Direct initiation of detonation with ignition tube

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Abstract. Experiments of direct initiation of hydrogen-oxygen by means of a hot turbulent jet were made . Results indicate that the length of ignition tube is the dominant factor in determining the ignition capability of hot turbulent jet, and that the ignition capability of turbulence jet increases with the length of ignition tube. Because this ignition capability can meet the demands of a gas-detonation-driver shock tunnel and it doesn't require additional facilities, the hot turbulent jet initiation method can be applied to large hydrogen-oxygen detonation-driver shock tunnels. Influences of obstacles on the ignition capability were also studied. It was found that the presence of obstacles weakens the ignition capability of a hot turbulent jet.

1 Introduction

Generally speaking, there are two modes of initiation: a slow mode in which the detonation is formed via an accelerating flame, and a fast mode in which the detonation is formed instantaneously when a sufficiently powerful igniter is used.

Only if the detonation is initiated directly will the test flow in a detonation-driver shock tunnel be highly repeatable [1] and the full thrust duration of a pulse detonation engine (PDE) approach maximum [2]. Therefore, the development of a powerful and suitable igniter is of great importance.

The parameter that characterizes the phenomenon of direct initiation detonation is the ignition energy. If the ignition energy exceeds the critical threshold value, the detonation can initiate directly. The general behavior of the critical energy versus mixture composition is in the form of a U-shaped curve, with the critical energy approaching infinity at the lean and rich limits [3]. In a detonation driver, the optimum ratio of hydrogen to oxygen for attaining strong shock waves is close to the rich limit. In a PDE, the oxidizer is air and the fuel may be a liquid hydrocarbon, for which it is difficult to initiate a detonation directly [4]. In either case, a powerful igniter is needed for the operation.

For guaranteeing the experimental flow quality in a shock tunnel and the physical security of the experimental apparatus, the igniter must be uncontaminated, have a simple structure, and be safe and reliable. These strict requirements limit application of many ignition routes. The ignition energy of electrical sparks [5] is not high enough to ignite directly mixed gases with the ratio of hydrogen to oxygen as high as 3.5. Although the ignition energies of the solid explosives [6] are very high, much pollution is generated in the shock tunnel, which influences the experimental flow quality. Shock-focusing ignition [7] is so complex as to operate highly inconveniently. Detonation-wave ignition ignites the fuel gas to generate detonation and then detonates the mixed gases [8]. However, it cannot be used in a shock tube equipped with a backward detonation driver because the traveling direction of the detonation wave is generally in parallel with experimental pipe, and the equipment is complex. Therefore, a novel ignition tube that functions by means of a turbulent gas jet has been developed.

2 Experimental details

The experiment was carried out in the driver section of a shock tube with a length of 5.65 m and an inside diameter of 100 mm. Figure 1 is schematic diagram of the experiment apparatus. The ignition tube was placed at the end of the driver section. Its role was to ignite the hydrogen-oxygen mixed gases in the driver section. One end of the ignition tube abutted the driver section. At the other end, the ignition end, of the ignition tube, a wire was charged with 2000V by use of a capacity charge device to ignite the mixed gases in the ignition tube. Detonation waves generated in the ignition tube or hot turbulent jets of high temperature and high pressure formed after combustion ignited the mixed gases in the driver section. The initial pressure of the hydrogen-oxygen mixed gases in the experiments was 0.3 MPa.

2.1 Design of the ignition tube

The ignition tube was designed as variable cross-section form. The reflected waves generated by the variable cross section interfered with the flame's wave front, which caused bending of the wave front. The combustion front was then enlarged, the spreading velocity of the flame was accelerated, and the pressure of the burnt gas was rose abruptly. It is obvious that the existence of the variable cross section promotes acceleration of the flame and it can increase the pressure of the burnt gas, which has a positive effect on the ignition capability of the ignition tube. In order to further understand the role of ignition tube, three types of ignition tubes were designed: The full-length of the A type ignition tube was 220 mm. The variable cross section was placed at 65 mm from the position of ignition, and the inside diameter of the 65 mm distance was 40 mm. From the variable cross section to the end of ignition tube, the inside diameter was 20 mm. The end of ignition tube was connected to driver section.

The B type ignition tube was designed by connecting a 100 mm length and 40 mm diameter pipe to the A type ignition tube. Inserts with various inside diameters could be installed as obstacles at the joint of the pipes. An additional pipe of 100 mm-length and 40mm-diameter was connected to the B type ignition tube, creating the C type ignition tube. The joint of the C type had the same action as that of the B type ignition tube. In the experiments, the ignition capabilities of the three types of ignition tube were first observed without obstacles, and then ignition capability was studied after adding various inside-diameter inserts as obstacles.

2.2 Criteria of direct initiation

Considering that the high initial pressure of hydrogen-oxygen mixed gases was difficult to determine optically, the experiment adopted a method of measuring pressure wave shape to judge whether the mixed gases detonated instantaneously in the driver section.

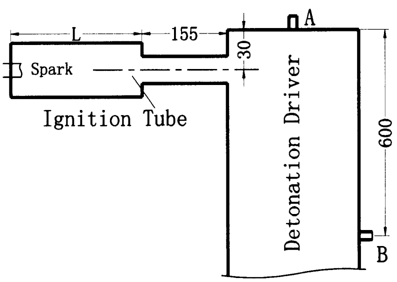

Fig. 1. Schematic diagram of experimental apparatus

Piezoelectric-pressure sensors were placed (Fig. 1) at the end cover (Point A) and at 0.6 m from the end cover (Point B). The pressure wave shape of the direct detonation and that of the deflagration-to-detonation transition (DDT) were different. Supposing detonation instantly at the exit of the ignition tube, the pressure at Point A and Point B jumps to maximum sequentially, and then attenuates to a certain value. After maintaining the value for some time, the pressure attenuates again. The process is shown in Fig. 2(a). If the measured value of pressure at Point B is equal to the theoretical value, we conclude that the mixed gases detonated instantaneously. Conversely, the process of DDT is shown in Fig. 2(b). Here, the pressure signals of Point A and Point B could be used as the criteria to judge whether the hydrogen-oxygen mixed gases detonated instantaneously in the driver section.

3 Results and discussion

1) Ignition capabilities of various ignition tubes

Numerical calculation results indicated [9] that the driving capability of a detonation driver strengthens as the ratio of hydrogen to oxygen increases and is the strongest when the ratio is 5.5. The ignition capabilities of the three ignition tubes are compared in Table 1.

The ignition capability strengthens as the length of the combustion chamber of the ignition tube increases. The type C ignition tube could directly detonate the hydrogen-oxygen mixed gases with the ratio being 5.5. Therefore, the length of ignition tube is the critical factor for the ignition capability of ignition tube. Consequently, to lengthen the ignition tube is an effective way to strengthen the ignition capability of ignition tube.

Table 1. Upper limits of H_2/O_2 versus length of combustion chamber at initial pressure of detonative mixture 0.3 MPa

Igniter	A	B	C
L(mm)	65	165	265
H_2/O_2	4.5	5	5.5

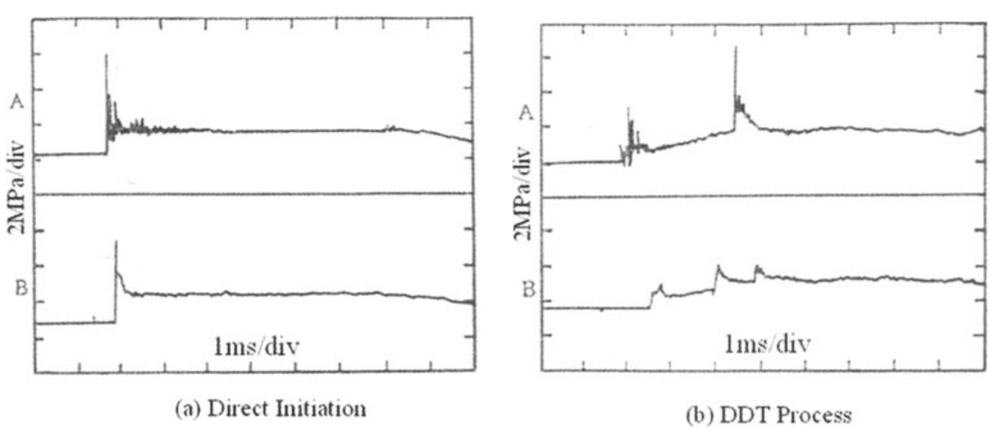

Fig. 2. Pressure curves at Points A and B in Fig. 1

2) The influence of obstacles on the ignition capability of an ignition tube

The results indicated that obstacles could accelerate the spreading velocity and greatly shorten the DDT distance. For studying the influence of the obstacles on the ignition capability of the ignition tube, inserts of various inside-diameter were placed in the type B and type C ignition tubes. The obstacles exerted a significant influence on the ignition capability of the ignition tube (Table 2).

As shown in the table, the ignition capability of either the type B or type C ignition tube was lowered with addition of obstacles. That indicates that the obstacles could weaken the ignition capability of the ignition tube. The experimental results also showed that the inside diameter and the position of the obstacle also influenced on the ignition capability of the ignition tube.

Table 2. The influence on the ignition capability of an ignition tube by obstacles (d and D are the inner and outer diameters of the insert, respectively, and S is the distance from the position of ignition to the insert)

Igniter	Φ (=d/D)	Ψ (=S/D)	H_2 / O_2
B	No obstacles		≤ 5
B	0.8	2.5	≤ 5
B	0.6	2.5	≤ 5
B	0.4	2.5	≤ 4.5
C	No obstacles		≤ 5.5
C	0.8	2.5	≤ 4.5
C	0.6	2.5	≤ 5
C	0.4	2.5	≤ 5
C	0.8	5	≤ 4
C	0.6	5	≤ 4.5

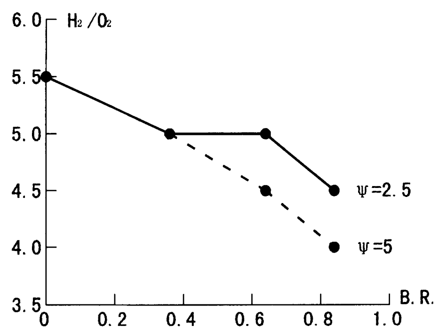

Fig. 3. Ignition capability of ignition tube versus B.R.

a) Influence of different inside-diameter of the inserts on the ignition capability of ignition tube:

The obstacle ratio of the inserts is defined as: $B.R. = 1 - \Phi^2$ $(here \ \ \Phi = d/D)$. Taking the type 3 ignition tube as an example, the ignition capability of the ignition tube varying with B.R. is shown in Fig. 3. The varying curve indicates that for constant Ψ the ignition capability of the ignition tube is lowered with increasing of B.R. This result means that the smaller the inside diameter of the insert, the stronger is the weakening of the ignition capability of the ignition tube.

b) Influence of different position of the insert on the ignition capability of ignition tube:

Under the condition that an insert with same inside diameter is placed at a different position (Ψ= S/D = 2.5 and S/D = 5), the ignition capability of the ignition tube was surveyed. Experimental results indicated that larger Ψ induced a weaker ignition capability. This finding means that the further the distance is between the obstacle and the ignition point, the greater is the weakening of the ignition capability of the ignition tube.

3) Ignition mode of ignition tube and its influence on the ignition capability

According to the analysis above, there are two ignition modes: the detonation-wave ignition mode and the hot-turbulent-jet ignition mode. Previous research results confirm that obstacles can greatly accelerate the spreading velocity of the flame, shorten the DDT distance, and accelerate initiation of the detonation. When the ratio of hydrogen to oxygen is rather high ($4 < H_2/O_2 < 5.5$), direct initiation detonation in the ignition tube is very difficult. Under these conditions, a jet flame forms at the exit of the ignition tube. This is the hot-turbulent-jet ignition mode. When obstacles are placed in the ignition tube, detonation waves are readily formed at the exit of the ignition tube. This is detonation-wave ignition mode.

Compared with the inside diameter of the driver section, the inside diameter of the exit section of ignition tube is much smaller. When using the detonation-wave ignition mode, the detonation wave entering the driver section can be almost considered to enter an infinite container. Therefore, the initial detonation wave in the driver section can be approximately considered as a spherical blast. However, the spherical blast attenuates abruptly with increase of spreading distance. If the temperature of the unburned gas behind the spherical blast falls below a certain temperature, or if the intensity of the spherical blast cannot maintain a given intensity for some period, then the detonation is not formed and the spherical blast attenuates to become an acoustic wave. As to ignition of the unburned hydrogen-oxygen mixed gases, active free radicals in the burnt gas are lacking because the mixed gases behind the detonation wave have reacted completely. Therefore, it is difficult for the detonation-wave ignition mode to achieve direct detonation under conditions of high hydrogen fraction.

Knystautas et al. [10] not only put forward the concept of hot turbulent jet, but also researched its mechanism. Their research indicated that the mechanism of the hot turbulent jet is the so-called the mechanism of turbulent mixing: a severe mixture composed of hot burnt products and unburned gas causes detonation.

4 Conclusion

The ignition tube shown in Fig.1 has some important and unique characteristics. First, its exit diameter is only 20 mm. Such a small orifice is not difficult to construct on the driver wall, even for high-pressure conditions. Second, there is no need for a diaphragm between the ignition tube and the driver, because the combustible mixture filled in the ignition tube is the same as that within the driver. Third, the size of the ignition tube is small. These features make the ignition tube convenient to operate. Fourth, the diameter of combustion chamber is larger than that of the exit section; thus the pressure of the burnt gas in the combustion chamber will exceed the initial pressure in the driver. Then high-pressure and high-temperature jets promote direct initiation of a detonation. Sixth, the intensity of the ignition tube depends on the length of combustion chamber. When the length of combustion chamber is longer, the intensity of the ignition tube becomes greater. Last, experimental results show that the ignition intensity of hot turbulent jet is stronger than that of the detonation wave that is formed in the exit section when obstructions are present in the combustion chamber.

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