Investigation of Detonative Combustion Characteristics

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Abstract: The pressure and deflagration-to-detonation transition (DDT) characteristics of acetylene and oxygen flame were studied in a detonation tube. The pressure history and the flame velocity along the tube were measured with high frequency pressure transducers and ion probes. By analyzing the data recorded in the experiment, the detonation wave pressure, post-wave pressure and DDT distance were obtained, together with the effects of the initial pressure varying from 2×10^4Pa to 10^5Pa, equivalence ration from 0.3 to 1.0, and mixture concentration from 60% to 100%. It was found that the detonation pressure was decreased respectively with the decrease of initial pressure, equivalence ratio and mixture concentration, but the DDT distance was enlarged. The DDT distance was found particularly sensitive to mixture concentration.

Key words: detonation; combustion; deflagration-to-detonation transition; pulse detonation engine

爆震燃烧的特性研究. 韩启祥, 王家骅, 王波. 中国航空学报(英文版). 2002, 15(2): 72-76.

摘　要: 研究了爆震管中爆震燃烧的压力特性及爆燃到爆震转捩(DDT)特性。在乙炔与氧气的预混气中, 通过高频响压力传感器及自行研制的离子探针, 测量了不同工况下爆震燃烧的压力与火焰传播速度的变化历程, 获得了爆震波峰值压力、波后压力及 DDT 距离随混气初始压力(2×10^4Pa～1×10^5Pa)、混气当量比(0.3～1.0)及混气浓度(60%～100%)的变化规律。试验结果表明: 降低预混气的压力、混气当量比及浓度会使爆震波的峰值压力、波后压力不同程度的下降, DDT 距离增大, 其中 DDT 距离对混气浓度最敏感。

关键词: 爆震; 燃烧; 爆燃到爆震转捩; 脉冲爆震发动机
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Recently, pulse detonation engines (PDE) have received considerable attention. Its principle and potential superiority[1] have been recognized. Yet there is still a significant amount of work to be done before it can be put to actual practice. The major problem here is a thorough understanding of the characteristics of detonative combustion.

Based on detonation characteristics, the deflagration to detonation transition (DDT) site can be judged upon examination of the pressure characteristic curve and the flame speed characteristic curve[2,3]. The pressure characteristic curve also serves as the basis for analysis of structure intensity and PDE specific impulse[4]. The DDT distance not only determines the length of the PDE but also has a significant effect on its performance. In this study, a mixture of acetylene and oxygen is considered. However, the conclusions obtained here are also applicable to cases other than this kind of mixture.

1 Experimental Setup and Experimental Procedure

1.1 Experimental setup

The experimental setup is shown in Fig. 1, including the detonation tube, induction system, ignition system, and instrumentation system. The detonation tube has a length of 1m with a diameter

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of 40mm. The induction system includes storage tanks for acetylene, oxygen and air, a vacuum pump, a partition membrane gas pump, a vacuum pressure gauge, tubing and valves. The ignition system consists of a high energy spark plug providing sparks of 1 joule energy. The instrumentation system consists of a set of pressure gauges that contains 4 fast response PCB pressure transducers (500 kHz response frequency and rise time of 1μs) and a 4 channel adaptor. Flame speed is measured with a self-made ion probe system (less than 1μs rise time). All signals are recorded by an 8-channel real-time recorder (1.25 MHz simultaneous sampling rate).

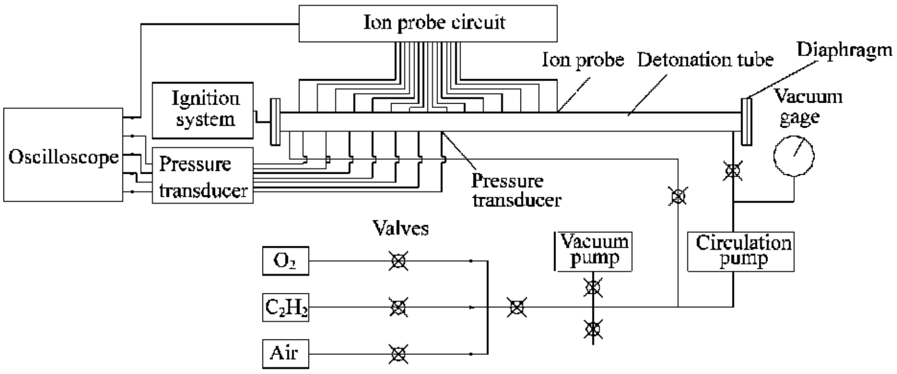

Fig. 1 Schematic of experimental setup

1.2 Experimental procedure

The detonation tube is first evacuated to an absolute pressure of 200Pa to eliminate residue gas effects. Fuel and oxygen are then introduced, the proportion of each being regulated by its partial pressure. A circulation pump is then used to enhance the mixing of the gases. Finally, an igniter ignites the mixture resulting in its detonative combustion. The detonation wave is transmitted to a diaphragm that is readily ruptured, rupture pressure of the diaphragm being about 1.5×10^5Pa. The detonation wave exits to the air finally. During the whole process, all pressure transducers and ion probes signals are recorded by the real-time recording system.

Flame speed of detonative combustion is measured by an ion probe system. In the flame, there is a large amount of ions with electric charge. the probe gives an impulse signal when these ions go past it. The distance between the two probes divided by the time lag of the second signal gives the flame speed.

2 Test Results and Analysis

2.1 Analysis of characteristics of detonative combustion

Fig. 2 shows the time history of pressure variation at a certain point in the tube in the course of a detonative combustion. In the figure, X is the distance from the igniter end of the tube, and P_1 is initial pressure of the mixture. The mixture pressure remains at its initial value in front of a very prominent pressure spike. This shows that the detonation wave which is composed of a shock wave and a combustion wave is transmitted at supersonic speed so that the mixture ahead of the wave is not affected by the disturbance of combustion. Upon arrival of the detonation wave, the local pressure jumps up to a peak value P_2 or P_{CJ}.

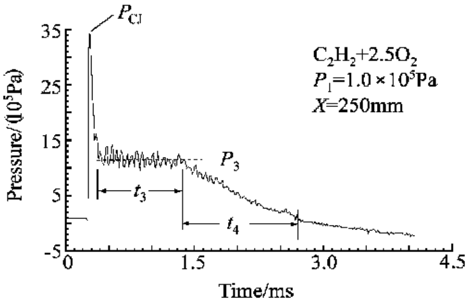

Fig. 2 The history of detonation pressure

While the detonation wave propagates forward, the burned gas follows up at a certain speed. Because one end of the tube is sealed a series of rarefaction waves is generated and transmitted forward from this end and pressure drops from P_2 to P_3. The gas pressure varies up and down around P_3 until the detonation wave exits the tube, a series of rarefaction waves emanating from the open end travel into the tube and expel the burned gas. The period while the gas pressure is maintained at P_3 is named the period of constant pressure expansion t_3. The period while the pressure drops from P_4 to ambient pressure is named the period of declining pressure expansion t_4, Referring to the pressure history on the thrust wall (the sealed end) it is noted that the peak pressure is never exerted on it. During t_3 a steady thrust is exerted on the end wall and during t_4 this thrust gradually drops to zero. Since the peak pressure P_{CJ} is never exerted on the thrust wall, it has no direct contribution to the thrust, but it certainly affects the structure intensity. After the gas has expanded to ambient pressure, over-expansion takes place and results in a negative thrust on the end wall. Design of the PDE aims at minimizing the negative thrust, and this is accomplished by opening the inlet valve in time to ensure the charging of the tube with fresh mixture, and the next PDE cycles begin.

After the mixture in the tube is ignited, the flame velocities along the tube are presented in Fig. 3. It is seen that the flame speed initially remains at a moderate value, but at a certain distance from the sealed end it suddenly jumps to a peak value. Farther away, it decreases somewhat and eventually remains at a relatively constant value. This is because in the case of limited ignition energy, while the ignition gives rise to deflagration combustion, it cannot immediately provoke detonative combustion. The flame speed of deflagration is subsonic. If the tube has a sufficient length, the pressure waves created by the deflagration flame pile up into a shock wave and eventually causes a transition of the combustion mode. The flame speed of the detonative wave is supersonic, so upon the transition of the combustion mode the flame speed experiences a sudden rise. In the course of DDT, there has one or more explosion centers forming and amplifying at a certain point in the turbulent reaction zone in the flame front[2]. Then a reinforced shock wave is formed in the mixture. At this stage, the detonation wave is a strong detonation wave, but it is not stable and soon degrades to a self-sustained C-J detonation wave. This is why the flame speed drops after an abrupt rise.

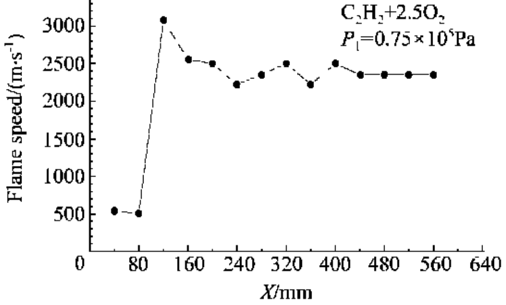

Fig. 3 Variation of flame speed

In the PDE, the shorter the DDT, the greater the benefit from detonative combustion. In Fig. 3 the DDT distance is 80 to 120 mm.

2.2 Effect of initial pressure on detonative combustion characteristics

Figs. 4 and 5 give respectively the dependence of the detonative combustion pressure and DDT distance on the initial pressure of the premixed gases. From the figures it is seen that the lower the initial pressure of the premixed gas, the lower the detonation pressure spike, and the larger the DDT distance. This is because at low initial pressure the speed of combustion reaction is low and the rate of heat release is low. This increases the DDT distance and decreases strength of the detonation wave. Variation of the peak pressure with the initial pressure is similar to that of the post-wave pressure P_3. The fact that the pressure behind the wave decreases more slowly than the peak pressure shows that when the rate of heat release is decreased the effect on the peak pressure is more prominent. But at very low initial pressures decrease of pressure behind the wave is sooner than that of the peak pressure. This is possibly due to the fact that when the heat release is lowered to a certain level, the effect of heat conduction from the wall is more important. At the same time, because the wave front is thin and the wave speed is high, heat conduction from the wall has a relatively small effect on the pressure peak.

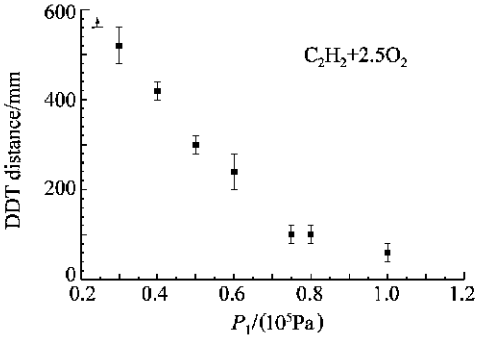

Fig.4 Effect of initial pressure on detonation pressure

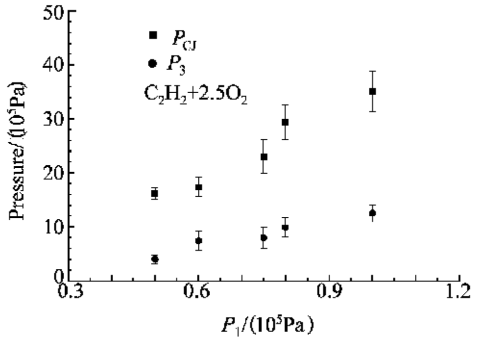

Fig.5 Effect of initial pressure on flame speed

From Fig. 5 it is seen that when the initial pressure is not seriously lowered, the DDT distance increment is small, and when the initial pressure falls below 0.75×10^5Pa the DDT distance quickly increases. At an initial pressure of 0.3×10^5Pa, no DDT is observed within the scope of instrumentation (40–560 mm). This shows that the dependence of DDT distance on initial pressure is nonlinear.

2.3 Effect of equivalence ratio and mixture concentration on characteristics of detonative combustion

Fig. 6 gives the variation of the detonative pressure with the equivalence ratio. As surplus oxygen is increased in the mixture, the peak pressure as well as the pressure behind the wave begins to drop because of reduction in heat release per unit volume of mixture. However, this drop is only moderate since a little surplus oxygen helps in the collision of molecules of different gases. But in the case of very low values of equivalence ratio the former effect is by far the more important and the pressure drop is then serious.

Fig. 7 gives the effect of the equivalence ratio on DDT distance. The DDT process is basically an accumulation of energy and therefore the amount of energy release per unit volume is a matter of much concern. This is why the DDT distance increases with the decreasing equivalence ratio.

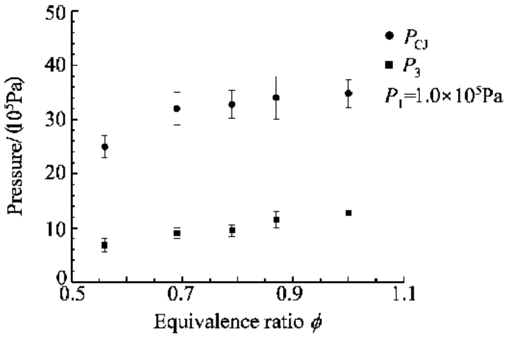

Fig. 6 Effect of equivalence ratio on detonation pressure

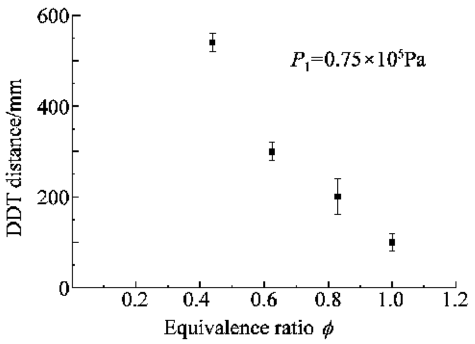

Fig. 7 Effect of equivalence ratio on detonation pressure

When inert gas nitrogen is introduced into a stoichiometric mixture of acetylene and oxygen,

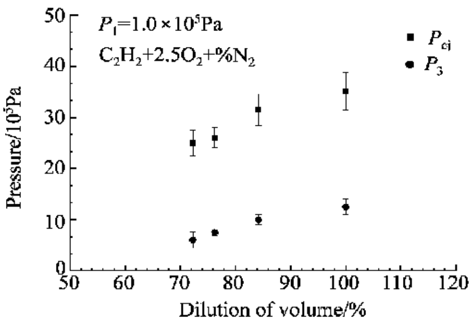

Fig.8 Effect of mixture concentration

mixture concentration is decreased. Variation of detonative combustion characteristics with concentration is shown in Fig. 8 and Fig. 9. With decrease of concentration not only does DDT distance increase remarkably but detonation pressure is also reduced. This is because with the introduction of nitrogen heat release from unit volume of mixture is reduced and chance of collision of the two kinds of molecules is also reduced. These facts all ill-effect the chemical reaction. When the volume percentage concentration falls below 60.5%, no DDT is observed within the scope of instrumentation. This means that DDT occurs beyond a distance of 650 mm.

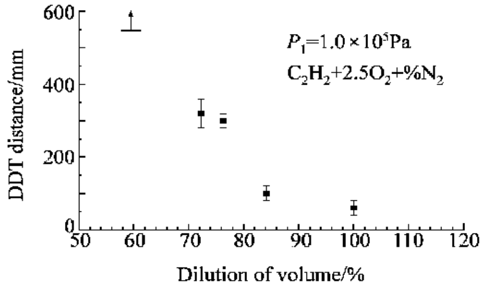

Fig.9 Effect of mixture concentration on DDT distance

3 Conclusions

History of pressure variation of detonative combustion can be divided into 3 periods, the pressure spike, the period of constant pressure expansion and the period of declining pressure expansion. The peak pressure is not exerted on the thrust wall, so it produces no thrust. During the constant pressure expansion period a steady thrust is exerted on the end wall. During the period of declining pressure expansion, the thrust gradually decreases. Thereafter, over-expansion produces a negative thrust. The PDE design aims at minimizing this negative thrust and this is accomplished by timely opening of the inlet valve to ensure quick charging of the tube with a fresh mixture.

DDT is clearly denoted by an abrupt rise in flame speed from subsonic to supersonic speed. In fact, the occurrence of DDT is identified by this change.

With the drop of the initial pressure, the detonation pressure drops. The pressure behind the wave drops more slowly than that of the peak. At the same time, DDT distance increases. When the initial pressure drops below 0. 75 × 10^5Pa, the DDT distance increases rapidly.

When the equivalence ratio drops from 1. 0, the detonative pressure drops only moderately, but the DDT distance increases rapidly, bearing a linear relation to the drop of the equivalence ratio.

When nitrogen is introduced into the acetylene-oxygen mixture, detonation pressure decreases while DDT distance increases rapidly. When percentage volume concentration drops to 60.5%, DDT is not observed within the scope of instrumentation. From this, it is concluded that using air instead of oxygen as oxidizer, DDT will occur at a distance far beyond 650mm.

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