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OXYHYDROGEN COMBUSTION AND DETONATION DRIVEN SHOCK TUBE*+

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ABSTRACT: The performance of combustion driver ignited by multi-spark plugs distributed along axial direction has been analysed and tested. An improved ignition method with three circumferential equidistributed ignitors at main diaphragm has been presented, by which the produced incident shock waves have higher repeatability, and better steadiness in the pressure, temperature and velocity fields of flow behind the incident shock, and thus meets the requirements of aerodynamic experiment. The attachment of a damping section at the end of the driver can eliminate the high reflection pressure produced by detonation wave, and the backward detonation driver can be employed to generate high enthalpy and high density test flow. The incident shock wave produced by this method is well repeated and with weak attenuation. The reflection wave caused by the contracted section at the main diaphragm will weaken the unfavorable effect of rarefaction wave behind the detonation wave, which indicates that the forward detonation driver can be applied in the practice. For incident shock wave of identical strength, the initial pressure of the forward detonation driver is about 1 order of magnitude lower than that of backward detonation.

KEY WORDS: combustion driver, detonation driver, gaseous detonation, shock tube, shock tunnel

1 INTRODUCTION

In the late spring of 1957, my supervisor, Professor Kuo Yonghuai assigned me a research work: trying to find a high temperature air supply for hypersonic wind tunnel by means of shock wave heating. He speculated that the aerospace techniques would be developed in China, and the huge hypersonic wind tunnel would be the essential simulating and testing facility on the ground for the research on flight. At that time, there were no enough funds, techniques and electricity to make a huge conventional heating hypersonic wind tunnel in China. Furthermore, the total temperature of the conventional heating wind tunnel is limited and unsuitable for investigating the high temperature effect accompanying the hypervelocity flight. He asked me to explore a new approach for hypervelocity aeroheating experiments which would befit Chinese situation.

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The key point of shock wave heating is the driving means adopted to produce the strong shock wave. Oxyhydrogen combustion imposes mild requirements on the facilities, together with its low expenses and strong driving ability, can well meet our requirements, and thus is chosen as the breakthrough. In the present paper, the improvements of oxyhydrogen combustion driver and the progresses of detonation driver are reviewed.

2 REQUIREMENTS FOR SHOCK TUBE DRIVER

Shock tubes have been developed to become a kind of facilities widely used in scientific experiments since 1950s. The typical shock tube (Fig.1) is composed of 2 pipes with constant cross-section, separated by a diaphragm. In the initial stage, they are charged with different gases to different pressure. When the diaphragm breaks up instantaneously, the high-pressure (driver) gas expands, accelerates, and compresses the low-pressure (driven) gas, while a shock wave generates and propagates forward. The flow heated and compressed by the shock wave between the interface and the shock wave (Regime 2) or the high-temperature and high-pressure gas produced by the reflected shock in the rear of driven section (Regime 5), is employed to perform the different kinds of scientific experiments.

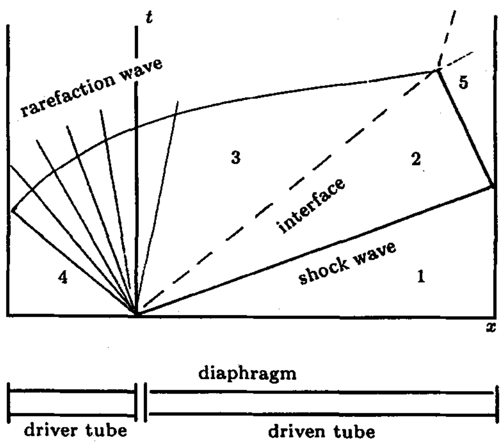

Fig.1 Wave diagram of flow in a shock tube of constant cross section

In order to simulate the hypervelocity flying phenomena in aerodynamics experiments, the velocity u_2 and the pressure p_2 should be elevated as much as possible. At both sides of the interface, the pressure and the velocity are equal ($p_2 = p_3$, $u_2 = u_3$). Therefore, for certain difference of pressure $\Delta p = p_4 - p_3$, the driver gas are required to reach a high speed u_3 as much as possible when it expands. The expansion in a pipe with constant cross-section is unsteady, $\left|\mathrm{d}u/\mathrm{d}p\right| = 1/(a\rho)$, where $a\rho$, the acoustic resistance, is the gas mass passing through the unit cross-section in the unit time because of acoustics perturbation. For fixed pressure reduction, the less the acoustic resistance, the higher the speed. For perfect gas, integrating the above differential equation, we obtain

$$\frac{p_3}{p_4} = \left(1 - \frac{\gamma_4 - 1}{2}\frac{u_3}{a_4}\right)^{2\gamma_4/(\gamma_4 - 1)}$$

where a is sound speed and γ is the specific heat ratio. From the above formula, for certain pressure ratio p_3/p_4, the velocity u_3 increases linearly with sound speed a_4, and slightly rises with the decrement of specific heat ratio. Therefore, the gas with small molecular weight, such as hydrogen or helium, should be chosen as the driver gas of shock tube. Furthermore, in order to enhance their driving ability, the gas should be heated.

3 OXYHYDROGEN COMBUSTION DRIVER

It is expected that it will be the most satisfactory technique to use the heat energy produced by oxyhydrogen combustion in the driver section to heat the surplus hydrogen or helium[1]. When hydrogen or helium is heated to a high temperature by oxyhydrogen combustion, although the steam mixed in it increases the molecular weight of the mixing gases, their low specific heat ratios will make due compensation. Therefore, their driving abilities are stronger than those of hydrogen or helium at room temperature. Because combustion heating will be accompanied with pressure increase, the operation at high pressure doesn't need the high-pressure compressor. In addition, gas consumption is low, and the cost is very cheap. Since the early 1950s on, many famous international laboratories, such as CAL, AVCO, GE, and NPL, have all adopted combustion driver technique ignited by the multi-spark plugs distributed along axial direction[2~5]. However, the results demonstrated that the test flow quality produced by the combustion driver is poor, and the facility has potential unsafety. Therefore, from the end 1950s on, the combustion driver technique has gradually been abandoned by these laboratories. Since the chemical industry had the experiences to elevate the pressure of hydrogen to 150 MPa, CAL adopted the high-pressure hydrogen to produce the strong shock wave rather than the combustion driver[6].

Based on the experimental results on the performance of combustion driver[7], GE laboratory insisted on combustion driver. In their experimental equipment, the inner diameter of the pipe is 152 mm, its length is 3.05 m, and its ends are closed. The effects of initial pressure, mixing ratio and number of ignition spark plugs on the maximum pressure of helium heated by oxyhydrogen combustion, and the time at which the pressure reaching maximum were investigated, which indicated that the combustion processes are identical and well repeated.

3.1 Combustion Driver Ignited by Multi-Spark Plugs Distributed Along Axial Direction

In order to determine which of the above viewpoint is correct, the performance of combustion driver is studied in our group. In our experiments, the inner diameter of driver section is 80 mm, and its length is 5.5 m, the inner diameter of driven section is the same as driver but its length is 12 m. The sparks of aero-engine are chosen as ignitors and placed along driver section at the interval of 1.1 m with identical initial conditions. The initial pressure of driver gas is 1.0 MPa with 90% H_2 and 10% O_2. The driven gas is air with the initial pressure of 13.3 kPa. The velocity distribution of incident shock wave along driven section is illustrated in Fig.2. The dash line represents the experimental results of 5 tests in which oxygen and hydrogen enter the driver section through single hole successively, and the solid represents the experimental results of 5 tests in which oxygen and hydrogen enter the driver section through triple holes. From Fig.2 we can see that, not only the results in different experiments are different, the shock wave velocity is also variable in the same experiment. It is difficult for combustion driver ignited by multi-spark plugs to meet the requirements of aerodynamic test. The experimental results demonstrate that

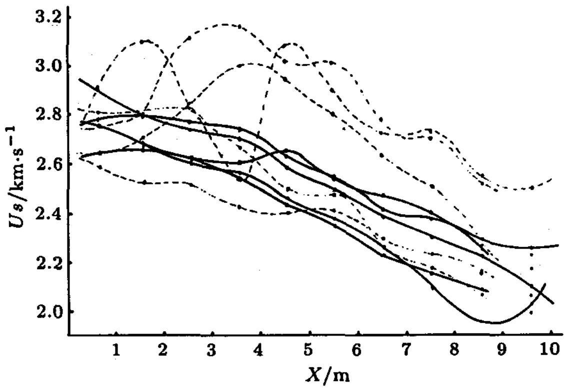

Fig.2 Distributions of incidence shock wave velocities produced by the combustion driver

the charge through triple holes has great advantage over that through single hole, because the mixing in the former case is better than in the latter.

GE Lab investigated only the pressure characteristics of combustion process in a closure vessel, however, the dominant temperature and sound speed field and the effect of diaphragm-breaking up are not involved, which can not illustrate the all-round performance of combustion driver.

Combustion science indicates that, because flame propagation velocity is much less than sound speed, combustion in a closure vessel ignited locally results in the basically identical pressure everywhere in shock tube driver section. At ignition point, gas burns at the initial pressure and releases energy, a part of which raises its own temperature, the other expands and compress the unburnt gas. The gas afterwards burnt makes conversely compressing work on it. Since the energy the first burning gas releases is less than that it receives later, at the end of combustion, the temperature of the first burning gas is higher than that burning later. The temperature field of the vessel is unhomogeneous[8]. Combustion ignited by multi-spark plugs has many flame surfaces, whose propagation velocities are random, and their difference are obvious, which means that the temperature field of burning gas is hard to control. It is an important reason that results in the poor quality of combustion driver ignited by multi-spark plugs. In addition, because the processes of burning and heat loss are very fast, it has to take the mode that diaphragm breaks up automatically, i.e., diaphragm will break up automatically while the pressure reaches its critical strength. In fact, it is difficult to realize the fact that the pressure of burning gas happens to be the critical value of diaphragm when it just burns out. Generally, after the diaphragm breaks up, there is some residual unburnt gas, which lies in uncertain position and will burn later. This is the source of velocity variation while the incident shock wave is propagating.

3.2 Combustion Driver Ignited by Multi-Spark Plugs Near Main Diaphragm

The homogeneous temperature field in combustion within a closure vessel requires that the gas simultaneously burn everywhere besides the homogeneous mixing, which is hard to accomplish. Furthermore, it is also difficult that the combustive mixture happens to burn out when the diaphragm breaks up.

The temperature field of combustion and the residual unignited gas relate to the number and location of the ignition. For example, when ignition take places at the end of a pipe container, where exists the maximum temperature, the temperature decreases monotonously because there is only one flame front, while the residual unignited gas lies at the other end. For shock tube driver section, if ignition take places at the upstream end, the temperature distribution is as follows, the maximum temperature lies at the upstream end, and the minimum temperature lies at the diaphragm. This kind of temperature field will speed up the velocity of incident shock wave, and make compensation for the attenuation of shock wave caused by the viscous boundary layer of driven section. However, the wall effect will raise gradually the pressure, temperature and velocity of the flow behind shock wave[9]. The above temperature field of driver gas makes it worse. In addition, the residual unburnt gas lies near the diaphragm and will burn after the diagram breaking up, which also results in a worse effect. If ignition take places at diaphragm, the variation of temperature is on the contrary. Although the attenuation of incident shock wave is enhanced, the rates of pressure, temperature and velocity variation after the shock wave front are becoming weak resulting from the interaction with the wall effect, which is favorable for meeting the practical requirements. Even if there is residual unburnt gas, since it lies at the end, the unfavourable effect is eased.

Based on the above analysis and the comparison between different ignition modes, oxyhydrogen combustion driver ignited by triple spark plugs well-distributed along circumferential direction at the diaphragm has successfully been developed, which can produce test flows meeting the practical requirements*. The difference of shock wave velocity in many experiments decreases from 10% $\sim$ 20%[1] (the case ignited by multi-spark plugs along axial direction) to 4.3%. The stability of flow pressure behind the shock wave is better than the cases ignited by multi-spark plugs along axial direction or helium driver and hydrogen driver[10].(Fig.3)

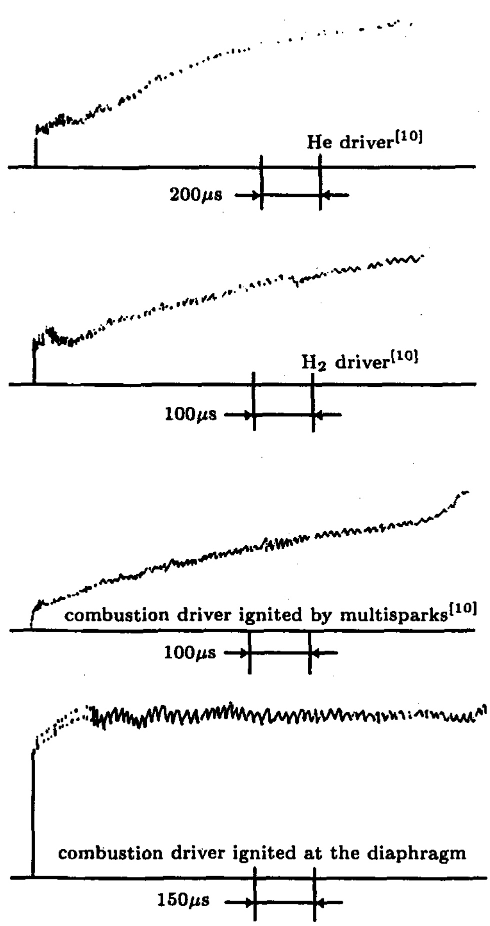

Fig.3 Pressure profiles of flow behind shock wave produced by various drivers

However, for the oxyhydrogen combustion driver ignited by multi-spark plugs at diaphragm, the propagation distance of flame is much longer than that in the case ignited by multi-spark plugs distributed along the axial direction, which raises the possibility of detonation. Once the detonation takes places, the unexpected high-pressure will damage the facilities. In addition, experiences indicate that it is hard to produce high pressure for combustion driver (generally below

* New means of oxyhydrogen combustion driven shock tunnel, Report,Institute of Mechanics, Chinese Academy of Sciences,1964

40 MPa)[11].

4 OXYHYDROGEN DETONATION DRIVER

In the experiment on combustion driver, Hertzberg[12] unexpectedly found that the strength of incident shock wave exceeded the calculation from the isovolume combustion assumption. Gerard attributed this phenomenon to detonation taking place in combustion. Bird[13] analyzed the combustion driver and the performance of forward and backward detonation driver. The results indicated that, the ability of forward detonation driver is obviously stronger than that of backward detonation driver, however, the attenuation of incident shock wave produced by forward detonation driver is enhanced, while the velocity of incident shock wave produced by backward detonation driver is nearly constant.

For the forward detonation driver, the detonation wave is initiated at the upstream end of driver section, and its moving direction is the same as the incident shock wave propagation. Because the expansion wave behind the detonation wave catches up with the incident shock wave, its strength becomes weaker and weaker. However, the detonation wave of the backward driver is initiated at the diaphragm, and its propagation direction is opposite to that of the incident shock wave, the state of gas behind the rarefaction wave is constant (which is employed to produce the incident shock wave), and there exists a quasi-steady region behind the wave.

Waldron[14] and Balcarzak[15] conducted the experiments on forward detonation driver, verified Bird's forecast, and pointed out that this kind of driver can not meet the requirements of aerodynamic test.

Yu H-r[16], Coates & Gaydon[17], Lee[18] and Gier & Jones[19] performed the experiments on backward detonation driver. Yu H-r's results demonstrated that the strength of incident shock wave by backward detonation driver is stronger than that by combustion driver, which is different from Bird's results, because Bird did not consider the effect of wall heat transfer on combustion or detonation. The propagation velocity of flame is much slower than that of detonation wave, so the heat loss of the former is stronger than that of the latter. The attenuation of shock wave caused by backward detonation driver is very weak, and can be well repeated. Professor Kuo Yonghuai paid much attention to this discovery, and asked me to go into detail. Because the strength of shock tube is weak, and its weight is light, when the initial pressure of driver section rises to 1.0 MPa, the shock tube vibrated heavily in detonation experiments and the binder bolts got loosen due to the reflection of detonation wave from the wall when reaching the end of pipe, and the peak value of reflection pressure is as much as hundreds times the initial pressure[20]. Hence the work had to be postponed due to the unsafety factor.

In the middle 1980s, the test flight data of American shuttle demonstrated that, high temperature effect has great influence not only on the aeroheating but also on the aeroforce. The matching angle of airfoil estimated according to the data from the conventionally heating hypersonic wind tunnel is less than half of that in practical case. This fact attracts much interest, and focuses the investigation on high temperature effect once again. Stalker[21] developed the free-piston technique in 1960s to meet the requirements of the high temperature effect test. Since the late eighties, several huge free-piston shock tunnels have been constructed such as T_5 in America, HEG in Germany, TCM2 in France and HIEST in Japan. These facilities have the ability to produce high enthalpy and high pressure test flows, complicated constructions and expensive costs. For example, the investment of HEG or HIEST exceeds 10 million dollars.

When worked in Aachen as a visiting professor in 1988, professor Yu H-r discussed the advantages/disadvantages of free-piston driver with professor Groenig, and proposed a method to eliminate the high reflection pressure caused by backward detonation wave at the end of driver, and suggested to investigate the oxyhydrogen detonation driver. A damping section is attached to the end of detonation driver, which is separated by a thin diaphragm with the detonation driver. When the detonation wave front reaches the end, it will break up the thin diaphragm and enters into the damping section, which will eliminates the formation of high reflection pressure[22]. Arranged by professor Groenig and assisted by Mr Zhang Fan and Andreas, professor Yu carried out some pioneer studies. In the spring of 1989, professor Yu got experimental evidences in Beijing which showed that the state of gas behind a detonation wave is steady and well-repeated. After professor Groenig received the results from professor Yu, both sides decided to expedite relevant research works. The intermediate results of investigation were published in 1992[23] and attracted many interests of international colleagues. From then on, many detonation driver shock tube/ tunnel have been investigated in different groups, and relevant publications gradually increased.

4.1 Performance of Backward Detonation Driver Section

The oxyhydrogen detonation driven shock tunnel with a damping section has been constructed in Laboratory of High Temperature Gasdynamics, Institute of Mechanics, Chinese Academy of Sciences (Fig.4). The work pressure of detonation driver is 300 MPa, and that of detonation driven section is 150 MPa. The igniter is located near the diaphragm, and the detonation wave propagates to the upstream, as sketched in Fig.5.

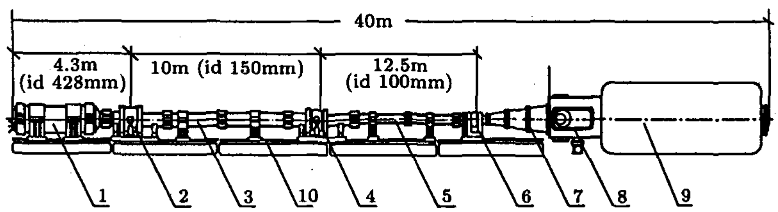

Fig.4 Configuration sketch of the detonation driven shock tunnel
1 buffer tube, 2,4,6 diaphragm clam device, 3 detonation driver, 5 driven tube
7 nozzle, 8 test section, 9 vacuum tank, 10 movable support

The detonation wave will break up the thin diaphragm located between driver and damping section when reaching there. Since the initial pressure of damping section is very low, the detonation wave will reflect rarefaction waves there, in the mean time produces a strong shock wave in the damping section (buffer tube). Although the shock wave is reflected at the end of damping section, the reflection pressure is not very high due to the low initial pressure there, which eliminates the danger of superhigh pressure. In addition, the velocity of reflection rarefaction wave produced by the detonation wave at the end of driver is lower than that of reflection shock wave, which prolongs the effective driving time. Generally, it will take a little time to break up the main diaphragm. Regime 4 in the wave diagram (Fig.5) is the region where the velocity of flow behind the detonation wave is zero, which

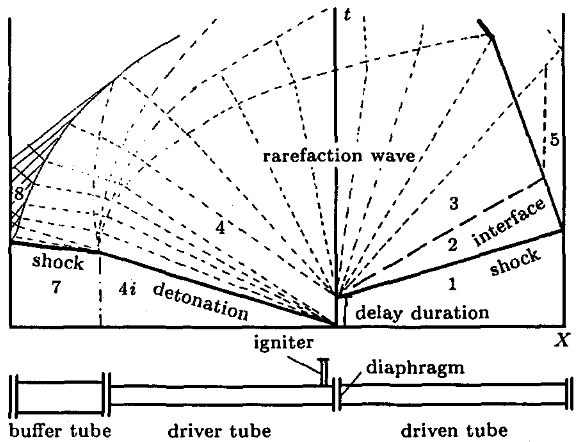

Fig.5 Diagram of flow in backward detonation driven shock tube

corresponds to the initial state of shock tube driver and the state parameters are uniform, thus its driver performance matches the conventional driver.

The experimental results on the attenuation of shock wave are illustrated in Fig.6, including the data of heating hydrogen (690K) driving nitrogen or air from CAL[24]. A comparison can be made from the performances of these two driver sections, since they have the identical inner diameter (100 mm) and similar initial pressure and length. From Fig.6 it can be seen that the quality of backward detonation driver corresponds to that of heating hydrogen driver. For the same driver pressure ratio, the driver ability of detonation is stronger while the cost is lower.

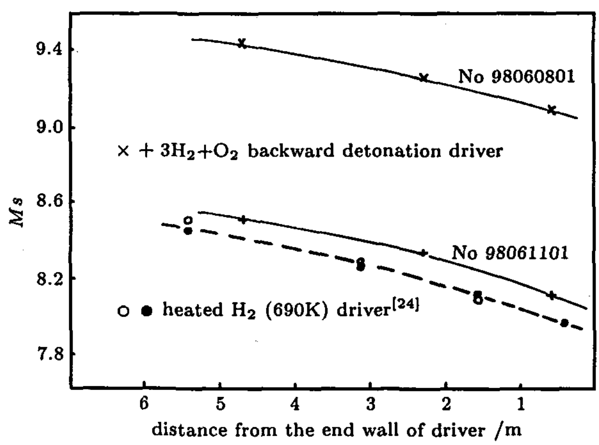

Fig.6 Attenuation characteristics of the incident shock waves

4.2 Forward Detonation Driver

In order to improve the performance of expansion tube/ tunnel immigrated from NASA Langley center, American General Applied Science Laboratory began to design the free-piston driver section (ϕ = 450 mm, l = 12 m) in the late eighties to replace the previous driver section[25]. But the costs of free-piston driver section is too expensive, in order to make a correct choice, they evaluated different competitive drivers[11]. The conclusions are drawn as follows, "The best choice for achieving the sort of performance required for currently anticipated hypervelocity systems research appears to be the detonation mode based on cost/benefit ratio, although the free piston driver remains the best cost-independent choice".

As indicated in the above, the driving ability of forward detonation is much stronger than that of backward detonation. If the unfavorable effect of rarefaction wave accompanying the detonation wave can be eased or avoided, the forward detonation driver can be used in the practice. In addition to its price advantage, the driving ability also match that of free-piston.

The longer the detonation driver section, the less the parameter variation of flow caused by the rarefaction wave behind the detonation wave, the weaker the attenuation of incident shock wave. Therefore, we adopt a long driver section, the ratio of length of driver section and driven section is 0.8, where the inner diameter of driver section ($\phi = 150\,\text{mm}$) is larger than that of driven section ($\phi = 100\,\text{mm}$). When the detonation wave reaches the contracted cross section, there will be a reflection shock wave, which will interact with the opposing rarefaction wave and thus weaken the attenuation of incident shock wave caused by the rarefaction wave (Fig.7). The experimental results demonstrate that the attenuation of incident shock wave have been reduced to an acceptable level (Fig.8). Furthermore, its driving ability is much stronger than that of backward detonation driver. For the same initial pressure of driven gas and the strength of incident shock, the initial pressure of detonation driver of the forward detonation driver is about 1 order of magnitude lower than that of the backward driver (Fig.9). Without the damping section, its construction is much simpler.

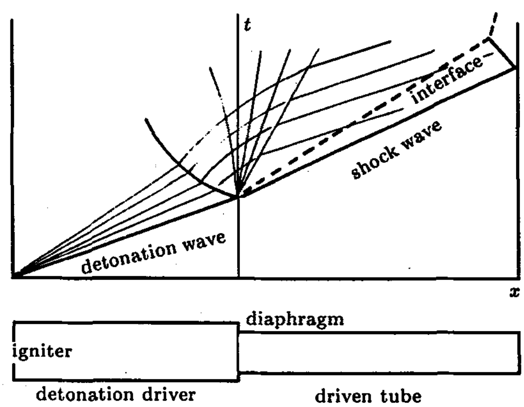

Fig.7 Diagram of flow in forward detonation driven shock tube

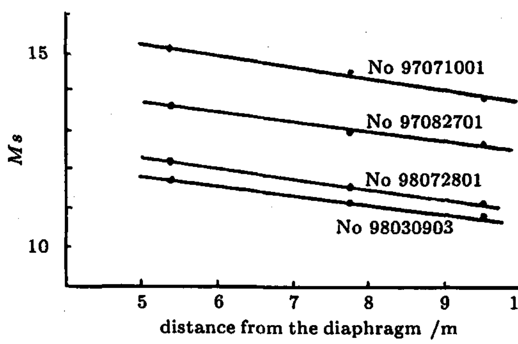

Fig.8 Attenuation characteristics of incident shock wave produced by forward detonation driver

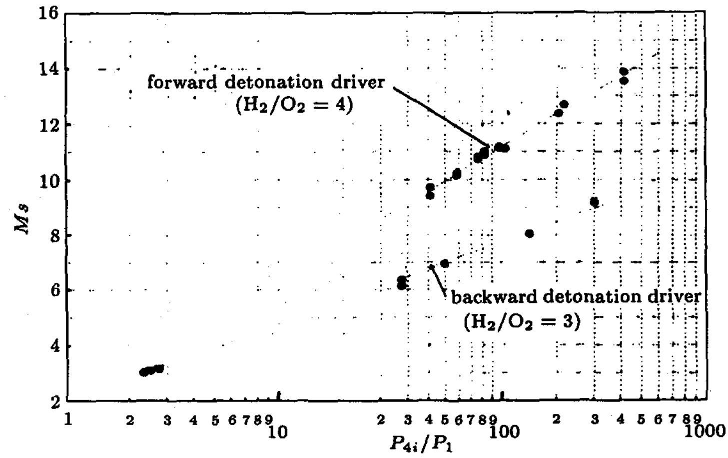

Fig.9 Shock wave Mach number near the end of driven section Ms vs p_4/p_1

5 CONCLUDING REMARKS

The improved oxyhydrogen combustion driver can produce test flow meeting the practical requirements. Its low cost heralds a new approach for conducting hypersonic experiments in our country.

Both backward detonation driver and forward detonation driver can produce high enthalpy and high density test flows. The construction of oxyhydrogen detonation shock tunnel paves the way for the investigation of high temperature effect, supersonic combustion and reentry physical phenomena.

Acknowledgement Combustion driver was accomplished under the direct supervision of Academician Kuo Yonghuai, and detonation driver was completed within research scope he pointed out. On the occasion of professor Kuo's 90th birthday and 30 anniversary of death, his earnest instruction is hereby greatly appreciated.

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