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Gas Dynamic Characteristics of the Helium Two Stage Shock Tube for MHD Power Generation Experiments*

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Gas dynamic performance of a helium two stage shock tube which is designed for a simulator of an MHD power generator is studied theoretically and experimentally. To obtain adequate working fluids behind the shock waves, a two stage shock tube with a diameter of 130 mm and a length of 13 m is designed. As a buffer gas argon and helium are chosen and their effects on the performance are studied. When helium is used, the performance well agrees with the theory in which the reduction of the shock velocity in the buffer chamber is considered. Obtained shock velocity is 3800 m/sec, which can produce shocked gas with 1 atm. and 2000°K. This is considered to fulfil the working conditions of an MHD generator. When the tailoring interface operation is made, we can obtain uniform gases of the duration time of 2.2 msec, which is 60% of the ideal value.

1. Introduction

Recently studies concerning a non-equilibrium MHD power generation have been made worldwide. The generator systems would consist of a high temperature gas cooled reactor as a toppler and a steam turbogenerator as an auxiliary generator. In a high temperature gas cooled reactor, high pressure and high temperature helium gas would be used as a cooling gas^{(1) (2)}.

On the other hand, effective generation of power in the generator is considered to be made when the plasma velocity in the generator is supersonic, because simple calculations reveal that in the generator the power density is proportional to M_s^2 where M_s is the flow Mach number⁽³⁾. For this reason many simulation experiments have been made using a shock tube⁽⁴⁾. Growth of a thick boundary layer after a shock front, short duration time and relatively small fluid velocity are considered to be defects in shock tube experiments. To avoid these difficulties we used a shock tunnel as a wind tunnel of high temperature and high pressure helium gas.

Compression of a light helium gas would meet difficulties of using a very high pressure driver gas. These difficulties could be overcome in a two stage shock tube. To obtain a gas flow with

2000°K and 1 atm. at static condition, a driver gas of 100 atm. of hydrogen must be used in a conventional shock tube, in contrast to 30 atm. in a two stage shock tube. For the duration time a two stage shock tube is superior to a conventional one when a tailored interface operation is possible. In the past, Bird et al.⁽⁵⁾ performed theoretical calculations of the gas dynamical characteristics of a two stage shock tube and revealed that the optimum performance was obtained using a gas composition and pressure ratio of a buffer and a low pressure chamber. In the optimum condition the shock velocity in a two stage shock tube was higher than that in a conventional shock tube. Schexnayder⁽⁶⁾ showed experimentally that the reduction of the shock velocity could be made smaller when helium was used as a buffer gas. Kamimoto et al.⁽⁷⁾ considered the tailoring conditions of a two stage shock tube.

In this paper we studied experimentally the performance of a two stage shock tube under a relatively peculiar condition, which is necessary for the MHD power generation. This condition is that the shock Mach number is from 3.8 to 4.0 in helium gas with initial pressure of 60 mmHg. The static temperature and pressure behind the shock wave might be 2000°K and 1 atm. respectively. When we would make an optimum seeding in the fluid behind the shock, we could obtain an electrical conductivity of 10 to 10² mho/m, which is considered to be sufficient for an MHD power generation.

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2. Nomenclature

P : pressure

T : temperature

u : velocity of gas

L : length of the shock tube

a : the sound velocity in the gas

t : time

M_s : Mach number of the shock wave
Suffices

1 : properties in the low pressure chamber

2 : region between the shock wave and the contact front in the low pressure chamber

3 : region behind the contact front

4 : region between the reflected shock wave and the contact front

5 : region behind the reflected shock wave

6 : properties in the buffer chamber

7 : properties behind the reflected shock wave at the second diaphragm

8 : properties in the driver chamber

P_{ij} : pressure ratio between i chamber and j chambers $= P_i/P_j$

T_{ij} : temperature ratio between i and j chambers $= T_i/T_j$

ρ_{ij} : density ratio between i and j chambers $= \rho_i/\rho_j$

3. Experimental and measuring apparatus

3.1 Experimental apparatus

The two stage shock tube is 13 m long and consists of 4 chambers, that is a high pressure

① Driver chamber	⑨ Sleeve of damp tank
② Buffer chamber	⑩ Vacuum seal
③ Compression chamber	⑪ Damp tank
④ Driver chamber	⑫ Aluminum diaphragm
⑤ The first diaphragm	⑬ Polyethylene-telephtalate dia.
⑥ Flange	⑭ Holder of the third diaph.
⑦ The second diaphragm	⑮ Pressure gauge
⑧ The third diaphragm	⑯ Pressure transducer

Fig. 1 Structure of a helium two stage shock tube

chamber, a middle pressure chamber, a low pressure chamber and a damp tank. The schematic of the apparatus is shown in Fig. 1. For operation of a shock tunnel a nozzle can be set between the low pressure chamber and the damp tank. The high pressure chamber is a cylinder of stainless steel of a diameter of 130 mm. The high pressure and the buffer chambers are connected by a joint which holds aluminium diaphragms. The diaphragms have a diameter of 198 mm and thickness of 3.0 and 1.0 mm. These are broken when pressure of the driver gas reaches 30 atm. and 17 atm. respectively.

The buffer chamber is a cylinder of stainless steel of a diameter of 130 mm. It is followed by a compression chamber which has a rectangular cross section of $70 \times 100 \text{ mm}^2$ and is made of a cast iron. For the working gases of this chamber argon and helium are selected. The buffer chamber is connected to the low pressure chamber by a joint which holds a polyethylene telephtalate diaphragm.

The low pressure chamber has a rectangular cross section of $70 \times 100 \text{ mm}^2$ of a cast iron. The working gas is mainly helium. The end of the low pressure chamber is connected to the damp tank by a vacuum joint. The damp tank has a volume of 1.5 m^3 and is made of a cast iron.

The apparatus are evacuated by rotary vacuum pumps with total outgas rate of 2650 liters per minute.

The experimental arrangement and its photo are given in Fig. 2 and Fig. 3 respectively.

Fig. 2 Schematics of an arrangement of exp. and meas. apparatus

Fig. 3 Photo of the helium two stage shock tube

3.2 Measuring apparatus

The shock speed, pressure of shocked gas and duration time of it were measured. The shock speed and the pressure were measured by a pressure transducer of quartz (Kistler No. 603 A). The duration time of the shocked gas was measured by a thin film thermometer of platinum which was made by making a platinum coating on the surface of a glass and desiccating it in an electric furnace at 800°C during 15 minutes. It has a resistivity of 150Ω. Because calibration of this thermometer is difficult, we have used this for measurements of the duration time of the shocked gases only.

The outputs of these apparatus were displayed on conventional synchroscopes and taken by a polaroid camera.

4. Experimental results and discussions

In order to examine whether this shock tube has sufficient performance for a wind tunnel of an MHD generation, we have firstly investigated characteristics of the buffer chamber and secondly that of the low pressure chamber.

4.1 Static pressure variation in the compression chamber is indicated in Fig. 4. These data are taken at the condition of $P_{s1}=4.2 \times 10^2$ and $P_{s1}=2.0$. The output indicates the pressure increase due to arrival of the first shock wave, the reflection of the shock wave at the second diaphragm and decrease of the pressure in the buffer chamber after breaking of the diaphragm. These data also indicate that in this pressure range of the buffer chamber the shock tube operates in "the reflected shock mode⁽⁸⁾", that is the flow behind the initial shock wave is stopped at the second diaphragm to expand nearly steadily.

When the initial pressure of the buffer cham-

$P_{s1}=4.2 \times 10^2$, $P_{s1}=2.0$, Sweep velocity 500μ sec/div
Pressure 2.72 atm/div.

Fig. 4 Pressure-time history at a stagnant in the buffer chamber

ber is over 480 mmHg, there is no shock reflection (the incident shock mode⁽⁸⁾), but the characteristics of the low pressure chamber would have no dependence on the operation mode⁽⁹⁾.

The best performance is obtained when the buffer pressure is from 120 mmHg to 240 mmHg, in which the shock tube would operate in the reflected shock mode.

4.2 The high pressure chamber and the low pressure chamber consist of a conventional one diaphragm shock tube and its performance is closely connected to the overall performance of the shock tube.

The shock wave velocity in the buffer chamber was measured with the values of P_{s6} varied. The results are indicated in Fig. 5. The solid lines in this figure indicate the theoretical values calculated from the following equation,

$$P_{s6} = \left[\frac{2\gamma_6 M_{s6}^2 - (\gamma_6 - 1)}{\gamma_6 + 1} \right] \times \left[\frac{1}{1 - \frac{(\gamma_8 - 1)}{(\gamma_6 + 1)} \frac{a_6}{a_8} \left(M_{s6} - \frac{1}{M_{s6}} \right)} \right]^{2\gamma_8/(\gamma_8 - 1)} \quad (1)$$

The shock velocity is reduced from the theoretical values about 24% in the case of hydrogen and helium in contrast to 10% in the case of hydrogen and argon. They are caused by a non-ideal breaking of the first diaphragm, effects of viscosity and non-ideal shock formation⁽¹⁰⁾.

4.3 The velocity of the second shock wave which runs in the low pressure chamber has important connection to the shock tube performance.

Fig. 5 Performance of the shock tube in the first stage

The velocity is measured by two pressure transducers which are set at the point of 4090 mm behind the second diaphragm and 450 mm apart from each other. In Fig. 6 the velocity is indicated by open circles in the case of the working gas composition of hydrogen, helium and helium. In this case initial pressure of the buffer chamber is varied with the pressure in the low pressure chamber held at 60 mmHg and that in the high pressure chamber at 30 atm. In Fig. 6 the velocity in a conventional one diaphragm shock tube of hydrogen and helium at the same initial condition is also indicated as solid circles.

The simple theoretical calculations in which the measured shock velocity in the buffer chamber is used are made and indicated in Fig. 6 with a dotted line. The ideal stagnation temperature and pressure are calculated from the equations,

$$\frac{T_7}{T_1} = \frac{2(\gamma_7 - 1)M_{s6exp}^2 + (3 - \gamma_7)}{\gamma_7 + 1} \quad (2)$$

$$\frac{P_7}{P_1} = \frac{\{2(2 - \gamma_7)/(\gamma_7 - 1)\}^{2/(\gamma_7 - 1)} (M_{s6exp}^2 - 1)^2}{\left(\frac{2}{\gamma_7 - 1}\right)^{(2 - \gamma_7)/(\gamma_7 - 1)} \left(\frac{2\gamma_7}{\gamma_7 - 1}\right)^{1/(\gamma_7 - 1)} \left(M_{s6exp}^2 + \frac{2}{\gamma_7 - 1}\right)} \times \left[1 - \frac{\left(M_{s6exp}^2 + \frac{2}{\gamma_7 - 1}\right) \left(\frac{2\gamma_7}{\gamma_7 - 1} M_{s6exp}^2 - 1\right)}{\left(\frac{2}{\gamma_7 - 1}\right)^2 \left(\frac{2\gamma_7}{\gamma_7 - 1}\right) (M_{s6exp}^2)^2} \right]^{-1/(\gamma_7 - 1)} \quad (3)$$

where M_{s6exp} is the measured shock Mach number in the buffer chamber and $\gamma_7 = \gamma_1$. The second shock wave velocity can be calculated from the Eq. (1) changing 6 to 1 and 8 to 7.

From these calculations it is shown that the shock wave velocity in the low pressure chamber has a maximum value according to P_{86} . In the case of the gas composition of hydrogen, helium and helium, an optimum value is obtained at $P_{61} = 4.0$ when P_{81} is equal to 4.2×10^2 . Measured values well agree with the theoretical values as shown in Fig. 6. The maximum shock velocity is a Mach number of 3.8 and is obtained in the pressure range of 2.0 to 4.0 of P_{61} . The velocity gain is 1.18 times the value of the one diaphragm shock tube, which is equivalent to a reduction of 1/3 of the driver pressure. Reduction of the speed of the shock wave in the buffer chamber might be canceled at the compression chamber due to reduction of the tube cross section.

The measured and theoretical values of the shock speed in the case of the gas composition of hydrogen, argon and helium are indicated in Fig.

7. The performance of the shock tube is lower than the theoretical characteristics. The theoretical calculations indicate that the maximum shock velocity is obtained when the initial pressure ratio P_{61} is smaller than 0.1, which can not be reached in the present experiments. The maximum value presently obtained is a Mach number of 2.8, which is smaller than that in the one diaphragm shock tube. This result indicates that a lighter buffer gas is better for the performance of the shock tube.

In Fig. 8 and Fig. 9 the velocities of the shock wave in the buffer and the low pressure chamber are compared. When the shock velocity increases in the low pressure chamber, values indicated in the ordinates of these figures are plus. The theoretical values are indicated with solid lines in these figures, in which line I indicates an ideal performance of the shock tube and line II indicates the performance calculated using the measured shock velocity in the buffer chamber. When argon is used as the buffer gas, the shock velocity always decreases in the low pressure

Fig. 6 Performance of the two stage shock tube (H₂-He-He)

Fig. 7 Performance of the two stage shock tube (H₂-Ar-He)

chamber.

4.4 The gas pressure behind the second shock wave is measured by the pressure transducers, the values of which are divided by the initial pressure and indicated in Fig. 10. The theoretical values calculated from the Rankine-Hugoniot equation are indicated in the same figure.

Discrepancies between the theoretical and mea-

Fig. 8 Velocity gain of the shock wave in the second stage ($\text{H}_2\text{-He-He}$)

Fig. 9 Velocity gain of the shock wave in the second stage ($\text{H}_2\text{-A-He}$)

Fig. 10 Pressure ratio behind the second shock wave

sured values are due to a vibration of the pressure transducer, which is estimated at about 5 to 10% of the signals. The temperature is calculated from the measured pressure assuming the Rankine-Hugoniot characteristics to be valid and it is estimated at Mach number of 3.8 the temperature reaches 2000°K behind the second shock wave. These are indicated in Fig. 11.

4.5 In order to get the performance of a two stage shock tunnel, a nozzle was set at the end of the low pressure chamber and its gasdynamic characteristics were measured. The longest dura-

Fig. 11 Temperature ratio behind the second shock wave

$P_{81} = 4.2 \times 10^2$, $P_{61} = 1.0$, Sweep velocity 500 $\mu\text{sec/div}$
Pressure 2.72 atm/div, Distance between the two pressure transducers is 450 mm.

Fig. 12 Pressure variation at the stagnant in over tailoring operation

$P_{81} = 4.2 \times 10^2$, $P_{61} = 4.0$, Sweep velocity 500 $\mu\text{sec/div}$
Pressure 6.8 atm/div, Distance between the two pressure transducers is 450 mm.

Fig. 13 Pressure variation at the stagnant in tailoring operation

tion time of the shock heated gases might be obtained when the shock tunnel is operated under the tailoring conditions in which a contact front remains to be stationary. The measured time history of the static pressure at the stagnant is indicated in Fig. 12, Fig. 13 and Fig. 14. They are obtained varying the value of P_{61} . The composition of the working gas is hydrogen, helium and helium in each chamber. The data in Fig. 12

$P_{81}=4.2 \times 10^2$, $P_{61}=10.0$, Sweep velocity $500 \mu\text{sec/div}$
Pressure 2.72 atm/div , Distance between the two pressure transducers is 450 mm

Fig. 14 Pressure variation at the stagnant in under tailoring operation

Fig. 15 X-T diagram of $\text{H}_2\text{-He-He}$ two stage shock tube (tailoring) $P_{61}=2.0$, $P_{81}=4.2 \times 10^2$

Sweep velocity $200 \mu\text{sec/div}$, Pressure 0.68 V/div
Temperature 0.02 V/div , Buffer gas= He Temperature is measured by a thin film gauge

Fig. 16 Variation of pressure (upp.) and temperature (low.) behind the incident shock wave in the driven chamber

show the pressure variation in the over tailoring condition in which the pressure increases with time. The data in Fig. 14 show the pressure variation in the under tailoring condition in which the pressure decreases with time. The tailoring operation is obtained as shown in Fig. 13 when $P_{81}=4.2 \times 10^2$ and $P_{61}=2.0$ which is nearly equal to the optimum condition of the shock tube.

4.6 A distance vs. time (so called X-T) diagram at the tailoring operation is indicated in

Fig. 17 Tailoring condition

Fig. 18 Pressure ratio at the stagnant when the nozzle is connected

Fig. 15. The theoretical X - T diagram is obtained as follows.

At the tailoring condition, since the contact front is stationary, we have for the fluid velocity behind the reflected shock and the contact front respectively,

$$u_2 = \frac{a_3(\gamma_7 - 1)(P_{52} - 1)}{(1 + \gamma_7)(1 + \gamma_7 P_{52})}$$

and

$$u_2 = \frac{2a_1}{\gamma_1 + 1} \left(M_{s1} - \frac{1}{M_{s1}} \right)$$

From these equations, when we put M_{s1} and P_{52} as measured velocity and pressure and γ_7 is equal to γ_1 , we can obtain a_3 . According to the measured data in Fig. 15 and since the velocity of the rarefaction wave which runs in the low pressure chamber is equal to

$$a_3 + u_3 = a_3 + u_2,$$

we obtain the experimental values F_R in Fig. 15. The velocity of the reflected wave is given from the measurements. Theoretical values $F_{R(th)}$ are given assuming the rarefaction wave is reflected at the first diaphragm.

The marks $\times$, $\circ$, $\triangle$, $\square$, $\bullet$ indicate measured values. The marks $\times$, $\circ$ indicates the duration time of the high temperature gas measured by thin film gauges. The typical data are shown in Fig. 16.

This diagram shows that the rarefaction wave does not emanate completely from the stagnant of the first shock wave and there are complex interactions of waves in the compression chamber, which reduce the duration time of the stagnant in the low pressure chamber. According to the measurement the duration time of uniform gases at the stagnant is 2.2 msec and is 60% of the ideal values. From calculations which are shown in Fig. 17, when the composition of the working gases is chosen as H_2 -He-He, P_{86} with which the tailoring operation can be obtained is in the working pressure range of this shock tube. However, when argon is chosen in the buffer chamber, P_{86} becomes smaller for the tailoring operation and goes out of the working range.

4.7 The measured pressure ratio at the stagnant in front of the nozzle is shown in Fig. 18. The theoretical values are indicated by a solid line. They are calculated assuming an ideal operation of the shock tube. When the shock velocity becomes larger, the measured pressure is smaller than the theory, which is caused by incomplete formation of a stagnant by the nozzle. When the

maximum Mach number becomes 3.8, the stagnation pressure reaches 5.0 atm.

5. Conclusions

The gasdynamic performance of the two stage shock tube in which helium was used as a test gas was measured and compared with the theoretical calculations.

(1) The shock tube performance well agrees with the theory in which the reduction of the shock velocity in the buffer chamber is considered.

(2) When argon is used as the buffer gas, the performance is reduced at small buffer pressure since a piston pressure of the shock wave in the low pressure chamber is reduced.

(3) The maximum shock velocity is obtained when the pressure ratio between the buffer and the low pressure chamber is from 2.0 to 4.0 and 1.2 times larger than that of the one diaphragm shock tube in the same initial conditions.

(4) The maximum shock speed is 3800 m/sec and the pressure and the temperature behind the shock wave well agree with the values calculated by the Rankine-Hugoniot theory.

(5) In the shock tunnel, a tailored interface operation is obtained when P_{61} is from 2.0 to 4.0. The duration time of the uniform gases is 2.2 msec at the maximum and is 60% of the ideal values.

(6) The pressure of the stagnant in the low pressure chamber becomes 5.0 atm. in spite of the reduction due to the existence of the nozzle.

We can conclude from these measurements that this shock tube could produce high temperature and high pressure helium gases which would fulfil the working conditions of an MHD generator.

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Discussion

K. MATSUO (Kyushu University):

The strength of a shock wave in a shock tube depends not only on the working gases and the working conditions but also on the distance of the position of the measurements from the diaphragm.

(1) What is the distances from the first diaphragm to the pressure taps used for the measurements of the data shown in Fig. 6? In what relations does the distance depend on the formation distance of the first shock wave? You mention that Ms_6 becomes smaller than the theoretical values when helium is used as a buffer gas because "a boundary layer becomes thicker in the case of helium than argon". However I think that in the case of helium a formation distance is longer due to a higher sound velocity than in the case of argon and it is more effective for reduction of Ms_6 .

(2) Where is the location of the pressure transducers of the data in Fig. 7 and Fig. 8? What is the method of calculations of the theoretical values of the one diaphragm shock tube? Why are the experimental data larger than the calculated values? You point out that the acceleration of the shock wave is due to reduction of the cross section. Is there any dependance of the non-ideal breaking of the diaphragm and reduction of the shock speed due to viscosity? Have you made any considerations of variation of the shock velocity taking account of these effects?

H. OHTA (Waseda University):

(3) In this paper, two methods are compared; one is a simulator of an MHD generator using a heated gas flow behind an incident shock wave in the low pressure chamber and the other is one using a shock tunnel. Which method is considered to be important for the simulator? In the latter case, the static pressure and the temperature might become smaller at the exit of the nozzle. Is it inferior for an MHD generator?

(4) How about connections between interactions of rarefaction waves at the second diaphragm and the theoretical values of Ms_1 ?

(5) How the tailoring condition is changed when helium is used as a test gas?

(6) How about the reliability of the pressure transducers used? What is the cause of discrepancies between the theoretical and the measured values in Fig. 11? These discrepancies must have effects on the data of temperature ratio in Fig. 12 and the pressure ratio at the stagnant in

Fig. 18. I think it is doubtful that reduction of the stagnant pressure is due only to the nozzle.

Authors' closure

(1) The distances between the two pressure transducers are 2.4 m and 3.1 m from the first diaphragm respectively. If the formation distance in helium is assumed to be 30 times the tube diameter, distance of the port of the measurement might be nearly the same as a formation distance.

(2) The distance of the measurement port is 4090 mm from the second diaphragm. The theoretical data of the one diaphragm shock tube are calculated using pressure ratio of the driver and the driven chamber by $P_{61} \times P_{86} = P_{81}$. Then the shock speed M_{s1} in this case has no dependance on P_{61} . Although we do not consider the effects of the reduction of the cross section, the effects of the viscosity and the shock formation, the formation effects might be smaller in this case since the length of the shock tube becomes large.

(3) The final aim of these experiments is to check the feasibility of a shock tunnel for an MHD power generator. The paper describes in part the measurements of properties behind a shock wave in the shock tube working in a conventional one diaphragm shock tube. The necessities for a shock tunnel arise from the fact that the most adequate method of operation of a generator is one of using supersonic flows which are given by the expansion of a cooling gas of a high temperature gas cooled reactor. The closest resemblance of operation mode is given by a shock tunnel. Then, when the effects of the Lorenz force are held smaller in the generator, a shock tunnel is considered to be a good simulator of the generator.

(4) Yes, M_{s1} might be affected by interaction processes. In fact, since the volume of the high temperature and high pressure gas behind a reflected shock wave in front of the second diaphragm is reduced by rarefaction waves which emanate from the driver chamber, the value of M_{s1} becomes smaller in the case when the rarefaction waves from the buffer chamber reach to s1. In the data in Fig. 14, M_{s1} would not be affected since the rarefaction wave cannot reach the shock wave before the measurement port.

(5) Helium gas is used depending on necessities of an MHD generator. A tailoring condition has no dependance on this choice.

(6) The signals of the pressure transducer contain high frequency oscillations which are pro-

duced by incomplete attachment of the transducers and the inherent oscillations of the gauge. The errors are estimated to be 10% of the signals. Reduction of pressure at the stagnant is consider-

ed to be due to expansion from the nozzle, which is revealed from the measurements. We could detect a part of an incident shock wave escaping from the nozzle.