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# Study of Direct-link Test of Oblique Detonation Engine

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# Study of Direct-link Test of Oblique Detonation Engine

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**Abstract**: Based on the shock tube wind tunnel driven by detonation, simulating the flight altitude of 30km and the incoming flow conditions of flight Mach number 9, this paper conducts a study of direct-link test of the oblique detonation engine with an oblique wedge angle of 30 degrees. The detonation process and stationing characteristics of the oblique detonation wave are analysed in detail by the engine wall pressure measurement combined with the high-speed camera for simultaneous shooting. During the test, the oblique detonation wave successfully detonates on the oblique wedge and is validly stationed. Under the collision effect of the shock waves system downstream the oblique wedge, the oblique detonation wave successfully detonates, and the oblique detonation wave spreads and develops upstream direction after the detonation, and finally, the oblique detonation wave is successfully stationed. Using shadow-graph method to observe the wave system in the combustion chamber, the typical flow field structure such as non-reactive shock wave, oblique detonation wave, transverse wave and triple point is clearly observed, and the angle of oblique detonation wave in the oblique detonation engine tested in this paper is greater than 80 degrees. The successful detonation and stationarity of oblique detonation wave in direct-link test proves the feasibility of oblique detonation wave to be applied to hypersonic propulsion.

## 1. Introduction

Currently, the scramjet engine is the best power device for aircraft to achieve hypersonic flight in the atmosphere, while high-performance propulsion technology based on scramjet engine is the core technology to achieve hypersonic propulsion. As a more efficient way of combustion organization, detonating combustion has a broad application prospect in improving the thrust performance of scramjet engine. At present, the scramjet engine using detonating combustion as the propulsion principle is mainly oblique detonation engine (ODE) [1-2], which works by: premixed gas detonates on the oblique wedge to produce oblique detonation wave (ODW), then the combustible gas is quickly burned after the surface of detonation wave and generates thrust. Figure 1 shows a diagram of how the oblique detonation engine works, as shown in the figure, because the ODW is stationed in the combustion chamber, a stable high Mach number flow becomes one of the important prerequisites for the stable operation of ODE. Also because of the high demand for inflow conditions of ODE, the current researches on ODE are mainly based on theoretical analysis and numerical simulation, while the test research is seldom carried out.

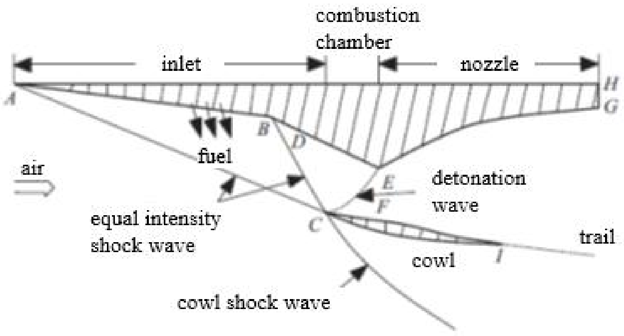


**Figure 1 Diagram of the structure of the oblique detonation ramjet**

Focusing on the study of ODW structure, Li [3] etc. has analyzed the ODW structure in detail and found that the basic structure of ODW includes non-reactive oblique shock waves, induction zone, deflagration wave systems, and reaction shock waves. Non-reactive shock waves and reactive shock waves are separated by triple point. Broda [4] has found a special structure of oblique detonation flow field without obvious triple point, but a smooth wave structure. Subsequently, the existence of this smooth oblique detonation wave structure is then verified by numerical simulation by Vlasenko [5]. At this point, the transition of the ODW is divided into two structures: the abrupt type and the smooth type, as shown in Figure 2.

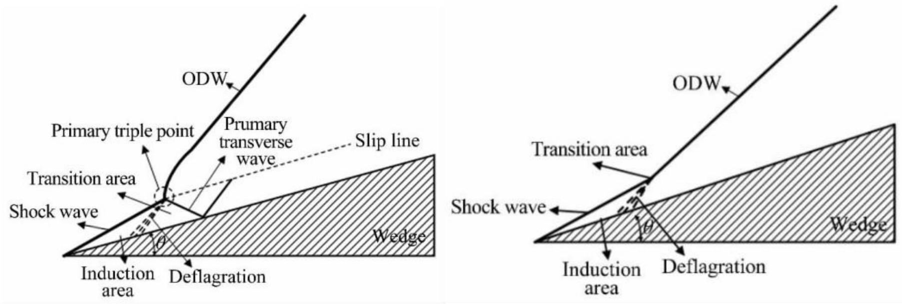


**Figure 2 The structure of the transition zone of the abrupt and smooth oblique detonation wave**

The successful detonation and effective stationing of ODW is an important prerequisite for the stabilization of ODE, and some results have been obtained in the current study of the detonation and stationarity of oblique detonation waves in ODE. Due to the short residence time of inflow premixed gas in the combustion chamber, ODW generally uses a direct detonation method. Initially, Zeldovich [6] and others used high-speed projectiles to study the problems of shock-induced combustion and detonation, and found that the ratio between flow-resident time and characteristic time of chemical reaction after bow shock wave are the key to induce the detonation combustion. Then, Vasiljev [7] and Lee [8] first proposed the theory of direct detonation ignition of high-speed projectiles based on critical detonation energy, named as the Vasiljev-Lee criterion. The criterion holds that in the process of projectile high-speed motion, resistance makes power to combustible gas, when the power resistance makes within the unit length is not less than the critical energy required within the unit length when the cylinder detonation detonates, the oblique detonation wave can successfully detonate. Lin Zhiyong [9] etc. used the high enthalpy supersonic wind tunnel to study the shock-induced combustion and detached ODW detonation process, and further studied the effects of shock intensity, premixed gas activity and angle of oblique wedge. Pratt [10] etc. first used the morphology of standing oblique detonation wave to make a theoretical analysis of the stationarity of ODW, they proposed the Mach number condition and geometric conditions of oblique wedge to achieve the stationarity of oblique wedge. Li [11] etc. found that to avoid ODW from separating from the leading edge of oblique wedge and propagating to the upstream, it needs to be ensured that the angle of oblique chopping is less than a critical value, and this critical value is related to the sound velocity after oblique shock waves. Han Xu [12] etc. studied the stationary characteristics of ODW in the high enthalpy hypersonic wind tunnel and found that ODW's reflection under wall constraints leads to the backward propagation of ODW.

## 2. Introduction of experimental system

*2.1 Introduction of the direct-link test bench driven by the detonation wave*
The diagram of the structure of the detonation driven direct-link test bench used in this paper is shown in figure 3, it shows that the main body of the test system is divided into two parts: the shock wave tube and the vacuum chamber. The total length of the shock wave tube part is 23m, consisting of the detonation vent section, the drive section and the driven section, the sections are separated by film of steel, the specific size parameters are shown in Table 1.

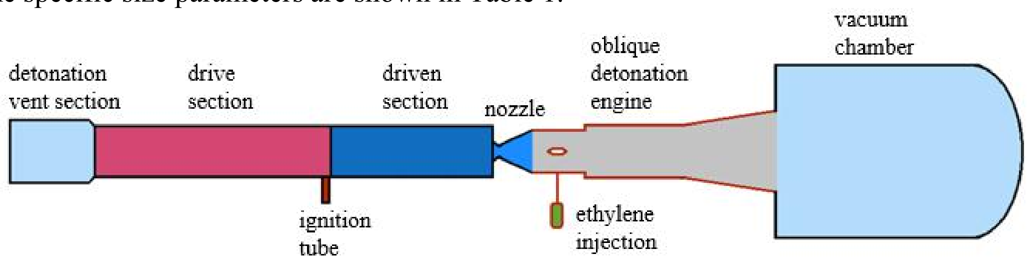


**Figure 3 Detonation driven direct-link test bench structure diagram**

**Table 1** geometrical size of detonation driven shock wave tube

| Parameter | Detonation vent section | Drive section | Driven Section |
|---|---|---|---|
| length（m） | 2.5 | 13 | 7.5 |
| Inside diameter（mm） | 260 | 130 | 130 |

The test use revers detonation drive technology to compress the air in the driven section with shock waves to achieve the total temperature and total pressure required for the test. The test gas accelerates to the design speed of the combustion chamber inlet through the Laval nozzle, which directly connect the test engine model, and the engine outlet is connected to the vacuum compartment to ensure back pressure conditions.

*2.2 Introduction of the oblique detonation engine test system*
According to the results of the previous numerical simulation, the direct-link oblique detonation test ramjet is designed and processed. Figure 4 shows the cross-sectional view of the oblique detonation test engine, which are mainly divided into gas premixing section and test section. The gas premixing section has three circular viewing windows on the single side, which are used for shooting with a high-speed camera to monitor the gas premixing section for early fuel combustion or flame backward propagation phenomenon. An oblique wedge with the angle of 30 degrees are used to induce an oblique detonation wave in the test section. Two square viewing windows are created on two sides of the test section, which are used for the high-speed camera combined with shadowgraph method to capture the combustion chamber flame and shock wave development. The shadow method shooting test uses two high-speed cameras to shoot at the same time, the high-speed camera 1 capture the flame state from a total of 4 windows of the gas premixing section, and high-speed camera 2 capture the shadowgraphs through square windows. The test also uses pressure measurement to monitor the detonation and operating status of the ODE, as shown in Figure 4, eight pressure sensors are installed on the wall of gas premixing section, five pressure sensors are installed on the upper wall of the combustion chamber and three sensors are installed on the bottom wall of the combustion chamber.

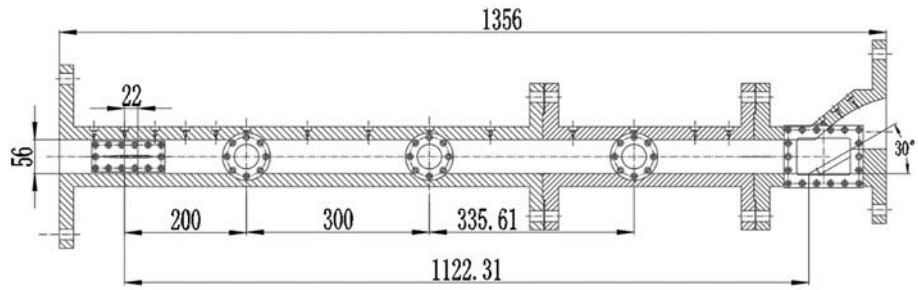


**Figure 4 Cross-section view of the oblique detonation engine**

## 3. Test process and analysis of results

*3.1 Debugging of the detonation driven direct-link test system*

In this paper, the direct-link test of the oblique detonation engine is carried out on the detonation-driven shock wave wind tunnel test bench, therefore the detonation-driven shock wave wind tunnel equipment requires debugging at first. Figure 5 shows the total pressure curves measured by the five repeat tests. As can be seen from the figure, the total pressure of the inflow is relatively stable, the pressure platform period can reach more than 16ms, and has a good repetition in five tests. The nozzle outlet reaches a speed of Mach number 5.0 in the test, and the test inflow has a total pressure of 15MPa, total temperature of 3200K as well as air quality flow rate of 1.363kg/s.

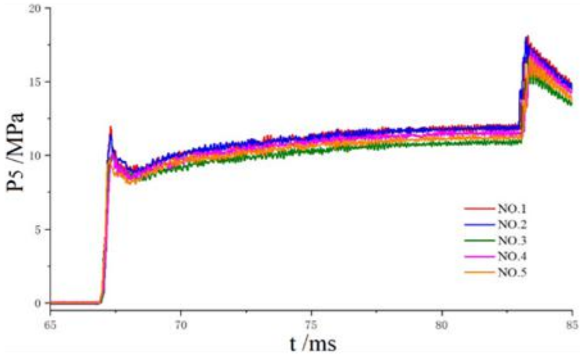


**Figure 5 Total pressure curves of the inflow condition debugging**

*3.2 Analysis of the direct-link test results of oblique detonation engine*

The direct-connected test is carried out on the detonation-driven shock wave wind tunnel test bench, simulating the inflight conditions of inflow with Mach number 9, flight altitude of 30km. The nozzle outlet reaches a speed of Mach number 5.0, total temperature of 3200K, total pressure of 15Mpa and air quality flow rate of 1.363kg/s. The fuel is based on a normal temperature ethylene, and Table 2 shows the operating table for the direct-connected test.

**Table 2** Table of operating condition in test

| Operating conditions code | Air | | | Fuel | | |
|---|---|---|---|---|---|---|
| | Mass flow rate (g/s) | Total temperature (K) | Mach number | Injection pressure (MPa) | Mass flow rate (g/s) | Equivalent ratio |
| #1 | 1363 | 3200 | 5 | 1.6 | 39.6 | 0.43 |

In order to verify the repeatability of the stable working state of the ODE designed in this paper, the test injection condition is shown as operating condition#1 in Table 2, the test equivalent ratio is 0.43. The laser light source combined with high-speed camera 2 are used at the same time for the flow filed shadow shooting in the combustion chamber, shooting frequency of high-speed camera is 40,000fps, and exposure time is 1/551000s under operating condition#1, A clear wave system structure is captured by a high-speed camera and the shadowgraph is shown in Figure 6.

As can be obtained from Figure 6, the oblique shock wave induced by oblique wedge in the combustion chamber collides with the upward oblique shock wave caused by the vortex zone in expansion section of nozzle, resulting in a local hot spot, then the local hot spot develops rapidly in the combustible gas, at the moment of 29.218ms (picture 1 of the Figure 6), the oblique detonation wave finally ignition, the length of initial ODW after detonation is short and its position is close to the downstream on the wedge, and then ODW in the combustible gas develops quickly and gradually propagates upstream, during the propagation process, the ODW gradually matched with the incoming flow speed with the length and detonation angle gradually increased, and at the moment of 32.918ms (picture 2 of the Figure 6) it successfully stands on the oblique wedge as shown in picture 2 of Figure 6. After the stationarity of ODW, the intensity, height and shock angle of the detonation wave gradually becomes stable, and under the operating condition#1, the angle of ODW after its stable stationary is over 80degrees. With shadowgraph method, high-speed cameras clearly capture typical flow field structures such as ODW, transverse wave, triple point, oblique shock wave and upward shock wave through the square windows of the combustion chamber, as shown in picture 2 of Figure 6, the oblique detonation engine designed in this paper has an abrupt structure in the transition zone [5].

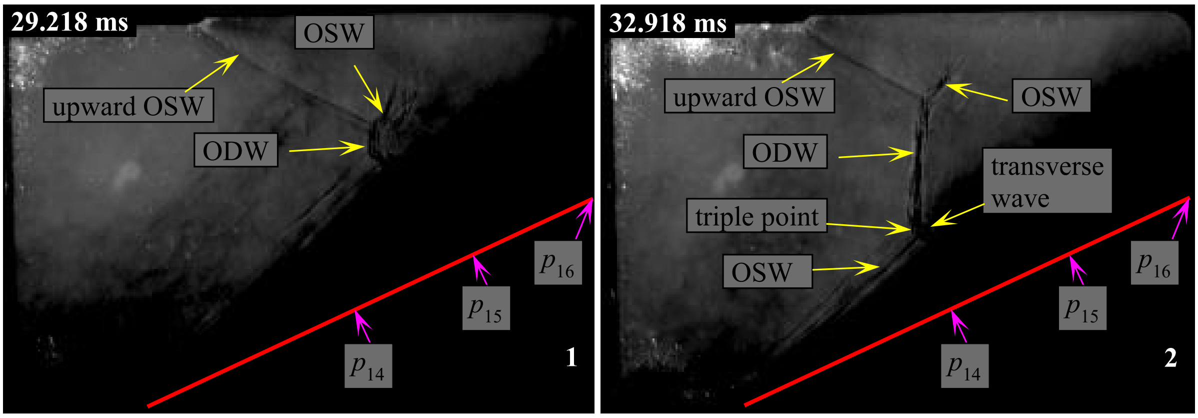


**Figure 6 The wave system structure of the oblique detonation flow field captured by the high-speed camera (operating condition#1,40,000fps).**

## 4. conclusions

Based on the detonation-driven shock wave wind tunnel, through pressure measurement combined with shadowgraph technology, this paper conducts a test of oblique detonation engine under the inflow simulation of flight altitude of 30km and flying Mach number 9. The following conclusions are obtained:

The collision of shock waves system downstream the oblique wedge causes the ignition of the oblique detonation wave, and oblique detonation wave gradually develops in the process of propagation, finally it is successfully stationed on the oblique wedge. Using shadowgraph technology, the typical wave structure in flow field such as oblique detonation wave, transverse wave, triple point,

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non-reactive oblique shock wave and upward oblique shock wave is clearly observed. Under the test conditions used in this paper, the angle of oblique detonation wave is over 80degrees. The successful detonation and stationarity of the oblique detonation in the direct-link test has verified the feasibility of the oblique burst shock wave to be applied to hypersonic propulsion.

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