Chinese Journal of Aeronautics, (2020), 33(5): 1468–1475

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics
cja@buaa.edu.cn
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Investigation of dual ignition for a detonation-driven shock tunnel in forward driving mode

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Received 4 April 2019; revised 1 June 2019; accepted 30 July 2019
Available online 19 March 2020

KEYWORDS

Shock tunnel;
Detonation driver;
Diaphragm;
Dual ignition;
High-enthalpy flow

Abstract A detonation-driven shock tunnel is useful as a ground test facility for hypersonic flow research. The forward detonation driving mode is usually used to achieve high-enthalpy flows due to its strong driving capability. Unfortunately, the strong detonation wave front results in diaphragm fragments that disturb the test flow and scratch the nozzle or test models. In this study, a dual ignition system was developed to burst a metal diaphragm without fragmentation in the forward driving mode. A series of experiments were conducted to validate the proposed technique. The influences of the delay time setting on the test conditions were investigated in detail. Numerical simulations were also conducted to obtain a better understanding of the wave processes in the shock tube. The results showed that the dual ignition system solved the diaphragm issues in the forward driving mode. The test time was shortened due to the additional ignition close to the primary diaphragm; the smaller the delay time, the shorter the effective test time. However, a small amount of time loss is considered worthwhile because the severe diaphragm problems have been solved.

1. Introduction

Hypersonic technology is one of the most important research issues for aerospace programs. The development of modern reentry vehicles requires extensive testing in ground hypersonic facilities that offer a combination of high stagnation pressure and high enthalpy. Among impulse facilities that cover hypersonic flows ranging from 2.5 to 45 MJ/kg, which corresponds to velocities from 2 to 10 km/s, respectively, shock tunnels have the advantages of accommodating relatively large-size models and low operational costs.[1] In the view of enthalpy and pressure requirements so that the shock tunnel is capable of simulating hypersonic flow conditions, it must incorporate a high-performance driver. Among the existing driving techniques, only a few of them are qualified for the high-performance driver. Detonation drivers are capable of producing high enthalpy and high-pressure test flows simultaneously in addition to simple operation.[2,3] The detonation driver was first proposed by Bird[4] and has since been investigated by several researchers.[5–7] Due to the success of several crucial techniques, such as spontaneous strong ignition and attenuation

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https://doi.org/10.1016/j.cja.2020.01.013
1000-9361

of the reflected waves, detonation drivers have been widely used for shock tubes and tunnels and have produced high-enthalpy flows for aerodynamic testing.[2,8] A detonation-driven shock tunnel can be operated in the backward detonation mode with a uniform driving quality to achieve a longer driving time at a relatively low enthalpy level, such as JF12, which is currently the largest shock tunnel in the world and is capable of reproducing pure airflow with longer than 100 ms test duration.[9,10] However, to date, detonation-driven facilities have achieved enthalpies that are somewhat lower than those achievable by free piston techniques.

To achieve higher enthalpy flows, the forward detonation driving mode was proposed because of its much stronger driving capability.[11,12] However, the Taylor rarefaction waves accompanying the detonation wave should be minimized or avoided because they reduce the incident shock wave intensity continuously. Jiang et al.[13] used a cavity ring to compensate for the pressure decrease due to the Taylor expansion waves under forward detonation and the experimental results demonstrated that this method improved the quality of the driving flows. Double detonation drivers have also been proven effective for improving and intensifying the driving capability of the forward detonation section.[12,14] Although much progress has been made in using detonation techniques to achieve high enthalpies, there are still practical limitations associated with the forward detonation driving technique.

The diaphragm, which is an important component in shock tunnels, separates the driver and driven section. Numerous studies have focused on diaphragm issues, such as the evolution of the shock wave,[15] the diaphragm opening process, and its influence on the shock wave propagation.[16] The diaphragm should ideally open instantaneously without producing any fragments. However, due to the strong impact of the high-pressure and high-velocity detonation wave on the diaphragm in the forward detonation driving mode, the production of fragments is extremely likely when the primary metal diaphragm is ruptured. There is considerable risk that the fragments or particles, which attain extremely high kinetic energies in the flow, will scratch the shock tube or nozzle surface, strike the test model or affect the test flow quality, especially at high stagnation pressures. Plastic diaphragms or metal disks are employed in some laboratories to solve this problem.[17] However, difficulties such as test gas contamination will exist. Thus, prior to the implementation of the forward detonation technique, problems related to fundamental physics and the assessment of the use of this technique in high-enthalpy shock tunnels have to be extensively investigated.

In the present study, a dual ignition system is developed and investigated in detail to burst a metal diaphragm without fragmentation in shock tunnels in the forward detonation driving mode. Experiments are carried out to validate the proposed technique. The influence of the delay time setting on the test conditions is investigated to perfect the technique, the wave processes in the shock tube are examined numerically, and the fundamental theory and mechanisms are discussed. The processes are investigated in an effort to provide theoretical guidance for the design of a dual ignition system and to improve the quality of the test conditions without producing fragments. The forward driving technique coupled with these improvements provides powerful support for the generation of high-enthalpy flows.

2. Physical problems and experimental results

2.1. Physical problems

The experiments in the present study were conducted in the JFX shock tunnel in the State Key Laboratory of High temperature gas Dynamics (LHD) at the Institute of Mechanics, Chinese Academy of Sciences (CAS). The facility consists of a dump section, a driving section, and a driven section, as shown in Fig. 1; the length of the driving and driven section is 6.6 m and 6.9 m, respectively and both have an inner diameter of 126 mm. Piezoelectric pressure transducers (CY-YD-205), with a resonant frequency of more than 100 kHz, were mounted on the tube sidewall to record the pressure histories. The transducers were labeled as P1, P2, and P3 in the present study. The dump section was only used in the backward detonation driving mode to decrease the reflected shock pressure, which might damage the facility. The nozzle and test sections were not considered in the present investigations. Detailed information on the shock tunnel can be found in the Ref. 18.

For high-pressure operation in shock tubes/tunnels, a flat-scored metal diaphragm (Fig. 2) is commonly used. The grooves in the form of a cross with different depths are important to adjust the critical rupture pressure of the diaphragm and minimize fragmentation. Upon reaching the predetermined burst pressure, the diaphragm ruptures along the base of the grooves, forming petals that are pressed against the sides of the holder. The steel plates used in the JFX shock tunnel have a diameter of 168 mm and a thickness of 2.0 mm. The groove depth of (1.37±0.02) mm with a critical rupture pressure of about 2.36 MPa was used for initial pressure of 1.2 MPa or 1.5 MPa in the detonation tube.

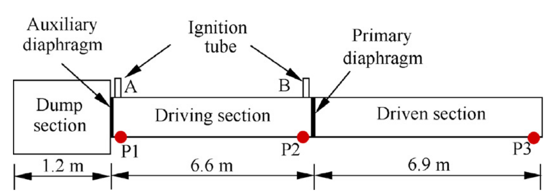


Fig. 1 Schematic diagram of detonation-driven shock tube of JFX.

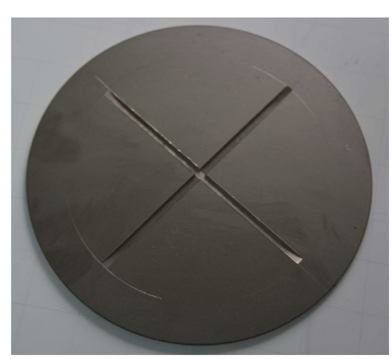
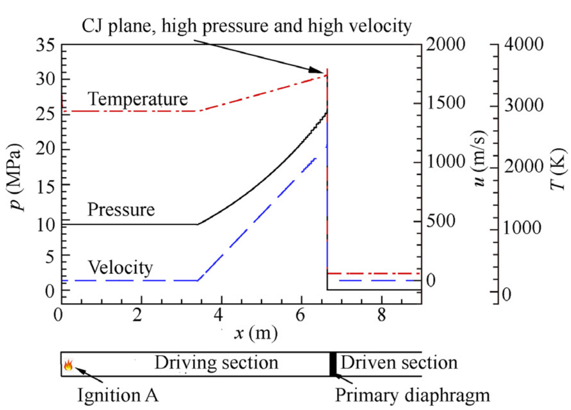


Fig. 2 Flat-scored steel diaphragm with four-petal configuration.

In the forward detonation driving mode, the detonation wave is ignited at ignition tube A and subsequently propagates downstream toward the primary diaphragm, as shown in Fig. 3(a), where p is the pressure, u is the velocity and T is the temperature. The mixtures in the ignition tube are first ignited by electrical sparks. A high-temperature jet would be formed which propagates into the driving section and then initiates the detonation.[2] The Chapman-Jouguet (CJ) plane, which has high pressure (about 25 MPa), high velocity (about 1400 m/s), and high temperature (about 3500 K), exerts a powerful impulsive force on the diaphragm, thereby breaking it and possibly causing fragments to be broken off. As shown in Fig. 3(b), fragments were sheared off from the diaphragm in the forward driving mode. A weight loss of about 35 g existed for a total diaphragm weight of 337 g in the present experiment. The shed fragments or metal particles can attain extremely high kinetic energies and produce disastrous results upon striking the models or tube surfaces. Fragmentation, obviously, should be minimized in shock tunnel experiments. The primary objective of the present study is to solve the diaphragm problems in a detonation shock tunnel in the forward driving mode.

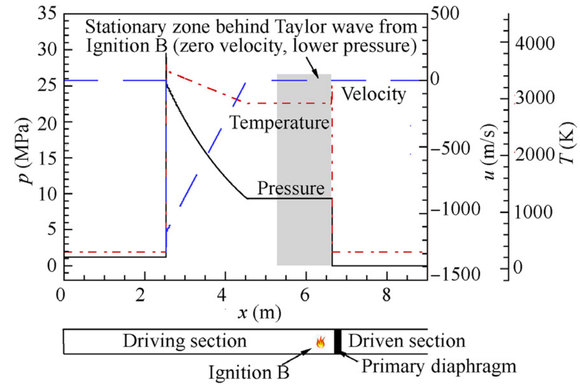
It should be noted that all experiments and numerical simulations (including the datas in Fig. 3(a), Fig. 4(a), Fig. 5) in the present study were conducted under the following conditions: the initial pressure of the driving section was p_{4i} = 1.2 MPa and the hydrogen–oxygen-nitrogen mixture ratio was $H_2 : O_2 : N_2$ = 2:1:1. The shock tube was filled with air at an initial pressure of 10 kPa and the experiment was conducted at room temperature.



(a) Schematic diagram

(b) Diaphragm after experiment

Fig. 3 Results of forward detonation driving mode.



(a) Schematic diagram

(b) Diaphragm after experiment

Fig. 4 Results of backward detonation driving mode.

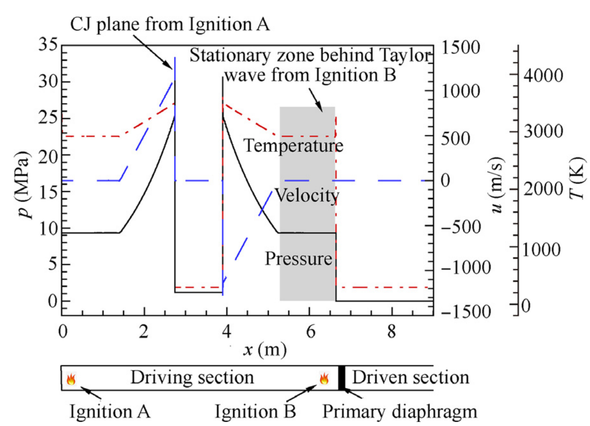


Fig. 5 Schematic diagram of working principle of dual ignition detonation system.

2.2. Dual ignition system

Fortunately, the fragmentation problem is negligible in the backward detonation mode. The detonation wave was ignited at Ignition tube B near the primary diaphragm and propagated upstream from the diaphragm, as shown in Fig. 4(a). Subsequently, the diaphragm was burst by the stationary zone behind the Taylor wave, where the pressure (about 9.3 MPa) and velocity (about 0) were much lower than in the CJ plane and the temperature (about 3000 K) was also slightly lower. The diaphragm after the experiment is shown in Fig. 4(b).

There was no significant cracking or fragments. Only a weight loss of about 0.6 g was found in the present experiment. Based on these results, a dual ignition detonation system was developed; the schematic diagram of the working principle is shown in Fig. 5. The Ignition tube A was first ignited at the left end of the driver section. The detonation wave propagated to the right toward the primary diaphragm. Then, the Ignition tube B close to the diaphragm position was ignited by a time schedule controller just prior to the arrival of the detonation wave that was generated by Ignition tube A. As a result, the diaphragm was ruptured by the stationary zone originating from Ignition tube B in advance to pass through the forward detonation wave without any interactions with the diaphragm. In this system, the advantages of bursting the metal diaphragm without fragmentation due to the backward driving mode and of generating high-enthalpy flows due to the higher driving capability of the forward driving mode are combined.

The dual igniters are shown in Fig. 6; Igniter A and B are used to ignite the Ignition tubes A and B, respectively. The time sequence in this system is important and delay time Δt is defined as the time difference between the Ignition tubes A and B. Δt depends on the detonation chamber length and the detonation wave speed. If Δt is too large, the detonation wave from the Ignition tube A would still exert a powerful impulsive force or energy on the diaphragm prior to the Ignition tube B. If Δt is too small, the detonation from Ignition tube B will compress the low-pressure air in the driven section before the arrival of the detonation energy from Ignition tube A and the wave processes will be complicated. Thus, it is necessary to define Δt precisely and investigate its influence on the stagnation parameters.

2.3. Experimental results

A forward detonation experiment was conducted to determine the delay time. The diaphragm after the experiment is shown in Fig. 2 and the pressure histories of the pressure transducers P1 and P2 mounted on the tube sidewall are shown in Fig. 7. P1 and P2 were mounted in the driving section. P1 was located at the position of Ignition tube A at 40 mm from the left end wall of the driving tube and P2 was located 40 mm from the primary diaphragm. As shown in Fig. 7, the time interval between P1 and P2 was 2.54 ms, which means that the detonation wave generated by Ignition tube A took 2.54 ms to propagate to the diaphragm. Thus, the delay time Δt should be equal to or smaller than this time interval. The higher pressure of P2 than P1 is due to the detonation reflection by the diaphragm. The diaphragm is expected to open prior to the arrival of the detonation wave that is generated by Ignition tube A. The travel time for this wave from A to the diaphragm was obtained from the experiments, as shown in Fig. 7. However, the opening time of the metal diaphragm has to be estimated to ensure that there is no strong interaction between the forward detonation wave and the diaphragm. Drewry and Walenta[19] conducted an in-depth theoretical and experimental study of the diaphragm opening process and developed the following equation for the diaphragm opening time:

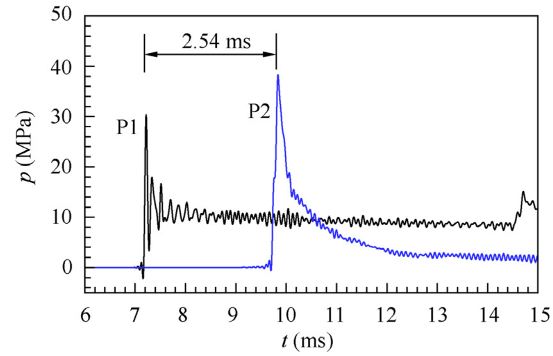


Fig. 7 Pressure histories of forward detonation experiment.

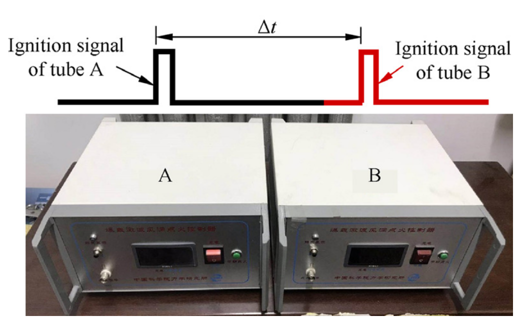
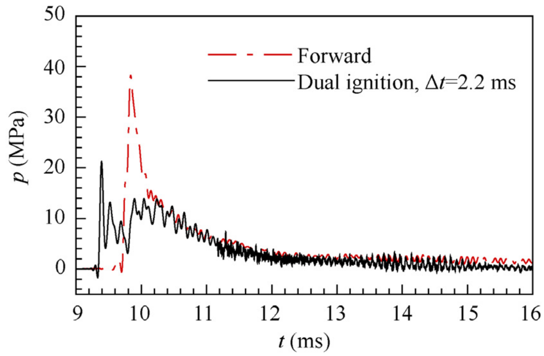


Fig. 6 Dual igniters used to ignite the two detonation tubes.

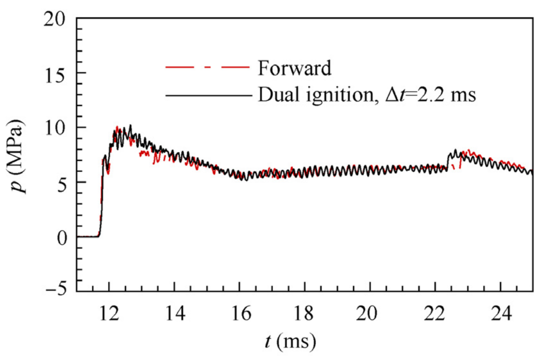
$$t_{\text{opening}} = 4.73\left(\frac{\rho_{\text{d}} b \tau}{p_{\text{r}}}\right)^{0.5} \times 10^4 \tag{1}$$

where ρ_{d} is the metal material density, b is the length of the petal base, τ is the diaphragm thickness at the score, and p_{r} is the rupture pressure. Thus, t_{opening} = 0.27 ms if p_{r} equals the pressure behind the Taylor wave ignited by Ignition tube B, i.e., p_{r} = 9.3 MPa. An exact diaphragm opening time is not required and a nearly completely open diaphragm is sufficient to avoid a strong interaction between the forward detonation force and the diaphragm. Moreover, the scored diaphragm exhibits considerable bulging during gas inflation process and the unsteady Taylor wave, with pressure decreased from 25 MPa to 9.3 MPa, as shown in Fig. 4, will also have an impact on the diaphragm. Thus, it is difficult to obtain a precise estimate of the opening time. The above-mentioned factors will decrease the opening time to less than 0.27 ms. Nevertheless, a delay time of Δt = 2.2 ms was used in our experiment under the current test conditions, i.e., the Ignition tube B was ignited 2.2 ms after the Ignitions A or B was ignited 0.34 ms prior to the arrival of the detonation wave generated by Ignition tube A. We needed to ensure that the diaphragm was opened by the backward detonation.

The stagnation pressure and effective test time attract the most attentions in shock tubes/tunnels, which in turn affect the quality of the free-stream flow. However, in this study, we did not particularly focus on the quality of the stagnation pressure or on reducing the adverse impact of the Taylor wave accompanying the CJ plane; instead, the influence of the dual ignition on the test conditions was analyzed in detail. The diaphragm condition after the dual ignition was found to be similar to that shown in Fig. 4(b) and no fragments were observed. This occurred because the diaphragm was ruptured by the backward detonation at Ignition tube B. The P2 pressure histories in the driving section close to the diaphragm are shown in Fig. 8(a). There was a noticeable pressure difference in the



(a) Pressure P2 in driving section



(b) Pressure P3 in driven section

Fig. 8 Experimental results of forward detonation.

initial stage between the two ignition experiments due to the presence of Ignition tube B in the dual ignition detonation. The dual ignition exhibited two pressure jumps which coincided with the detonation wave generated by Ignition tubes B and A, respectively. Subsequently, the two curves exhibited nearly the same variation. The stagnation pressure values of the two ignition modes for P3, which was located in the driven section at 40 mm from the right wall, are shown in Fig. 8(b). There was no significant difference between the pressure values, especially from 16 to 22 ms when the values were relatively stable. The slight difference at the beginning of the second pressure increase coincided with the reflection of the detonation wave from the left side wall. The details of the wave processes will be discussed in the simulation results. The pressure increases occurred at 22.4 ms for the dual ignition and 22.8 ms for the forward detonation. The additional ignition at position B resulted in test time that was shortened by about 0.4 ms.

In the above-mentioned experiments, the detonation wave generated by Ignition tube A took about 2.54 ms to propagate to the diaphragm. Unfortunately, this time interval may differ for different shots because the detonation speed is affected by the mixing quality of the hydrogen-oxygen-nitrogen mixture, the ignition process, and the surface cleanliness of the detonation tube. These are also the reasons that an estimate of the theoretical detonation wave speed was not applied here. Meanwhile, the time required to open the diaphragm is also affected by machining errors when the grooves are created in the diaphragm. And it is difficult to determine this value by experiments in such a high-pressure facility. Thus, it is difficult to set the delay time exactly as expected, i.e., the diaphragm is opened just right on the arrival of the detonation wave generated by the Ignition tube A. In this study, we determine the influence of the delay time setting on the test conditions and provide theoretical guidance for the design of the dual ignition system for a high-enthalpy shock tunnel. Therefore, a series of additional experiments were conducted, including backward detonation, forward detonation, and dual ignition with delay times of Δt = 2.2, 1.7, 1.1 ms. The stagnation pressure histories of these cases are shown in Fig. 9. There were significant differences between the case of Δt = 1.1 ms and the other forward detonation tests in the initial stage. Instead, the pressure curve of this case was similar to that of the backward detonation driving mode. Since the Ignition tube B ignited long before the arrival of the detonation wave from A, the energy from detonation B compressed the air in the driven section and was reflected from the right end wall. This resulted in the first pressure increase at 11.7 ms. Subsequently, the detonation from A compressed the air again, which resulted in the second pressure increase at 12.4 ms. Yet, it was also found that the plateau pressure was almost the same value of 5.7 MPa for all cases. Unfortunately, the delay time Δt affected the effective test time. It should be noted that the effective test time considered here took into account only the wave propagation structure but not the gas reserves in the shock tube or driving gas contamination. Without considering the diaphragm issues, the forward mode had the longest effective test time of 6.8 ms, lasting from 16 to 22.8 ms (Fig. 9). The shorter the delay time, the shorter the effective test time was; the test time lasted from 16 to 20.5 ms for Δt = 1.1 ms and from 16 to 21.1 ms for Δt = 1.7 ms. Nevertheless, a delay time of Δt = 1.1 ms would not be used in actual situations generally.

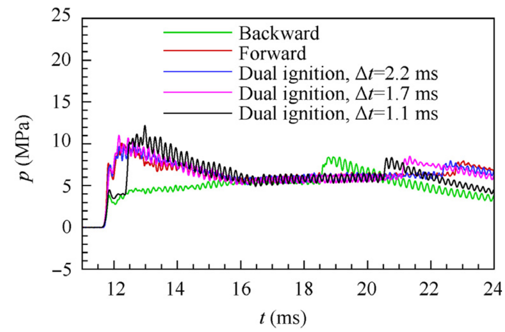


Fig. 9 Comparison of stagnation pressure histories of P3 under different detonation driving modes.

The results indicated that the dual ignition system was successfully applied in the forward detonation shock tube/shock tunnel without producing fragments from the metal diaphragm. The delay time should be investigated carefully if we do not want to lose the test time. However, a small amount of time loss is worthwhile because the severe diaphragm problems have been solved.

3. Numerical simulations

3.1. Simulation methodology

To complement the experimental results and provide a better understanding of the wave processes in the shock tube, especially the modeling of the reflection of the detonation and shock waves from the solid wall and their interactions, numerical simulations were conducted.

A shock tube test consists of detonation of flammable mixtures in the detonation chamber and dissociation of the test gas (air in the present study), which are rather complex processes. It is unrealistic to model all phenomena in detail. In this study, the viscous term, heat conduction, and rupture process of the diaphragm are neglected. The numerical method is based on a quasi-one-dimensional chemical nonequilibrium flow model in which the equations are written in conservation form:

$$A\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial A\boldsymbol{F}(\boldsymbol{U})}{\partial x}-\frac{\partial A}{\partial x}\boldsymbol{H}-\boldsymbol{S}_{\mathrm{c}}=\boldsymbol{0} \tag{2}$$

where the state vector $\boldsymbol{U}=[\rho_i,\rho,\rho u,e,\rho\alpha,\rho\beta]^{\mathrm{T}}$, the flux vector $\boldsymbol{F}=[\rho_i u,\rho u,\rho u^2+p,(e+p)u,\rho\alpha u,\rho\beta u]^{\mathrm{T}}$, the chemical reaction source term $\boldsymbol{S}_{\mathrm{c}}=[\dot{\omega}_i,0,0,0,\dot{\omega}_\alpha,\dot{\omega}_\beta]^{\mathrm{T}}$, and the wall pressure source term $\boldsymbol{H}=[0,0,p,0,0,0]^{\mathrm{T}}$, where ρ,u,e, and p are the density, velocity, total energy, and pressure of gas respectively and A is the cross-sectional area. The subscript "i" denotes the species (O_2, N_2, O, N). α and β are the process parameters of the chemical induction and the chemical transformation, respectively; $\dot{\omega}_\alpha$ and $\dot{\omega}_\beta$ are the rates of the chemical induction and the chemical transformation, respectively; $\dot{\omega}_i$ is the chemical source term for species i. The quasi-one-dimensional equations can take account of the variation in the cross-sectional area in the shock tube. However, since the driving and driven sections have the same inner diameter in the present study, it's one dimensional simulation.

A two-step chemical reaction model was used for the detonation process and the details of this model can be found in the Ref. [20]. Additionally, the finite-rate chemistry developed by Park[21] was used for air in the shock tube without ionization and five components were considered, i.e., O_2, N_2, O, N, and NO. Based on these chemical reaction models and the dispersion-controlled dissipation scheme proposed by Jiang et al.,[22] a code was developed and successfully applied to the simulations of a detonation-driven shock tube.[23]

3.2. Wave processes

The *x*-*t* wave diagrams of the four cases are shown in Fig. 10 to visualize the wave propagation. The results of four typical simulations are shown, namely, backward detonation, forward detonation, and dual ignition at Δt = 2.2 ms and Δt = 1.1 ms. The results show that the detonation-driven shock tube, unlike the classical shock tube, induces additional detonation waves, as well as Taylor waves; the differences between the four cases are the relative locations at which the detonation waves are reflected or intersect.

The characteristics of the backward detonation were similar to that of a classical shock tube, whereas the effective test time was affected to a greater degree by the wave reflected from the left end wall. In the forward detonation, the detonation wave

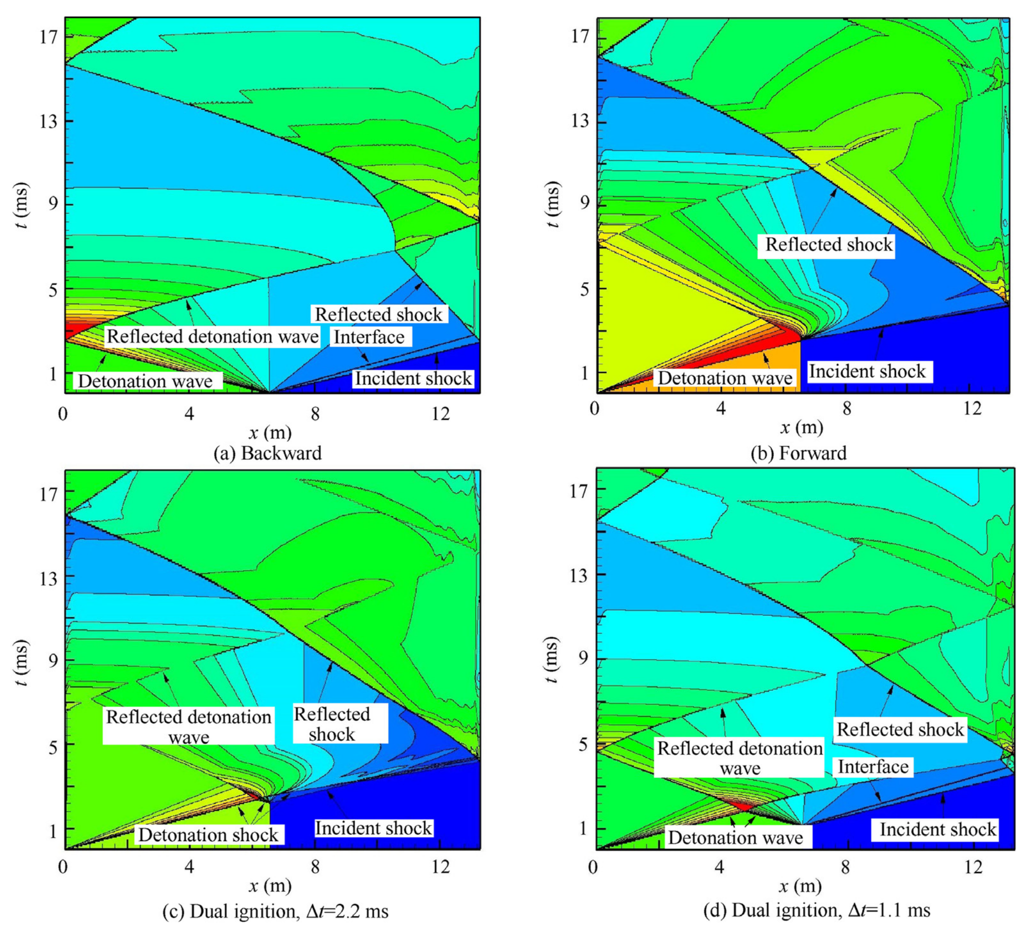


Fig. 10 *x*-*t* wave diagrams of four cases.

was first reflected by the diaphragm. It subsequently reflected off the left end wall and propagated downstream, which resulted in the pressure increase at 23 ms (Fig. 8(b)). The Taylor waves behind the detonation wave affected the stagnation conditions, i.e., the sharp decrease from 12.5 to 16 ms, as shown in Fig. 8(b). Thus, ideal tailored conditions cannot be obtained in a forward detonation driving mode.

Two detonation waves were observed in the two dual ignition conditions. The wave that was generated close to the diaphragm propagated upstream and the other propagated downstream. The detonation wave close to the diaphragm compressed the low-pressure air in the driven section and generated an incident shock. Then, the downstream detonation wave passed through the already opened diaphragm and run after the incident shock. At a delay time of $\Delta t = 2.2$ ms, the detonation wave overtook the incident shock at around $x = 9.5$ m and had an enhancement on it. In contrast, at a delay time of $\Delta t = 1.1$ ms, the detonation wave did not overtake the incident shock before it was reflected off the right end wall. Thus, the ignition close to the diaphragm in the backward detonation driving mode had an antecedent effect on the stagnation parameters. This resulted in the pressure distribution in the initial stage shown in Fig. 9. Besides, the reflected wave from the upstream detonation affected the effective test times, i.e., the pressure increases at around 21 ms, as shown in Fig. 9. The shorter the delay time, the sooner the upstream detonation wave was reflected and the shorter the effective test time was.

The stagnation temperature is another important parameter in shock tunnel experiments and is difficult to measure in detonation facilities with high pressures and high temperature. Thus, the temperature histories by the simulations are displayed in Fig. 11. The plateau temperature was about 50% higher for the forward mode than the backward mode. In other words, it was easier to obtain a high-enthalpy test flow in the forward driving mode due to the high driving capability. This is the reason for the continuous development of this method. In addition, although the plateau pressure values were similar for all cases, as shown in Fig. 9; the stagnation temperature of the 1.1 ms dual ignition was much lower than that of the forward detonations, whereas the temperature of the 2.2 ms dual ignition was almost the same as that of the forward detonation. In other words, the stagnation temperature was lower if the detonation wave did not overtake the incident shock wave before it was reflected from the end wall.

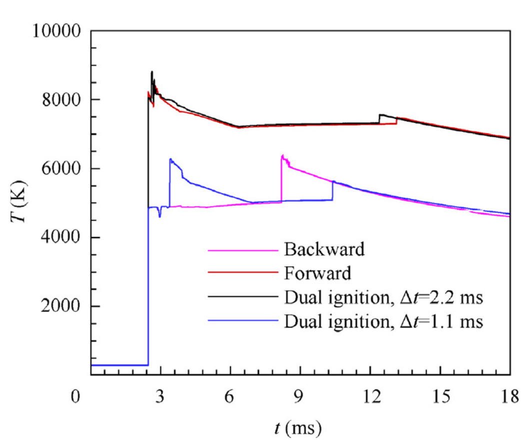


Fig. 11 Comparison of stagnation temperature histories under different detonation driving modes.

4. Conclusions

In this study, a dual ignition system was developed for a shock tunnel in the forward driving mode. Experiments and numerical simulations were conducted to investigate the proposed technique in detail. The dual ignition system solved the diaphragm issues in the forward driving mode. However, the additional ignition source close to the primary diaphragm resulted in a shorter test time; the shorter the delay time, the larger the influence on the test time was. A delay time of 2.2 ms shortened the test time by about 0.4 ms and a delay time of 1.7 ms shortened the test time by about 1.7 ms. However, a time loss of 0.4 ms is worthwhile because the diaphragm problems have been solved. The stagnation temperature was lower if the detonation wave did not overtake the incident shock wave before it was reflected from the end wall. In all, the delay time should be set as exactly as possible to maintain sufficient test time and the forward driving capacity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Nos. 11402275, 11727901 and 11472280).

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