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Investigation of the Starting Process of a Supersonic Wind Tunnel*

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The starting process of a supersonic wind tunnel with a diffuser with contraction has been studied in detail by schlieren optical observations and pressure measurements.

As the result, it has been shown that the wind tunnel starts when the flow is even sonic but not choked at the second throat. Based on this fact, the flow in the starting process has been classified into three patterns according to the area ratio of the second throat to the test section. Furthermore, the differences between the theoretical values and the experimental results of the starting pressure ratio and the minimum starting area at the second throat have been well explained, taking into consideration the fact that a normal shock wave assumed in the previous one-dimensional theory becomes a pseudo-shock wave due to the interaction with the wall boundary layer.

1. Introduction

The starting and operating pressures must be decreased if possible to improve the efficiency of a supersonic wind tunnel. According to the previous one-dimensional theory⁽¹⁾ (abbreviated N.S. theory) where a normal shock wave is assumed, when the contraction ratio defined as the area ratio of the test section to the second throat is not larger than a certain critical value determined by the Mach number of the test section, the normal shock wave is instantaneously swallowed from the test section to the downstream side of the second throat. And the starting pressure ratio is equal to the total pressure ratio across the normal shock and is independent of the contraction ratio.

On the other hand, previous experimental results^{(2)~(6)} have shown that the starting pressure ratio varies with the contraction ratio, and the difference between the theoretical values and the experimental results increases as the Mach number of the test section increases. Furthermore, the maximum contraction ratio where the wind tunnel can start does not agree with the theoretical value.^{(3)~(5)}

It may be due to the fact that the normal shock assumed in the N.S. theory extends over a great distance interacting with the boundary layer and becomes a pseudo-shock wave.^{(7)~(9)} A lot of experimental investigations^{(2)~(6)} have been reported so far on the effects of the diffuser configuration on the starting pressure ratio, but it is not yet understood why the starting pressure ratio varies with the contraction ratio.

In this paper, experiments have been performed in detail to investigate the behavior of the pseudo-shock in the starting process by schlieren optical observations and pressure measurements, and the phenomena described above have been clarified.

2. Experimental apparatus and procedures

The supersonic blow-down tunnel and measuring system used in this work are shown schematically in Fig.1. Figure (a)

Fig.1 Experimental apparatus

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shows the flow and measurement system, and Fig.(b) shows the configuration and dimensions of the wind tunnel. The high pressure dry air in a reservoir flows into the stagnation chamber and, accelerated to supersonic in the Laval nozzle, it goes into the test section and then is discharged into the atmosphere through the diffuser, the settling chamber, and the silencer. The tunnel is two-dimensional and has a width of 60mm. The heights at the test section and the diffuser exit are held constant at 60mm and 111mm, respectively as shown in the figure. The heights at the nozzle throat and the second throat are variable, and in this work, these are set so as to obtain the Mach number at the test section M_t of 1.80 and 2.80, and the area ratio of the second throat to the test section $\Psi \equiv A_2/A_t$ (i.e., the inverse of the contraction ratio) of 1.00 ~ 0.800 (for $M_t=1.80$) and 1.00 ~ 0.700 (for $M_t=2.80$), respectively.

The axial static pressure distributions along the duct wall are measured by a multi-limb mercury manometer. The pressure variations with time are measured by pressure transducers. A pitot-probe with an outer diameter of 0.8mm is set at the center of the second throat, and the total pressures at the second throat P_{02} and the stagnation chamber P_{08} are simultaneously recorded by a data recorder, and then reproduced by an X-Y plotter. The flow is visualized by a schlieren optical system with two light sources, that is, a xenon continuous light for high-speed photography and a magnesium spark light for single one.

In the experiments, the stagnation pressure P_{08} is so gradually increased that the flow may be regarded as quasi-steady. And it has been confirmed that the flow and the starting pressure ratio are not affected by insertion of the pitot-probe because its cross section is extremely small compared with that of the second throat.

3. Experimental results and discussions

3.1 Axial static pressure distributions and classification of flow patterns

An example of the static pressure distributions on the duct wall is shown in Fig.2 where the abscissa is the distance from the nozzle throat x and the ordinate is the ratio P/P_{08} of the local static pressure P to the stagnation pressure P_{08} . The broken line shows the value calculated by Tucker's method⁽¹⁰⁾ where wall boundary layers are taken into account. The wind tunnel pressure ratio Φ is defined as the ratio of P_{08} to atmospheric pressure P_a . For $\Phi \equiv P_{08}/P_a = 1.69$ (Curve ①), the shock wave generated at the nozzle throat (called S -shock in this paper) reaches the test section, and it is observed that the static pressure decreases a little in the contracted section because of the accel-

ation of the flow. For the cases of $\Phi = 1.76$ and 2.13, the wind tunnel is started and S -shock is located downstream of the second throat. As evident from the pressure distributions, S -shock is not a normal shock but a pseudo-shock. In this paper, the starting of the wind tunnel is defined as the moment when the head of S -shock moves downstream and the test section becomes fully supersonic, and it is determined by pressure measurements.

The pressure distributions for the same M_t as that of Fig.2 and a smaller Ψ are shown in Fig.3. As evident from Curves ① ($\Phi=1.79$) and ② ($\Phi=2.54$), besides S -shock, another shock wave is observed downstream of the second throat. The existence of this shock, called T -shock in this paper, means that the flow is sonic at the second throat.

According to the N.S. theory, the flow is assumed to be isentropic except the section where a normal shock is located, and the sonic state of the flow at the second throat is equivalent to a choking of flow at that section, and so, once the flow is choked at the second throat, the flow pattern upstream of the second throat and the position of S -shock do not change and the wind tunnel does not start even if Φ increases. However, in the case of $\Phi=3.99$ (Curve ③), S -shock has been

Fig.2 Wall static pressure distributions ($M_t=1.80$, $\Psi=0.950$, Pattern I)

Fig.3 Wall static pressure distributions ($M_t=1.80$, $\Psi=0.833$, Pattern II)

swallowed downstream of the second throat, and the wind tunnel is started. This means that the sonic state of the flow at the second throat is not equivalent to the choking in actual flows. That is to say, as will be shown in Fig.5(a) later, the flow does not fill the whole cross section of the second throat due to the boundary-layer separation caused by S -shock. Therefore, if the separation region at the second throat decreases with an increase of Φ , the flow rate through the second throat increases and the wind tunnel can start. In other words, the flow is not choked at the second throat in this case.

For a still smaller Ψ , for example for $\Psi=0.817$ and $M_t=1.80$, S - and T -shocks were observed and the wind tunnel did not start in the present experimental range of $\Phi \leq 6.0$. This may be due to the fact that the flow is not only sonic but also choked at the second throat, and the position of S -shock is fixed. The description above refers to the case of $M_t=1.80$, and the same phenomena are also observed in the case of $M_t=2.80$.

Based on the facts described above, the flow in the starting process is classified into the following three patterns according to Ψ .

Pattern I: The flow is choked at the nozzle throat, and S -shock is generated. When Φ increases, the wind tunnel starts as shown in Fig.2. The range of this pattern was $0.917 < \Psi < 1.00$ for $M_t=1.80$ and $0.817 < \Psi < 1.00$ for $M_t=2.80$.

Pattern II: The flow is choked at the nozzle throat and is sonic at the second throat, and so S - and T -shocks are generated. When Φ increases, the wind tunnel starts as shown in Fig.3. The range of this pattern was $0.833 < \Psi < 0.900$ for $M_t=1.80$ and $0.725 < \Psi < 0.800$ for $M_t=2.80$.

Pattern III: The flow is choked not only at the nozzle throat but also at the second throat. In this case, the wind tunnel never starts even if Φ increases. The range of this pattern was $\Psi < 0.817$ for $M_t=1.80$ and $\Psi < 0.717$ for $M_t=2.80$. When Ψ is very small, the flow is choked at the second throat at first when Φ increases. Therefore, there exists a lower limit of Ψ for Pattern III. However, this limit has no relationship with the starting process, and so it is not discussed here.

3.2 Optical observations by high speed camera

The behavior of S -shock in the starting process was observed using a high speed schlieren method. A series of pictures for Patterns I and II are shown in Figs.4 and 5 respectively, where the time t is counted from the moment of Fig.(a). The value of Φ slightly increased from 1.67 to 1.78 in the time interval between Figs.4(a) and (c) and from 2.53 to 2.75 in the time interval between Figs.5(a) and (e). In the case of Pattern I, each shock wave constituting S -pseudo-shock passes successively through the second throat, as shown in Figs.4(a)~(c). The moving rates

Fig.4 Schlieren photographs in the starting process
($M_t=1.80$, $\Psi=0.967$, Pattern I)

Fig.5 Schlieren photographs in the starting process
($M_t=1.80$, $\Psi=0.850$, Pattern II)

of S -shock measured from the time intervals between Figs.(a) and (b), and Figs. (b) and (c) are about 0.3m/s and 70m/s, respectively, and so the moving speed of S -shock is very slow up to the second throat and very fast after that.

A sketch of Fig.5(a) is shown under the figure. In these figures, three shock waves constituting S -pseudo-shock are observed. The flow is sonic at the second throat and supersonic downstream of it, and T -shock generated at the second throat locates downstream of the right end of the sight. When ϕ increases a little from this state, each shock wave reaches successively the second throat, and as evident from Figs.(b)~(d), each shock weakens as it approaches the second throat and eventually it can not be observed downstream of the second throat. This is due to the fact that each shock becomes weaker and finally it becomes a compression wave as it approaches the second throat, and also that its moving speed increases downstream of the second throat shown in Fig. (4). After passing through the second throat, each shock merges into T -shock, and strengthens the latter. Figure (e) shows a fully supersonic flow after S -shock has passed through the second throat.

One example of the motion of S - and T -shocks in the starting process is shown in Fig.6. The position of each shock wave (indicated by numbers) constituting S - and T -pseudo-shocks is plotted against the time t counted from the moment when the flow is choked at the second throat. In the figure, T -shock stays a little downstream of the second throat and does not move even when the second, third, and fourth shock waves of S -pseudo-shock pass through the second throat and merge into T -shock because these shocks are considerably weak. When the head of S -pseudo-shock passes through the second throat and merges into T -shock, however, T -shock moves downstream gradually with an increasing ϕ .

3.3 Starting pressure ratio

The starting pressure ratio $\phi_s \equiv (p_{0s}/p_a)_s$ obtained in the present experiment is shown against $\psi = A_2/A_t$ in Fig.7. The range of Patterns I~III mentioned before and the values of ϕ_s calculated by the following equation (N.S. theory) are also indicated.

$$\phi_s = \left[\frac{(\kappa-1)M_t^2+2}{(\kappa+1)M_t^2} \right]^{\frac{\kappa}{\kappa-1}} \left[\frac{2\kappa M_t^2-(\kappa-1)}{\kappa+1} \right]^{\frac{1}{\kappa-1}} \quad (1)$$

where κ is the ratio of specific heats. The minimum starting area ratio $\psi_{\min}$, i.e., the ratio of the minimum area A_2^* of the second throat where the flow is choked at that section to the area at the test section A_t , is represented by the following equation.

$$\psi_{\min} = \frac{A_2^*}{A_t} = \frac{A_2^*}{A_1^*} \frac{A_1^*}{A_t} = \frac{p_{0s}}{p_{02}} \frac{A_1^*}{A_t} \quad (2)$$

where A_1^* is the area of the nozzle throat. According to the N.S. theory, p_{0s}/p_{02} in Eq.(2) is equal to the total pressure ratio across the normal shock for M_t , and A_1^*/A_t can be represented by M_t . Substituting these p_{0s}/p_{02} and A_1^*/A_t into Eq.(2), we obtain

$$\psi_{\min} = \left[\frac{(\kappa-1)M_t^2+2}{(\kappa+1)M_t^2} \right]^{\frac{1}{2}} \left[\frac{2\kappa M_t^2-(\kappa-1)}{(\kappa+1)M_t^2} \right]^{\frac{1}{\kappa-1}} \quad (3)$$

The values of $\psi_{\min}$ by Eq.(3) are indicated for each M_t on the abscissa of Fig.7. As mentioned before, according to the N.S. theory, the area ratio ψ^* where the flow becomes sonic at the second throat is equal to the area ratio ψ_c where the flow is choked there, and these values are given by Eq.(3). Therefore,

$$\psi_{\min} = \psi^* = \psi_c \quad (4)$$

On the other hand, in actual flows, ψ^* and ψ_c are the boundary values between Patterns I and II, and II and III in Fig.7, respectively. Therefore,

$$\psi_{\min} = \psi_c < \psi^* \quad (5)$$

The reason why the experimental value of ψ^* is larger than the value calculated by Eq.(3) is because the effective flow area

Fig.6 Motion of S - and T -shock waves ($M_t=1.80$, $\psi=0.833$, Pattern II)

Fig.7 Relation between starting pressure ratios and area ratios

at the second throat becomes smaller due to the separation of the boundary-layer interacting with S -shock in the test section.

From Fig.7, the experimental results of ϕ_s are larger than the theoretical values, and the difference is larger for $M_t=2.80$ than for $M_t=1.80$. This is because the normal shock assumed in the N.S. theory becomes actually a pseudo-shock, and the loss in the total pressure across the pseudo-shock is larger than that of the normal shock, as will be shown in Fig. 10, and also the frictional loss occurs in the diffuser. Moreover, although ϕ_s of the theory is independent of Ψ , the experimental values decrease with a decreasing Ψ in the range of Pattern I. The main reason for this is considered as follows: the separated region becomes smaller in the contracted section as shown in Fig.2. After becoming minimum near the boundary of Patterns I and II, ϕ_s increases gradually in the region of Pattern II and steeply near the region of Pattern III with a decreasing Ψ . This is due to the increase of losses with the development of T -shock.

Figure 8 represents the comparison of the minimum starting area ratio $\Psi_{\min}$ in the present experiment with the experimental values in References (11) and (3), in which the solid line indicates the calculated value by Eq.(3). For M_t near unity, the experimental values are nearly equal to or a little larger than the theoretical ones, and for a larger M_t , the former is smaller than the latter and the difference increases as M_t increases. The reason for this will be explained in the following section.

3.4 Total pressure distribution within a pseudo-shock

In Eq.(2), $\Psi_{\min}$ is proportional to P_{0s}/P_{02} since A_1^*/A_t in the right side is constant for a given M_t . The value of P_{0s}/P_{02} in actual flows must be estimated

Fig.8 Relation between minimum starting area ratios and test section Mach numbers

taking into consideration the fact that S - and T -shocks are pseudo-shocks.

The motion of S - and T -shocks for $M_t=1.80$ and $\Psi=0.833$ is shown in Fig.9, where the abscissa is a dimensionless distance x/D from the nozzle throat non-dimensionalized by the equivalent diameter D of the test section and the ordinate is ϕ . In the figure, the head of S - and T -shocks and the end of the visible shock region of S -shock were experimentally obtained, and the tail of S -shock was estimated by the diffusion model⁽⁷⁾ in case of a straight duct with constant cross section. It may be pointed out from the figure that the value of P_{0s}/P_{02} in the state that the head of S -shock reaches the inlet of the test section (the state of the point a in Figs.9 and 11) depends both on the relative value of the length of S -shock and the distance from the inlet of the test section to the second throat, and on the axial total pressure distribution in S -shock.

Hence the axial total pressure distribution in the pseudo-shock for $M_t=1.80$ was measured using a straight duct with constant crosssectional area. The results are shown in Fig.10 where the abscissa is a dimensionless distance from the head of a pseudo-shock x/L non-dimensionalized by the length of the pseudo-shock L determined by the static pressure distributions

Fig.9 Motion of S - and T -shocks ($M_t=1.80$, $\Psi=0.833$, Pattern II)

Fig.10 Total pressure distributions in pseudo-shock waves

and the ordinate is the ratio of the local pressure P_0 to P_{0S} . The dash-dotted line indicates the value calculated by the diffusion model⁽⁷⁾ and it is equal to the value across a normal shock at $x/L=1.0$. The experimental values by Tamaki and others⁽⁸⁾⁽⁹⁾ are also shown. In the case of $M_t=1.62$, P_0/P_{0S} decreases steeply in the head region of the pseudo-shock, and it is kept nearly constant in the rear region. Therefore, the pseudo-shock for a smaller M_t is like a normal shock. On the other hand, for a larger M_t , P_0/P_{0S} decreases nearly linearly with x/L , and the experimental value at $x/L=1.0$ is considerably smaller than that of a normal shock, as evident from the results of the present experiment ($M_t=1.80$) and Ref. (9) ($M_t=1.99$).

Based on the facts described above, the relation between $\psi_{\min}$ and M_t in Fig. 8 will be explained as follows. For the case that M_t is a little larger than unity, the total pressure ratio $(P_{0x}/P_{0y})_{PS}$ across the pseudo-shock is a little larger than the total pressure ratio $(P_{0x}/P_{0y})_{NS}$ across the normal shock and the flow suffers the total pressure loss mostly in the head region of the pseudo-shock, therefore P_{0S}/P_{02} in Eq. (2) and $\psi_{\min}$ are a little larger than the theoretical value. On the other hand, for a larger M_t , $(P_{0x}/P_{0y})_{PS}$ is considerably larger than $(P_{0x}/P_{0y})_{NS}$. In this case, however, since P_0 decreases nearly linearly with x in the pseudo-shock and the distance from the inlet of the test section to the second throat (2.67D in this experiment) is considerably small in comparison with the length of the pseudo-shock ($L/D=8.80$ in this experiment), P_{0S}/P_{02} in Eq. (2) becomes smaller than $(P_{0x}/P_{0y})_{NS}$, and so the experimental values of $\psi_{\min}$ become smaller than the theoretical one.

3.5 Relation between total pressures at stagnation chamber and second throat in starting process

The relation between $\Phi \equiv P_{0S}/P_a$ and P_{02}/P_a in the starting process is shown for $M_t=1.80$ in Fig. 11. The representative

Fig. 11 Relation between total pressures at stagnation chamber and second throat ($M_t=1.80$)

examples of Patterns I, II and III are indicated by the curves labelled ①~③, respectively. The oblique straight lines indicate the relation of $P_{02}/P_{0S}=\text{const.}$, and the line labelled $P_{02}/P_{0S}=0.813$ means the total pressure ratio across the normal shock for $M_t=1.80$. As evident from the figure, P_{02}/P_a increases gradually for any curve when Φ increases from unity, but P_{02}/P_{0S} decreases and becomes minimum at the point a (open circle point). This decrease in P_{02}/P_{0S} is due to the development of S -shock. According to optical observations, the point a , that is, the state that the total pressure loss between the stagnation chamber and the second throat is maximum, corresponds to the state that the head of S -shock reaches the inlet of the test section, and the strength of S -shock no more increases.

When Φ increases beyond this point, P_{02}/P_{0S} increases up to the point b (closed circle point) for the curves ① and ②, but P_{02}/P_{0S} for the curve ③ remains constant. The increase in P_{02}/P_{0S} between the points a and b for the curves 1 and 2 may be due to the fact that S -pseudo-shock moves downstream and, as the total pressure in the pseudo-shock decreases nearly linearly along the duct axis as shown in Fig. 10, P_{02} eventually increases since the loss between the stagnation chamber and the second throat decreases. According to optical observations, the point b corresponds to the state that the tail of the shock series constituting S -pseudo-shock reaches the second throat.

When Φ more increases, the wind tunnel starts at the point s (open triangle point) for the curves ① and ②, that is, the value on the abscissa of the point s represents the starting pressure ratio Φ_s in Fig. 7. On the other hand, in the case of Pattern III (curve ③) where the wind tunnel does not start, P_{02}/P_{0S} remains constant after the point a , because the location and the strength of S -shock are fixed by choking of the flow at the second throat. It should be noted that for a larger Φ than that of the point b , P_{02}/P_a is not necessarily a true value since the flow just upstream of the pitot-probe may be supersonic under certain circumstances.

The relation between P_{02}/P_a and Φ in the case of $M_t=2.80$ is shown in Fig. 12. The points a , b , and s have the same meaning as in Fig. 11, and a steep decrease in P_{02}/P_{0S} between the points c and a is observed in this case. Optical observations show that this decrease is due to a rapid strengthening of S -shock, and such phenomenon is not observed for $M_t=1.80$ because the curvature of the nozzle wall is small. In the same way as in Fig. 11, an increase in P_{02}/P_{0S} between the points a and b is observed when the wind tunnel starts (Patterns I and II, Curves ①~③) and it is not observed when the wind tunnel never starts (Pattern III, Curve ④).

The ratio $(P_{0S}-P_{02})/P_{0S}$ of the total pressure loss $P_{0S}-P_{02}$ to P_{0S} at the points

Fig.12 Relation between total pressures at stagnation chamber and second throat ($M_t=2.80$)

Fig.13 Relation between total pressure losses up to second throat and area ratios

a , b , and c in Figs.11 and 12 is plotted against Ψ in Fig.13. From the figure, the total pressure loss at the points a and c is almost independent of Ψ . This means that the effect of contraction at the second throat on S -shock is small at these states of flow. On the other hand, the value at the point b decreases with a decreasing Ψ in Pattern I, and it conversely increases in Pattern II. This result agrees qualitatively with the relation between ϕ_s and Ψ in Fig.7. Therefore, it may be concluded that the difference of $(P_{0s}-P_{02})/P_{0s}$ between the points a and b decreases with a decreasing Ψ in Pattern II, and when the difference finally disappears, the wind tunnel never starts.

4. Conclusions

The starting process of a supersonic wind tunnel with a diffuser with contraction was studied in detail by schlieren optical observations and pressure measurements. The results are summarized as follows.

(1) According to the previous theory, the sonic state of the flow at the second throat means a choking state of flow there. In actual flows, these states are not

equivalent, and the wind tunnel starts when the flow is even sonic but not choked at the second throat.

(2) Based on this fact, the flow in the starting process was classified into three patterns according to the area ratio of the second throat to the test section $\Psi=A_2/A_t$: Patterns I and II where the wind tunnel starts and Pattern III where it does not start. The region of each pattern was shown for the test section Mach number M_t of 1.80 and 2.80.

(3) The starting pressure ratio decreases with a decreasing Ψ in Pattern I and increases in Pattern II. The reasons are well explained.

(4) The behaviors of the shock waves generated at the nozzle throat and the second throat in the starting process were clarified by means of optical observations.

(5) The reason why the experimental value of the minimum starting area of the second throat is different from the theoretical one is explained using the experimental results of the total pressure distributions in the pseudo-shock.

(6) When the wind tunnel pressure ratio ϕ increases from unity, the total pressure ratio of the second throat to the stagnation chamber P_{02}/P_{0s} decreases from unity up to a certain minimum value. When ϕ increases further, P_{02}/P_{0s} increases for Pattern I and II, but remains constant for Pattern III. The reasons are well explained.

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