The Effect of Different Gas Mediums on the Reflected Shock Pressure and Temperature in Shock Tubes

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***Abstract*—The choice of gas mediums will affect the reflected shock pressure and temperature during analyzing the shock tube. Different mediums in driver and driven section result in the Mach number disparity in the process of shock wave propagating, adversely affecting the reflected shock wave. Based on the ideal conditions, to study the higher or lower reflected shock pressure and temperature circumstance, this paper compared several kinds of gas mediums as driver and driven section. Combined with FLUENT simulation verification, it could be confirmed that proper cases of mediums would provide meaningful direction for experiment and project need.**

Keywords-gas medium; reflected shock wave; pressure step

I. INTRODUCTION

Shock tubes, as traditional devices have been used to provide a pressure change with a very fast rise time and calculable amplitude, also been tools for studying high speed aerodynamics and shock wave characteristics as well as the response of material to blast loading [1]. For traditional shock tubes, the designs are based on how the simulated blast wave is created: compression-driven [2]. This pressure step could provide the basis for the calibration of pressure transducers used in highly dynamic applications. Based on the Knudsen number, which indicates the rarefaction gas effect, Arun K.R. et al [3] performed computational studies to investigate the shock wave propagation under different pressure ratios, shock tube diameters with slip condition and no slip wall boundary conditions. For the propagating process of the shock wave, Park J.O et al [4] performed an experimental study to investigate shock wave propagation. Due to the pressure step, Du Shuiyou et al [5] analyze the duration of the step by using pressure sensor. In order to obtain lower pressure step, Lin Jianmin et al [6] explore two methods which contain changing the area of driver and driven section and adding orifice plates downstream of the diaphragm in shock tube. From another perspective, A. Hertzberg [7] studied the way to gain strong shock wave. Currently, most direct method for adjusting the strength of pressure and temperature step is changing the area of sections. However, for material and specific application, it is an inconvenient choice, and regulating gas mediums can solve more practical issues.

II. THEORETICAL STUDY

A) *Theoretical Analysis*

A simple shock tube contains two straight tubes of the same circular cross section that are separated by a diaphragm. One tube consists a low-pressure driven gas, and the other is filled with a driver gas. When the difference in pressure reaches a certain value leading to the diaphragm rupture, the driver gas will generate a series of compression waves within the driven gas which coalesce to form a shock wave that propagates into the remaining undisturbed driven gas. As the shock wave gets to the end face of low-pressure driven gas section, it will reflect back with a higher pressure and temperature [8]. In the condition of inviscid, the relation between the driver pressure P_4, the driven pressure P_1 and the Mach number M_S is given as follows [9]:

$$\frac{p_4}{p_1}=\frac{1}{\alpha_1}\left(\frac{2\gamma_1 M_S^2}{\gamma_1-1}-1\right)\left(1-\frac{(1/\alpha_4)(a_1/a_4)(M_S^2-1)}{M_S}\right)^{-2\gamma_4/(\gamma_4-1)} \tag{1}$$

Where $\alpha_1=(\gamma_1+1)/(\gamma_1-1)$, and γ_1 is the ratio of the specific heat at constant pressure to that at constant volume for the driven gas. Similarly, $\alpha_4=(\gamma_4+1)/(\gamma_4-1)$ and γ_4 is the ratio of the specific heat for driver gas a_1 and a_4 is the speed of sound in driven and driver section. It can be calculated by the formula $a=\sqrt{\gamma RT/m}$, where T is the measured initial temperature (in kelvin) of the gas, m is its molecular weight and R is the gas constant. When the initial state of these two parts and the ratio of pressure are known, the Mach number of the advancing shock wave can be gotten.

After the diaphragm breaking up, the shock front is propagating into the driven gas with a constant pressure p_2 behind the shock, whose pressure can be expressed as:

$$p_2=p_1\left(1+\frac{2\gamma_1}{\gamma_1+1}\left(M_S^2-1\right)\right) \tag{2}$$

And the temperature which is accompanied by the change of p_2 satisfy the relationship as follows:

$$\frac{T_2}{T_1}=\frac{p_2}{p_1}\left(\frac{\alpha_1+\left(p_2/p_1\right)}{1+\alpha_1\left(p_2/p_1\right)}\right) \tag{3}$$

When the shock wave reaches the end of the shock tube, it will reflect with the pressure in the end section rising to p_5 with an associated temperature T_5.

The value of p_5 can be gotten though the formula below:

$$p_5=p_2\left(\frac{(\alpha_1+2)\left(p_2/p_1\right)-1}{\left(p_2/p_1\right)+\alpha_1}\right) \tag{4}$$

While the expression of T_5 is similar to T_2 which is shown as follows:

$$\frac{T_5}{T_2}=\frac{p_5}{p_2}\left(\frac{\alpha_1+\left(p_5/p_2\right)}{1+\alpha_1\left(p_5/p_2\right)}\right) \tag{5}$$

According to relationship above, it can be judged that the reflected wave pressure and temperature vary with different gas mediums. So on the basis of fitting pressure step size, the theory contains guiding significance.

B) Theoretical Result

When the gas mediums in driver and driven section are the same, the Eq. (1) could be simplified as:

$$\frac{p_4}{p_1}=\frac{1}{\alpha}\left(\frac{2\gamma M_S^2}{\gamma-1}-1\right)\left(1-\frac{(1/\alpha)\left(M_S^2-1\right)}{M_S}\right)^{-2\gamma/(\gamma-1)} \tag{6}$$

Several kinds of gas mediums have been listed here to improve the effect of medium on the pressure and temperature step. It is not difficult to find that the diverse mediums leads to the Mach number varying with the propagating speed of shock wave directly. To analyze the influence of gas types only, the initial pressure in the driven section is setting to 0.1MPa in each condition, and the driver section pressure can be gotten by the given pressure ratio. Also the initial temperature is 300K in both sections during the calculation. The specific results are shown as the following table, which reflect the relationship among the different gas mediums.

TABLE I. MACH NUMBER IN DIFFERENT GAS MEDIUMS AND PRESSURE RADIO

PR \ GM (Ms)	H2	He	N2	Air	Ar
2	1.1595	1.1479	1.1595	1.1595	1.1479
3	1.2627	1.2426	1.2627	1.2627	1.2426
5	1.4024	1.3694	1.4024	1.4024	1.3694
10	1.6075	1.5521	1.6075	1.6075	1.5521

Note: GM stands for the gas medium in both driver section and driven section.

M_S is the Mach number which is producing after diaphragm crushing.

PR means the initial pressure ratio before diaphragm rupture.

It can be gotten that the Mach number is only relevant to the specific heat ratio of gas, and nothing with the type of gas medium. For most diatomic gas, such as hydrogen, nitrogen and air, the specific heat ratio is 1.4. Due to the monatomic gas, such as helium and argon, the specific heat ratio is 5/3 [10]. With the pressure ratio growing, the Mach number will be higher.

III. SIMULATION

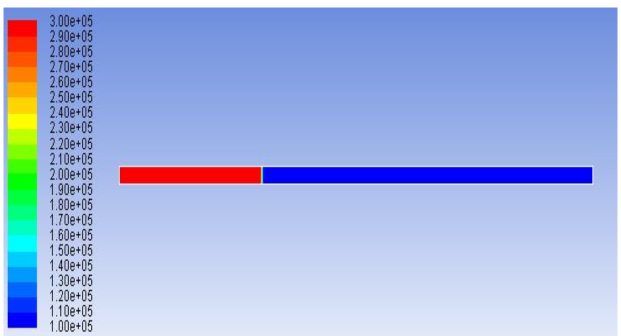
FLUENT has been a popular software which is applied to the flow field simulation. Two-dimensional model is set up to simulate the whole process of shock tube. The length of shock tube is 200mm and the width is 5mm.In the ideal situation, there is no heat exchange between the shock tube wall and external environment. Based on the fundamental equation of thermodynamics, the starting conditions of simulation can be defined regardless of the viscous.

A) The Propagating of Shock Wave

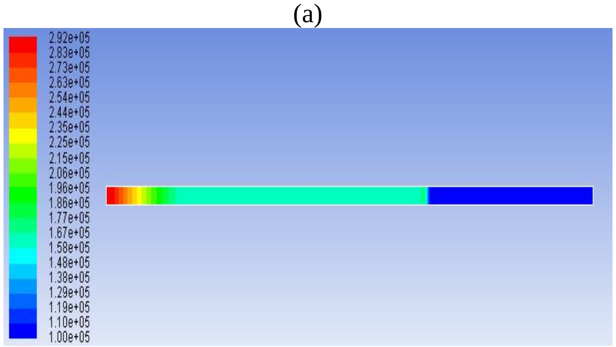
Before the diaphragm breaking up, it is considered that status of gas in driver and driven section keeps still. At an instant moment, the diaphragm crushes and forms a shock tube whose Mach number is higher than 1. The pressure and temperature in the driver section will decline, and on the contrary they would be ascended in the driven section. When the shock wave reaches the end of shock tube, the pressure and temperature in the local area will rise up sharply within millisecond or even sub-millisecond.

The size of the shock tube has been set up before. In the ideal circumstance, it can be assure that the result is irrelevant to shape and size of the shock tube from the relationship between pressure or temperature and gas medium. When the size of shock tube is known and the gas mediums in driver and driven section are given, the platform of pressure and temperature step will be confirmed.

The process of changing in pressure is shown as following figure from the diaphragm rupture to reflected shock wave forming.



(a)



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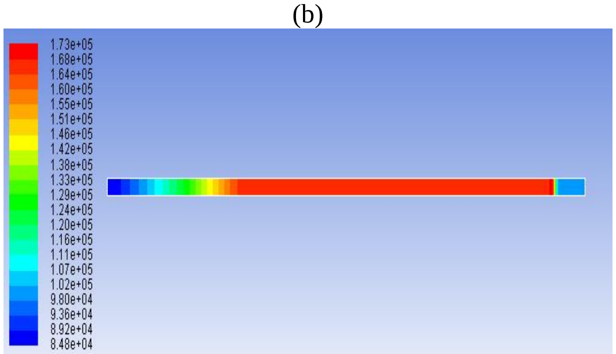

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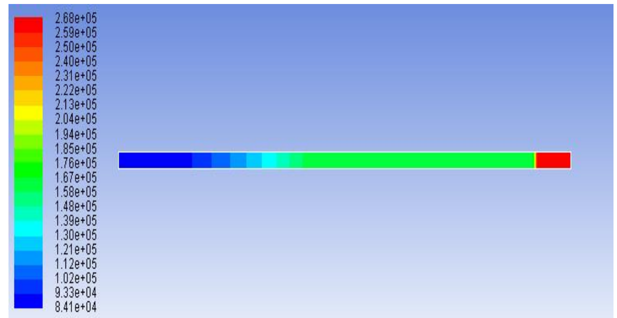

(d)

FIGURE I. THE PROCESS OF SHOCK WAVE PROPAGATING

(a) Before the diaphragm rupture, the pressure shows in the driver and driven section.

(b) After the diaphragm rupture, the pressure in driver section declines and ascends in driven part.

(c) Rarefaction wave reflects in the driver section, which leads to the pressure going down.

(d) Reflected shock wave results in the pressure rising up.

B) The Comparison between Theory and Simulation with the Same Medium

When the gas medium in the driver and driven section are the same, the ratio of speed of sound a1/a4 will equal 1. Mach number can be calculated as the initial film pressure ratio is determined. Take the situation of initial value equaling 3 for example and four kinds of gas mediums are listed here which contain hydrogen, helium, air and argon. Meanwhile, the initial temperature in both sections is 300K. The results of the theory value and simulation are shown as Figure 2.

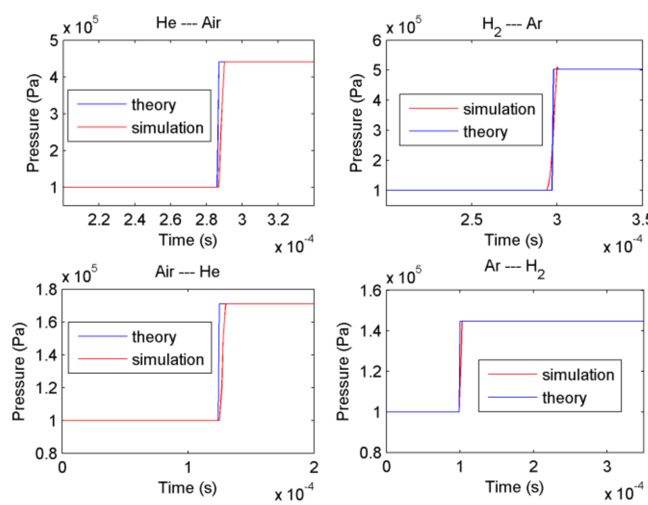

FIGURE II. THE PRESSURE STEP OF THE THEORY VALUE AND SIMULATION

In the ideal theoretical circumstance, the pressure step take place on a moment. While the simulation is close to the practical situation, of which rising time works in milliseconds. Though recording the time which takes place at the moment of changing from original value, the speed of shock wave can be gotten. Then the ratio of shock wave speed and the speed of sound is Mach number that is used to calculate the pressure and temperature step later.

So the comparisons of pressure step between the theoretical and emulation results are shown as following table:

TABLE II. THE COMPARISON OF PRESSURE STEP BETWEEN THEORETICAL AND EMULATION RESULTS

GM \ Type	Theoretical pressure step	Emulation pressure step	Error ratio
H2	0.2762MPa	0.2757MPa	0.18%
He	0.2686MPa	0.2685MPa	0.04%
Air	0.2762MPa	0.2764MPa	0.07%
Ar	0.2686MPa	0.2685MPa	0.04%

Meanwhile the comparisons of temperature step are shown as following table:

TABLE III. THE COMPARISON OF TEMPERATURE STEP BETWEEN THEORETICAL AND EMULATION RESULTS

GM \ Type	Theoretical temperature step	Emulation temperature step	Error ratio
H2	404.07K	403.33K	0.18%
He	448.83K	448.09K	0.16%
Air	404.07K	403.78K	0.07%
Ar	448.83K	448.06K	0.17%

From the above figure, it is not difficult to find out that error between theory and simulation is nearly less than 0.2%. So the software FLUENT can emulate the process of shock wave perfectly. With the density of mesh which is generated rising up, the accuracy will get better.

C) The Comparison between Theory and Simulation with the Different Medium

When the gas medium in the driver and driven section are different, the pressure and temperature step will vary considerably among distinct circumstance. Different gas mediums possess own molar mass and specific heat ratio, which lead to the Mach number is diverse from each other. In order to make this comparison, four kinds of situation have been enumerated here. The first kind of situation is helium as driver gas and air as driven gas. The second is hydrogen as driver gas and argon as driven gas. The third is air as driver gas and helium is full of driven section. The last situation is that argon acts as driver gas and hydrogen is driven part. So the theoretical and emulation results are shown as following figure.

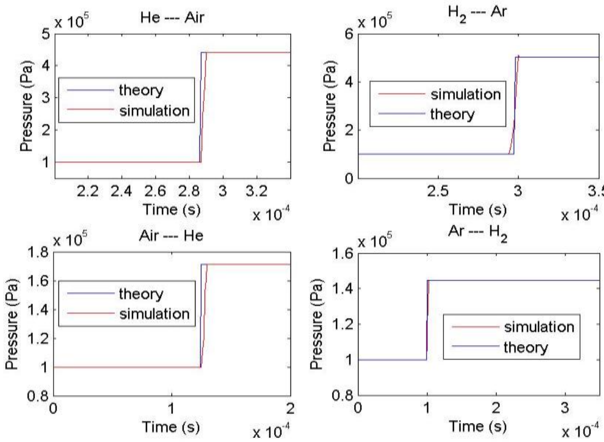

FIGURE III. THE PRESSURE STEP OF THE THEORY VALUE AND SIMULATION

According to the results above, the pressure steps of the first two cases are higher than the last two status. The comparisons between the theoretical and emulation results are shown as following table:

TABLE IV. THE COMPARISON OF PRESSURE STEP BETWEEN THEORETICAL AND EMULATION RESULTS

GM \ Type	Theoretical pressure step	Emulation pressure step	Error ratio
He—Air	0.4414MPa	0.4407MPa	0.15%
H2—Ar	0.5029MPa	0.5026MPa	0.05%
Air—He	0.1710MPa	0.1709MPa	0.06%
Ar—H2	0.1447MPa	0.1446MPa	0.08%

TABLE V. THE COMPARISON OF TEMPERATURE STEP BETWEEN THEORETICAL AND EMULATION RESULTS

GM \ Type	Theoretical temperature step	Emulation temperature step	Error ratio
He—Air	469.53K	468.82K	0.15%
H2—Ar	591.87K	591.57K	0.05%
Air—He	372.65K	372.43K	0.06%
Ar—H2	333.52K	333.25K	0.08%

Note: GM means gas medium. The left gas fills with the driver section and right is driven part.

So, the above data provides an obvious support for the relationship between the gas medium and pressure step. By a preliminary inspection, the gas which owns smaller molar mass as driver section and bigger molar mass gas as driven gas will produce higher pressure or temperature step. On the contrary, as the driver gas medium, bigger molar mass gas will generate lower step.

In order to prove the above conclusion, more kinds of situation have been given as follows. Though these cases, it can be assure that higher pressure ratio between the two sections will lead to higher Mach number. At the same time, the pressure and temperature step get more.

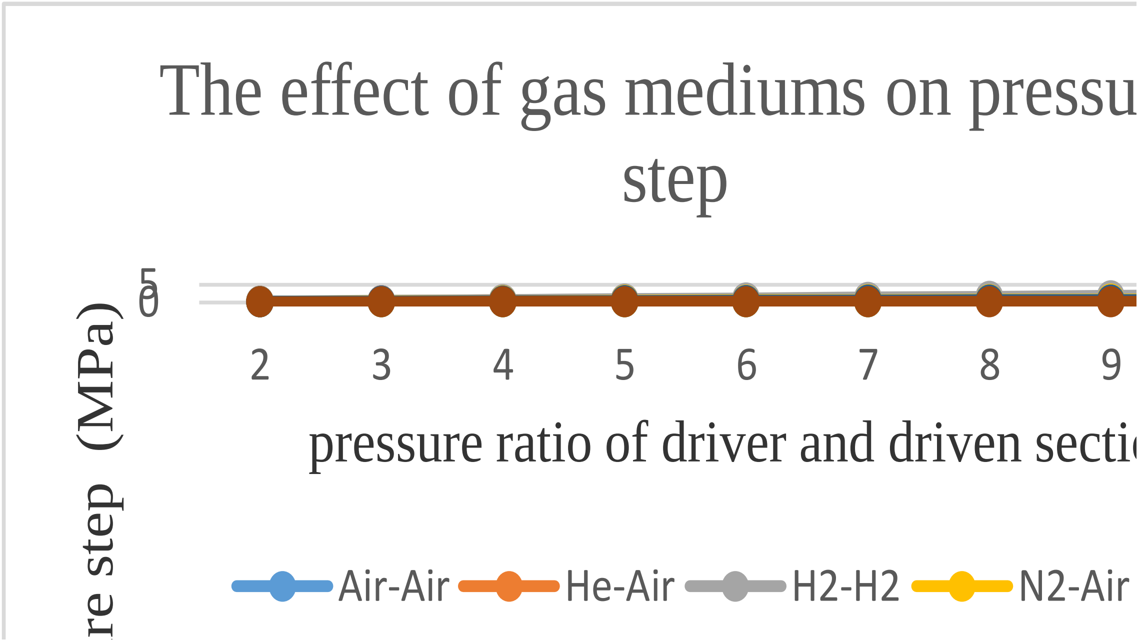

FIGURE IV. THE EFFECT OF GAS MEDIUMS ON PRESSURE STEP

IV. CONCLUSION

The paper analyze the effect of gas mediums on the pressure and temperature step, which is used the method of combining the theoretical analysis with FLUENT simulation. It can be concluded that the steps are influenced by the gas molar mass and specific heat ratio directly in the ideal situation. On the one hand, in the case of same medium in the driver and driven section, the gas molar mass is irrelevant to the final result, yet only affect the time of arriving at the end of shock tube for shock wave. While the specific heat ratio is the determining factor. In the case of different gas medium, aiming to gain higher step, lower molar mass gas should be considered firstly. To the contrary, higher molar mass gas will result in the lower step. On the other hand, the pressure step keeps pace with the temperature step. The temperature varies with the pressure changing.

So, in accordance with the content of this paper, proper gas medium can be chosen for the need of concrete experiment or project, which is taken advantage of the pressure or temperature step. In the future, an experimental study will be performed to validate the present theoretical conclusions and numerical results.

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