An Experimental Study on Aerodynamic Characteristics of the External Nozzle in Clustered Airframe-Integrated Propulsion System Equipped with the RLV

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To elucidate the effects of non-uniformity (due to engine clustering) at the entrance of the external nozzle on wall pressure distribution and thrust performances of the external nozzle, wind tunnel tests had been conducted using room-temperature inert test gases. A clustered three cell test nozzle was used to simulate clustered engines and a non-clustered one cell test nozzle was also used as a reference. A straight expansion test ramp was used to simulate the external nozzle. Wall pressure on the test ramp and cell base pressure were measured. Test results showed that the effects of clustering on the aerodynamic characteristics of the external nozzle became remarkable with the flight altitude. This was because the magnitude of the spanwise expansion caused by cell bases became larger with the simulated altitude. Pressure thrusts generated by the external nozzle with clustered entrance were much the same as those with non-clustered entrance, when Nozzle Pressure Ratios (NPRs) were matched with each case. Therefore, we can neglect the presence of cell bases in prediction of the nozzle pressure thrusts. However, the cell base pressure always acts as the sizable drag at the external nozzle entrance, so that its value should be predictable. The present results showed that the cell base pressure could be estimated from the experimental expression.

Key Words: Wind Tunnel Test, Supersonic Flow, Nozzle Flow, Clustered Entrance, Cell Base Flow

Nomenclature

\[ A_{i,j} \] : divided ramp wall surface area, mm²
\[ A_{RS} \] : measured area on ramp surface, mm²
\[ C_p \] : pressure coefficient
\[ NPR \] : Nozzle Pressure Ratio
\[ p_{0n} \] : test nozzle total pressure, kPa
\[ p_a \] : facility nozzle exit pressure (ambient pressure), kPa
\[ p_s \] : static pressure in a test chamber (ambient pressure), kPa
\[ p_b \] : cell base pressure, kPa
\[ p_{fp} \] : flowpath exit pressure after the 10 degrees isentropic expansion, kPa
\[ p_w \] : ramp wall pressure, kPa
\[ x, y, z \] : Cartesian coordinates, mm
\[ \xi \] : streamwise coordinate located on ramp wall surface (=x/cos10°), mm
\[ \sigma \] : standard deviation of spanwise variation in normalized wall pressure

Subscripts

\( i, j \) : class number of pressure ports
\( 0 \) : stagnation condition
\( \text{ave} \) : spanwise-averaged value
\( 1\text{Cell} \) : the case of non-clustered test nozzle
\( 3\text{Cell} \) : the case of clustered test nozzle
\( \text{over} \) : over-expanded condition
\( \text{under} \) : under-expanded condition

1. Introduction

The aerodynamic performances of Reusable Launch Vehicles (RLVs) or hypersonic flight vehicles are greatly improved, when a so-called Single Expansion Ramp Nozzle (SERN) is integrated into the afterbody airframe as the extension of the engine internal nozzle (Figs. 1 and 2).1-3) It is proposed that the bottom wall (termed as the cowl) of the nozzle is truncated4) to reduce the nozzle weight, friction loss, and cooling requirement. The truncation is also to attain the altitude compensating effects.5-7) Allowing the engine exhaust to interfere with the ambient flow, the truncated nozzle is called an external nozzle (Fig. 2). From the points of view of structural strength, operability, and maintainability, the propulsion system must be modularized, and thus, the external nozzle entrance would be clustered. This type of nozzle is called external nozzles with clustered entrance (Fig. 2). In such case, the cell bases8) must be presented between engine modules.

There have been some experiments and numerical simulations on SERN type external nozzles. Some remarkable examples were summarized as follows. Pittman9) experimentally showed that the external nozzle ramp angle, the cowl trailing edge angle, the external nozzle flow fence, and the nozzle static pressure ratio significantly affected the nozzle flow field. Mitani, et al.10) conducted both combustion and non-combustion experiments, and they elucidated chemical kinetic, two-dimensional, and fluid friction losses in the external nozzles. Harloff, et al.11) conducted...
two-dimensional Reynolds Averaged Navier Storkes (RANS) simulations by using PARC2D code and summarized overall nozzle performances under the conditions of various ambient flow Mach numbers. Engblom carried out three dimensional RANS simulations by using WIND code and showed that three dimensional separation regions were generated on the nozzle ramp by either lateral or vertical traveling shock waves.

The ultimate goal of our research series is to develop the easy-to-handle prediction model of external nozzle performance with ambient flow and clustered entrance, which has sufficient accuracy for the system performance analysis and appropriate nozzle design. As mentioned above, some CFD studies have been conducted, however, the CFD took too much time for parametric study. Hence, CFD cannot be utilized for system analysis.

Unlike SERN with full-length cowl, the external nozzle has a jet boundary open to the ambient flow. Our targeting nozzle (Fig. 2) also has the clustered entrance with the cell bases. Thus, these two major characteristics must be considered in the performance prediction model, if those effects on nozzle performances cannot be neglected. The effects of ambient flow had been investigated in our previous study. It was revealed that the flow field in the external nozzle with ambient flow was dominated by the expansion wave from initial inclination, the pressure waves emerging from the trailing edge of cowl (termed as the cowl lip), and the reflection of pressure waves at both ramp surface and the jet boundary. Accordingly, in conclusion, the ambient flow directly affected the nozzle performances through the impingement of the pressure waves, generated by the interference between the external nozzle flow and the ambient flow, on the nozzle ramp (Fig. 2).

As next step of our research series, the effects of clustered entrance (or cell bases) on wall pressure distribution and thrust performances were investigated in the present study.

Wind tunnel tests had been carried out under wind-on condition, using both clustered three cell test nozzle, simulating engine clustering, and non-clustered one cell test nozzle. Pressure measurements were carried out. By comparing data between non-clustered and clustered cases, we showed the effects of the presence of clustered entrance on wall pressure distribution and thrust performances of the external nozzle.

2. Experimental Setup

2.1. Wind tunnel facility and test model

The experiments were carried out at supersonic semi-free jet wind tunnel, named Pilot Wind Tunnel (PWT) located on Japan Aerospace Exploration Agency – Kakuda Space Center (JAXA-KSPC).

In order to focus on the aerodynamic aspects of the external nozzle flow, room-temperature inert test gases were employed in the present experiments. The total temperature of each test gas was around 280 K. Test model was located in a test chamber. Figures 3 and 4 show the inside of the test chamber and test model in the chamber, respectively. Figure 5 and Table 1 show the schematic sketch of the test model and correspondence of the test model to the actual engine system, respectively. The test nozzle exhaust and facility dry air flow simulated the exhaust from the general hypersonic air-breathing engines and ambient flow surrounding the vehicle, respectively. Each component displayed in Fig. 5 (test model) corresponded to that in Fig. 1 (actual engine system), as shown in Table1.

An air-driven ejector system was connected to the test chamber through a diffuser tube. The inside of the test chamber was depressurized from around 7.0 to 12.0 kPa by driving the ejector. A facility nozzle was furnished at left side of the test chamber and cross-sectional area of this nozzle exit was 100 mm x 100 mm square (Fig. 5). The facility nozzle injected M2.0 dry air.

The test nozzles were installed at the upper side of the facility nozzle and two different types of test nozzles were employed. One was with non-clustered exit, thus, it was called 1Cell nozzle. The other was with three clustered test nozzle at the exit, so that, it was called 3Cell nozzle (Fig. 5). Only 3Cell nozzle had cell bases between test nozzles. The ratio of cell base width to flowpath one was 17/22 (see Fig. 5). From the points of view of cooling requirement and structural strength of the actual engine system, the minimum required ratio is thought to be around 1/5, in our research group, so that the...
ratio in the present study was larger than the actual design. However, the above configuration was selected in the present tests to highlight the effects of clustering on nozzle aerodynamic characteristics. It is expected that as the cell base width become larger, structural strength of the engine are more improved, on the other hand, thrust performances are more worsened and system weight become larger.

Table 2 shows the cross-sectional area of the throat and exit, expansion ratio, and expanding direction of the each test nozzle. Due to manufacturing limitation, the expanding directions of 1Cell and 3Cell nozzles were set to be height-direction (z-direction) and width-direction (y-direction), respectively. Therefore, the cross-sectional area of the nozzle throat and exit were 2.95 mm (height) x 100 mm (width) and 22 mm x 100 mm, respectively, for the 1Cell nozzle. On the other hand, they were 20 mm x 2.95 mm and 20 mm x 22 mm (one-set), respectively, for the 3Cell nozzle. As shown in Table 2, the cross-sectional area of the 1Cell nozzle throat was larger than that of the 3Cell one, due to presence of the base areas in the latter case (Fig. 5). Difference in the cross-sectional areas of the nozzle throats resulted in different mass flow rate in 3Cell nozzle from that in 1Cell nozzle.

Pressure ports were located on the cell base surface. The test nozzles injected M3.5 gaseous nitrogen which simulated the engine exhaust for actual engines. Assuming the actual engine system, this exhaust contains many gas species including combustion products. However, gas species in the exhaust can be considered in the performance prediction model of the external nozzle as the input variables.

The test nozzle exhaust, then, flowed along the straight expansion ramp (termed as the test ramp) which was directly attached to the test nozzle. Inclination angle, total width, and length were 10 degrees (deg.), 100 mm (equal to that of test nozzle and facility nozzle), and 400 mm, respectively. This ramp simulated the ramp wall of the external nozzle. The test nozzle exhaust (or the test ramp flow) contacted with the ambient flow along the jet boundary shown in Fig. 5, that is, the boundary emerging from the bottom side trailing edge of the test nozzle, termed as the nozzle lip representing the cowl lip for the actual engine. A pair of side walls was assembled at both lateral sides of the test ramp. These walls simulated the pair of side fences for the actual engine.

Figure 6 shows location of pressure ports on the ramp wall surface. Each pressure port was arranged on the ramp wall surface in both streamwise (ξ) and spanwise (γ) directions. Due to limitation in the number of pressure ports, wall pressure distributions only on half of the ramp wall in the spanwise direction were measured, as shown in Fig. 6, expecting symmetry in the spanwise direction. Electrical-scanning pressure measurement system (Pressure Systems, Inc., 15-PSIESP-64-HD, range 0-100 kPa) was used in the present experiments with 10Hz sampling frequency.

Table 1. Correspondence of the test model to the actual engine system.

<table>
<thead>
<tr>
<th>In test model</th>
<th>In actual engine system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test nozzle exhaust</td>
<td>Engine exhaust</td>
</tr>
<tr>
<td>Facility dry air flow</td>
<td>Ambient flow</td>
</tr>
<tr>
<td>Test ramp</td>
<td>Ramp wall of external nozzle</td>
</tr>
<tr>
<td>Nozzle lip</td>
<td>Cowl lip</td>
</tr>
<tr>
<td>Side walls</td>
<td>Side fences</td>
</tr>
</tbody>
</table>

Fig. 3. Photograph of the inside of the test chamber including the test model.

Fig. 4. Photograph of the test model in the chamber.

Fig. 5. Schematic sketch of the test model applying the 3Cell test nozzle.

Fig. 6. Pressure ports located on the ramp wall surface.

Table 2. Cross-sectional area, expansion ratio, and expanding direction of each test nozzle.

<table>
<thead>
<tr>
<th>Test nozzle type</th>
<th>1Cell</th>
<th>3Cell (one-set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throat (height x width)</td>
<td>2.95 mm x 100 mm</td>
<td>20 mm x 1.95 mm</td>
</tr>
<tr>
<td>Exit (height x width)</td>
<td>22 mm x 100 mm</td>
<td>20 mm x 22 mm</td>
</tr>
<tr>
<td>Expansion ratio</td>
<td>22/2.95</td>
<td>22/2.95</td>
</tr>
<tr>
<td>Expanding direction</td>
<td>Height (z)</td>
<td>Width (y)</td>
</tr>
</tbody>
</table>

2.2. Data reduction

Assuming the actual flight condition, the facility nozzle exit pressure $p_a$ should be equal to the test chamber pressure $p_{0n}$ because both of them represent the ambient pressure. This condition was attained by sweeping $p_a$ (see Fig. 7). When $p_a$ took the close value to $p_{0n}$, a time series of the measured data were averaged over 1 second duration centered around this time. To confirm a steady state assumption, when both $p_a$ and $p_{0n}$ satisfied the steady condition (but $p_a\neq p_{0n}$), the time series was also averaged over 1 second duration. The time-averaged data in $p_a=p_{0n}$ condition was compared with those in the above steady condition. Note that compared data were the ramp wall pressure measured at five points on most upstream side pressure ports (see Fig. 6), where the chamber pressure did not affect the wall pressure. In addition, each pressure value, measured at those five points, was averaged over both spanwise ($y$) and streamwise ($\xi$) directions. The difference between these averaged pressures under $p_a=p_{0n}$ and steady conditions was smaller than 1.5%, thus, the test results measured around $p_a=p_{0n}$ condition satisfied the steady condition.

Measured wall pressures on the test ramp were averaged for 1 second and then were arranged as two-dimensional array $p_a(\xi, y)$ over $\xi$ and $y$ direction. This two-dimensional pressure distribution $p_a(\xi, y)$ were further averaged in spanwise ($y$) direction and normalized by $p_{0n}$, to derive $(p_a/p_{0n})_{\text{ave}}(\xi)$, termed as the one-dimensional streamwise ramp wall pressure distribution, by the procedure described in Eq. (1). Note that symmetry in the spanwise direction was assumed so that the number of data points in the spanwise direction was 5 in the data processing, as shown in Eqs. (1) and (2).

$$y_j = 75 - 12.5(j - 1)$$

$$\left(p_a/p_{0n}\right)_{\text{ave}}(\xi) = \frac{1}{p_{0n}} \left\{ \frac{1}{5} \sum_{j=1}^{5} p_a(\xi, y_j) \right\}$$

(1)

Standard deviation of spanwise pressure variation $\sigma(\xi)$ was also calculated by the following equation to show the error bars displayed in diagrams of the streamwise pressure distribution $(p_a/p_{0n})_{\text{ave}}(\xi)$.

$$\sigma(\xi) = \sqrt{\frac{1}{5} \sum_{j=1}^{5} \left[ \left(p_a/p_{0n}\right)(\xi, y_j) - \left(p_a/p_{0n}\right)_{\text{ave}}(\xi) \right]^2}$$

(2)

Equation (3) showed the expression of coefficient $C_p$. Pressure coefficient $C_p$ was derived from surface integral of two-dimensional pressure distribution $p_a(\xi, y)$ normalized by ramp surface area and $p_{0n}$. The pressure thrusts were evaluated by the integral of $C_p$ over the ramp surface.

Note that $C_p$ was only utilized as quantification of differences between $C_{p\text{1Cell}}$ and $C_{p\text{3Cell}}$ in the cases that their NPRs, of which details will be described in the following section, were equal to each other. In these cases, as mentioned above, due to differences between total cross-sectional areas of 1Cell and 3Cell nozzle throats, total mass flow rates of each test nozzle were also different, even if their NPRs were equal. For this reason, comparisons of $C_p$ would not show the nozzle thrust performances.

$$C_p = \frac{1}{p_{0n}^2 A_{RS}} \sum_{i,j} p_a(\xi_i, y_j) A_{i,j}$$

(3)

Fig. 7. Example of time history of the ambient pressure.

2.3. Test condition

As mentioned above, the test nozzle flow was used to simulate the exhaust from air-breathing engines. For convenience, Nozzle Pressure Ratio (NPR) derived from $p_{0n}/p_a$ was employed as dimensionless parameter which gave the test condition in the present study. In the case of actual engine system, that is, air-breathing engines, this parameter would be difficult to define, because stagnation conditions do not appear within the actual air-breathing engines. On the other hand, it could be defined in the case of experimental system, because the engine exhaust was simulated by test nozzle exhaust which had the stagnation conditions.

Design NPR of the test nozzle (not test ramp) is 76, hence NPR<76, NPR=76, and NPR>76 mean over-, correctly-, and under-expanded conditions for the test nozzle flow, respectively. For a fixed total pressure of the test nozzle flow, NPR represents the flight altitude for the actual flight condition. As NPR increases, simulated flight altitude also becomes higher, and vice versa.

Table 3 shows the test conditions, that is, the range of NPR in each test nozzle case. In order to investigate the clustering effects over the wide range of the flight condition, NPR was allocated as widely as the test facility permitted. Each result in the 1Cell nozzle case was compared with corresponding result in the 3Cell nozzle case at equal NPR.

Table 3. Test condition.

<table>
<thead>
<tr>
<th>Test nozzle</th>
<th>Maximum NPR</th>
<th>Minimum NPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Cell nozzle</td>
<td>96</td>
<td>21</td>
</tr>
<tr>
<td>3Cell nozzle</td>
<td>118</td>
<td>26</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1. Streamwise pressure distributions in each case

Streamwise pressure distributions \( p_{\text{w}} / p_{\text{n}} \text{ave}(\xi) \) in each case are shown in Figs. 8 and 9. Error bars mean the standard deviation of spanwise pressure variation at \( \xi \) coordinates \( \pm \sigma_y(\xi) \). The black straight line represents the test nozzle exit pressure level (before the 10 deg. expansion) derived from isentropic relation. Figures 8 and 9 showed the results in the 1Cell nozzle cases and the 3Cell nozzle cases, respectively. Figures 8 (a) and 9 (a) show the results in the over-expanded conditions. Figures 8 (b) and 9 (b) show the results in the under-expanded conditions. Although the 1Cell nozzle was employed, slight spanwise pressure variation on the ramp wall was observed due to slight non-uniformity of the test nozzle internal flow field. Of course, the spanwise variation (error bars in figures) in the 3Cell nozzle cases was much larger than that in the 1Cell nozzle cases.

As shown in each figure, ramp wall pressure immediately decreased by expansion at the onset of the 10 deg. inclination, regardless of the test conditions. After that, pressure fluctuated in streamwise direction resulting from impingement of shock or compression waves and expansion waves on the ramp wall, in all the cases. Only in the case with the 1Cell nozzle at \( \text{NPR}=96 \), rapid pressure rise was observed at the end of the ramp, which resulted from boundary layer separation on the ramp wall. Since shock wave emanated from the nozzle lip to the ramp wall in the over-expanded conditions, first change in the distribution was an increase, as shown in Figs. 8 (a) and 9 (a). On the other hand, in the under-expanded conditions, expansion waves emanated from nozzle lip, hence, first change should be a decrease, as shown in Fig. 8 (b). However, Fig. 9 (b) shows that first change of the distribution was an increase. This difference was caused by clustering of the test nozzle exit, that is, flow from the test nozzle expanded in the spanwise direction in the 3Cell nozzle cases.

3.2. Effects of clustering on pressure distributions

Figures 10 and 11 show two-dimensional pressure contours \( p_{\text{w}} / p_{\text{n}}(\xi, y) \) in the over- (\( \text{NPR}=26 \)) and under-expanded (\( \text{NPR}=86 \)) conditions, respectively. As mentioned in the preceding section, slight spanwise (\( y \) direction) pressure variation was observed even in the 1Cell nozzle cases.

As shown in Figs. 10 and 11, the spanwise variations in the 3Cell nozzle cases was larger than those in the 1Cell nozzle cases, in both over- and under-expanded conditions. In the over-expanded condition, \( p_{\text{w}} / p_{\text{n}}(\xi, y)_{\text{1Cell}} \) (Fig. 10 (b)) indicated similar trend to \( p_{\text{w}} / p_{\text{n}}(\xi, y)_{\text{3Cell}} \) (Fig. 10 (a)). In contrast, \( p_{\text{w}} / p_{\text{n}}(\xi, y)_{\text{1Cell}} \) (Fig. 11 (b)) indicated completely different trend from \( p_{\text{w}} / p_{\text{n}}(\xi, y)_{\text{3Cell}} \) (Fig. 11 (a)) in the under-expanded condition. Concerning the 3Cell nozzle cases, the spanwise variation in the under-expanded condition was more remarkable than that in the over-expanded condition. This was because wall pressure difference between the test nozzle flowpath region and the base wake region (around the test nozzle exit) in the under-expanded condition (Fig. 11 (b)) was larger than that in the over-expanded condition (Fig. 10 (b)), hence, stronger expansion waves were shaped. Although first pressure change in the streamwise direction in the under-expanded condition should be a decrease as shown in Fig. 11 (a), it was an increase in the 3Cell nozzle cases, as
shown in Fig. 11 (b). This was because an expansion condition of the test nozzle exhaust was changed into the over-expanded condition by low pressure regions existing at the cell bases.

Streamwise pressure distributions \( \frac{p_{w}}{p_{0w}}(\xi) \) were compared in Figs. 12 and 13. Figures 12 and 13 show \( \frac{p_{w}}{p_{0w}}(\xi) \) in the over- and under-expanded conditions, respectively, reproduced from Figs. 10 and 11. Blue and red symbols represent the results with the 1Cell nozzle cases and those with the 3Cell nozzle cases, respectively.

Spanwise pressure variations (standard deviation \( \sigma_{\xi}(\xi) \)) in the 3Cell nozzle cases were larger than those in the 1Cell nozzle cases, in both over- and under-expanded conditions. Especially in the streamwise region with high wall pressure level, spanwise variation \( \sigma_{\xi}(\xi) \) took large value. As shown in Figs. 12 and 13, \( \sigma_{\xi}(10)_{\text{over}} \) of 0.00177 was larger than \( \sigma_{\xi}(10)_{\text{over}} \) of 0.00118, hence, it was also shown that stronger expansion waves traveling in the spanwise direction were shaped in the under-expanded condition, in comparison to the over-expanded condition.

3.3. Effects of clustering on pressure coefficients

Pressure coefficients \( C_{p} \) in each case were calculated by Eq. (3). The relation between \( C_{p} \) and NPR is shown in Fig. 14. Expansion condition and corresponding flight altitude were also shown on the topside of this figure. The simulated flight altitude became higher as NPR increased. Table 4 shows the difference (%) between \( C_{p} \) in the 1Cell and the 3Cell nozzle cases. If experimental results were not given, \( C_{p} \) was derived from linear interpolation from Fig. 14.
Both $C_{p,1\text{Cell}}$ and $C_{p,3\text{Cell}}$ indicated the similar trend (Fig. 14). The difference between $C_{p,1\text{Cell}}$ and $C_{p,3\text{Cell}}$ became larger with $NPR$, however, this difference did not exceed 10 %. It was shown by Table 4 that the pressure thrusts generated by the external nozzle with the clustered entrance were approximately equal to those with the non-clustered entrance regardless of $NPR$. Accordingly, the effects of the cell bases can be neglected in evaluations of the nozzle pressure thrusts.

| $NPR$ | $C_{p,1\text{Cell}}$ | $C_{p,3\text{Cell}}$ | $|C_{p,1\text{Cell}}/C_{p,3\text{Cell}}-1|\times 100$ |
|-------|---------------------|---------------------|---------------------------------------------|
| 26    | 0.0203              | 0.0205              | 0.781                                       |
| 37    | 0.0140              | 0.0145              | 3.66                                        |
| 69    | 0.00721             | 0.00752             | 4.20                                        |
| 86    | 0.00554             | 0.00599             | 8.13                                        |

### 3.4. Cell base pressure

In order to investigate the effects of the clustering on the thrust performances at the external nozzle entrance (test nozzle exit), the cell base pressure was focused on, in this section. Figure 15 shows variations of the cell base pressure $p_{cb}$ normalized by the ambient pressure (facility nozzle exit pressure) $p_a$ against $NPR$. The cell base pressure was always smaller than the ambient pressure, regardless of $NPR$. Thus, the cell bases always generate the low pressure region, that is, recirculation zone regardless of the flight altitude. The normalized cell base pressure $p_{cb}/p_a$ monotonically increased with $NPR$. In addition, $p_{cb}/p_a$ indicated the approximately linear increase against $NPR$, as shown by the black straight line (Fig. 15). Thus, for a fixed cross-sectional area ratio of the cell base to the flowpath, the cell base pressure would vary linearly with $NPR$. In the present nozzle configuration, the cell base pressure could be estimated from the following linear expression.

$$p_{cb} = 1.10 \times 10^{-3} \cdot p_{on} + 8.24 \times 10^{-2} \cdot p_a$$ \hspace{1cm} (4)

![Fig. 15. Test plots of the normalized cell base pressure $p_{cb}/p_a$ versus $NPR$ with approximate straight line.](image)

The cell bases made the test nozzle exhaust expanded in the spanwise direction. The strength of this spanwise expansion at the test nozzle exit was quantified as a ratio of the flowpath exit pressure $p_{fp}$ (after the 10 deg. turning) to the cell base pressure $p_{cb}$. The flowpath exit pressure $p_{fp}$ was calculated by isentropic 10 deg. expansion. It was assumed in the calculations that the external nozzle flow experienced height ($z$) direction 10 deg. expansion, and then, spanwise ($y$ direction) expansion. Therefore, the external nozzle flow after the 10 deg. turning ($p_{fp}$) expanded toward spanwise direction up to $p_{cb}$ through spanwise expansion waves. For this reason, the spanwise expansion became stronger as $p_{fp}/p_{cb}$ increased. This additional expansion reduced the thrust performances at the test nozzle exit. Thus, $p_{fp}/p_{cb}$ could be regarded as the index value evaluating the effects of the spanwise expansion caused by the cell bases on the thrust performances at the test nozzle exit (the external nozzle entrance).

Figure 16 shows $p_{fp}/p_{cb}$ against $NPR$. The pressure ratio $p_{fp}/p_{cb}$ increased monotonically with $NPR$. As the cell base pressure was much smaller than the flowpath pressure, the cell bases caused the sizable drag rise at the external nozzle entrance (the test nozzle exit). Additionally, the thrust reduction at the entrance may become larger with the flight altitude. Once the cross-sectional area ratio of the cell base to the engine flowpath is determined from the standpoints of the structural strength, the cell base pressure can be estimated from the linear expression obtained from the experimental results of element tests using the model having the determined cross-sectional area ratio.

![Fig. 16. Pressure ratio $p_{fp}/p_{cb}$ versus $NPR$.](image)

### 4. Conclusion

In order to elucidate the effects of the clustered entrance on the ramp wall pressure distribution and the thrust performances of the external nozzle, as preliminary step of the modeling, wind tunnel tests had been carried out using both non-clustered one cell and clustered three cell test nozzles, at supersonic semi-free jet wind tunnel. The ramp wall and cell base pressures were measured. Main findings obtained through the present study are summarized as follows.

1. The wall pressure distribution on the external nozzle with the clustered entrance was similar to that with the non-clustered entrance in the over-expanded conditions. On the other hand, the pressure distribution with the clustered entrance showed different trend from that with the non-clustered entrance in the under-expanded conditions.

2. The strength of the spanwise expansion caused by the clustering became larger with the flight altitude, which resulted in the differences in the wall pressure distributions.

3. The presence of the cell bases can be neglected in the
evaluations of the nozzle pressure thrusts, because only a little difference in the pressure coefficients was found regardless of the arrangement of the clustered nozzles.

(4) The cell base pressure took much smaller value than the pressure in engine flowpath region, thus, the cell bases caused the sizable drag rise at the entrance of the external nozzle.

(5) Once the entrance configuration has been fixed, the cell base pressure can be estimated by the linear expression with respect to NPR, which will be obtained from the experimental data for a model with the identical configuration in the same way as presented in this study.

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