An experimental investigation on effect of ambient flow on aerodynamic performances of an external nozzle

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Abstract

For space plane with air-breathing engines, equipping Single Expansion Ramp Nozzle on its aft-body is beneficial for thrust augmentation. The cowl of this nozzle is truncated (thus, termed as an external nozzle), in order to reduce its weight, friction drag, and cooling requirement, and also to attain pressure recovery (so-called altitude compensation) on the ramp wall by the impingement of pressure waves generated by the interference between external nozzle flow and ambient flow on ramp wall surface, in case of over-expanded condition. The present study is to evaluate the effects of ambient flow on the external nozzle flow field, as little research has been conducted to elucidate the effects. Room temperature nitrogen gas was injected to simulate air-breathing engine exhaust in cases without and with ambient flow at a supersonic semi-free jet wind tunnel. A straight expansion ramp was employed as the external nozzle. Pressure distributions on the ramp wall were measured and results without and with ambient flow were compared. Comparison showed that presence of ambient flow reduced the magnitude of ramp wall pressure induced by the impingement of pressure waves, and thus, the strength of pressure waves generated by the interference. Flow characterization by pressure wave tracking showed that spatial variation in ambient flow pressure caused this weakening of the incident pressure wave upon the ramp surface. Thus, altitude compensation effect in the over-expanded condition became smaller than that without ambient flow.

Key words: Wind tunnel test, Supersonic flow, Nozzle flow, Altitude compensating nozzle, Ambient flow

1. Introduction

Research and development of future reusable space transportation system termed as “reference system,” have been carried out actively at Japan Aerospace Exploration Agency (JAXA) and several universities (Yoshida, et al., 2012). The reference system aims at Two-Stage-To-Orbit, Reusable Launch Vehicle (TSTO-RLV), its booster stage having a lifting body airframe and air-breathing propulsion system (Kanda and Kudo, 2003) for Horizontal Takeoff and Horizontal Landing (HTHL) operation. It is critically important problem for the booster stage how the propulsion system is integrated into airframe from the points of view of improvement in aerodynamic and control performances, especially in hypersonic flight condition (Dusa, 1991). This design technology is called Propulsion Airframe Integration (PAI). One of the solutions is that the propulsion system is installed on underbelly of the vehicle airframe. In this case, the fore-body works as a pre-compression intake and aft-body acts as an extension of the engine nozzle.

For example, Fig. 1 shows the side view of the conceptual image of the above-mentioned booster stage proposed at JAXA (Sakata, et al., 1988). In order to attain the efficient PAI to extract thrust from the high-pressure flow on the aft-body (Wasiko, 1968; Snyder and Pinckney, 1991), the extension of the engine nozzle should be a Two Dimensional Single Expansion Ramp Nozzle (2D-SERN). In addition, it has been proposed that the bottom wall (termed as cowl) of the nozzle is truncated to reduce the nozzle weight, friction and cooling requirement. The truncation is also to attain the effect of ramp wall pressure recovery, what is called as altitude compensation effect (Korte, et al., 2001; Hagemann, et
al., 1998), caused by the impingement of compression waves, generated by the interference between the nozzle flow and ambient environment on ramp wall surface (Fig. 2). Allowing the interference with the ambient flow, the truncated nozzle is called as an external nozzle.

There have been many experimental and numerical studies on 2D-SERN external nozzles, or so-called Airframe Integrated Scramjet (AIS) nozzles. Pittman (1989) experimentally showed that the external nozzle ramp angle, the cowl trailing edge angle, presence of external nozzle flow fences, and nozzle static pressure ratio significantly affected the nozzle flow field. Mitani, et al. (1993) conducted hot combustion gas and cold nitrogen gas injections to simulate air-breathing engine exhaust, and elucidated chemical kinetic (non-equilibrium) loss, divergence loss, and friction loss in AIS nozzles. Harloff, et al. (1988) conducted two-dimensional Reynolds Averaged Navier Storkes (RANS) simulations and summarized overall nozzle performances under the condition of various free-stream Mach numbers. Engblom (2003) carried out three-dimensional RANS simulations and showed that three-dimensional separation regions were generated by either lateral or vertical traveling shock waves within the external nozzle under over-expanded conditions. Furthermore, many studies about flow separation behavior of the nozzle have been conducted. For example, Frey and Hagemann (1998) studied about flow separation in axisymmetric rocket nozzle, while Yu, et al. (2014) studied about that in asymmetric SERN.

Our major concern was to evaluate how the presence of the ambient flow affects the performance of the cowl-truncated type 2D-SERN, viz. the external nozzle. However, there has been little research, especially experimental ones, about the altitude compensation effect in the external nozzle with ambient flow condition. As mentioned above, some CFD studies have been conducted, however, the CFD took too much time for system analysis, so that easy-to-handle prediction method on the nozzle flow field and performance should be constructed with sufficient accuracy for the system analysis and according nozzle design optimization. Wave tracking method was expected be suitable for the above mentioned prediction. Therefore, it was necessary for constructing the prediction method to evaluate the effect of ambient flow on the nozzle performances, by the experimental investigation, as the first step.

In the present study, the experiments were conducted in both without and with ambient flow conditions. Wall pressure distributions on the nozzle ramp were measured and then pressure coefficients were calculated by surface integration of this pressure distribution. Wave tracking method was applied to explain the change in the nozzle flow field by the presence of the ambient flow. By comparing data without and with ambient flow, we showed how much the nozzle performance improvement contributed by the altitude compensation effect was varied due to the presence of the ambient flow.

Fig. 1 Side view of the conceptual image of booster stage applied PAI technology.

Fig. 2 Schematics of cowl truncation effects on the nozzle flow in over-expanded condition.

2. Nomenclature

- $A_{g,h} \quad \text{: divided ramp wall surface area centered around the } (x_g, y_h) \text{ measurement point, mm}^2$
- $A_{th} \quad \text{: test nozzle throat total cross-sectional area, mm}^2$
- $C_p \quad \text{: pressure coefficient (surface integral of dimensionless ramp wall pressure)}$
- NPR \quad \text{: Nozzle Pressure Ratio}$
- $p_{th} \quad \text{: test nozzle total pressure, kPa}$
- $p_a \quad \text{: facility nozzle exit pressure (termed as ambient flow static pressure), kPa}$
3. Experimental setup

The experiments had been carried out at a semi-free jet wind tunnel, named Pilot Wind Tunnel (PWT) located in JAXA - Kakuda Space Center (JAXA-KSPC). In order to focus on the aerodynamic characteristics of the external nozzle, room temperature nitrogen gas was employed as the test fluid which simulated the incoming flow to the external nozzle, that is, the present experiments had been carried out under the room temperature and non-reacting flow field, hence, the total temperature of the nozzle flow was approximately 280K. A simplified SERN with a straight expansion ramp was employed as the test piece, because the altitude compensation effect of the nozzle became more visible thanks to such simple design and the geometric condition of the nozzle could be easily altered.

3.1 Experimental facility and test pieces

Figures 3, 4 and Table 1 show the side view of the PWT test chamber, that of the test apparatus, and correspondence of the experiment to the actual vehicle (Tomioka, et al., 2014), respectively. A diffuser was installed at the bottom right side of the test chamber. This was connected to an air-driven facility ejector, and the test chamber was depressurized by driving this ejector. A facility nozzle was furnished at bottom left side of the test chamber. The cross-sectional shape of this facility nozzle exit was 100 mm x 100 mm square (Fig. 5). This nozzle was to simulate ambient supersonic flow.

Test apparatus was located between the facility nozzle and the diffuser. Two-dimensional nozzle to simulate the exhaust flow from the air-breathing engine, termed as the test nozzle, was installed at the upper side of the facility nozzle, of which exit had rectangle cross-sectional shape with the height and width of 22 mm and 100 mm, respectively (Fig. 5). Room temperature nitrogen gas was injected from this nozzle at M3.5. This test nozzle exhaust, then, flew along the test ramp attached to the test nozzle directly. Inclination angle, total width, and total length of the test ramp were 10 degrees, 100 mm (equal to that of test nozzle and facility nozzle), and 400 mm, respectively. The test ramp simulated the external nozzle for the actual vehicle. The 10-degrees-inclination-angle was selected considering the balance between the total weight (total length) of the actual external nozzle and rapid expansion loss (Tomioka, et al., 2014). Room temperature dry air was injected from the facility nozzle at M2.0 and it simulated the ambient flow for the actual vehicle. The test nozzle exhaust (or test ramp flow) contacted with the ambient flow along the boundary shown in Figs. 3 and 4, that is, the boundary emerging from the bottom side trailing edge of test nozzle, termed as the nozzle lip representing the cowl lip for the actual vehicle. A pair of acrylic walls was assembled at both lateral sides of the test ramp. This wall simulated the pair of side fences for the actual vehicle.

Figure 6 shows pressure measurement points on the ramp wall surface. Measurement points were arranged on the ramp wall surface in both streamwise ($\xi$) and spanwise ($y$) directions. Due to limitation in the number of measurement points, 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 sampling frequency was 10 Hz.

Table 1  Correspondence of the experiment to the actual vehicle.

| Experiment               | Actual vehicle |
|--------------------------|----------------|
| Test nozzle              | Internal nozzle|
| Test ramp                | External nozzle|
| Facility nozzle exhaust  | Ambient flow   |
| Nozzle lip               | Cowl lip       |
| Acrylic walls            | Side fences    |

3.2 Data processing

In this section, data processing methods are described. First of all, it is major premise that all the experimental results adopted in the present study satisfied the steady flow condition. As mentioned above, ramp wall pressure was measured as two dimensional plane data during the run. Raw data were time-averaged for 1 second duration, and then they were arranged as two dimensional array \( p_s(\xi, y) \) over \( \xi \) and \( y \) direction, respectively. This two-dimensional data \( p_s(\xi, y) \) were spanwise (y direction)-averaged and divided by \( p_0 \), to derive \( (p_s/p_0)_{ave}(\xi) \), the one-dimensional, streamwise ramp wall pressure distribution by the following equations. Note that symmetry in the spanwise direction was assumed so that data points in the spanwise direction were 5 in the data processing.
\[
\begin{align*}
\left\{ \begin{array}{l}
y_h = 75 - 12.5(h - 1) \\
\left( \frac{p_s}{p_{0r}} \right)_{\text{ave}}(\xi) = \frac{1}{5} \sum_{h=1}^{5} p_s(\xi, y_h)
\end{array} \right.
\end{align*}
\] (1)

Standard deviation of spanwise pressure distribution \( \sigma(\xi) \) was also calculated by the following equation to show the error bars displayed in the diagram of the streamwise pressure distribution.

\[
\sigma(\xi) = \sqrt{\frac{1}{5} \sum_{h=1}^{5} \left( \frac{p_s}{p_{0r}} \right)(\xi, y_h) - \left( \frac{p_s}{p_{0r}} \right)_{\text{ave}}(\xi)^2}
\] (2)

Pressure coefficient \( C_p \) was derived by Eq. (3), and was utilized as the index value representing the aerodynamic performances of the external nozzle.

\[
C_p = \frac{1}{p_{0r} \cdot A_{th}} \sum_{y_h} p_s(\xi, y_h) \cdot A_{y,h}
\] (3)

3.3 Test condition

As mentioned above, the test nozzle flow was used to simulate the exhaust of the air-breathing engine. Nozzle Pressure Ratio (NPR) derived from \( p_0/p_a \) was employed as dimensionless parameter as representation of the test condition in the present study for convenience, while it would be difficult to define in the air-breathing engine case without stagnant condition within the engine. For a fixed total pressure of the test nozzle flow, the NPR represents the flight altitude for the actual flight condition, i.e., the larger the NPR is, the higher flight altitude the test condition simulates, and vice versa. Optimum NPR of the test nozzle (not test ramp) was 76.0, hence \( \text{NPR}>76.0, \text{NPR}=76.0, \text{and NPR}<76.0 \) mean under-expanded, optimum, and over-expanded conditions as the test nozzle flow, respectively.

Table 2 shows the test conditions. Cases 1 to 4 and 5 to 11 are without and with ambient flow conditions, respectively. In order to investigate the aerodynamic characteristics of the external nozzle over the wide range of the flight altitude, the NPR was allocated as widely as the wind tunnel facility permitted for both under-expanded and over-expanded conditions. Each result with ambient flow was compared with corresponding result without ambient flow, at close NPR value.

| Case | Ambient flow | Expansion condition | NPR   |
|------|--------------|---------------------|-------|
| 1    | without      | Under-expanded      | 128.9 |
| 2    |              | Over-expanded       | 106.0 |
| 3    |              |                     | 68.7  |
| 4    |              |                     | 37.0  |
| 5    | with         | Under-expanded      | 96.2  |
| 6    |              | Over-expanded       | 86.5  |
| 7    |              |                     | 79.8  |
| 8    |              |                     | 60.2  |
| 9    |              |                     | 37.0  |
| 10   |              |                     | 25.6  |
| 11   |              |                     | 21.0  |
4. Results and discussion

In this section, streamwise ramp wall pressure distributions and the corresponding pressure wave (shock, compression, and expansion waves) patterns in certain cases were shown first, and it was discussed what determined the structure of flow field in the external nozzle. Pressure distributions in all cases described in Table 2 were shown and it was discussed how the structure was varied by changing the NPR. Next, the streamwise ramp wall pressure distributions with ambient flow were compared with that without ambient flow. It was elucidated how the ambient flow affected the ramp wall pressure distribution of the external nozzle, and it was discussed what caused these effects by focusing on the pressure wave pattern under each condition and by comparing them with each other. Finally, the variation of the pressure coefficients against the NPR in cases without and with ambient flow was shown. Then, it was discussed how the improvement of aerodynamic performances of the external nozzle given by the altitude focusing on the pressure wave pattern under each condition and by comparing them with each other. Finally, it was discussed how the structure was varied by changing the NPR. Next, the streamwise ramp wall pressure distributions with ambient flow were compared with that without ambient flow. It was elucidated how the ambient flow affected the ramp wall pressure distribution of the external nozzle, and it was discussed what caused these effects by focusing on the pressure wave pattern under each condition and by comparing them with each other. Finally, the variation of the pressure coefficients against the NPR in cases without and with ambient flow was shown. Then, it was discussed how the improvement of aerodynamic performances of the external nozzle given by the altitude

4.1 Pressure distribution and corresponding wave pattern

Figure 7 shows the measured streamwise ramp wall pressure distributions \( \frac{p}{p_0} \) (Eq. (1)) with corresponding pressure wave patterns in certain cases, with error bars estimated as \( \pm \sigma \) (Eq. (2)). Although two-dimensional nozzle was employed as the test nozzle, slight spanwise pressure variation on the ramp wall surface was observed due to slight non-uniformity of the test nozzle internal flow field. The black straight line in the diagrams of pressure distribution represents the test nozzle exit pressure level \( (p_{\text{exit}}/p_0=0.0132) \) derived from isentropic relation. In the diagrams of wave patterns, red straight lines mean shock waves, and dark and light green straight lines mean compression and expansion waves, respectively. Orange straight lines mean jet boundary. These compression and expansion waves took form of fans (a series of weak waves), hence, they were actually curved whenever the wave interactions occurred. However they were replaced by the single representative wave in the present study to make wave tracking easy and clear, like the case in the wave method for the nozzle design (Liepman and Roshko, 1957), hence, each wave was described by polygonal line in Figs. 7 and 10. Each pressure wave and pressure variation resulting from the impingement of the wave was marked by the character, e.g. UA or OB in the figure, where U and O mean under-expanded condition and over-expanded condition respectively.

First, the flow patterns without ambient flow (Figs. 7(a) and (b)) are discussed. Ramp wall pressure was immediately decreased by the expansion wave (UA or OA) generated by the rapid expansion at the onset of the 10-degrees inclination regardless of the NPR. In the under-expanded condition (Fig. 7(a)), wall pressure again decreased by the incidence of the expansion wave (UB) emanating from the nozzle lip, and then, increased by the incidence of the compression wave (UD) resulting from reflection of the expansion wave at the jet boundary marked as UA. Subsequently, as shown in Fig. 7, the reflected compression (UF) and expansion waves (UG) entered the ramp wall surface, hence, the wall pressure increased and decreased in this order. On the other hand, in the over-expanded condition (Fig. 7(b)), wall pressure increased by the incidence of the shock wave (OB) after it decreased by the expansion wave (OA). Wall pressure again increased by the reflected compression wave (OD), and then, decreased by incidence of the expansion waves marked OF and OH. This compression and expansion wave pattern repeated (OI, OL, ON, OP), and finally, ramp wall pressure was increased by impingement of the compression wave marked as OR.

Next, the flow patterns with the ambient flow (Figs. 7(c) and (d)) are discussed. Compression and expansion wave patterns were similarly observed. The corresponding wall pressure variations caused by each pressure wave were also observed in these figures. However, only in the case with ambient flow in the under-expanded condition (Fig. 7(c)), rapid pressure rise was observed on the downstream part of the ramp wall surface. It was caused by boundary layer separation resulting from the difference between wall pressure and ambient pressure.

Thus, ramp wall pressure distributions and pressure wave patterns revealed that flow field in the simplified cowl truncated type external nozzle is dominated by the expansion wave derived from initial inclination, the pressure waves emerging from the cowl lip, and the reflection of pressure waves by each boundary, viz. rigid boundary and jet boundary. Figure 8 shows the pressure distributions \( \frac{p}{p_0} \) in all cases described in Table 2. It was revealed that the wall pressure decrements caused by the incidence of the expansion waves emanating from the nozzle lip became larger as the NPR increased in the under-expanded conditions (Figs. 8(a) and (c)), whereas in the over-expanded conditions (Figs. 8(b) and (d)), the wall pressure increments caused by the incidence of the shock wave became larger as the NPR
decreased. Therefore, it became clear that the pressure variation caused by the incidence of the first left traveling waves became larger as the NPR moved away from the optimum value of 76.0. This is because the difference between the test nozzle flow pressure and ambient one became larger, and as a result, the above waves became stronger, as the NPR moved away from 76.0. Moreover, these waves were generated by the interference between the test nozzle exhaust and ambient environment, hence, the effects of ambient environment appeared more clearly as the expansion condition moved away from optimum one, regardless of whether the ambient flow existed.

(a) Case 2: without ambient flow and under-expanded condition (NPR=106.0).

(b) Case 4: without ambient flow and over-expanded condition (NPR=37.0).

(c) Case 5: with ambient flow and under-expanded condition (NPR=96.2).

(d) Case 9: with ambient flow and over-expanded condition (NPR=37.0).

Fig. 7 Streamwise ramp wall pressure distributions with corresponding pressure wave patterns.
4.2 Effect of ambient flow

4.2.1 Pressure distribution

Figure 9(a) shows the streamwise ramp wall pressure distribution in under-expanded condition, while, both Figs. 9(b) and (c) show those in over-expanded conditions. Red and blue colored curves represent results without (wof) and with ambient flow (wf), respectively. Except for Fig. 9(c), both cases shown in each figure had the close (not equal) NPRs to each other, while slight differences in these NPR were observed due to the performance limit of wind tunnel operation. However, the effect of such a difference in the NPR (around 10.0) on pressure distribution was much smaller than that of the difference in ambient flow presence. Accordingly, the above mentioned difference in the NPR could be neglected in this situation.

These results show that ambient flow had an effect of reducing the magnitude of the ramp wall pressure level induced by the impingement of pressure waves regardless of the NPR value. In other words, the pressure wave strengths were weakened. Furthermore, the pressure distribution with ambient flow was maintained at approximately constant level, compared with without ambient flow especially in over-expanded condition, since each pressure wave was weakened whenever it entered the jet boundary and was reflected to be further weakened.

The jet structure was discussed by highlighting the pressure wave pattern under each condition to confirm the above mentioned ambient flow effects. In the following discussion, cases 4 (NPR=37.0 and without ambient flow) and 9 (NPR=37.0 and with ambient flow) were selected as the typical examples. In the case of under-expanded condition like Figs. 7(a) and 8(a), on the other hand, first left traveling wave of the test ramp flow side should be an expansion wave instead of a shock wave, on the other hand, first right traveling wave of ambient flow side should be a shock wave instead of an expansion wave.

The major difference in the wave patterns between without and with ambient flow conditions is that, only in the case with ambient flow, the pressure waves are also generated in the ambient flow side. Consequently, a slip line is shaped as jet boundary in the case with ambient flow, while a free boundary is shaped in the case without ambient flow.

Fig. 8 Streamwise ramp wall pressure distributions.

(a) Without ambient flow and under-expanded condition (cases 1 and 2).
(b) Without ambient flow and over-expanded conditions (cases 3 and 4).
(c) With ambient flow and under-expanded conditions (cases 5 to 7).
(d) With ambient flow and over-expanded conditions (cases 8 to 11).
Figures 10(a) and (b) show the wave patterns around the nozzle lip without and with ambient flow, respectively. Figure 10(c) shows the corresponding pressure distributions within the range from $\xi=0$mm to 150mm in both cases. Without ambient flow, $p_{a2}$ is equal to $p_{a1}$ due to the absence of the pressure waves in the ambient flow side. On the other hand, $p_{a2}$ is smaller than $p_{a1}$ with ambient flow due to the presence of the pressure waves in the ambient flow side, in more specific description, the ambient flow pressure takes suitable value for each expansion condition of the test nozzle flow. Moreover, the pressure values in the each region divided by the jet boundary were equal to each other in the both cases, so that the following relations are deduced.

$$p_{a2} = p_{a2} = p_{a1} \quad \text{(without ambient flow)} \quad (4)$$

$$p_{a2} = p_{a2} < p_{a1} \quad \text{(with ambient flow)} \quad (5)$$

In addition, the following inequality is deduced from Eq. (4) and (5) through some isentropic calculations for matched NPR value cases.

$$(p_{n2}/p_{n1})_{wof} > (p_{n2}/p_{n1})_{nf} \quad (6)$$

Furthermore, both pressure wave (OB) angle and flow direction angle in $n2$ region without ambient flow were shown to be larger than that with the ambient flow from Eq. (6), the following inequality being deduced.

$$\phi_{wofn2} > \phi_{wfn2} \quad (7)$$

$$\theta_{wofn2} > \theta_{wfn2} \quad (8)$$

Equation (6)-(8) show the effect of the ambient flow on the pressure waves (OB) emerging from the nozzle lip to the ramp wall surface, i.e., the strength of first left traveling pressure wave (OB) being weakened due to the presence of ambient flow. This effect was also observed in these pressure distributions, as the pressure increments and incident coordinates of the OB wave with the ambient flow (Fig. 10(b)) were smaller and more downstream, respectively, than that without ambient flow (Fig. 10(a)).

Next, reflection of pressure waves by each boundary was discussed. The wave reflection is also shown in Fig. 10. Like the above discussion, $p_{o5}$ was equal to $p_{o2}$ in the case without ambient flow, while, $p_{o5}$ is smaller than $p_{o2}$ in the case with the ambient flow. Thus, Eqs. (9)-(11) were deduced for same NPR.

$$(p_{n5}/p_{n2})_{wof} > (p_{n5}/p_{n2})_{nf} \quad (9)$$

$$\phi_{wofn5} > \phi_{wfn5} \quad (10)$$

$$\theta_{wofn5} > \theta_{wfn5} \quad (11)$$

With Eqs. (9)-(11), the strength of each pressure wave with the ambient flow was found to become weaker and weaker than that without ambient flow, whenever those waves entered the slip line and were reflected by it, so that it was observed in Fig. 10(c) that the strength of OD wave (reflected wave) with the ambient flow became much weaker than that without ambient flow. Hence the variation in ramp wall pressure value also became smaller and smaller, and finally, negligibly small. In addition, incident coordinates of pressure waves became farther downstream, as shown in Fig. 10(c).
According to the above discussion, it was shown that the ambient flow had an effect of weakening the strength of the pressure waves in the test ramp flow side whenever reflection of the waves occurred at the jet boundary, because the pressure waves were also generated in the ambient flow side.

Fig. 9 Comparison between pressure distributions without and with ambient flow.

(a) Under-expanded condition, $NPR=100.0$ (cases 2 and 5).

(b) Over-expanded condition, $NPR=65.0$ (cases 3 and 8).

(c) Over-expanded condition, $NPR=37.0$ (cases 4 and 8).

Fig. 10 Comparison of the wave patterns and corresponding pressure distributions (case 4 and 9).

(a) Case 4: $NPR=37.0$, without ambient flow (wof).

(b) Case 9: $NPR=37.0$, with ambient flow (wf).

(c) Ramp wall pressure distribution.
4.2.2 Pressure coefficients

When the pressure waves generated by the interference between the test ramp flow and the ambient environment do not impinge on the ramp wall surface (i.e., altitude compensation effect is not attained in this situation), $C_p$ theoretically takes a constant value regardless of the NPR. Thus, $C_p$ can be adopted as the index of the altitude compensation effect on the aerodynamic performances of the external nozzle.

In the beginning, $C_{pnac}$ was theoretically derived from isentropic relation and Eq. (3), which was the pressure coefficient in the case without altitude compensation effect. This value was $0.401$ regardless of the NPR, because none of the waves impinged the ramp wall surface in this situation. Next, $C_{pwof}$ and $C_{pwf}$ were derived from experimental results and Eq. (3). Contribution of the altitude compensation effect to the external nozzle performances was converted into numerical values by calculating the difference between $C_{pwof}$ or $C_{pwf}$ and $C_{pnac}$.

Figure 11 shows the relation between $C_p$ and NPR. Expansion conditions were shown on the top side of this figure. As mentioned in the section 3.3, the simulated flight altitude became higher as the NPR increased. It was observed in Fig. 11 that the $C_p$ monotonically decreased with increase in the NPR regardless of presence of the ambient flow. In other words, the performance improvement of the external nozzle given by the altitude compensation effect became smaller as the flight altitude became higher. As mentioned in the section 4.1, the strength of first left traveling pressure waves (shock or expansion waves) entering into the nozzle flow became stronger as the expansion condition moved away from optimum in both over- and under-expanded conditions. According to Fig. 11, the nozzle performances ($C_p$) decreased by the altitude compensation effect in high altitude flight and under-expanded conditions because strong expansion waves entered into the nozzle flow in this case. However, in actual under-expanded conditions, the angle of first left traveling expansion waves becomes smaller and smaller with increase of flight altitude and flight Mach number, and finally, these waves do not enter into the nozzle flow, hence, the above-mentioned disadvantages have little effects on overall nozzle performances in actual flight conditions.

Table 3 shows how much the altitude compensation effect contributed the improvement of the nozzle performances in cases without and with the ambient flow with almost identical NPR. If experimental results did not exist, $C_p$ was derived from linear interpolation from Fig. 11. For the above-mentioned reason, $C_{pwof}$ and $C_{pwf}$ were smaller than $C_{pnac}$ in under-expanded conditions. It was shown by Table 3 that the difference between $C_p$ and $C_{pnac}$ was reduced by $30.3\%$ to $43.2\%$ due to the presence of the ambient flow in under-expanded conditions (NPR ranging from $68.7$ to $37.0$). Hence, the improvement of aerodynamic performances of the external nozzle given by the altitude compensation effect was similarly reduced by the presence of the ambient flow. Besides, the reduction rate became larger with decrease in the NPR, hence, the influence of the presence of the ambient flow on the altitude compensation effect also became larger with decrease in the flight altitude. In conclusion, the presence of the ambient flow is the factor which cannot be neglected for the performance prediction and optimization of the external nozzle design.
Table 3  Difference of the $C_p$ value between without and with ambient flow.

| NPR  | $C_{pwf} - C_{pnac}$ | $C_{pwf} - C_{pnac}$ | $\frac{C_{pwf} - C_{pnac}}{C_{pnac}} \cdot 100, \%$ |
|------|----------------------|----------------------|---------------------------------|
| 128.9| -0.0163              | -0.106               | -                               |
| 106.0| 0.212                | -0.0241              | -                               |
| 68.7 | 0.611                | 0.185                | 30.3                            |
| 37.0 | 1.64                 | 0.708                | 43.2                            |

5. Conclusion

In order to elucidate the effect of ambient flow on aerodynamic performances of the external nozzle, aerodynamic experiments had been conducted in the cases without and with ambient supersonic airflow with room temperature nitrogen gas injection to simulate the (air-breathing) engine exhaust, and ramp wall pressure was measured. The major results obtained through the present study are summarized as follows.

1) Flow field in the cowl truncated type external nozzle was dominated by the expansion wave derived from initial inclination, the pressure waves emerging from the cowl lip, and the reflection of pressure waves at both ramp surface and the jet boundary.

2) The ambient flow had an effect of weakening the strength of the pressure waves in the external nozzle flow side because of the pressure variation within the ambient flow, resulting in slip line formation between the nozzle flow and the ambient flow.

3) The improvement of aerodynamic performances of the external nozzle given by the altitude compensation effect was reduced around from 30 to 40 % by the presence of the ambient flow, in over-expanded condition. Hence, the presence of the ambient flow is the factor which cannot be neglected for the performance prediction and optimization of the external nozzle design.

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