Design of Diaphragmless Shock Tube and Research on its Normal Temperature Characteristics

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Abstract. Shock wave is an important physical phenomenon in supersonic airflow. The shock tube is an experimental device that generates shock wave. It generates shock wave by generating a pressure difference between its high-pressure section and low-pressure section. Most researchers in the world use diaphragm shock tubes to generate shock wave, such as single diaphragm structure and double diaphragm structure type shock tubes. Although the type of shock tube can generate an incident shock wave with a wide range of Mach numbers, in the process of producing shock wave and breaking film, there will be broken film fragments interfering with the flow field. And every time the researcher needs to replace the diaphragm after the experiment, the efficiency of the experiment is low. In this paper, a diaphragmless shock tube is designed. The high-speed reciprocating motion of two pistons in the high-pressure section is used to replace the process of membrane rupture. And the normal temperature characteristics of the shock tube are researched.

1. Introduction

The conventional shock tube is a tube made of metal such as stainless steel, and a high-pressure gas with a pressure of about 2-3 atmospheres and a low-pressure gas with a pressure of about 50 mmHg are charged into the shock tube. High-pressure gas is called driving gas. Low-pressure gas is called driven gas, and it is affected by shock wave. The diaphragm is made of polyethylene terephthalate or other materials to separate the two sections. It must be strong enough to resist the pressure difference between the high-pressure section and the low-pressure section. In order to damage the membrane to generate shock wave, the firing pin can be driven by electric, hydraulic, pneumatic or spring actuation to make the tip break the diaphragm. The diaphragm can also be made into a cross-shaped perforated aluminum wafer with adjustable depth. This diaphragm is broken by the method when the specified pressure difference is reached. Another method is to use a flammable mixture as a high-pressure gas and ignite it when the specified pressure is reached. Then the pressure is rapidly increased due to the explosion and the diaphragm is destroyed [1].

Because of the gas exchange resulting from the membrane rupture, membrane fragments flow into the tube at the completion of each experiment. It will impair the surface accuracy of the inner wall of the tube and hinder shock wave experiments. Therefore, after the experiment is completed, the shock tube needs to be cleaned before the next experiment [2]. In the shock wave experiment, it needs to change other experimental conditions and repeat the measurement. As the result, the experiment efficiency will be greatly reduced. The larger the device, the greater the burden. Therefore, it is necessary to design a shock tube to improve the efficiency of the experiment [3].
2. Diaphragmless shock tube

2.1. Equipment overview
The high-pressure section is made of ASTM1045, with a mass of about 100 kg and a volume of $2.7 \times 10^{-3}$ m$^3$. The outer and inner surfaces are chrome plated to prevent rust, and the airtightness is maintained by O-rings. The structure inside the high-pressure section is shown schematically in Figure 1 and Figure 2. It can be seen from the picture that the main part of the high-pressure warehouse is composed of the main piston, the auxiliary piston, the pipeline system and the high-pressure section. The diameter of the main piston is 49.7 mm, and the diameter of the auxiliary piston is 30 mm. The auxiliary is driven by the main piston at high speed. The piston material is composed of nylon material. Nylon material is a self-lubricating polymer. It is generally used when mechanical facilities are not suitable for oil lubrication. Nylon pistons have many advantages; it has high strength, excellent wear resistance and strong corrosion resistance. Besides, it can bear huge loads, maintain a certain toughness and resist impact repeatedly. It can be firmly fitted to the friction surface to protect the friction surface. It can form a film with the friction surface. The film has excellent physical and chemical adsorption, so it has excellent film-forming properties. Nylon has low shear strength, the inevitable resistance due to friction is smaller than other materials, and there is less power loss. At the same time, the stability of nylon is superior, including the impact of physical heat and chemical heat. It has a stronger bearing capacity, is not easy to age, and has no harmful effects such as corrosion [4]. In this experiment, the leak rate of the verified nylon piston is only 2%, which is within the controllable error range. The piping system must use the same material as the outer wall, and hoses cannot be used. Otherwise, during the inflation and deflation process, it is easy to cause the pressure difference between the inside and outside of the pipe to cause the deformation of the pipeline and the pipeline is not smooth. The cavity of the diaphragmless shock tube is connected to the vacuum cylinder through a normally open solenoid valve. Because when the vacuum cylinder is in the vacuum state, if the normally closed solenoid valve is used to energize, it cannot be heated when it is working, which eventually leads to damage. Therefore, the normally open solenoid valve is used to connect the vacuum cylinder and the rotary air pump, and the movement of the piston is controlled by the physical properties of the gas. The low-pressure section is a horizontal pipe with an inner diameter of 19.4 mm and a length of about 1.3 m connected to the experimental observation section. Adding a pressure sensor in the experimental section can sense the arrival of the shock wave and measure the pressure of the shock wave. At the same time, the round tube in the low-pressure section needs to be smoothly changed into a square tube in the experimental section in order to install the observation port. The observation port is composed of optical glass for visual experiment [5,6].

2.2. Principle of operation
First, the required Mach number should be determined, and then the predetermined pressure required for the high-pressure section and the low-pressure section should be determined. When the shock tube is working, the high-pressure section should be pressurized, and the driving gas passes through the high-pressure gas valve to enter the inner cavity of the high-pressure section. At this time, the solenoid valve is energized, the valve port is closed. The waste tank valve is also closed. When the driving gas enters the inner cavity of the high-pressure section, the main piston and the auxiliary piston will move to the left because of the gas pressure. When reaching the leftmost end, the main piston collides with the impact block to block the gas flow between the high-pressure section and the low-pressure section. Moving the auxiliary piston to the left will open the stomata at the right end of the connecting pipe and then connect the connecting area, so that the driving gas enters the high-pressure section. Observe the pressure gauge of the high-pressure section and close the valve driving the gas pump when the predetermined pressure is reached. Subsequently, the driven gas is introduced through the low-pressure gas valves and the pressure gauge of the low-pressure section is observed. When the predetermined pressure is reached, the low-pressure gas valves is closed. At this point, the preparation work before the shock wave is completed. Then open the vacuum valve and connect the rotary air pump to evacuate the vacuum zone. When the vacuum zone reaches the vacuum state, the solenoid valve is de-energized and the valve port
is opened. Due to the air pressure, the main piston and the auxiliary piston move quickly to the right. At this time, the high-pressure section and the low-pressure end will be connected, and the gas in the high-pressure section will pour into the low-pressure section to generate a shock wave. Observe, measure and research the shock wave when the shock wave reaches the experimental area. After the experiment, the waste tank valve and the connected rotary pump were opened to exhaust the shock tube. Finally, the waste tank valve and the rotary pump are closed in preparation for the next experiment.

3. Research on normal temperature characteristics

After the design and manufacture of the shock tube, the normal temperature characteristics of the shock tube need to be researched. This experiment should be completed under the following assumptions: ○1 Flow is one-dimensional flow. ○2Gas is an ideal gas, isentropic flow. There is no viscosity and heat conduction except for shock wave. ○3 There is no dissipation effect due to viscosity and heat conduction.

The pressure of each stage before and after the shock wave can be obtained through the sensor in the observation section. The Mach number of the shock wave is calculated by the time difference of the data obtained by the two sensors. Figure 3 is a set of sensor data graphs. In the research, the driving gas is Helium and the driven gas is Ethanol.
In the shock tube, the initial states of the low-pressure section is indicated by subscripts 1. The area in the low-pressure section heated and accelerated by the shock wave is indicated by subscript 2. The area after the reflected shock is indicated by subscript 5. The following three equations are the basic equations related to the pressure, density, and velocity of the gas before and after the shock wave.

Mass conservation equation

\[ \rho_1 u_1 = \rho_2 u_2 \]  

Momentum conservation equation

\[ p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2 \]  

Energy conservation equation

\[ \frac{\gamma}{\gamma - 1} \frac{p_1}{\rho_1} + \frac{1}{2} u_1^2 = \frac{\gamma}{\gamma - 1} \frac{p_2}{\rho_2} + \frac{1}{2} u_2^2 \]  

The following equation is derived from the basic equation

\[ \frac{p_2}{p_1} = \frac{\gamma + 1}{\gamma - 1} \frac{\rho_1}{\rho_2} - 1 \]  

\[ \frac{p_2}{p_1} = \frac{\gamma + 1}{\gamma - 1} \frac{M_1^2}{1} \]  

In order to calculate the state change caused by the shock wave, the state change can be expressed as the Mach number \( M_1 = u_1 / a_1 \) of the following relationship upstream of the shock wave. Equation (5) can be obtained through the basic equation, the corresponding theoretical curve and experimental points are shown in Figure 4. It can be observed from the figure that the experimental value is slightly lower than the theoretical value. Because the driving gas is Helium. Its molecular weight is relatively small. In the range of strong shock wave, there occurs difference between the distribution of the experimental value and the theoretical value, because the molecular weight influent the experiment.
In the case of an incident shock wave, the front side of the shock wave is at rest, while the rear side is in a flowing state, and the reflected shock wave differs only in that the flow in the opposite direction to the wave front occurs in the area in front of the shock wave. Therefore, by changing the subscripts 1, 2 of the equation before and after the incident shock wave to 2, 5, a new equation can be derived. Equation (6) can be derived in the same manner. The incident shock Mach number and reflected shock Mach number are expressed as $M_i$ and $M_r$. The corresponding theoretical curve and experimental points are shown in Figure 5. It can be observed from the figure that the growth trend of the experimental value is the same as the theoretical value. But the experimental value is slightly lower than the theoretical value. Because the movement of the piston takes a small amount of time, the shock wave is delayed.

$$M_r = \left[ \frac{2\gamma_1 M_i^2 - (\gamma_1 - 1)}{(\gamma_1 - 1) M_i^2 + 2} \right]^{\frac{1}{2}}$$

(6)

Figure 5. Relationship between incident shock wave Mach number $M_i$ and reflected shock wave Mach number $M_r$

4. Conclusion
In this paper, a diaphragmless shock tube is designed and its characteristics are also researched. Through measurement and calculation of the physical quantities such as pressure, density and Mach number before and after the shock wave, the theoretical value of the ideal shock tube is compared with the
experimental measured value of the diaphragmless shock tube. It can be concluded that the measured value is basically consistent with the theoretical value of the ideal shock tube qualitatively. The reflection shock wave Mach number is slightly smaller than the theoretical value quantitatively, because the process of the piston moving to generate the shock wave requires a small amount of time. It can prove that the experimental data of the shock tube is credible and the shock tube can be tested repeatedly.

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