533. 6. 011. 5 : 532. 59

Investigations of the Aerodynamic Characteristics of the Shock Tubes*

(Part 1, The Effects of Tube Diameter on the Tube Performance)

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The effects of tube diameter on the propagation behavior of a shock front were investigated by using two shock tubes with different sizes and by comparing with the other data. The process of the formation of a shock front when the diaphragm was ruptured was observed by schlieren method. From this experiment, it was found that the observed shock Mach numbers were larger than the values obtained by the simple theory. Such result depends on the opening time of the diaphragm and the diameter of the tube. Therefore, the various factors influencing the opening time of the diaphragm and the shock formation distance were discussed and the functional relations between these factors were clarified using the dimensional analysis. The expression for the shock formation distance derived by the dimensional analysis was in satisfactory agreement with the experimental results.

1. Introduction

The experimental values on the propagation behavior of a shock front along the axis of the shock tube obtained from the previous investigations do not always agree with the theoretical values predicted by the simple model of a shock tube flow. The following two reasons will be considered as the main origins of the disagreement. First, due to the viscous and heat conducting effects of the gas, a wall boundary layer will be formed between the shock front and the head of the rarefaction wave. By this effect, the shock speed decelerates monotonously from the ideal speed predicted by simple theory as the shock propagates along the tube^{(1)~(3)}. Therefore the discrepancy between the real shock speed and the ideal one by the boundary layer grows dominant at the distance far from the diaphragm location. Second, the opening of the diaphragm is not instantaneous, i. e. the bursting time of the diaphragm is finite. For this reason, the shock front will be composed of continuous compression waves which are produced during the process of the bursting of the diaphragm⁽⁴⁾, and whether the

propagating shock speed becomes larger than the ideal one or not depends on the kinds of working gases and the initial conditions.

In the practical shock tube flow, the growth rate of the wall boundary layer and the bursting time of the diaphragm depend on the hydraulic diameter of the tube, the material property of the diaphragm, the kind of working gas and the working conditions and so on. Therefore the performance of the shock tube will be influenced by these factors. However, no papers which could explain comprehensively the effects of these factors have been published to date.

Most of the previous experiments on the variation of the shock speed along the axis of the tube have been done by using the tube with a comparatively small hydraulic diameter. The influence of the bursting time of the diaphragm may be neglected in the small tube but can not be disregarded in the case of a large hydraulic diameter, because the bursting time is considered to become larger with an increasing hydraulic diameter.

In this paper, the effects of tube diameter on the propagation behavior of the shock front have been investigated by using two shock tubes; one with a comparatively large hydraulic diameter, and the other with a small one. Moreover, we observed the flow near the diaphragm by the schlieren method

* Received 27th May, 1968.

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when the diaphragm was ruptured and the process of the formation of a shock front was clarified. Based on these experimental results, the various factors influencing the bursting time of the diaphragm and the shock formation distance were discussed, and the functional relations between these factors were obtained using the dimensional analysis.

Nomenclature

- a : speed of sound
 D : hydraulic diameter of the tube
 $= \frac{4 \text{ (cross sectional area)}}{\text{(wetted perimeter of cross section)}}$
 h : thickness of diaphragm material
 l : length of contact region
 M_1 : shock Mach number ($=U_s/a_1$)
 p : static pressure
 P_{41} : diaphragm pressure ratio ($=p_4/p_1$)
 ΔP : initial pressure difference across diaphragm
 $(=p_4-p_1)$
 t : time
 u : gas speed
 U_s : propagation speed of shock front
 x : distance from diaphragm location
 x_f : shock formation distance
 γ : ratio of specific heats
 ρ_D : density of diaphragm material
 σ_B : ultimate stress of diaphragm material
 τ_{op} : opening time of diaphragm (diaphragm bursting time)
Subscripts
 1: initial state of driven section
 4: initial state of driver section
 th: value estimated by simple theory

2. Simple theory⁽⁵⁾

Simple theory of the shock tube flow is based on the following assumptions:

- (1) the flow is one-dimensional,
- (2) the working gas is ideal, that is, inviscid and non-heat conductive fluid,
- (3) the diaphragm separating two compartments of the tube ruptures instantaneously and at that moment, a shock front is formed with a finite strength which is determined by initial conditions.

The shock tube flow obtained under these assumptions is displayed in Fig. 1. A thick solid line and a wave line in Fig. 1 (b) represent the shock front and the contact surface respectively, and the broken lines mean rarefaction waves. The shock front propagates into the low pressure channel with constant strength p_2/p_1 which is, as shown in Fig. 1 (c), determined uniquely by the relation of simple rarefaction and shock wave. The shock Mach number M_{1th} is calculated by the following equation⁽⁵⁾.

$$\frac{p_4}{p_1} = \frac{2\gamma_1 M_{1th}^2 - (\gamma_1 - 1)}{\gamma_1 + 1} \times \left[1 - \frac{\gamma_4 - 1}{\gamma_1 + 1} \frac{a_1}{a_4} \left(M_{1th} - \frac{1}{M_{1th}} \right) \right]^{-\frac{2\gamma_4}{\gamma_4 - 1}} \dots (1)$$

3. Experimental procedures

3.1 Shock tube

The larger one of the two shock tubes used in this work is shown schematically in Fig. 2. This consists of nine tube elements and each cross section is 90×180 mm ($D=120$ mm) except the dump tank at the tube end. The elements of low pressure side are interchangeable with each other. At the side wall of each element, some measuring holes in which the pressure-transducer detectors are mounted are arranged. As the working gas, air is used. The pressure of the driver section is the atmospheric pressure, and that of the driven section is controlled between 5~380 mmHg ab. using a vacuum pump. The experiments are carried out after the temperature in the low pressure section has recovered to the room temperature. Three or four sheets of cellophane each 40μ in thickness are used in a pile as a diaphragm. A spring-driven plunger is set in the high pressure chamber, and it ruptures the diaphragm on the signal from the x-joint of the camera, as shown in Fig. 2.

The other small shock tube has a cross-section of 38 mm square ($D=38$ mm), and the lengths of

Fig. 1 Flow pattern by the simple theory

the high- and low-pressure sections are 1.35 and 6.0 m respectively. Working gas, working conditions and the diaphragm for this tube are the same as those of the larger tube, and so the sketch of this facility is omitted.

3.2 Measurements of shock speed

A strain gauge or a piezo-gauge is used as the pressure-transducer detector. The shock speed U_s is determined from the time interval between the voltage signals recorded by the two detectors (e. g. ② and ③ in Fig. 2) using the oscillograph display. The distance between these two detectors is chosen in the range from 300 to 500 mm. Shock Mach number M_1 is obtained by dividing U_s by the sound speed a_1 at the room temperature. M_1 thus obtained is the average shock Mach number between these two sections of the tube. In the following figures, however, M_1 is plotted as the shock Mach number at the middle point of these two sections. Typical oscillograms by a strain-gauge or a piezo-gauge detector are shown by (a) and (b) in Fig. 3 respectively.

4. Experimental results and discussion

4.1 Propagation velocity of a shock front

Representative data of 90×180 mm tube showing

Fig. 2 Shock tube facility and its measuring system

Fig. 3 Typical oscillogram detecting a shock front (diaphragm pressure ratio=45.0, $x=6\,690$ mm)

the variation of the shock Mach number M_1 with the distance x from the diaphragm position are given in Fig. 4. As is evident from this figure, M_1 at a given pressure ratio P_{41} increases at first rapidly with an increasing x , and becomes maximum at a certain distance. After that M_1 decreases monotonously with an increasing x and approaches asymptotically a constant value. The shock formation distance x_f is defined as x where M_1 becomes maximum⁽⁶⁾. The acceleration of the shock front in the region of $x < x_f$ is due to the successive compression waves generated during the opening process of the diaphragm, while the deceleration of the shock front in the range of $x > x_f$ results from the viscous effect of the gas. These effects will be discussed in detail in the following report.

To clarify the influence of the tube diameter on M_1 , the present data are compared with those given by Emrich and Curtis⁽⁷⁾. The result is shown in Fig. 5. As their measurements were obtained from the shocks moving into air at atmospheric

Fig. 4 Experimental results of the variation of shock Mach number along the tube

Fig. 5 Influence of the cross-sectional area of the tube on the shock Mach number

pressure, the working condition was somewhat different from the present experiment. Figure 5 shows that at the same diaphragm pressure ratio, the larger is the hydraulic diameter of the tube, the larger become M_1 and x_f . This phenomenon is closely related to the fact that the opening time of the diaphragm is finite, and it will be discussed later. Also Fig. 5 shows that the rate of decrease of M_1 becomes larger in the case of a smaller diameter tube. This can, as is generally known, be explained by the shock attenuation theory⁽²⁾.

4.2 Observation of the formation process of a shock front by schlieren method

Figure 6 shows the series of schlieren photographs taken during the formation process of the

shock front near the diaphragm of the 38 mm square tube at the diaphragm pressure ratio of 10. At the left end of Fig. 6 (a), we can see that the cellophane diaphragm bulging to the low pressure side is in the state just before bursting. If the diaphragm is pierced by the prod, a small opening near the center is formed, and thereafter high pressure air flows into the low pressure section like a jet, as shown in (b). As represented in (c), the diaphragm is broken completely step by step with time by the outward tearing of the diaphragm, and the flows over the whole cross sectional area of the tube are induced. During this process, the successive compression waves are formed and these compression waves overtake each other and coalesce to form a shock front. At the distance from the diaphragm of about 50 mm ($=1.3D$) in (d), a weak shock

Fig. 6 Schlieren photographs showing the formation process of a shock front ($P_{d1}=10.0$)

front (this is represented as SF in Fig. 6) is observed, but in this state it looks not like a plane front but like a three-dimensional surface. It becomes strong gradually as it travels along the tube. At a distance from the diaphragm of about 90 mm ($=2.4D$), as is observed in (f), it appears to be plane and normal. As the shock formation distance of this tube at $P_{41}=10$ was about 550 mm, it became evident that at a distance of one-sixth of the shock formation distance the shock front was quite plane and normal.

Henshall⁽⁸⁾ explained the process of the formation of a shock front as follows. When a spherical curved diaphragm is ruptured, a number of compression waves are propagated into the channel. These compression waves very quickly coalesce to form a spherical shock wave. Since the center of curvature of the spherical shock is on the center of the diaphragm, the shock profile will become a plane form gradually as it propagates downstream. The regular reflection of this curved shock will take place at the walls of the tube until the angle of incidence of the shock becomes inappropriate to the regular reflection of the shock and consequently the shock will change to a Mach reflection. The triple points of the Mach reflection move toward the center of the tube, and in consequence a plane shock wave will be produced. According to his explanation, behind two triple points on the shock front, the reflected shock waves and the slip lines will follow. However, as is evident from Fig. 6, such wave system was not observed in this experiment. Moreover the distance from the diaphragm to the position where the plane shock was formed was considerably shorter than that of Henshall's estimation. From these considerations, the center of curvature of the three dimensional shock front formed by the successive compression waves will not necessarily agree with the center of the diaphragm. Rather, although the bursting process of the diaphragm is a three-dimensional phenomenon, the formation process of a shock front by successive compression waves produced by bursting the diaphragm may be considered as one-dimensional.

In the simple theory, the contact surface separating the driver gas from the driven gas is assumed as a normal plane in which the discontinuity of density and temperature exists. But in a real shock tube flow, due to the fact that the bursting of the diaphragm is not instantaneous, as shown by CZ in Fig. 6, a contact region of mixed hot and cold air which is convex to the downstream may be formed. Representative data showing the relation between the dimensionless length of the contact region l/D and the dimensionless distance from the diaphragm

to the center of the contact region x/D are given in Fig. 7. This relation has been obtained from schlieren photographs. Near the diaphragm (region I in Fig. 7), the growth rate of l is comparatively large due to the continuous opening of the diaphragm, and in this region l is nearly equivalent to x , as is known from Fig. 7. After the diaphragm opens completely, in spite of the increase of l being expected to cease, l continues to grow with time (region II in the Fig. 7). This is due to the breaking of the initial steep temperature gradient owing to the heat conduction and the turbulent diffusion. However, the growth rate of l in region II is small as compared with that in region I. Emrich and Wheeler⁽⁹⁾ had taken the spark shadowgraphs near the diaphragm just after the rupture and showed that the hot and cold gas were mixed in a region occupying only 1 or 2 tube diameters. Their results agree very well with the present results (Fig. 7).

From the above discussions, we may conclude that the shock front is not formed instantaneously as assumed in the simple theory, but is generated by a series of compression waves produced during the opening process of the diaphragm and is accelerated by the following successive compression waves. Therefore, in order to clarify the propagation behavior of the shock front and the following flow state, it is necessary to discuss the diaphragm bursting time and the shock formation distance.

4.3 Factors influencing the diaphragm bursting time

The quantities having primary influence the diaphragm bursting time τ_{op} are considered as follows:

- (1) initial pressure difference across the diaphragm $\Delta P (=p_1 - p_2)$ kg/m²,
- (2) hydraulic diameter of the shock tube D m,
- (3) thickness of the diaphragm material h m,
- (4) density of the diaphragm material ρ_D kg sec²/m⁴,
- (5) ultimate stress of the diaphragm material σ_B kg/m².

Further, the initial pressure in a low pressure

Fig. 7 Variation of the length of the contact region along the tube ($P_{41}=10.0$)

channel, the diaphragm pressure ratio* and the Young's modulus of the diaphragm material will have influences on the diaphragm bursting time. However, the effects of these factors are considered secondary as compared with those of the above five quantities, and so neglected here for simplicity. Therefore, the following relation is obtained.

$$f(\tau_{0p}, \Delta P, D, h, \rho_D, \sigma_B) = 0 \quad (2)$$

Applying the π theorem in Eq. (2), we obtain the three dimensionless quantities, i.e.

$$f\left(\frac{\tau_{0p}\Delta P^{1/2}}{D\rho_D^{1/2}}, \frac{h}{D}, \frac{\sigma_B}{\Delta P}\right) = 0 \quad (3)$$

Combining the first and the second dimensionless quantities of Eq. (3), the relation on the diaphragm bursting time obtained by Kireyev⁽¹⁰⁾ may be given as:

$$\tau_{0p} \propto (\rho_D h D / \Delta P)^{1/2} \quad (4)$$

Equation (4) which shows that τ_{0p} is proportional to the square root of D is not consistent with the present experimental data, as shown in the following article. Combining the first and the third dimensionless quantities of Eq. (3), we obtain the relation on the diaphragm bursting time derived by Liepmann et al.,⁽¹¹⁾ in the case of ΔP being constant.

$$\tau_{0p} \propto D(\rho_D / \sigma_B)^{1/2} \quad (5)$$

Rearranging Eq. (3) yields

$$\tau_{0p} = D \left(\frac{\rho_D}{\Delta P} \right)^{1/2} f_1 \left(\frac{h}{D}, \frac{\sigma_B}{\Delta P} \right) \quad (6)$$

This equation means that τ_{0p} is proportional to

Fig. 8 Relation between the shock formation distance and the diaphragm pressure ratio

* When the diaphragm pressure ratio and the initial pressure difference across the diaphragm are given, the initial pressures in driver and driven sections are uniquely determined. Therefore, to determine the initial conditions related to the pressure, it is sufficient to consider only two quantities concerning the initial pressure as the independent variables having influence on the shock tube flow. In this work, the diaphragm pressure ratio and the initial pressure difference are considered respectively as the quantities having influence on the shock formation distance and the diaphragm bursting time. But the formation distance is affected by the diaphragm bursting time. As the result, two quantities concerning the initial pressure are considered in this paper, therefore the initial conditions on the pressure are uniquely determined.

D and the square root of ρ_D and inversely proportional to the square root of ΔP , if h/D and $\sigma_B/\Delta P$ remain constant. This relation is, as will be shown in the following article, in satisfactory agreement with the experimental results.

4.4 Shock formation distance

The shock formation distance is obtained from the M_1-x curve (Fig. 4). Experimental data of the dimensionless shock formation distance x_f/D are plotted against the diaphragm pressure ratio P_{41} in Fig. 8. In this figure, the experimental data of 38 mm square tube are also shown. The effects of tube diameter on the formation distance will be discussed later in this article.

When p_4 remains constant, the increase of ΔP by the increasing of P_{41} , as shown in Fig. 9, is extremely small if P_{41} is comparatively large. Therefore, within the limits of this experiment, ΔP in Eq. (6) may be considered to remain constant, and so the effect of P_{41} on the variation of τ_{0p} will be neglected. Remembering this, $t-x$ diagram showing the variations of shock formation distance with diaphragm pressure ratio will be described as Fig. 10. The broken line in this figure corresponds to the case of large diaphragm pressure ratio as compared with the case represented by the solid line. The shock front starts with the sound speed

Fig. 9 Relation between the diaphragm pressure ratio and the diaphragm pressure difference

Fig. 10 Variation of the shock formation distance with the variation of the diaphragm pressure ratio ($\tau_{0p} = \text{const.}$)

a_1 . (When the opening area of the diaphragm is infinitesimally small, the disturbance propagating into the low pressure gas is a sound wave). Then the shock front is accelerated continuously and its speed becomes maximum, when the tail of compression wave, which may be assumed to be generated from the contact surface at the moment of the diaphragm being completely opened, overtakes the shock front. Therefore, the shock formation distance depends on the growth rates of shock speed and the speed of the tail of compression wave. These are determined from initial condition, and may become larger when P_{41} is set larger. So we cannot generalize the variation of x_f with P_{41} . Experimentally, Fig. 8 shows that, under the conditions that the same tube is used and the driver pressure p_4 remains constant, the larger is P_{41} , the larger x_f becomes. Therefore, we may estimate that, as shown in Fig. 10, the growth rate of shock speed with an increasing P_{41} becomes larger than that of the tail of compression wave. However, as the tail of compression wave passes through the continuously varied entropy band resulting from the continuous variation of the strength of shock front, the locus of it is, strictly speaking, not represented by a straight line as in Fig. 10.

It may be concluded from these considerations that the shock formation distance will be primarily affected by τ_{op} , a_1 and P_{41} . The effects of the other factors are considered secondary and are neglected here. So the following equation is obtained,

$$x_f = x_f(\tau_{op}, a_1, P_{41}) \quad (7)$$

According to the dimensional analysis, we obtain

$$g(x_f/\tau_{op}a_1, P_{41}) = 0 \quad (8)$$

therefore,

$$x_f = \tau_{op} a_1 f_2(P_{41}) \quad (9)$$

Substituting Eq. (6) into τ_{op} of Eq. (9), we have

$$x_f = D a_1 \left(\frac{\rho_D}{\Delta P} \right)^{1/2} f_1 \left(\frac{h}{D}, \frac{\sigma_B}{\Delta P} \right) f_2 \left(\frac{p_4}{p_1} \right) \quad (10)$$

We can know the factors influencing the shock formation distance from Eq. (10).

As described previously, the experimental results shown in Fig. 8 for two shock tubes have been

obtained under the same working conditions. Therefore, $\rho_D/\Delta P$ and $\sigma_B/\Delta P$ in Eq. (10) remain constant for both tubes at the same diaphragm pressure ratio. In this experiment, the values of h/D in Eq. (10) are nearly the same for both tubes. Therefore, at the same diaphragm pressure ratio the functions f_1 and f_2 of Eq. (10) are constant for both tubes, and x_f is proportional to D . On the other hand, if the shock formation distance is varied from x_f to x'_f assuming that x_f is proportional to the n th power of D under the condition of the hydraulic diameter of the shock tube being changed from D to D' , we obtain

$$n = 1 + \log \left(\frac{x_f/D}{x'_f/D'} \right) / \log(D/D') \quad (11)$$

Substituting the experimental values for two shock tubes shown in Fig. 8 into Eq. (11), n is about 0.88, as shown in Fig. 11. Therefore, it may be reasonable to consider that x_f is proportional to D . Further, as is evident from Fig. 5, x_f becomes larger with an increasing D at the same diaphragm pressure ratio, which can easily be explained from Eq. (10).

ШТЕМЕНКО⁽¹²⁾ measured the shock speed with a few different opening times of the diaphragm using a 34×72 mm shock tube ($D=46$ mm, length of high pressure section=0.35 m, length of low pressure section=1.3 m, driver gas is a mixture of air and helium, driven gas is air, $p_4=3 \sim 7.5$ atm, $p_1=1$ atm ~ 50 mmHg ab). His results are shown in Fig. 12 taking τ_{op} as the parameter. These experiments were done under the conditions that the initial temperatures of the working gases were kept constant and that the diaphragm pressure ratio was 45. From this figure, in the cases of $\tau_{op}=420, 680$ and $750 \mu\text{sec}$, x_f is found to be 50, 80 and 90 cm respectively. Hence, these results indicate that x_f is nearly proportional to τ_{op} . On the other hand, as P_{41} and a_1 were kept constant in these experiments, according to Eq. (9), x_f is proportional to

Fig. 11 Variation of n with the diaphragm pressure ratio

Fig. 12 Experimental results on the shock speed by ШТЕМЕНКО⁽¹²⁾ ($P_{41}=45$)

τ_{op} . So we may conclude that the ШТЕМЕНКО's results satisfy the relation of Eq. (9).

4.5 The phenomenon in which the observed shock Mach number may be larger than the predicted value by the simple theory

In the former comparisons⁽⁴⁾ between the shock Mach number M_{1th} expected by the simple theory and the observed shock Mach number M_1 , M_1 which is larger than M_{1th} may be observed, for a diaphragm pressure ratio P_{41} above the order of 10^4 , but M_1 is equal or slightly smaller than M_{1th} with P_{41} less than 10^3 . In order to compare the present experimental results of M_1 represented in Fig. 4 with M_{1th} calculated from Eq. (1), the percentage of M_1/M_{1th} is plotted against x/D in Fig. 13. From this, it is evident that, even with P_{41} less than 10^3 , M_1 becomes larger than M_{1th} in the range of x/D between about 10 and 45. The main reasons for M_1 becoming larger than M_{1th} are considered as the following two; (1) imperfect diaphragm rupture (2) mixing of gases in the contact region. The latter effect does not arise in the case of the specific heats at the constant pressure of driver and driven gases being equal to each other⁽⁴⁾. The former effect will become dominant with an increasing D , because τ_{op} is proportional to D according to Eq. (6), which is shown to coincide with experimental results. This is also explained experimentally as follows. Although in the experiment by Duff⁽¹³⁾ ($D=28$ mm) M_1 was smaller than M_{1th} with $P_{41}=10^4$, in the experiment by White⁽⁴⁾ ($D=82$ mm) M_1 became larger than M_{1th} with the same diaphragm pressure ratio. Further Tajima et al.⁽¹⁴⁾ reported that M_1 became larger than M_{1th} with $P_{41}=500$ in the tube with $D=100$ mm. In the present experiment ($D=120$ mm), as described previously, M_1 became larger than M_{1th} even with P_{41} less than 10^3 . From these considerations, although the working conditions of the experiments described above are not the same, it may be concluded that, if the working condition remains constant, the phenomenon of $M_1 > M_{1th}$ will possibly happen as D becomes larger.

Fig. 13 Ratio of the experimental value to the theoretical value of the shock Mach number

5. Conclusions

The effects of tube diameter on the shock tube performance were investigated by using two shock tubes with different diameters and compared with other experimental data. And the formation process of a shock front by bursting the diaphragm was observed by the optical method. As the result, the following conclusions were obtained.

(1) In the case of a shock tube with a large hydraulic diameter, the finite opening time of the diaphragm has large influence on the shock tube performance.

(2) The functional relationship between the various factors which have primary influence on the diaphragm opening time was clarified by the dimensional analysis. We can derive from that relation the results obtained by Kireyev⁽¹⁰⁾ and by Liepmann et al.⁽¹¹⁾ However, the former results did not agree with the present experimental values.

(3) In like manner, the functional relation between the various factors influencing the shock formation distance was clarified. The equation for the shock formation distance which was derived from this relation was in satisfactory agreement with the experimental results by ШТЕМЕНКО⁽¹²⁾. According to the present data, if the hydraulic diameter of the tube is changed under the constant working conditions, the shock formation distance changes in proportion to the 0.88th power of the hydraulic diameter of the tube.

(4) In the process in which a shock is formed, at first a weak shock front is generated by a series of compression waves produced during the continuous opening of the diaphragm and then it is accelerated by the following successive compression waves. In this process, the distance from the diaphragm to the position where a plane normal shock front is formed is about one-sixth of the shock formation distance in the present data, which is considerably shorter than that by the Henshall's estimation.

(5) The growth rate of the length of the contact region near the diaphragm is larger than that in the region far from the diaphragm. Near the diaphragm, the increase of the contact region length depends upon the continuous opening of the diaphragm, but the increase in the downstream may result in the flattening of the temperature gradient due to the heat conduction and the turbulent diffusion.

(6) If the working conditions remain constant, the phenomenon that the observed shock Mach number may be larger than the predicted value by the simple theory will possibly happen as the hydraulic diameter of shock tube becomes larger. In this

experiment, shock Mach numbers larger than the predicted values by the simple theory were observed even with the diaphragm pressure ratio less than 10^2 .

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