compress the inflow. Assuming that the fuel is fully premixed with the compressed air in the inlet, supersonic combustible mixture is obtained and enters the combustor. In the calculation domain of finite length wedge, $L_d$ represents the projection length of the multi-wave point of ODW on the wedge when the wedge is infinite, and $L_w$ represents the length of the wedge. The wedge angle is fixed at 19°, and the combustible mixture is a homogeneous stoichiometric hydrogen-air mixture with $H_2$ : $O_2$ : $N_2$=2 : 1 : 3.76. The lower boundary in the calculation domain represents the surface of the wedge and the rear wall of the wedge, set as the slip boundary condition. Both the left and upper boundaries of the computational domain have inflow conditions fixed at the values determined by the inlet parameters of the combustor, and the right boundary is set as the zero gradient outlet boundary.

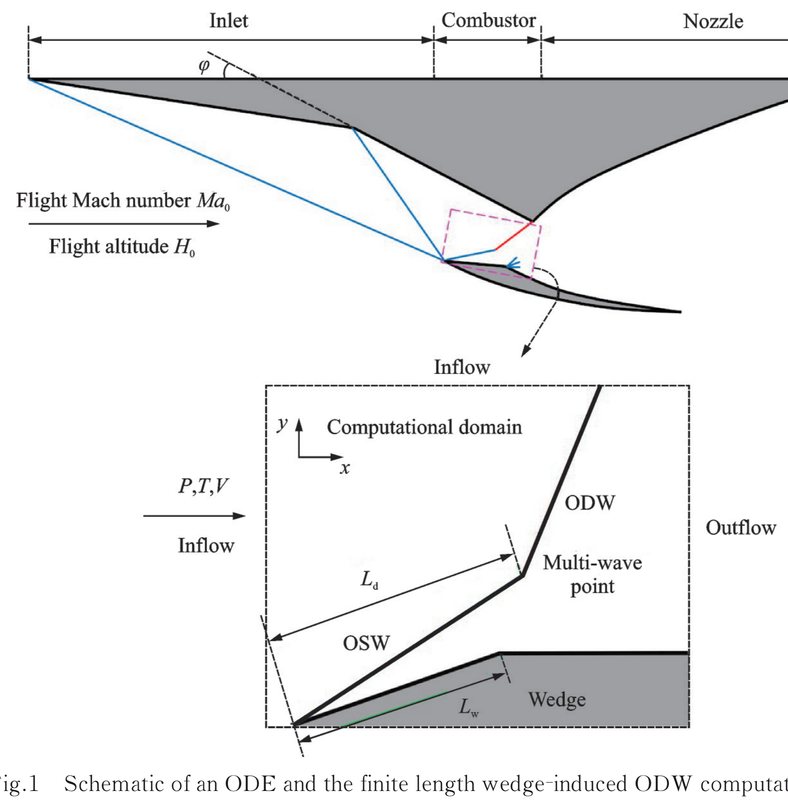



Fig.1 Schematic of an ODE and the finite length wedge-induced ODW computation domain

In order to better simulate the flow in the engine, flight altitude ($H_0$) and flight Mach number ($Ma_0$) are selected as the control parameters, and the combustor inlet parameters are theoretically calculated in combination with OSW theory and standard atmospheric parameters[23]. The specific process is as follows. Firstly, obtain the atmospheric parameters through the flight altitude, and then calculate the inflow parameters after the oblique shock compression of the inlet according to the flight Mach number. Finally, assume that the compressed inflow and fuel are completely mixed without loss, and obtain the flow parameters of mixture, that is, the combustor inlet parameters. Table 1 shows the corresponding combustor inlet parameters under the condition of a fixed $H_0$=30 km and $Ma_0$=8—10. The total deflection angle $\varphi$ is fixed at 24° in different operating conditions. Through this method, the combustor inlet parameters can be obtained without artificial parameters, and can cover a wide range of flight conditions, which is more consistent with the real working conditions of the engine, and has more reference value for the engineering design of ODEs.

**Table 1 Inflow parameters of combustor at different flight conditions**

| Flight altitude $H_0$/km | Flight Mach number $Ma_0$ | Pressure of mixture $p$/Pa | Temperature of mixture $T$/K | Velocity of mixture $V$/(m·s$^{-1}$) | Mach number of mixture $Ma_0$ |
|---|---|---|---|---|---|
| 30 | 10 | 54 433.5 | 972.1 | 2 757.7 | 3.82 |
| 30 | 9 | 43 497.0 | 851.5 | 2 473.4 | 3.65 |
| 30 | 8 | 32 526.9 | 742.8 | 2 188.2 | 3.44 |

The ODW initiation length is quite different in different flight conditions. When the flight Mach number is low, the inflow temperature of the combustor is also low, so the initiation length is also long. It is found that the ODW initiation length at $Ma_0$=8 is about 5 times that at $Ma_0$=10. Therefore, this paper defines the non-dimensional wedge length $L_n=L_w/L_d$, which is used to quantitatively analyze the influence of the wedge length at different flight conditions.

Some early studies, such as Ref.[24], indicated that viscous effects are thought to be negligible because the Reynold number is very high. For the cases in this study, *Re* is comparable to the scale of 106 and basically the combustion of ODW is mainly induced by strong compression of lead shock. Therefore, the viscous and turbulent effects are neglected following many successive research[19-23] based on the inviscid assumption, and two-dimensional multi-species Euler equations are adopted as the governing equations in this paper. CFD++ software is used for numerical calculation, and the numerical scheme is a second-order conservation TVD scheme[25]. The HLLC (Harter-Lax-van Leer Contact) approximate Riemann solver[26] is used to solve the interface flux. The fourth-order Runge-Kutta method is used for explicit discretization of time. The chemical kinetic model is taken from a simplified kinetic mechanism modified by Wilson and MacCormack[27], which involves 19 reversible elementary reactions among 9 species ($H_2$, $O_2$, $H_2O$, H, O, OH, $HO_2$, $H_2O_2$, $N_2$).

## 2 Results and Discussion

### 2.1 Effects of the wedge length and rear inclined angle

Firstly, temperature fields with pressure contours of ODW induced by an infinite wedge for $Ma_0$=9 and $H_0$=30 km is shown in Fig.2(a). The supersonic combustible mixture flows through the wedge and first generates an OSW. After the mixture is compressed by OSW, the temperature of the mixture gradually increases, and chemical reaction

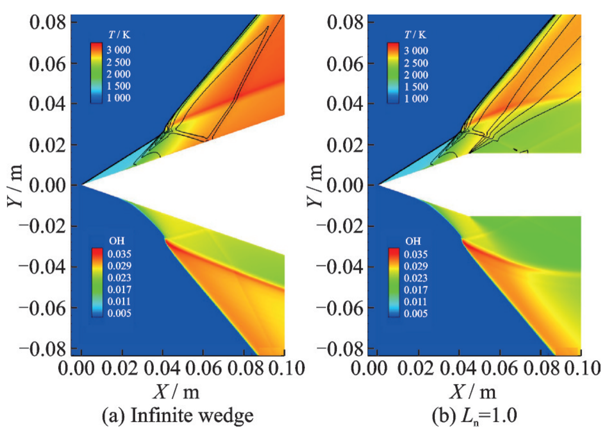



Fig.2 Temperature fields with pressure contours and mass fraction of OH fields for $Ma_0$=9 and $H_0$=30 km

takes place in the downstream to release heat. The heat release in the supersonic gas flow forms CWs, which is shown as the pressure contour in the initiation zone in the flow field. Therefore, the morphology changes of pressure contour are used to represent the change of wave system structure of ODW initiation zone in this paper. In this case, the CWs converge into a point and the convergence point happens to intersect with the OSW, where the OSW is transformed into the ODW. Although there is a multi-wave point in the flow field, this structure is between smooth and abrupt initiation from the view of CW convergence, which is called intermediate initiation in this paper. For the case of length shortened wedge, Fig.2(b) shows the simulation result of $L_n$=1.0, that is, the wedge length is equal to the projection length of the multi-wave point of ODW on the wedge.

By comparing Figs.2(a,b), it can be seen that when the wedge length is shortened to $L_n$=1.0, the structure of ODW initiation zone and the ODW angle in the flow field are basically consistent with those in the infinite wedge. Although the expansion effect exists at the end of the wedge, it does not affect the initiation process of the ODW in the current computation domain, so the initiation structure and the ODW angle remain unchanged. However, by careful comparison of the flow field, it can be found that the expansion wave generated by the finite length wedge significantly reduces the ODW downstream temperature, and the transverse wave reflection in the initiation zone of the ODW on the wedge surface is also significantly weakened. According to the above analysis, it can be deduced that the influence of the expansion wave at the end of the wedge on the ODW will be weaker when $L_n$>1.0, so the ODW structure will not change.

To examine the effect of the numerical grid size, a resolution study is conducted by doubling the mesh number in each direction. The density field for $Ma_0$=9 and $H_0$=30 km generated using the default mesh size of 200 μm is presented in Fig.3, compared with the simulation result obtained by a finer mesh size of 100 μm. It is evident that there is almost no difference between the two wave structures

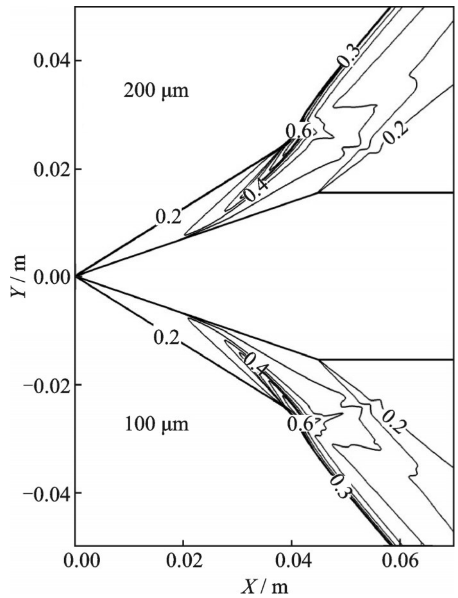



Fig.3 Density fields with different grid scales for $Ma_0$=9 and $H_0$=30 km

with different grid length scales. The additional quantitative comparisons shown in Fig.4 provide the detailed distributions of pressure and temperature along three typical streamlines (i. e., $y$=0, 0.02 and 0.04 m) corresponding to different regions of the unique ODW morphology. These regions represent the oblique shock, initiation structure and

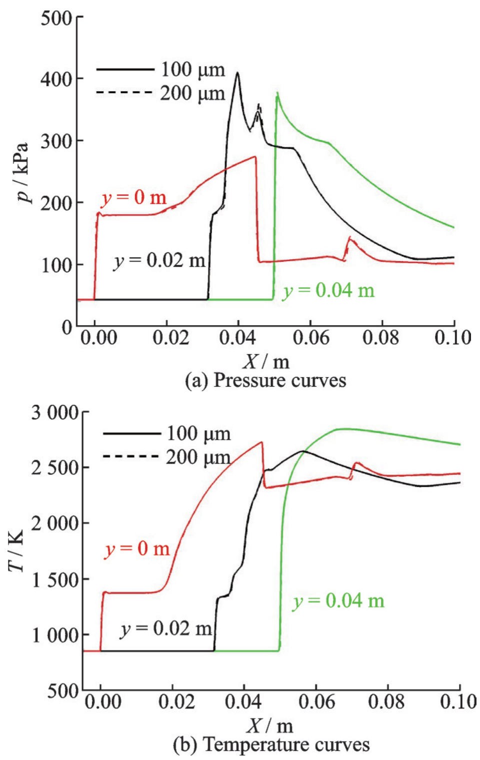



Fig.4 Pressure and temperature curves along three streamlines of $y$ = 0, 0.02 and 0.04 m with different grid scales for $Ma_0$=9 and $H_0$=30 km

steady ODW surface, respectively. The curves with different grid scales can be seen to almost coincide with one another, indicating that the default mesh size used in this case is sufficient to capture the main features of the ODW structure. For other cases with different $Ma_0$, similar resolution studies have been performed to confirm the grid-independence of the simulation results in this study.

### 2.1.1 Effects of the wedge length

By further shortening wedge, Fig.5 shows temperature fields with pressure contours when $L_n$=0.6, 0.55 and 0.5, respectively. When $L_n$=0.6, compared with the case of $L_n$=1.0, the angle of ODW decreases slightly and the initiation point moves downstream slightly. At this time, the ODW initiation process is affected by the wedge length. The flow and heat release process near the wedge is limited by the wedge length. The CW convergence degree is weakened, so the initiation point moves downstream slightly. The shortening of the wedge also makes the position of the expansion wave move forward. Under the expansion effect, the temperature and pressure of the ODW downstream decrease, which leads to the reduction of the ODW angle. But overall, the change of ODW structure is still not obvious.

However, when the wedge length is reduced to $L_n$=0.55, the ODW structure changes significantly as the initiation point disappears. The OSW and ODW are connected by a curved shock wave and the pressure peak formed by the initiation point disappears as shown in Fig.5(b), so the initiation type changes from intermediate to smooth. For the above phenomena, this paper defines the wedge length when the ODW structure is significantly changed as the critical wedge length, and the corresponding ODW structure as the critical structure. That is, the critical wedge length is $L_c$=0.55 for the above case. At critical wedge length, the position of the expansion wave is close to the position of the mixture chemical reaction happening on the wedge surface. The mixture temperature at the wedge end increases slightly but decreases rapidly because of expansion. Thus, the CW intensity is greatly weakened, so that the CW originally converging to a point can only interact with the OSW gradually, raising the OSW angle, and forming a curved shock wave, when the OSW finally transforms into ODW.

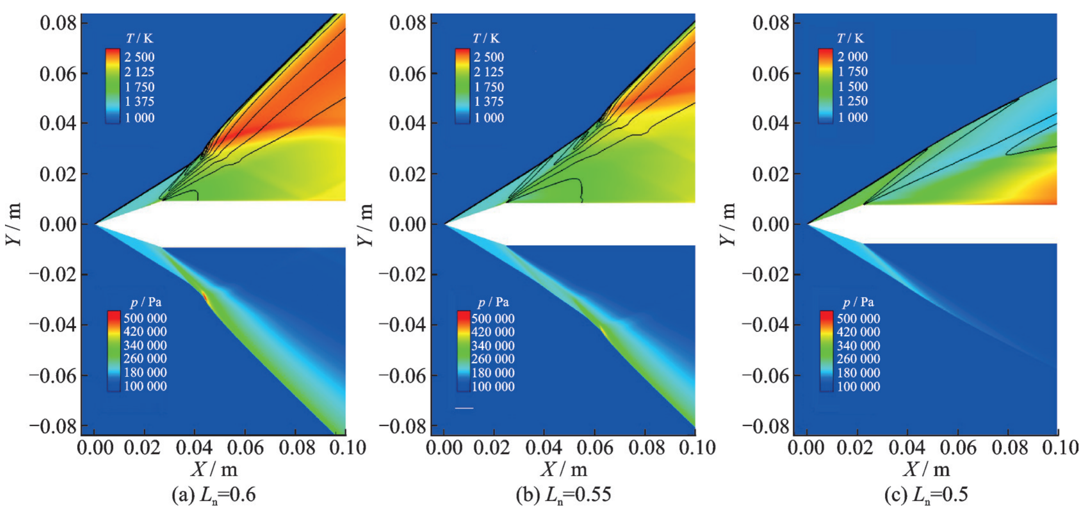



Fig.5 Temperature fields with pressure contours and pressure fields for $Ma_0$=9 and $H_0$=30 km

When the wedge length is further shortened to $L_n$=0.5, ODW will quench because the distance required for chemical reaction on wedge surface is greater than the wedge length at this time. That is, the heat release is difficult to occur on the wedge surface, so the CW is very weak. Due to the expansion wave, the OSW angle downstream decreases gradually, and cannot be transformed into ODW. It can be seen that when the wedge length is less than the critical wedge length, the temperature and pressure of the mixture compressed by the OSW decrease under the effects of the expansion wave, which inhibits the process of heat release, thus leading to the quench of the ODW.

### 2.1.2 Effects of the rear inclined angle of finite length wedge

In the above study, when the wedge length is shortened, the rear wall of the finite length wedge is always horizontal, that is, the inclination angle $\theta = 0^{\circ}$. But in the actual ODE, the combustion chamber and nozzle are closely coupled, and the influence of the rear inclined angle of the finite length wedge on the ODW combustion characteristics is also worthy of attention. Therefore, in order to study the influence of the rear inclined angle of the wedge on the ODW structure, on the basis of above $\theta = 0^{\circ}$ cases research, both reducing the expansion angle by $10^{\circ}(\theta = 10^{\circ})$ and increasing expansion angle by $10^{\circ}(\theta = -10^{\circ})$ are simulated. At the same time, considering that the ODW structure will change significantly under the critical wedge length, the conditions greater than the critical length ($L_n = 0.6$) and under the critical length ($L_n = L_c = 0.55$) are studied respectively, whose results are shown in Figs.6 and 7, respectively.

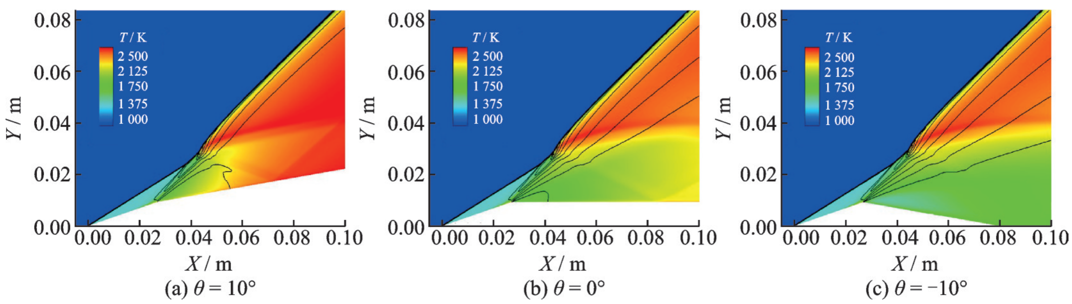



Fig.6 Temperature fields with pressure contours for $Ma_0 = 9$, $H_0 = 30$ km, and $L_n = 0.6$

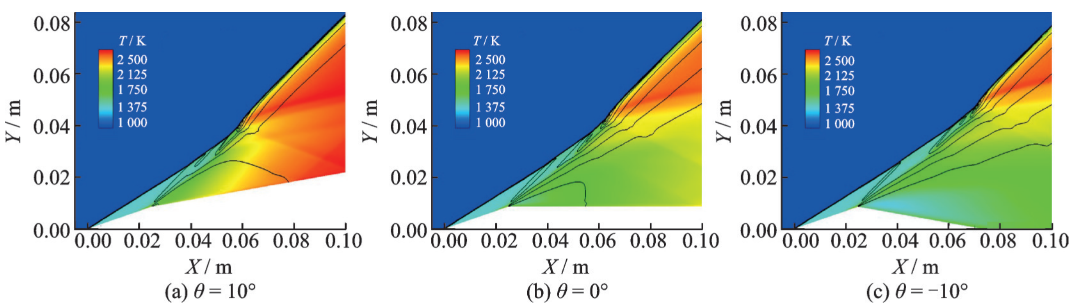



Fig.7 Temperature fields with pressure contours for $Ma_0 = 9$, $H_0 = 30$ km, and $L_n = 0.55$

It can be seen from Fig.6 that when the wedge length is greater than the critical wedge length ($L_n =$ 0.60, with the increase of the rear inclined angle of the wedge, the angle of ODW and the initiation type have not changed, and the initiation position has not moved backward due to the enhancement of expansion. It can be seen that when $L_n = 0.6$, the expansion wave at the end of the wedge will not affect the ODW initiation process, so when $L_n > 0.6$ the change of the rear inclined angle of the wedge will not change the ODW structure. In addition, although the detonation combustion area behind the ODW is not sensitive to the change of the expansion wave strength at the end of the wedge, the expansion effect reduces the temperature and pressure of the mixed gas in the shock induced combustion area behind the OSW, leading to the delay of the chemical reaction. With the increase of the rear inclined angle, the strength of the reflected shock wave gradually becomes weaker.

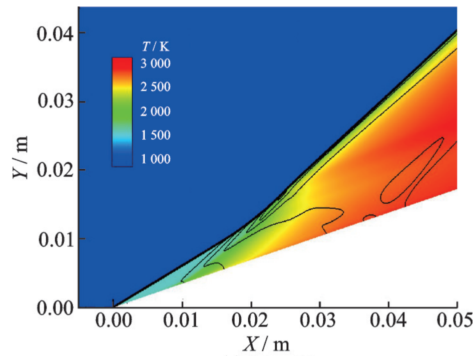
At the critical length ($L_n = 0.55$), it can be seen from the result of $\theta = 10^{\circ}$ case that the weak expansion at the wedge end will lead to a significant change in the ODW structure, and with the increase of the rear inclined angle of the wedge, the initiation position will gradually move backward, and the initiation type will gradually evolve from the intermediate structure to the smooth structure. Compared with the conclusion in Fig.6, when the wedge length is greater than the critical one, even if the wall behind the wedge is inclined at a large angle, the initiation position will not change. When the wedge length is equal to the critical length, the smaller rear inclined angle will lead to a large backward movement of the initiation position and a significant change in the structure of the initiation zone. It can be seen that the wedge length change has a greater impact on the ODW structure than the rear inclined angle change.

In conclusion, there is a critical wedge length for finite length wedge-induced ODW in this case. When the wedge length is greater than it, the change of the wedge length has little effect on the ODW structure. When the wedge length is equal to it, the ODW structure will change significantly, the initiation point will move back significantly, and the initiation type will evolve from the intermediate to smooth initiation. At the critical wedge length, further shortening the wedge will lead to ODW quenching, while increasing the rear inclined angle of the finite length wedge will lead to further backward movement of the initiation position.

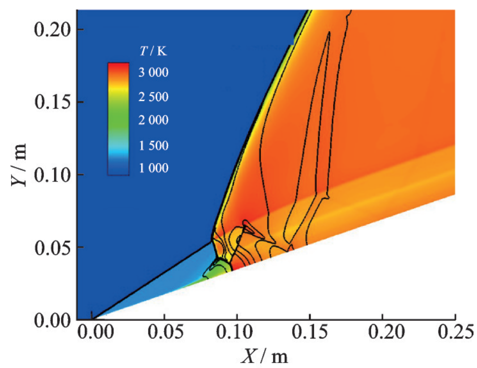
### 2.2 Effects of the finite length wedge on ODW structure in wide range flight conditions

The ODE with more engineering application value must work in wide flight speed conditions, at which previous studies have shown that the ODW initiation structure is more complex. Therefore, the flight altitude ($H_0$) is fixed and the flight Mach number ($Ma_0$) is changed in this section to explore the influence of the finite length wedge on ODW structures in different flight speed conditions. First of all, temperature fields with pressure contours of ODW induced by an infinite wedge for $H_0$ =30 km and $Ma_0$ =10 and 8 is obtained through simulation, as shown in Fig.8.

It can be seen that the structure of the ODW initiation zone and the ODW angle have changed significantly with the change of $Ma_0$. When $Ma_0$ increases to 10, the OSW angle decreases, and the OSW and the ODW are connected by a curved shock wave, which is a smooth initiation. At this time, the CWs generated by heat release on the wedge surface slowly converge and interact with the



(a) $Ma_0$=10



(b) $Ma_0$=8

Fig.8 Temperature fields with pressure contours for $H_0$= 30 km and different $Ma_0$

OSW gradually, and the OSW angle gradually increases and finally transforms into ODW. However, when $Ma_0$ decreases to 8, the ODW angle increases, and the angle difference between OSW and ODW increases significantly. The OSW and ODW are connected through multi-wave points, which is an obvious abrupt initiation. At this time, the CWs converge rapidly, forming an NDW that is nearly perpendicular to the wedge surface between the CW convergence point and the initiation point, At the downstream of the NDW, a strong reflected shock wave generates and secondary reflection occurs on the wedge. It can be seen that the change of flight conditions will lead to more complex structure of ODW initiation zone. It is necessary to deeply explore the effects of finite length wedge on ODW structures in flight conditions for triggering and stabilization of ODW in the engine.

#### 2.2.1 Effects of the finite length wedge at $Ma_0$= 10 flight conditions

First of all, research is carried out on the common smooth initiation structure with gradually shortening the wedge length on the basis of the infinite wedge cases. The results of temperature fields with pressure contours of ODW when $L_n=1.0$, 0.5, 0.45 and 0.40 are shown in Fig.9. When $L_n=1.0$, there is no significant difference between the results of the ODW initiation structure and ODW angle with those of infinite wedge. When $L_n=0.5$, due to the effect of the expansion wave, the ODW angle decreases, but the initiation type is still smooth. When $L_n=0.45$, the ODW structure changes significantly, which is called the critical structure in this case, i.e. $L_c=0.45$. At this time, the temperature in the flow field rises within a certain distance downstream of the OSW, and the OSW angle does not rise significantly, indicating that the oblique shock is decoupled from the heat release at this time. So the OSW will not be transformed into the ODW, and there is no initiation zone. When the wedge length is further shortened to 0.4, the wedge is too short for heat release to occur, and the ODW cannot be initiated.

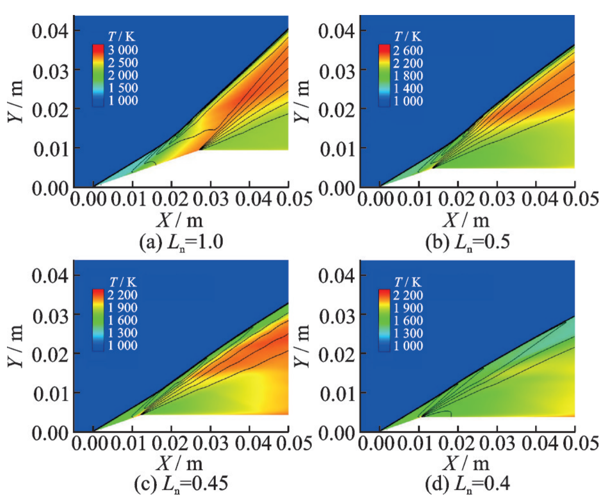



Fig.9 Temperature fields with pressure contours for $Ma_0=10$ and $H_0=30$ km

Previous research[20] also found that oblique shock and reactive surface were decoupled in smooth initiation with a certain wedge length, but the reason for decoupling was not analyzed in depth. In this paper, when the $L_n=L_c=0.45$, the finite length wedge inhibits the heat release in the near-wedge flow, and the CW generated on the wedge is very weak, and it is difficult to raise OSW angle when interacting with the OSW. In addition, the combustible mixture compressed by the OSW is affected by the expansion wave. Due to the suppression of expansion effect, the heat release lags behind the OSW. Therefore, a certain distance is generated between the oblique shock and the reactive surface, and the two cannot be coupled to form the ODW.

Further, two cases with wedge length greater than the critical length ($L_n=0.6$) and equal to the critical length ($L_n=L_c=0.55$) are studied to study the effects of rear inclined angle on the smooth structure. It is found that when $L_n=0.5$, the ODW structure is basically unchanged under different rear inclined angles of the wedge, which is consistent with the above conclusion. Therefore, no specific analysis will be carried out here in this paper. Fig.10 shows the ODW flow field under different rear inclined angles the wedge at the critical wedge length ($L_n=L_c=0.45$). It can be seen that at $\theta=10°$, the shock wave in the flow field is decoupled from the combustion. When the rear inclined angle continues to increase, the distance between the combustion surface and the shock wave surface does not change significantly, but the temperature in the combustion area decreases significantly. Therefore, under the critical wedge length, for smooth structures, even weak expansion can lead to the decoupling of

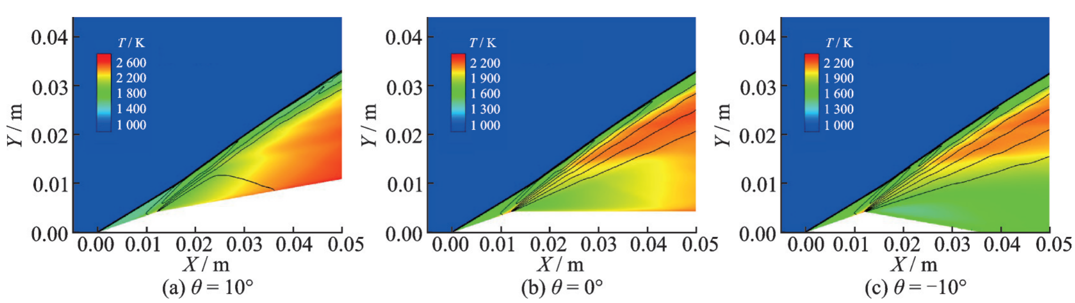



Fig.10 Temperature fields with pressure contours for $Ma_0=10$, $H_0=30$ km, and $L_n=L_c=0.45$

ODW, and ODW structures are also very sensitive to the change of rear inclined angle.

### 2.2.2 Effects of the finite length wedge at $Ma_0$=8 flight conditions

Secondly, research is carried out on the more complex abrupt initiation for $Ma_0$=8 case. Fig.11 shows the temperature fields with pressure contours of ODW when $L_n$=1.0, 0.8, 0.77 and 0.76. When $L_n$=1.0, the initiation point and the structure of ODW initiation zone do not change obviously, but the ODW angle slightly decreases, which is slightly different in smooth and intermediate initiation with $L_n$=1.0. When $L_n$=1.0 in the abrupt initiation, the expansion wave will cause ODW angle decreases (the white line in Fig.9(a) stands for ODW induced by an infinite wedge). However, the expansion wave will not affect heat release in near-wedge flow and CW convergence degree, thus the position of initiation point and structure of initiation zone remains the same. When $L_n$=0.8, the ODW angle continues to decrease, and the initiation point is slightly downstream. Although the initiation type is still abrupt initiation, compared with $L_n$=1.0, the length of NDW in the initiation zone is significantly shortened. Based on the above analysis, it is shown that the expansion effect inhibits the heat release of the mixture on the wedge surface, which weakens the degree of the CW convergence, and then leads to the backward of the initiation point and the reduction of the NDW length.

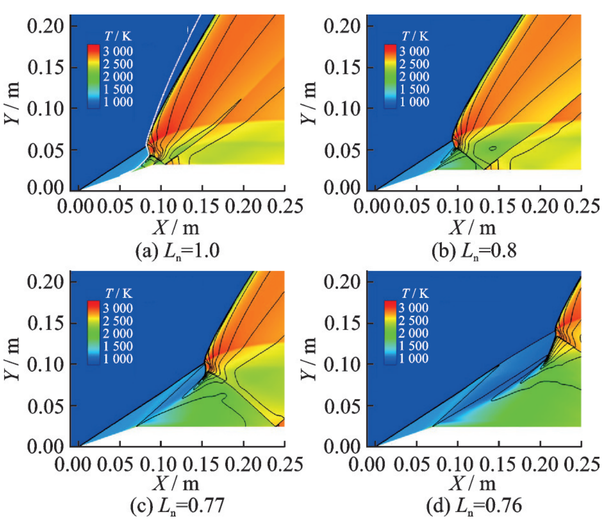



Fig.11 Temperature fields with pressure contours for $Ma_0$=8 and $H_0$=30 km

When the wedge length is further shortened to $L_n$=0.77, the ODW structure changes significantly, the initiation point moves backward significantly, and the NDW in the initiation zone gradually attenuates to a secondary ODW. This structure is the critical structure at this time, and the critical wedge length $L_c$=0.77. The heat release along wedge surface is limited by the wedge length, and under the suppression of the expansion effect, only very weak CWs can be generated, which is not enough to initiate the ODW. However, the expansion effect only prolongs the time needed for the heat release to occur, the mixture will continue to react on the downstream of the wedge. Therefore, the CWs will be generated and converge under the OSW, making the OSW transform to ODW, but the initiation point is greatly delayed. Obviously, compared with the degree of CW convergence on wedge, the CWs formed on the downstream of wedge have weaker convergence degree. Therefore, the NDW with strong strength at $L_n$=1.0 cannot be formed in the initiation zone, and the secondary ODW is more inclined to be formed.

When $L_n$=0.76, the initiation point continues to move backward. A large amount of mixture will flow out of the combustor without sufficient combustion, so this paper considers this case as the quenching. It should be noted that in this paper, the width of the calculation domain is increased for the case where the initiation point is very far back, to ensure that the outlet boundary is all supersonic, so as to avoid the influence of boundary conditions on the simulation results.

Similarly, when the wedge length is greater than the critical length of the wedge, the change of the rear inclined angle has less influence on the ODW structure, which is consistent with the laws of smooth and intermediate structure. Therefore, no specific analysis will be carried out here in this paper. However, when the wedge length is equal to the critical wedge length ($L_n$=$L_c$=0.77), as shown in Fig.12, the ODW structure changes significantly with the increase of the rear inclined angle of the wedge. When $\theta$=10°, compared with the infinite length wedge cases (the white line in Fig.12(a)), the angle of ODW is greatly reduced, with the initiation position obviously moved backward, and the structure of the initiation zone is also changed. First, the NDW length in the initiation zone is slightly reduced, second, the intensity of the reflected shock wave, along with the subsquent secondary reflected shock wave is weakened. Further increase the rear inclined angle, the initiation position moves further backward, the reflected shock wave also moves backward and its strength gradually weakens, and a series of complex wave structures formed by the reflected shock wave also disappear accordingly. At the same time, with the increase of the rear inclined angle ($\theta=-10°$), the NDW intensity in the initiation zone gradually attenuates, and gradually changes into the secondary ODW, but the initiation type is still a abrupt change structure. Therefore, under the critical wedge length, for the abrupt structure, the rear inclined angle of the wedge will also have a significant impact on the initiation characteristics of the ODW. With the increase of the inclination angle, on the one hand, the initiation position will move significantly backward, on the other hand, the NDW structure in the initiation area will gradually attenuate to a secondary ODW structure, accompanied by a significant reduction in the strength of the ODW.

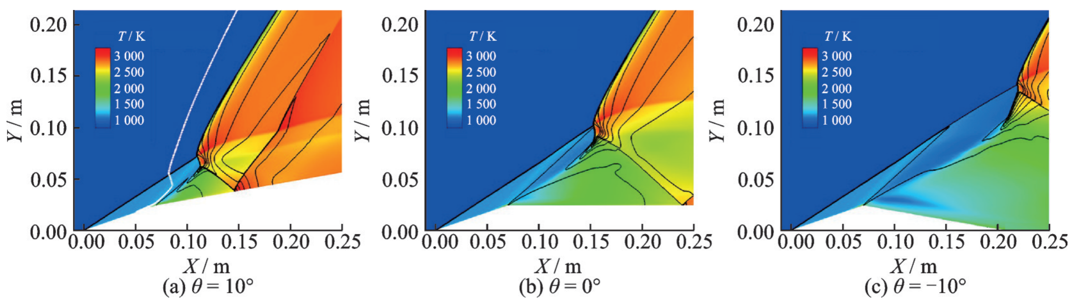



Fig.12 Temperature fields with pressure contours for $Ma_0=8$, $H_0=30$ km, and $L_n=L_c=0.77$

## 2.3 Prediction of critical wedge length in wide range flight conditions

Among the three initiation types of smooth, the intermediate and abrupt initiation corresponding to different flight conditions, although the ODW structures are quite different, there is a critical wedge length in the finite length wedge. When the wedge length is equal to or less than it, the ODW structure will be significantly affected by the wedge length, otherwise, there will be no impact. By comparing the critical structure, it can be seen that for smooth initiation, the critical structure shows the decoupling of oblique shock and reactive surface, while in intermediate initiation, the initiation type evolves from intermediate to smooth initiation, and for abrupt initiation structure, the initiation point in the critical structure moves significantly backward. In conclusion, the critical structure of ODW is a critical state between the initiation and quenching.

The stable ODW combustion is the basis and key of the ODE, so the wedge length cannot be less than the critical wedge length in engineering design. In addition, the wedge length should not be too long. On the one hand, the space of the flow channel is limited, too long wedge means that the throat area is reduced, which leads to a problem of thermal congestion. On the other hand, the longer wedge means the greater the resistance and heat load on the wedge, which restricts the improvement of engine performance. In conclusion, the wedge length of the ODE combustor should be as short as possible on the basis of ensuring the ODW stable combustion. Therefore, the accurate prediction of the critical wedge length has important guiding significance for the design of the wedge.

The CW convergence model adopted in the above analysis has considered the flow and heat release process of mixture on the wedge surface from the perspective of the physical mechanism, which can describe the wave system structure near the wedge, and further reflects the initiation process of ODW. In the previous study[14], a criterion for predicting the initiation type was proposed by the relationship between the CW convergence point and the OSW. The CW is generated by the heat release of the mixture compressed by the OSW in the supersonic flow, but the process of heat release requires a certain induction distance, so the wedge length affects the generation and convergence of the CW. When it is at the wedge critical length, the heat release has not been completed at the end of the wedge. Under the influence of the expansion effect, the heat cannot be fully released, resulting in degree of CW convergence is weakened.

For the smooth initiation, the CWs interact with the OSW in dispersed manner, and eventually converge above the OSW. The weakening of the convergence degree results that the OSW cannot be deflected and cannot be converted into ODW. At this time, the temperature of mixture is high, and the fuel will still spontaneously ignite downstream of OSW, but the reactive surface cannot be coupled with the oblique shock. For the intermediate structure, the CW convergence point happens to intersect with the OSW. When the degree of CW convergence is weakened due to the shortening of the wedge length, the CWs finally converges above the OSW, so the initiation type changes to the smooth initiation. For the abrupt initiation, the CW intersection point is below the OSW. The weakening of the convergence degree causes the NDW in the initiation zone to change into the weak secondary ODW, causing the obvious backward of the initiation point.

Although the critical structures under the three initiation types are different, their physical mechanism is similar, that is, the critical wedge length is related to the heat release along the streamlines of wedge surface. Fig.13 shows the temperature and heat release rate distribution along the streamlines of wedge surface with different lengths for $Ma_0=9$ and $H_0=30$ km. The temperature of the combustible mixture in the infinite wedge immediately rises after being compressed by the OSW, but the process of heat release has not yet occurred, i.e., heat release rate $\dot{\sigma}\approx 0$. After a certain distance, the heat release starts, $\dot{\sigma}$ gradually increases, and the temperature starts to rise. In a very short distance, $\dot{\sigma}$ rapidly increases to the peak value, and then decreases rapidly. With the increase of distance, the change rate of $\dot{\sigma}$ also gradually slows down. For the finite length wedge, $\dot{\sigma}$ and temperature along the streamlines of wedge surface decrease rapidly at the end of the wedge. Under the influence of expansion effect, $\dot{\sigma}$ has been maintained at a low level and the temperature rises slowly. It can be seen that the ODW initiation characteristics are indeed related to the heat release rate along the streamlines of the wedge surface, and the critical wedge length is very close to the location of the maximum of $\dot{\sigma}$. Therefore, the critical wedge length can be estimated by the position of the maximum of $\dot{\sigma}$ along the streamlines of wedge surface, which can provide a theoretical criterion for the design of the ODE combustor in engineering.

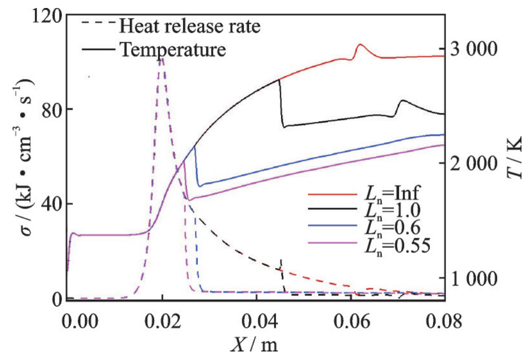



Fig.13 Heat release rate and temperature along the streamlines of wedge surface with different wedge lengths for $Ma_0=9$ and $H_0=30$ km

The detailed interaction of flow and heat release along the wedge surface streamline can be easily estimated using the methods of calculating Zel'dovich-von Neumann-Döring (ZND) structures of one-dimensional steady detonations. Given the mixture inflow parameters $P$, $T$, $V$, and the wedge angle $\theta$, we can calculate the gas parameters after compression by the main OSW using the Rankine-Hugoniot relations for the given OSW angle $\beta$. Then, the following equations[28] are integrated from the post-shock state and the beginning of the wedge surface.

$$\frac{\mathrm{d}\rho}{\mathrm{d}x}=-\frac{\rho\dot{\sigma}}{V(1-Ma^2)} \tag{1}$$

$$\frac{\mathrm{d}V}{\mathrm{d}x}=\frac{\dot{\sigma}}{1-Ma^2} \tag{2}$$

$$\frac{\mathrm{d}p}{\mathrm{d}x}=-\frac{\rho V\dot{\bar{\sigma}}}{1-Ma^2} \tag{3}$$

$$\frac{\mathrm{d}Y_i}{\mathrm{d}x}=-\frac{\omega_i}{\rho V} \tag{4}$$

The normalized heat release rate $\dot{\bar{\sigma}}$ is calculated via

$$\dot{\bar{\sigma}}=\sum_{i=1}^{n}\left(\frac{\bar{w}}{w_i}-\frac{h_i}{c_pT}\right)\frac{\mathrm{d}Y_i}{\mathrm{d}t} \tag{5}$$

where $\bar{w}$ is the mean molecular weight of the mixture, $c_p$ the frozen specific heat of the mixture, and $Y_i$ the mass fraction of the species. Once the equations are solved, the heat release rate and Mach number along the wedge streamline can be obtained. Therefore, the position $X_{\max}$ corresponding to the maximum of heat release rate can be obtained easily. In addition, the non-dimensional critical wedge length $L_c$ and $L_d$ are multiplied to obtain the actual critical wedge length ($L_c\times L_d$).

Fig.14 shows the comparison and error analysis of theoretical and simulation results for critical wedge length for $Ma_0$=8—10 and $H_0$=30 km. As $Ma_0$ increases, the critical wedge length decreases, and the theoretical and the simulation results of the critical wedge length accord well with those of change trend. Although the error is bigger when $Ma_0$=10, the temperature in this case is quite high and the fuel is prone to spontaneous combustion right after the OSW compression. Under the critical wedge length, although it cannot be initiate ODW in the combustor, the fuel can still be fully burned, which is also feasible in engineering. In conclusion, the prediction criterion of critical wedge length performs well in different flight conditions, which can meet the requirements of engineering applications. In fact, further simulation shows the ODW initiation structure changes when the wedge angle or flight condition changes, but there still has a critical wedge length for different ODW initiation structures. At the same time, the proposed theoretical method still performs well to predict the critical wedge length, indicating the universality of the method.

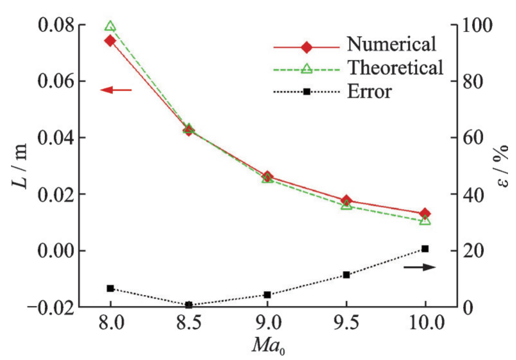



Fig.14 Comparison and error analysis of theoretical and simulation results for critical wedge length for $Ma_0$=8—10 and $H_0$=30 km

## 3 Conclusions

Based on the high-altitude flight condition of ODE, the effects of wedge length and rear inclined angle on ODW initiation characteristics and structures are studied through numerical simulation, and the following conclusions are obtained.

(1) Compared with the infinite wedge, when the wedge length is longer, the shortening of the wedge length may reduce the ODW angle, but will not change the structure of the initiation zone. As the wedge length is shortened to the critical wedge length, the structure of the ODW initiation zone will change significantly, and the initiation type will also change accordingly. Shortening the wedge length again will lead to ODW quenching.

(2) Under different wedge lengths, the influence of the rear inclined angle of wedge change is different. When the wedge length is greater than the critical wedge length, the change of the rear inclined angle has little influence on the ODW structure. When the wedge length is equal to the critical wedge length, the increase of the rear inclined angle causes the initiation position to move backward, and the structure of the ODW initiation zone changes significantly.

(3) For a wide range flight conditions with $Ma_0$=8—10, it is found that there is a critical wedge length in different ODW initiation types. Although the critical structure is different, its evolution is consistent, that is, when the wedge length is equal to or less than the critical wedge length, the change of the wedge length and the rear inclined angle will affect the ODW structure; otherwise, there

will be no impact.

(4) Based on the CW convergence, a theoretical prediction criterion for the critical wedge length is proposed from the perspective of the heat release on the wedge surface, which is independent of simulation results. Numerical results demonstrate that the criterion performs well in the wide range flight conditions of $Ma_0=8—10$, providing theoretical support for the design of the ODE combustor.

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**Author contributions** Prof. **LING Wenhui** designed the study and complied the models. Mr. **ZHOU Lin** conducted the analysis and interpreted the results. Mr. **XIE Haopin** wrote the manuscript and contributed to the simulation results for the analysis. Mr. **TU Shengjia** contributed to the simulation results for the analysis. Prof. **ZHANG Yining** contributed to the discussion and background of the study. All authors commended on the manuscript draft and approved the submission.

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# 有限长度斜劈对燃烧室斜爆震波起爆结构影响研究

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**摘要:**斜爆震发动机利用斜劈在超声速可燃混气中产生的斜爆震波实现快速高效的燃烧,在更高马赫数吸气推进领域极具应用潜力。面向斜爆震发动机工程应用,首先需要明确飞行条件下燃烧室内斜爆震波的起爆结构特征。但以往的研究大多采用无限长斜劈假设,不能真实反映实际燃烧室中有限长斜劈下的斜爆震燃烧特性。基于此,本文针对斜劈长度和斜劈后壁面倾斜角度两个关键设计参数,研究了在飞行马赫数8～10条件下,有限长度斜劈对斜爆震波起爆结构的影响。结果表明,对于不同高空飞行工况对应的不同起爆区结构斜爆震波,均存在一个临界斜劈长度,只有当斜劈长度缩短至临界斜劈长度时,斜爆震结构才会明显改变。相反,有限长度斜劈末端产生的膨胀波不会影响斜劈表面热释放和压缩波的汇聚过程,因此不会影响斜爆震波起爆结构。通过分析斜劈表面热释放过程,提出了一种理论的临界斜劈长度预测方法,其在不同飞行工况下的计算结果与仿真结果吻合较好。

**关键词:**斜爆震;起爆类型;有限长度斜劈;理论预测方法