Supersonic Ejector-Driving System under Low Pressure: A Performance Evaluation*

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We have developed a low-density wind tunnel that simulates Martian atmospheric flight on the ground. This wind tunnel employs a supersonic ejector-drive system to realize high-speed flow under low-density conditions. This study presents a general evaluation method for the ejector driver of the wind tunnel under low-pressure conditions. As an evaluation parameter for the pressure-recovery ratio, which is a representative value of the driving performance, the ejector-drive parameter (EDP) determined from the design and operating conditions is applied, verifying its effectiveness under atmospheric conditions. Accordingly, we investigate the effectiveness of the EDP at low pressures and its scalability to complex multiple supersonic nozzles. Our results suggest that the pressure-recovery ratio is correlated with the EDP even when the ambient pressure, system configuration, and operational conditions change. The EDP allows us to predict the Mach number, and can provide us with an appropriate framework for ejector design optimization.

Key Words: Compressible Flows, Wind Tunnel Testing, Design

Nomenclature

| Symbol | Description |
|--------|-------------|
| a      | sound velocity |
| A      | cross-sectional area |
| cₚ     | specific heat at constant pressure |
| d₀ₙ    | diameter of outlet of the orifice |
| d₁ₙ    | diameter of outlet of the primary nozzle |
| d₁ₙₜ   | throat diameter of the primary nozzle |
| E      | ejector drive parameter |
| I      | momentum |
| m      | mass flow |
| M      | Mach number |
| Mᵦ     | molecular weight |
| P₀     | total pressure |
| Pₚ     | wall pressure |
| Pambient | ambient pressure |
| P      | static pressure |
| R      | gas constant |
| T₀     | total temperature |
| T      | static temperature |
| U      | velocity |
| x      | distance |
| R      | gas constant |
| γ      | specific heat ratio |
| μ      | density |

Subscripts

1: primary flow
2: secondary flow
3: mixing flow

1. Introduction

Several aerial vehicle concepts for Mars exploration, such as the Mars airplane with fixed wings and the Mars helicopter, have been proposed by major space development agencies and universities.1–4 The CO₂-based atmosphere of Mars is much thinner than that of Earth, with its average surface pressure being 1/100th of Earth’s. Furthermore, the average temperature on Mars is roughly −60°C. In such a unique flight environment, the flight Reynolds number is low (i.e., 10⁴–10⁵), and compressible effects on the flow around the wing are likely due to the low-speed-of-sound, being minimal compared to Earth. Because of these rare flight conditions, an optimal aerodynamic design is vital. For the aerodynamic design of Martian aerial vehicles, we have developed a low-density wind tunnel, the Mars wind tunnel (MWT) (Fig. 1).5 In order to realize a low-pressure environment and CO₂ operation, an indraft wind tunnel is located inside a vacuum chamber. In order to induce a high subsonic flow (M = 0.1 to 0.6) under low-pressure conditions, the MWT employs an ejector-driving system with multiple supersonic nozzles instead of a blower fan by referencing to the MARSWIT at NASA Ames Research Center,6 which can attain flow speeds up to 180 m/s at 0.5 kPa. The MWT achieves a maximum flow velocity of 238 m/s at 1 kPa, allowing us to test with air and CO₂. In previous operational tests,7 we succeeded in developing a unique wind tunnel that can independently evaluate the effects of the Reynolds number, Mach number, and specific heat ratio on aerodynamic performance by adjusting the flow velocity and total pressure. Although the MWT has been used to elucidate the var-
ious aerodynamic characteristics of low-Reynolds-number airfoils, we have also developed pressure-sensitive paint measurement techniques for the MWT tests, which can be applied under low-pressure conditions. For the optimum design of the ejector driver, it is necessary to derive an evaluation method that can predict the pressure-recovery ratio, attempting to correlate the obtained results with the mass-flow rate and the Mach number of the secondary flows. However, the obtained pressure-recovery ratio has strong sensitivity to other parameters, such as the Mach number of the secondary flow and gas species. Fabri and Paulson also attempted to correlate the pressure-recovery ratio with the total pressure ratio; however, his results indicate a dependence of the pressure ratio on the primary nozzle shape. Similar examples can be found in the research on ejectors for driving wind tunnels. Arkadov and Roukavets evaluated various ejectors as wind tunnel drivers, research on ejectors for driving wind tunnels. 

In these research papers, the pressure-recovery ratio is evaluated as a function of the mass-flow ratio or the total pressure ratio between the primary and secondary flows. Dutton et al. conducted parametric studies on the pressure-recovery ratio using an ejector system with a constant-area mixing section, attempting to correlate the obtained results with the mass-flow ratio. However, the obtained pressure-recovery ratio has strong sensitivity to other parameters, such as the Mach number of the secondary flow and gas species. Fabri and Paulson also attempted to correlate the pressure-recovery ratio with the total pressure ratio; however, his results indicate a dependence of the pressure ratio on the primary nozzle shape. Similar examples can be found in the research on ejectors for driving wind tunnels. Arkadov and Roukavets evaluated various ejectors as wind tunnel drivers, research on ejectors for driving wind tunnels. 

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In this study, the effective range of the EDP is evaluated under low-pressure conditions using the same model ejector as Kitamura et al. Then, the scalability of the EDP for evaluating the driving performance of the MWT is verified. Finally, a design improvement guideline for expanding the operational envelope of the MWT is proposed.

2. One-dimensional Analysis and EDP

A schematic image of the one-dimensional flow model inside a mixing duct with a constant-cross-sectional area is shown in Fig. 2. Herein, the primary flow enters the mixing section at supersonic speeds, and the Mach number of the secondary flow changes depending on the suction power of the ejector. The primary and secondary flows enter the mixing section, where they are thoroughly mixed. The mixed flow decelerates to a subsonic speed after passing through the vertical shock wave, exiting the mixing section thereafter. For simplicity, the effect of wall friction is neglected here.

The specific heat ratio of the flow in the mixing section, denoted by $\gamma_3$, is expressed by:

$$\gamma_3 = \frac{\gamma_2 \left( \frac{\gamma_1 \gamma_2 - 1}{\gamma_1 - 1} m_1 M_{w_2} \right)}{\gamma_2 \left( \frac{\gamma_1 \gamma_2 - 1}{\gamma_1 - 1} m_2 M_{w_1} \right)} + 1.$$  

The total temperature in the mixing section ($T_{03}$) is derived as follows:

$$T_{03} = M_{w_1} \gamma_3 \left( 1 - \mu \right) \left( \frac{T_{01}}{\gamma_1 - 1 M_{w_1}} + \mu \right) \left( \frac{T_{02}}{\gamma_2 - 1 M_{w_2}} \right),$$

where
The Mach number at the mixing section \( (M_3) \) can be expressed as

\[
M_3^2 = \frac{B^2 - 2\gamma_3}{2\left(\frac{\gamma_3 - 1}{2} - B^2 - \gamma_3^2\right)},
\]

where

\[
B = \frac{\gamma_3 M_{w,s} T_{02}}{\gamma_2 M_{w,s} T_{03} M_2} \left(\frac{\gamma_2 M_2^2 + 1}{1 + \frac{\gamma_2 - 1}{2} M_2^2}\right)^{-1/2} + \frac{\gamma_3 M_{w,s} T_{01}}{\gamma_1 M_{w,s} T_{03}} \left(\frac{\gamma_1 M_1^2 + 1}{1 + \frac{\gamma_1 - 1}{2} M_1^2}\right)^{-1/2}.
\]

The pressure-recovery ratio \( (P_{03}/P_{02}) \) is given by the following equation:

\[
P_{03} = \frac{1}{M_3^2} \left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right)^{\frac{\gamma_3 + 1}{\gamma_3 - 1}} \beta.
\]

where

\[
\beta = \frac{\gamma_3 M_{w,s} T_{02}}{\gamma_2 M_{w,s} T_{03} M_2} \left(1 + \frac{\gamma_2 - 1}{2} M_2^2\right)^{\frac{\gamma_2 + 1}{\gamma_2 - 1}} + \frac{P_{02}}{P_{01}} \frac{\gamma_3 M_{w,s} T_{01}}{\gamma_1 M_{w,s} T_{03} M_1} \left(1 + \frac{\gamma_1 - 1}{2} M_1^2\right)^{\frac{\gamma_1 + 1}{\gamma_1 - 1}}.
\]

By substituting the subsonic solution obtained from Eq. (5) and the inflow condition of Eq. (7), we can obtain the pressure recovery.

For details on deriving the EDP and consideration of the physical properties, see Kitamura et al. Here, the summary of the EDP is described below.

The following two equations are obtained from the isentropic equations:

\[
\frac{A_1^*}{A_3} = M_1 \left[\frac{\gamma_1 + 1}{\gamma_1 - 1} M_1^2 + 2\right]^{\frac{\gamma_1 + 1}{\gamma_1 - 1}}.
\]

\[
P_{01} = \frac{1}{M_1^2} \left(1 + \frac{\gamma_1 - 1}{2} M_1^2\right)^{\frac{\gamma_1 + 1}{\gamma_1 - 1}}.
\]

From Eq. (9) and Eq. (10), the following equation can be obtained:

\[
\frac{P_{01}}{P_{02}} \frac{A_1^*}{A_3} = \frac{(\gamma_1 + 1)^{1/2}}{2} \frac{M_1^2}{M_3^2} \left(1 + \frac{\gamma_1 - 1}{2} M_1^2\right)^{\frac{1}{2}}.
\]

The left-hand side of Eq. (11) is defined as the EDP, which is mathematically denoted by \( E \),

\[
E = \frac{P_{01} A_1^*}{P_{02} A_3},
\]

where \( P_{01} \) and \( P_{02} \) are determined from the operational conditions, and \( A_1^* \) and \( A_3 \) are determined from the system configuration.

From Eq. (11) and Eq. (12), it is evident that \( M_1 \) is a function of \( E \) and \( \gamma_1 \). From Eq. (5), \( M_3 \) is expressed by the following equation when \( m_2 = 0 \) and \( M_3 \neq M_1 \):

\[
M_3^2 = \frac{(\gamma_3 - 1) M_2^2 + 2}{2\gamma_3 M_2^2 - (\gamma_3 - 1)}.
\]

Equation (13) corresponds to the relation between Mach numbers in front of and back of the normal shock wave. From Eqs. (11), (12) and (13), it is evident that \( M_3 \) is a function of \( E \) and \( \gamma_1 \). Accordingly, the pressure-recovery ratio can be expressed as

\[
P_{03} = \frac{1}{M_3} \left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right)^{\frac{\gamma_3 + 1}{\gamma_3 - 1}} E.
\]

It is evident that the pressure-recovery ratio is also a function of \( E \) and \( \gamma_1 \). Thus, the EDP is the dominant parameter with respect to the strength of the normal shock wave in the primary flow when the ejector starts without secondary mass flow. As a consequence, the pressure-recovery ratio can be expressed as

\[
P_{03} = \frac{F(M_2, A_1^*, \gamma_1, T_{01}, A_3)}{P_{02} A_1 A_3}.
\]

3. Evaluating Single-Nozzle Model Ejectors

3.1. Experimental setup and measurement method

In order to evaluate the effectiveness of the ejector-driving parameter under low pressure, a model ejector with the same configuration established by Kitamura et al. was used, which is shown in Fig. 3. We note that this model ejector is not a part of the MWT but an individual small device. The model ejector was installed inside the vacuum chamber of the MWT. At this time, the MWT itself was not driven and was just used as a vacuum chamber. The ejector is axisymmetric and has a constant circular cross-sectional area. The inner diameter and length of the mixing section are 22 and 655 mm, respectively. Three primary nozzles with throat diameters ranging from 3 to 17 mm were used. The flow coefficients of each nozzle were 0.93, 0.83, and 0.77, respectively. Orifices with throat diameters ranging from 3 to 17 mm were installed in the inlet of the secondary flow in order to control the secondary mass flow.
respectively. The high-pressure gas-supply system of the MWT was used to drive the model ejector. The pressure and temperature of the primary gas were measured using a supply-pressure sensor (KELLER, PR-21Y) and a resistance-temperature detector, respectively. The primary mass supply-pressure sensor (KELLER, PR-21Y) and a resistand temperature of the primary gas were measured using a MWT was used to drive the model ejector. The pressure was changed from 101 to 10 kPa in the air mode and from 60 to 10 kPa in the CO2 mode. The total pressure of the primary flow was varied from 0.1 to 1.0 MPa. Here, “the basic case” is defined as the experimental condition when the primary throat nozzle diameter is 4 mm, the orifice diameter is 6 mm, and the test gas is air.

3.2.2. Results and discussion

Figure 4 compares the wall-pressure ($P_w$) distributions in the basic case for $P_{ambient} = 101$, 40, and 10 kPa, respectively. The total pressure of the primary flow ($P_{01}$) was changed from 0.2 MPa to 1.0 MPa in 0.2 MPa steps. The origin of the horizontal axis coincides with the outlet of the primary nozzle. At $P_{ambient} = 101$ and 40 kPa, the primary flow starts mixing with the secondary flow from the primary-nozzle outlet, causing a rapid increase in wall pressure. Eventually, the wall pressure completely recovers to the ambient pressure at the outlet of the mixing section. Therefore, the static pressure at the outlet of the mixing section is $P_f$ for all cases for $P_{ambient} = 101$ and 40 kPa. In contrast, the wall pressure at $P_{ambient} = 10$ kPa increases further downstream at $x/d = 18.6$, when the ratio of the ambient pressure to the primary pressure ($P_{ambient}/P_{01}$) falls below 0.027, which is the boundary between overexpansion and underexpansion. When $P_{ambient}/P_{01}$ is less than 0.027, the primary flow is in the underexpansion condition and “Fabri choke” occurs in the mixing section. Fabri choke is induced when the secondary flow reaches a sonic condition as the primary plume expands rapidly, forming an aerodynamic throat in the mixing section. A shock train, which decelerates the primary flow to subsonic velocities, is formed in the primary plume, followed by an increase in wall pressure due to the mixing of the primary flow and secondary flow. For $P_{ambient}/P_{01}$ less than 0.027, the wall pressure does not recover completely at the mixing-section outlet. The following investigation covers the cases where mixing is completed, and the wall pressure recovers sufficiently at the mixing-section outlet (except for specific cases such as Fabri choke).

Table 1. Experimental conditions of the model-ejector tests.

| Objective                | Variable            | Fixed parameter and condition |
|--------------------------|---------------------|--------------------------------|
| Primary nozzle shape     | $d_{01}^+ = 3, 4, 5 \text{mm}$ | $d_0 = 6 \text{mm}, \text{Air-Air}$ |
| Secondary nozzle shape   | $d_{02} = 6, 8, 17 \text{mm}$ | $d_{01}^+ = 4 \text{mm}, \text{Air-Air}$ |
| Gas species (primary-secondary) | Air-Air, CO2-CO2, Air-CO2, CO2-Air | $d_{01}^+ = 4 \text{mm}, d_0 = 6 \text{mm}$ |

The experimental conditions of the model-ejector tests are tabulated in Table 1. In order to investigate the effective pressure range of the EDP at low pressures, the relation between the pressure-recovery ratio and the EDP is evaluated for three different geometric configurations as well as various operational conditions. Air and CO2 were used as the primary and secondary gases, respectively, with a total of four cases carried out for each gas combination. The ambient pressure was changed from 101 to 10 kPa in the air mode and from 60 to 10 kPa in the CO2 mode. The total pressure of the primary flow was varied from 0.1 to 1.0 MPa. Here, “the basic case” is defined as the experimental condition when the primary throat nozzle diameter is 4 mm, the orifice diameter is 6 mm, and the test gas is air.

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The high-pressure gas-supply system of the MWT was used to drive the model ejector. The pressure and temperature of the primary gas were measured using a supply-pressure sensor (KELLER, PR-21Y) and a resistance-temperature detector, respectively. The primary mass flow was obtained from $P_{01}$ and $T_{01}$ using the following isentropic equation:

$$m_1 = \frac{A_1^* P_{01}}{\sqrt{T_{01}}} \left( \frac{2}{\gamma_1 + 1} \right)^{\frac{\gamma_1+1}{\gamma_1}} \left( \frac{\gamma_1}{R_1} \right)^{\frac{\gamma_1+1}{2(\gamma_1-1)}}. \quad (16)$$

In addition, the pressure and the temperature of the secondary flow were measured using multiple pressure scanners and a thermocouple, respectively. Although the secondary mass flow can be defined from the static pressure at the inlet and the outlet of the orifice, the total pressure loss of the secondary flow occurs at the step behind the outlet of the orifice. Therefore, the total pressure and the static pressure of the secondary flow were measured downstream of the outlet of the orifice, as shown in Fig. 3.

Static-pressure taps were provided along the duct wall, and wall-pressure distribution was simultaneously measured using a pressure scanner with 16 channels.

From the mass conservation equation, the total pressure of the mixing section ($P_{03}$) can be expressed as

$$P_{03} = \left( \frac{P_3^{\frac{x+1}{2}} \pm \sqrt{P_3^{\frac{2(x+1)}{2}} + 4 \left( \frac{m_1^2}{ab} \right) P_3^{\frac{1}{2}}}}{2 P_3^{\frac{1}{2}}} \right)^{\frac{1}{x+1}}, \quad (17)$$

where

$$a = \frac{A_3}{\sqrt{RT_0}}, \quad b = \frac{2\gamma}{\gamma - 1}. \quad (18)$$

Substituting the measured static pressure at the mixing section outlet into Eq. (17), $P_{03}$ can be obtained.

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The experimental conditions of the model-ejector tests are tabulated in Table 1. In order to investigate the effective pressure range of the EDP at low pressures, the relation between the pressure-recovery ratio and the EDP is evaluated for three different geometric configurations as well as various operational conditions. Air and CO2 were used as the primary and secondary gases, respectively, with a total of four cases carried out for each gas combination. The ambient pressure was changed from 101 to 10 kPa in the air mode and from 60 to 10 kPa in the CO2 mode. The total pressure of the primary flow was varied from 0.1 to 1.0 MPa. Here, “the basic case” is defined as the experimental condition when the primary throat nozzle diameter is 4 mm, the orifice diameter is 6 mm, and the test gas is air.
In order to evaluate the effectiveness of EDP under low-pressure conditions, the effect of the ambient pressure was investigated for the basic case. Figure 5 compares the pressure-recovery ratio to EDP, total pressure ratio, and mass-flow ratio. In Fig. 5(a), the theoretical solution obtained from the one-dimensional analysis (Eq. (7)) and the results obtained by Kitamura et al.15) at one atmosphere are also plotted for comparison. The data obtained for different ambient pressures collapse into a single curve, indicating that the experimental data is consistent with the one-dimensional analysis. Both the pressure-recovery ratio and EDP as the ambient pressure decreases. The maximum difference between the one-dimensional analysis results and each plot is approximately 7.9%. Moreover, the extrapolation curve of the one-dimensional analysis results corresponds to the results established by Kitamura et al., albeit with a small error, especially in the case of large EDP. Accordingly, the EDP is an effective parameter for evaluating supersonic ejector performance under low-pressure conditions as well as atmospheric conditions. Similarly, both the total pressure ratio and the mass-flow ratio collapse into a single curve; moreover, they correlate the pressure-recovery ratio without being dependent on the ambient pressure. Hence, the pressure-recovery ratio can be evaluated using the EDP, total pressure ratio, and mass-flow ratio, unless the configurations of the ejector system and gas change.

Figure 6 compares the primary-nozzle-shape dependence of each evaluation parameter for the pressure-recovery ratio when the throat diameter of the primary nozzle (\(d_{r}^*\)) changes in the basic mode. It is evident that the pressure-recovery ratio correlates with the EDP without depending on the primary nozzle diameter. In contrast, when the pressure-recovery ratio is evaluated using the total pressure ratio, it strongly depends on the primary nozzle diameter. In addition, from Fig. 6, it is evident that the mass-flow ratio does not collapse into a single curve. Therefore, only the EDP correlates with the pressure-recovery ratio without depending on the primary nozzle diameter. In Fig. 7, the effect of the orifice diameter of the secondary flow on each evaluation parameter is shown, from which it is evident that the pressure-recovery ratio has a linear correlation with the EDP and the total pressure ratio. Accordingly, the EDP is equivalent to the total...
pressure ratio multiplied by the constant cross-sectional ratio, as expressed by Eq. (12). This means that the two evaluation methods shown in Fig. 7(a) and (b) have the same physical meaning. Moreover, the pressure ratio is the only parameter that does not correlate to the mass-flow ratio, as shown in Fig. 7(c).

Figure 8 indicates the effect of the gas species on the pressure-recovery ratio, from which it is evident that the pressure-recovery ratio has a linear correlation to both the EDP and the total pressure ratio. These two evaluation methods have the same physical meaning because they have the same cross-section. Additionally, the parametric studies in one-dimensional analysis by Kitamura et al.\cite{15} reveal that the pressure ratio cannot correlate to the EDP when the difference of the specific heat ratio is sufficiently large between the primary and secondary gases. Accordingly, a good correlation between the pressure-recovery ratio and the EDP can be seen in Fig. 8(a) and (b), since the difference in the specific heat ratio between air ($\gamma = 1.4$) and CO$_2$ ($\gamma = 1.3$) is small. However, said correlation will deteriorate if a different gas species with a larger specific heat ratio, such as helium ($\gamma = 1.66$), is used as the test gas. In contrast, as shown in Fig. 8(c), the pressure ratio correlates to the mass-flow ratio when the gas species of the primary and secondary flows are the same; however, it does not correlate to the mass-flow ratio when different gases are used.

4. Application to the MWT Supersonic Ejector System

In the previous section, it was verified that the EDP is an effective parameter for evaluating the pressure-recovery ratio under low-pressure conditions. In this section, the EDP is applied in order to evaluate the MWT ejector-driving performance.

4.1. Experimental setup and measurement method

The experimental setup for the MWT ejector-driving performance tests is illustrated in Fig. 9. The origin of the x-direction is set at the most upstream part of the contraction section. Eleven wall-pressure taps were installed in the in-draft wind tunnel in order to measure the wall-pressure distribution. The effect of the boundary layer on the wall pressure was neglected. Similar to the model-ejector tests, the
total pressure and the total temperature of the primary gas were measured using a pressure sensor and a resistance-temperature detector, respectively. The primary mass flow was obtained from Eq. (16). The total pressure and total temperature of the test-section flow were measured using a kulite sensor and thermocouple installed upstream of the contraction section, respectively.

The Mach number at the test-section center, denoted by $M_c$, can be obtained using the following equation:

$$M_c = \sqrt{\frac{2}{\gamma_2 - 1} \left( \frac{P_{0c}}{P_c} \right)^{\frac{\gamma_2 - 1}{\gamma_2}} - 1},$$

where the Mach number of the secondary flow ($M_2$) is defined as the Mach number immediately before the test-section flow enters the ejector part, as shown in Fig. 9. $M_c$ is converted into the Mach number of the secondary flow ($M_2$) using the cross-sectional area ratio:

$$\frac{A_2}{A_c} = \frac{M_c}{M_2} \left( \frac{\gamma_2 - 1}{\gamma_2} \right) M_2^2 + 2 \left( \frac{\gamma_2 - 1}{\gamma_2} \right) M_2^4 + 2,$$

where $A_c$ and $A_2$ indicate the cross-sectional area at the test-section center and immediately before the ejector part, respectively. The static pressure at the mixing section ($P_3$) was measured, with its total pressure ($P_{03}$) obtained from Eq. (17).

Figure 10 shows the ejector part of the MWT. The multiple supersonic nozzles are located at the end of the first diffuser, inducing flow in the test section using an ejector effect. The ejector consists of five circular pipes, each with six equally spaced small orifices having a diameter of 1 mm. The nozzle cross-sectional area ($A_1^{*}$) is defined as the sum of the cross-sectional areas of each nozzle-outlet orifice.

The experimental conditions are listed in Table 2. A series of tests was performed in air- and CO$_2$-operation modes at room temperature (roughly 288 K). The gas pressure supplied to the ejector was changed from 0.1 to 1.0 MPa for the air mode and from 0.1 to 0.61 MPa for the CO$_2$ mode.

4.2. Results and discussion

Figure 11 shows the wall-pressure distribution at $P_{ambient} = 1$ kPa for the modes of air and CO$_2$. The test section and its center correspond to the positions of $x = 1,265$ to 1,940 mm and $x = 1,490$ mm, respectively. The ejector was installed at $x = 2,490$ mm. The overall wall pressures de-
crease as the primary pressure increases, which can be attributed to an increase in flow velocity. The static-pressure distribution in the test section was not kept constant in some driving conditions due to development of a boundary layer. The upper and lower walls of the test section were given a fixed inclination-angle in order to adapt to the boundary layer. Therefore, although nonuniformity occurs in the static-pressure distribution under all conditions other than the design point of the inclination angle, static pressure remains constant at $\frac{P_{\text{ambient}}}{P_0} = 0.0094$ in the air mode.

Considering one orifice nozzle and using Eq. (9), the Mach number of the primary flow ($M_1$) is 2.94. Accordingly, the pressure ratio ($\frac{P_{\text{ambient}}}{P_0}$) for the underexpansion limit is approximately 0.027. In Fig. 11, Fabri choke cannot be found, even when underexpansion occurs at large primary pressures. The mixing of the primary flow and secondary flow is further facilitated by the primary gas ejection from 30 supersonic nozzles. Therefore, the wall pressure rapidly recovers from immediately behind the ejector in both gas modes. Considering the isentropic curve for CO$_2$ for different primary pressures and the sublimation curve of CO$_2$, we can say that solidification theoretically occurs. However, there is no noticeable effect of CO$_2$ solidification on wall-pressure distribution; moreover, there are no special operational problems over the entire operational envelope of the MWT. This can be attributed to the heater installed near the ejector valve, which supplied heat through the gas-supply pipeline and, in turn, alleviated CO$_2$ solidification.

The pressure-recovery ratio of the MWT evaluated by the EDP is compared with that of the model ejector in Fig. 12. In both cases, the operational conditions are common, but the cross-sectional ratio defining EDP is different. This means that the EDP of the MWT is much smaller than that of the model ejector. According to Fig. 12, the results of the model ejector are well-fitted to the extrapolation curve of the MWT results, whereas approximately 5% of errors can be seen in the crossover range of EDP. This suggests that EDP is an effective parameter with high generality that, despite a large difference in the ejector configuration, can evaluate the pressure-recovery ratio of the MWT.

The pressure-recovery ratios evaluated by EDP in the modes of air and CO$_2$ are compared in Fig. 13. The results of the one-dimensional analysis are also shown for comparison purposes. The pressure-recovery ratio correlates to EDP, with no dependence on gas species. Moreover, the one-dimensional analysis is consistent with the experimental results. We note that, in Fig. 13, it seems that the difference between the theoretical curve and the experimental results is large, especially in the range where EDP is $1 \times 10^{-1}$ or more corresponding to the condition of $P_{\text{ambient}} = 1$ kPa. How-

![Fig. 11. Wall-pressure distribution of the MWT at $P_{\text{ambient}} = 1$ kPa.]()

![Fig. 12. Comparing the pressure ratio of the MWT with that of the model ejector.]

![Fig. 13. Pressure ratio of air and CO$_2$ modes.]

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ever, this difference is estimated to be at most 3.5%. Comparing the experimental and theoretical pressure-ratios for the same EDP, the smaller $P_{\text{ambient}}$ became, the worse the measurement accuracy of $P_3$ required for $P_0$ using Eq. (17). Consequently, the difference in the pressure ratio becomes relatively large.

As previously described, the pressure-recovery ratio can be expressed by the seven parameters shown in Eq. (15). If the operational conditions and the configuration of the ejector system are fixed, the Mach number of the secondary flow ($M_2$) is the only unknown parameter. The relation between EDP and the pressure-recovery ratio can be predicted using Fig. 13. In other words, the pressure-recovery ratio can be obtained from the design parameter, EDP, and $M_2$ can also be acquired from the pressure-recovery ratio. Consequently, we can predict the Mach number in the test section from the operational and configuration conditions.

These results indicate that a higher Mach number in the test section can be realized by increasing EDP; that is, by increasing the cross-sectional area ratio or the total pressure ratio. In the present configuration of the MWT ejector system, a higher Mach number can be attained by simply increasing the primary pressure or by reducing the ambient pressure for the same primary pressure. In contrast, when a change in the system configuration is allowed, either the primary throat nozzle-diameter or the number of nozzles must be increased accordingly. However, it is also important to pay attention to changes in mixing state such as the occurrence of Fabri choke.

Future modifications of the MWT are currently being considered for airfoil tests under low-temperature conditions. Herein, the supply pressure will be a limiting factor in restricting operation in the low-pressure region due to the concern of CO$_2$ solidification. One possible solution to this problem is to reduce the supply pressure by increasing the number of primary nozzles while maintaining the same primary mass flow.

5. Conclusion

In this study, the EDP was used as a parameter to predict the flow velocity at the MWT driven by an ejector with multiple supersonic nozzles. The effective range of the EDP was evaluated under low-pressure conditions using a model ejector. In doing so, the impact of system configurations and operational conditions on the effectiveness of the EDP was investigated. The results of the model-ejector tests were then applied in order to evaluate the MWT ejector-driving performance.

The pressure-recovery ratio does not necessarily correlate to the total pressure ratio and the mass-flow ratio. Rather, this depends on ambient pressure, system configuration, and operational conditions including the test-gas species.

The pressure-recovery ratio correlates to the EDP even when the ambient pressure, system configuration, and operational conditions change. Furthermore, the experimental results are consistent with the one-dimensional analysis conducted. Accordingly, the EDP is an effective parameter for predicting the pressure ratio at one atmosphere as well as under low-pressure conditions.

The pressure-recovery ratio of the MWT can be expressed as a common function of EDP in both air and CO$_2$ modes. In addition, the experimental results are consistent with the one-dimensional analysis. Moreover, the extrapolation curve of the MWT results corresponds to the results of the model ejector. Thus, the EDP is a universal parameter for predicting the pressure-recovery ratio.

The evaluation methodology using the EDP allows us to predict the Mach number in the test section from the pressure ratio. Based on this evaluation methodology, we established a design guideline for ejector design optimization.

References

1) Balaram, J., Canham, T., Duncan, C., Golombek, M., Grip, H. F., Johnson, W., Maki, J., Quon, A., Stem, R., and Zhu, D.: Mars Helicopter Technology Demonstrator, AIAA Paper 2018-0023, 2018.
2) Braun, R. D. and Spencer, D. A.: Design of the ARES Mars Airplane and Mission Architecture, J. Spacecr. Rockets., 43 (2006), pp. 1026–1034.
3) Nagai, H. and Mars Airplane Working Group: Aerodynamic Challenge to Realize Mars Airplane, Proceeding of 30th International Symposium on Space Technology and Science, Kobe, Japan, 2015-k-47, 2015.
4) Fujita, K., Nagai, H., and Asai, K.: Conceptual Design of a Miniature, Propeller-Driven Airplane for Mars, AIAA Paper 2012-0847, 2012.
5) Anyoji, M., Nose, K., Ida, S., Numata, D., Nagai, H., and Asai, K.: Development of a Low-Density Wind Tunnel for Simulating Martian Atmospheric Flight, Trans. JSASS Aerospace Technology Japan, 9 (2011), pp. 21–27.
6) White, B. R.: A Low-Density Boundary-Layer Wind Tunnel Facility, AIAA Paper 87-0291, 1987.
7) Anyoji, M., Ida, S., Nose, K., Numata, D., Nagai, H., and Asai, K.: Characteristics of the Mars Wind Tunnel at Tohoku University in CO$_2$ Operation Mode, AIAA Paper 2010-1490, 2010.
8) Anyoji, M., Numata, D., Nagai, H., and Asai, K.: Effects of Mach Number and Specific Heat Ratio on Low-Reynolds-Number Airfoil Flows, AIAA J., 53 (2015), pp. 1640–1654.
9) Anyoji, M., Numata, D., Nagai, H., and Asai, K.: Pressure-sensitive Paint Technique for Surface Pressure Measurements in a Low-density Wind Tunnel, J. Visual., 18 (2015), pp. 297–309.
10) Porter, J., Squyers, R., and Nagaraja, K.: An Overview of Ejector Technology, AIAA Paper 81-1678, 1981.
11) Fabri, J. and Paulson, J.: Theory and Experiments on Supersonic Air-to-Air Ejectors, NACA TM 1410, 1958.
12) Dutton, J. C., Mikkelsen, C. D., and Addy, A. L.: A Theoretical and Experimental Investigation of the Constant-Area Supersonic-Supersonic Ejectors, AIAA J., 2 (1974), pp. 775–816.
13) Crocco, L.: One-Dimensional Treatment of Steady Gas Dynamics, Fundamental of Gas Dynamics, Emmons, H. W., ed., Princeton University Press, New Jersey, 1958, pp. 281–293.
14) Arkadov, Y. K. and Roukavets, V. P.: Ejector-driven Wind Tunnels, AGARD Conference Proceedings, AGARD-CP-585, 1997, pp. 1–22.
15) Kitamura, E., Tomiska, S., Sakuranaka, N., Watanabe, S., and Masuya, G.: Dominant Parameter for Pressure Recovery Performance of Constant-Area Mixing Tubes of Ejector Jets, J. Jpn. Soc. Aeronaut. Space Sci., 57 (2009), pp. 1–8.
16) Angus, S., Armstrong, B., and de Reuk, K. M.: Carbon Dioxide, International Thermodynamic Tables of the Fluid State, IUPAC, Pergamon Press, Oxford, 1976.

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