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# The Effect of Diffuser Geometry on the Starting Pressure Ratio of a Supersonic Wind Tunnel

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**To reduce the starting and stopping loads at intermittent blow-down supersonic wind tunnels, diffuser performance is important to keep the starting pressure ratio as low as possible. A parametric study on diffuser performance for the JAXA 1m x 1m supersonic wind tunnel (JSWT) was conducted by numerical simulation. It was found that it is difficult to estimate performance by using only quasi-1D non-viscous theory because of shock wave-boundary layer interactions. To improve the diffuser performance, a modified diffuser configuration was designed with a viewpoint of shock train phenomena. The modified JSWT diffuser is more slender than the original and its higher performance was confirmed by numerical simulation. This design concept was also validated experimentally with a 10% scale model tunnel at a Mach number of 3.0.**

## Nomenclature

| | | |
|---|---|---|
| $A$ | = | cross sectional area [m$^2$] |
| $M$ | = | Mach number |
| $P0$ | = | tunnel stagnation pressure [Pa] |
| $ps$ | = | static pressure [Pa] |
| $p$ | = | pressure [Pa] |
| $x$ | = | position along the flow direction [m] |
| $h$ | = | height [m] |
| $d$ | = | diameter [m] |
| $\phi$ | = | starting pressure ratio |
| $\gamma$ | = | specific heat ratio |
| $\theta$ | = | diffuser expansion angle [$^\circ$] |
| $\eta$ | = | isentropic diffuser efficiency |

subscripts

| | | |
|---|---|---|
| *1* | = | before shock train region |
| *2* | = | behind shock train region |
| $t$ | = | test section |
| $w$ | = | wall |

## I. Introduction

INTERMITTENT blow-down supersonic tunnels have advantages of easier construction and lower operating cost compared to continuous wind tunnels. However, at supersonic speeds, it become more difficult to design the test models for intermittent wind tunnels because they have to withstand the shock loads when the wind tunnel is started and stopped[2,3]. Figure1 shows a Schlieren photograph when a tunnel started and figure 2 shows the loads measured by an internal balance. Starting and stopping loads are often greater than the aerodynamic forces in the steady state. Generally, to minimize these starting and stopping loads, it is desirable to start the tunnel at the low pressure ratio as possible.

The pressure ratio necessary for starting the tunnel, i.e., the starting pressure ratio, is calculated principally using quasi-1D normal shock wave theory[1], but it is difficult to estimate the performance accurately because of its

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dependence on the wind tunnel geometry. It is suggested that geometry of the wind tunnel diffuser including the second throat influences the starting pressure ratio and the starting process as reported in refs 4–8. However, in those studies, the starting pressure ratio was also influenced by other parts of the wind tunnel and so the effect of diffuser geometry alone has not been sufficiently clarified.

Practical wind tunnel diffusers also require short length and high pressure recovery at various Mach numbers. However, it is difficult to design the diffuser geometry using both quasi-1D normal shock wave theory and a conventional subsonic diffuser design because of the shock wave-boundary layer interactions. Two aims of our present research are to investigate the effect of diffuser geometry on the starting pressure ratio of a supersonic wind tunnel and to develop a concept to determine the diffuser geometry. As an example of a typical blow-down type supersonic wind tunnel, a numerical investigation was conducted for the JAXA 1m by 1m supersonic wind tunnel (JSWT). Diffuser design for the supersonic wind tunnel taking shock trains into account is discussed, and the modified diffuser geometries are validated both numerically and experimentally by a scaled model test.

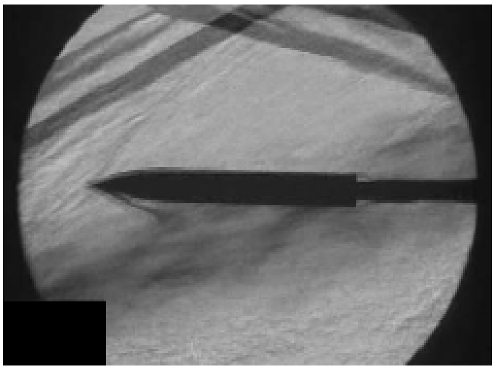

**Figure 1. Schlieren photograph at tunnel start.**

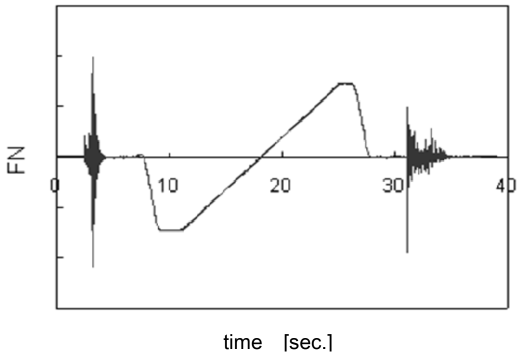


**Figure 2. Starting and stopping load measured by internal balance.**

## II. The starting pressure ratio at supersonic wind tunnel

### A. Quasi-1D Theory

The starting pressure ratio $\phi$ based on quasi-1D normal shock wave theory is expressed as follows:

$$\phi = \left(1 + \frac{\gamma - 1}{2} M_t^{\,2}\right)^{\frac{\gamma}{\gamma-1}} \left\{ \frac{\gamma + 1}{2\gamma M_t^{\,2} - (\gamma - 1)} \right\} \tag{1}$$

Eq. (1) is the case without a subsonic diffuser. If a subsonic diffuser is installed, the starting pressure ratio is as expressed below:

$$\phi = \left(1 + \frac{\gamma - 1}{2} M_t^{\,2}\right)^{\frac{\gamma}{\gamma-1}} \left\{ \frac{\gamma + 1}{2\gamma M_t^{\,2} - (\gamma - 1)} \right\} \left(1 + \frac{\gamma - 1}{2} \eta \frac{(\gamma - 1) M_t^{\,2} + 2}{2\gamma M_t^{\,2} - (\gamma - 1)}\right)^{-\frac{\gamma}{\gamma-1}} \tag{2}$$

where $\eta$ is the isentropic diffuser efficiency. If isentropic flow is assumed in the subsonic diffuser, $\eta$ =1.0 and the starting pressure ratio is equal to the total pressure ratio across a normal shock wave. If $\eta$ =0, the starting pressure ratio is equal to that given by Eq. (1). The relationship between the geometries and $\eta$ for typical subsonic diffusers has been investigated by many researchers using both theoretical and experimental approaches. [15,16]

### B. Actual starting pressure ratio

Although the theory to predict the starting pressure ratio is simple, more complicated phenomena are seen in actual wind tunnels. Figure 3 shows the minimum starting pressure ratios at several blow-down type supersonic wind tunnels. For blow-down wind tunnels exhausting to the atmosphere, $\phi$ is the ratio of tunnel stagnation pressure to atmospheric pressure. In Fig. 3, it is found that each tunnel has a different starting pressure and that the minimum pressure ratios are greater than those predicted by Eq. (1) for almost all wind tunnels. This indicates that the effects of tunnel geometry including the subsonic diffuser is not negligible because of viscosity.

Figure 4 shows a schematic of the JAXA 1 m × 1 m supersonic wind tunnel (JSWT). It is a typical blow-down type supersonic wind tunnel. Its 1.8m-long test section has a 1 m x 1 m cross section, and the Mach number can be varied between 1.4 to 4.0 by a 2D variable nozzle. The maximum duration time is about 40 seconds, and it can run every 30 minutes. The second throat area is varied by wedges installed in the tunnel side walls according to the test Mach number. The unit Reynolds number range is from $2.0 \times 10^7$ to $6.0 \times 10^7$ [1/m].

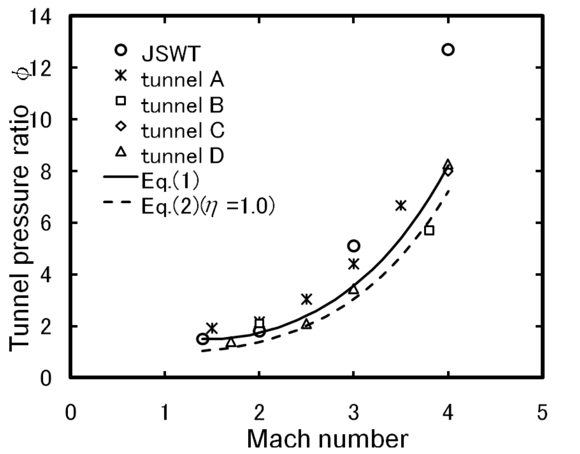


**Figure 3. Starting pressure ratio at practical wind tunnels**

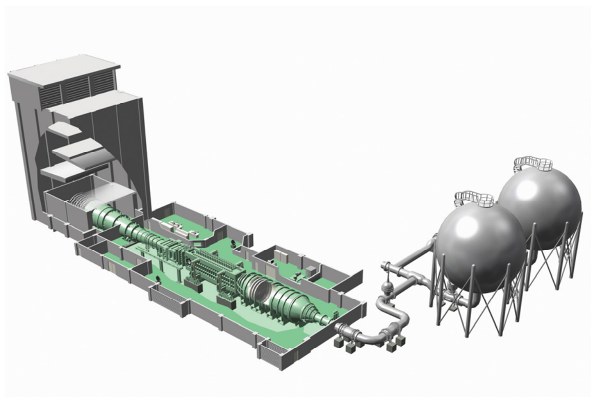

**Figure 4. Schematic of JAXA 1m x 1m supersonic wind tunnel.**

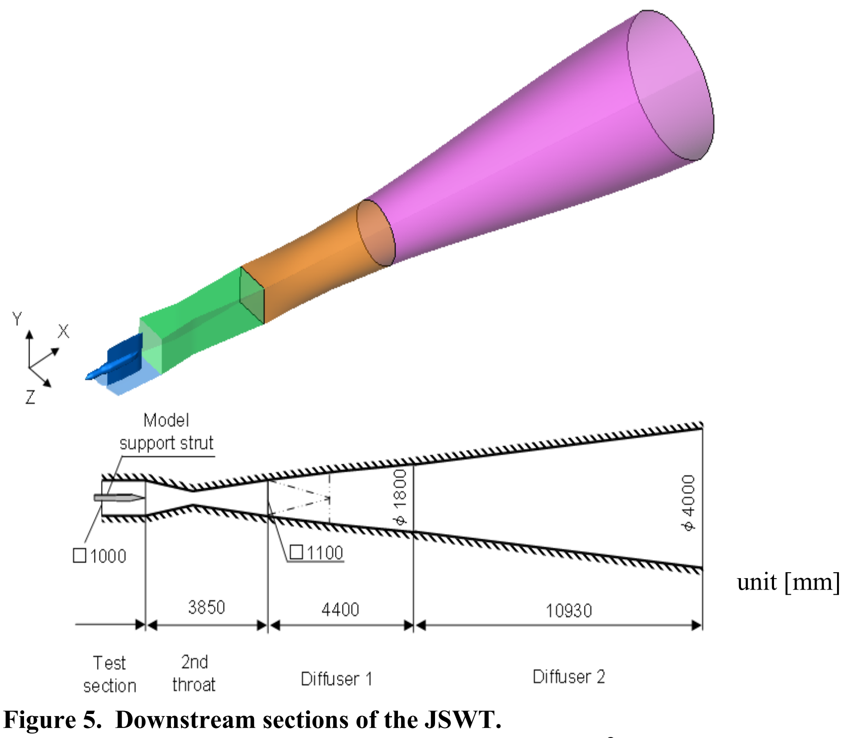


**Figure 5. Downstream sections of the JSWT.**

The downstream sections of the JSWT are shown in Fig. 5. The “Diffuser 1” and “Diffuser 2” sections are designed as conventional subsonic diffusers with the expansion angle gradually increasing from 3.6° to 7.3°. The configuration of the downstream sections seems to be quite conventional; the flow is intended to decelerate to subsonic speed in the second throat. However, as shown in Fig. 3, the starting pressure ratios at the JSWT are significantly higher than the theoretical values at Mach numbers greater than 3.0.

## III. Numerical analyses of wind tunnel diffuser

Numerical analysis of the JSWT was performed to examine the influence of the diffuser geometry on the starting pressure ratio. The analysis used the JAXA-developed UPACS code[13] based on the finite volume method. The equation was assumed to be the RANS equation, and the Spalart-Allmaras turbulence model[14] was used. The number of grid points was set at $8.4 \times 10^5$ by a multi-block method.

First of all, numerical analysis was carried out for the original JSWT geometry. The predicted starting pressure ratio is shown in Fig. 6. This is in good agreement with experimental results. Figure 7 shows an example of Mach number distribution in the steady state at a Mach number of 3.0. Figure 7 reveals a typical shock train with boundary layer separations located around the second throat. It is also found that the sonic line is located in the subsonic diffuser; meaning that the flow does not fully decelerate to subsonic flow at the subsonic diffuser entrance. These boundary layer separations induced by shock-boundary layer interactions cause the starting pressure ratio to be greater than the value predicted by quasi-1D theory.

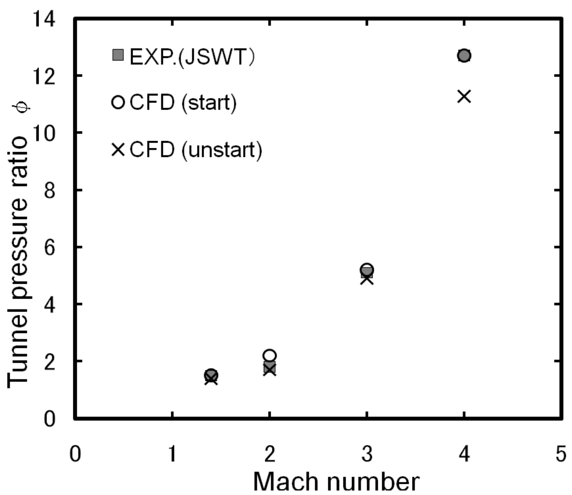


Figure 6. CFD predictions of starting pressure ratio.

**Table 1. Sensitivity of starting pressure ratio to tunnel geometry at *M*t=3.0**

| 2nd throat | Diffuser 1 | Diffuser2 | Gain |
|---|---|---|---|
| – | – | – | base |
| $A_{2nd} \rightarrow 1.5A_{2nd}$ | – | – | unstart |
| $A_{2nd} \rightarrow$ full open | – | – | unstart |
| L→2L | – | – | +2% |
| – | L→2L | – | +12% |
| – | – | L→2L | ±0 |

–: Nominal configuration at *M*t=3.0

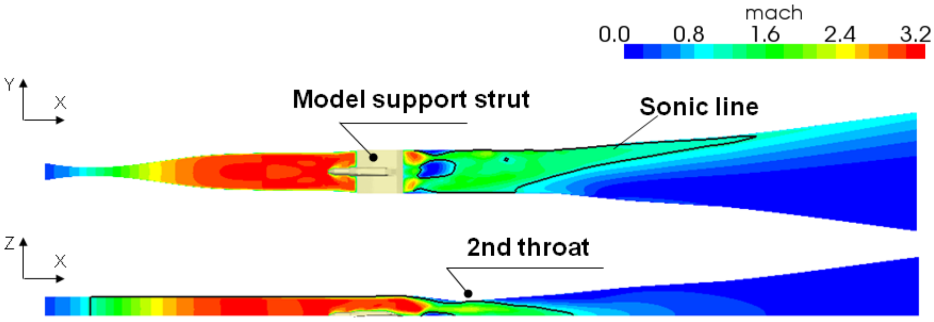


Figure 7. Mach number distribution (*M*t=3.0).

Numerical analysis was also conducted to investigate the sensitivity of starting pressure ratio to the geometries of the diffuser sections at a Mach number of 3.0. The results are shown in Table 1. The starting pressure ratio is reduced from the baseline if the "Diffuser 1" section is extended, while extending of "Diffuser 2" does not yield any improvement. Increasing the 2nd throat area results in unstart at the nominal pressure ratio. These results indicate that both shock wave compression and suppression of shock-induced separation are important for reducing the starting pressure ratio.

## IV. New design concept and its predicted performance

For a combination of a wedge-type 2nd throat and a subsonic diffuser as seen in the JSWT, it is difficult to eliminate separation without any devices because of the presence of the upstream boundary layer in the tunnel. There are two ways to improve the performance in such cases:

(1)Addition of flow control devices (vortex generator, bleed, injection etc.) to reduce separation .

(2) Modification of the diffuser configuration considering the shock-boundary layer interaction.

Our present research adopted latter approach.

### A. Diffuser design considering shock train

A typical shock train is seen in the tunnel duct because of the thick boundary layer. The characteristics of shock trains have been investigated by some researchers.[9-12] In the region of the shock train, static pressure rises in the streamwise direction. The length required to decelerate from supersonic to subsonic speed depends on the inlet Mach number. Moreover, the diffuser expansion angle that gives the highest pressure recovery differs from that of a conventional subsonic diffuser. Therefore, it is necessary to re-design the length and expansion angle required for the shock train region.

According to the empirical model proposed by Ikui *et al.* (ref.12), the pressure distribution in the shock train region is given as follows:

$$\frac{p-p_1}{p_2-p_1}=\left\{1-\left(1-\frac{x-x_1}{x_2-x_1}\right)^n\right\}^{\frac{1}{n}} \tag{3}$$

where $n$ is a factor that depends on the expansion angle of conical diffuser, $\theta c$. Typically, $n = 2.0$ if $\theta c = 0^\circ$, and $n = 2.4$ if $\theta c = 4.2^\circ$. If the diffuser is conical, $x$ can replace cross-sectional area $A$,

$$\frac{p-p_1}{p_2-p_1}=\left\{1-\left(1-\frac{A-A_1}{A_2-A_1}\right)^n\right\}^{\frac{1}{n}} \tag{4}$$

Combining Eq. (4) with the continuity, momentum and energy equations, the pressure ratio through the shock train region is expressed as

$$\frac{p_2}{p_1}=\frac{\gamma A_1 M_1^2+A_2-(A_2-A_1)\beta(1/n+1,1/n)/n}{A_2(\gamma M_2^2+1)-(A_2-A_1)\beta(1/n+1,1/n)/n} \tag{5}$$

where $\beta$ is a beta function, and $M_2$ is as follows:

$$
\begin{aligned}
M_2^2 &= \frac{2c_1c_2 + c_3 - \left\{4c_1c_2c_3 + 2(\gamma-1)c_1c_2^2c_3 + c_3^3\right\}^{1/2}}{2c_1 - (\gamma-1)c_3} \\
c_1 &= 1 + \frac{(\gamma-1)}{2}M_1^2 \\
c_2 &= \left\{\frac{A_2 - A_1}{n}\beta\left(\frac{1}{n}+1, \frac{1}{n}\right) - A_2\right\} \Big/ \gamma A_2 \\
c_3 &= \left[M_1 - \left\{\frac{A_2 - A_1}{n}\beta\left(\frac{1}{n}+1, \frac{1}{n}\right) - A_2\right\} \Big/ \gamma M_1 A_1\right]^2
\end{aligned}
\tag{6}
$$

If $\theta c$ is given, $n$ is determined by interpolation and then Eq. (5) depends only on $A_2$. Figure 8 shows starting pressure ratio predicted by the empirical model as a function of $\theta c$. Expansion angles $\theta c$ of 0.0°, 1.0° and 3.6° were chosen. "Diffuser 1" section at the JSWT is equivalent to the conical diffuser whose expansion angle is 3.6°.

Figure 8 also shows the CFD estimates for the JSWT with various simple transitional diffusers in place of the "Diffuser 1" and "Diffuser 2. These diffusers have the same length as the original diffusers and their equivalent cone angles are correspond to 0.0°, 1.0° and 3.6°. Consequently, each exit area is different. According to the empirical model and CFD analysis, it is found that as expansion angle increases, the starting pressure ratio increases if the Mach number is greater than 2.0. A diffuser with an expansion angle of 1.0° shows relatively high performance over the entire Mach number range from 1.4 to 4.0. This expansion angle of 1.0° is smaller than that of a conventionally designed subsonic diffuser.

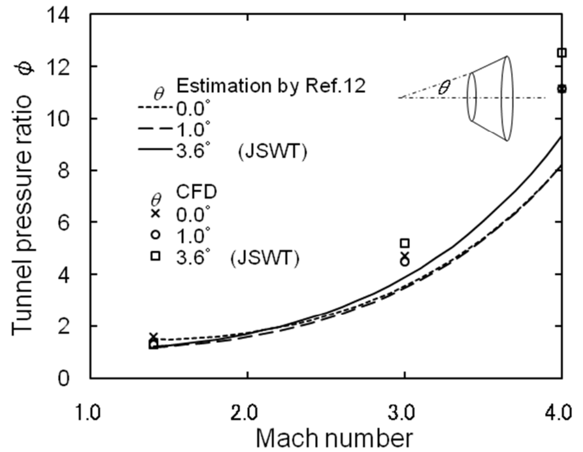


**Figure 8. Estimates of starting pressure ratio considering shock train.**

The length of the shock train region was also estimated by several empirical models[11]. Regardless of the chosen empirical model, it is necessary to increase the expansion angle gradually from the shock train region to the subsonic diffuser region to minimize diffuser length.

### B. Modified diffuser configuration and its performance

The diffuser geometry of the JSWT was re-designed using an empirical shock train model at a selected design point of Mach number of 3.0. In the present study, to replace the original diffuser with the modified one, two restrictions are added: (1) The expansion ratio between the inlet and exit of the diffuser is fixed, and (2) the entire length is fixed. The modified diffuser configuration is shown in Fig. 9.

Numerical analyses of the modified diffuser were carried out. Figure 10 compares the starting pressure ratio of the modified diffuser to the original. With the modified diffuser, it is possible to start the tunnel at the lower pressure ratio than that with the original at Mach numbers higher than 3.0. Consequently, the starting pressure ratio can be reduced without extending the diffuser if the cross-sectional area distribution is modified with a consideration of the shock train system.

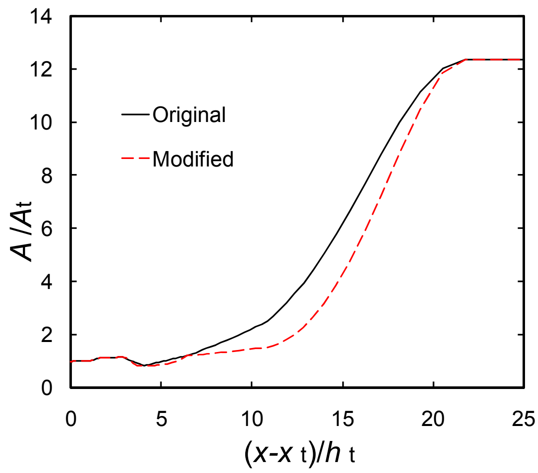


**Figure 9. Cross sectional area distribution of the modified diffuser.**

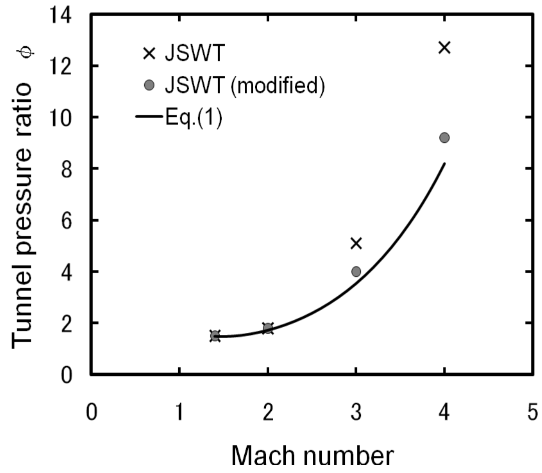


**Figure 10. Comparison of starting pressure ratio between the original and modified diffuser s by CFD.**

## V. Experimental validation

### A. Experimental set up

Experimental investigations were performed with an indraft 10% scale wind tunnel of the JSWT to validate the design concept taking into account the shock train system. A schematic of the experiment is shown in Fig. 11. The vacuum tank has a volume of 18m$^3$. A 2D fixed convergent-divergent nozzle designed for $M$=3.0 was used. The subsonic diffuser and 2nd throat sections were interchangeable to allow configuration effects to be investigated.

Wall pressures were measured at the upper and lower walls with a Pressure Systems ESP-64 measurement system (15psi differential module with an accuracy of 0.03% F.S.). The total pressure in the test section was measured by a total pressure probe. The configuration of the probe holder was also a scaled model of the JSWT model support system.

Pressure sensors (Kulite XT-140-25D) were installed in the test section and the diffuser exit to measure wall pressures. These were used to judge when the supersonic flow in the test section started or broke, and their data were sampled at a rate of 1 kHz. These sensors were calibrated on site with a pressure standard (RUSKA model 7215xi, reading accuracy of 0.011%).

The scale model tunnel was equipped with two optical windows for Schlieren photography, one located around the test section, and the other around the 2nd throat section. Schlieren photographs were taken using a Nikon D1 digital camera and a micro-flash lamp with a 1.2 μsec flash duration.

The procedure used to examine the starting pressure ratio was as follows. The pressure in the vacuum tank was first set according to the desired starting pressure ratio (in this case, the ratio of vacuum tank pressure to atmospheric pressure). When the gate valve was opened, the flow and the measurements started. In the scale model tests, the starting pressure ratio is defined as the minimum pressure ratio at which supersonic flow in the test section was maintained at least for 0.5 seconds because the exit pressure continued to increase during the tests. The unit Reynolds number was 8.0x10$^6$ [1/m]. The ratio of displacement thickness to test section height $\delta^*/h_t$ was 0.028.

### B. Results of experiments

Table 2 shows the starting pressure ratio of the JSWT and its 10% scale model. In the scale model tests, the modified diffuser geometries reduced the starting pressure ratio by about 13%. Although this is slightly less than that predicted by numerical analysis, it is considered that our design concept was sufficiently validated by this result. Since numerical analysis showed us the scaling effect, the modified diffuser design is certainly expected to reduce starting pressure ratio for the full-scale JSWT as well.

Figure 12 shows pressure distributions measured just before the flow breaks for each diffuser configuration. It is found that the wall pressure of the modified diffuser exit is higher than that of the original. Comparisons of numerical analyses with experimental data show good qualitative agreement, but the pressure values in the middle part of the diffusers differ. It is supposed that the numerical analyses did not fully simulate separations induced by shock waves.

Schlieren photographs around the 2nd throat are shown in Fig. 13. The pressure ratio $P_0/p_{ex}$ is the ratio of the stagnation pressure, i.e, atmospheric pressure to the wall pressure of the diffuser exit. It is clearly shown that the modified diffuser is able to maintain supersonic flow in the test section at lower pressure ratios than the original.

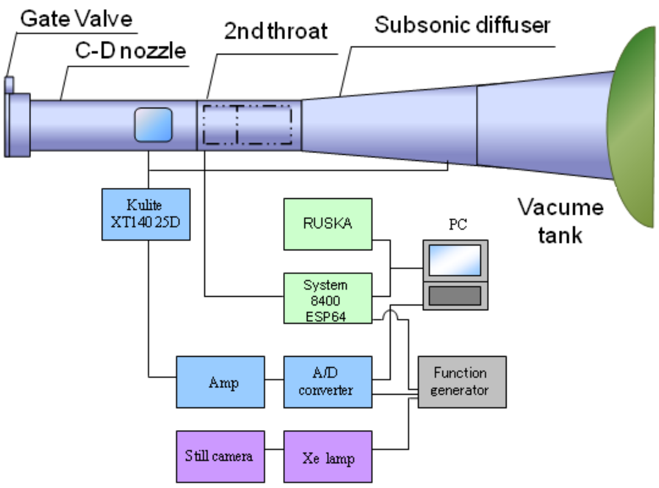


**Figure 11. Schematic diagram of experimental set up.**

**Table2. Comparison of the starting pressure ratio.**

10% scale indraft tunnel

| | CFD | EXP. |
|---|---|---|
| Original | 5.0 | 4.8 |
| Modified | 4.1 | 4.2 |

Full scale tunnel (JSWT)

| | CFD | EXP. |
|---|---|---|
| Original | 5.2 | 5.1 |
| Modified | 4.0 | – |

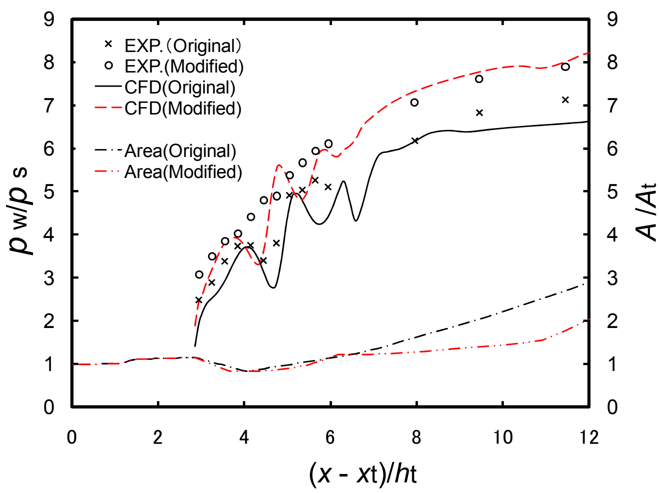


**Figure 12. Pressure distributions in the original diffuser and modified diffuser**

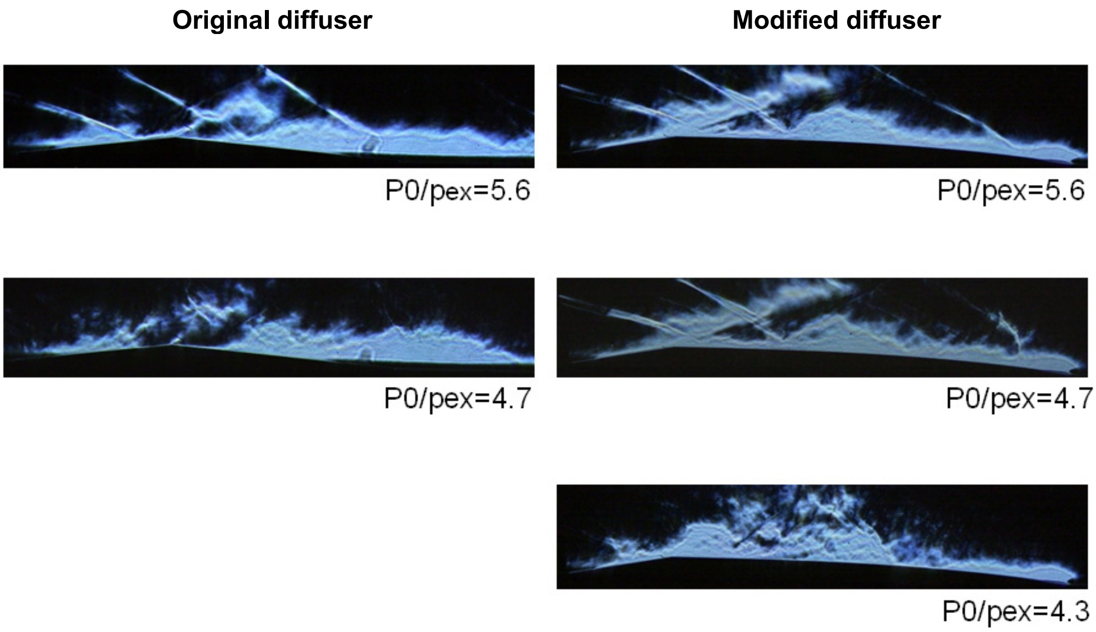


**Figure 13. Shliren photographs around the 2nd throat**

## VI. Conclusion

To reduce the starting and stopping loads of intermittent blow-down supersonic wind tunnels, the effects of diffuser geometry on the starting pressure ratio are discussed. Numerical analyses indicate that starting pressure ratio depends on the diffuser geometry because it is affected by not only shock wave compressions but also by shock induced separations. If strong interactions are assumed, the diffuser design taking shock trains into account is an useful approach to improve the diffuser performance. As an example of applying this concept, the diffuser geometry of the JSWT was re-designed with an empirical shock train model. Although the modified diffuser had the same length and expansion ratio as the original, it was confirmed that the performance was successfully improved by both numerical simulations and subscale model tests.

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