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Investigation of Supersonic Air Ejectors*

(Part 1. Performance in the Case of Zero-Secondary Flow)

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The performance of a supersonic air ejector in the case of zero-secondary flow was studied by varying the Mach number of the primary nozzle and the throat area ratio of the mixing tube to the primary nozzle. As the result, it has been shown that an optimum throat area ratio exists for each Mach number of the primary nozzle in which case the vacuum performance of the ejector becomes maximum with a minimum stagnation pressure of the primary flow. The physical meanings of the optimum throat area ratio and other ejector characteristics have been clarified from the results of pressure measurements and optical observations. Furthermore, modifying a previous method in the case of a constant-area mixing tube, the ejector performance was calculated for a variable-area mixing tube in the case of a larger throat area ratio than the optimum one. Calculated values agree well with the experimental results.

1. Introduction

From old, ejectors have been utilized as vacuum and exhaust pumps⁽¹⁾⁽²⁾, thermo-compressors⁽³⁾, high-altitude simulators for rocket-engine testing⁽⁴⁾, thrust augmentation of V/STOL aircraft⁽⁵⁾, and so on. Many investigations have been reported so far, and performance diagrams for designing ejectors have been proposed⁽¹⁾⁽²⁾⁽⁶⁾⁻⁽⁸⁾. However, the flow behaviors in the ejector have not yet been well understood and the physical verification of the performance diagram has not been adequate. In particular, as for a supersonic air ejector, there are two types: straight tube⁽⁴⁾⁽⁷⁾⁽⁸⁾ and second-throat⁽²⁾⁽⁶⁾⁽⁹⁾⁽¹⁰⁾ ejectors. And, at present, the effect of the ejector throat on its performance is not well clarified.

The purpose of the present investigation is to clarify the flow behaviors and the physical meanings of the performance diagram of supersonic second-throat air-ejectors, and to give useful data to design high performance ejectors. In the present report, the vacuum characteristics

of the ejector were experimentally investigated over a range of primary nozzle Mach numbers and throat area ratios (ratio of ejector throat area to primary nozzle throat area). Furthermore, the ejector performance was calculated by modifying a previous method of calculation⁽⁴⁾ for supersonic base pressure and the results were compared with the experimental values.

2. Experimental apparatus and procedures

The ejector and a measuring system used in this work are schematically shown in Fig.1. The cross section of the ejector is rectangular so that optical observation is possible. The high pressure dry air in the reservoir flows into the primary chamber and, accelerated to supersonic in the primary nozzle, it enters the mixing section and then is discharged into the atmosphere through the settling chamber and the silencer. The valve located

Fig.1 Experimental apparatus

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upstream of the secondary stagnation chamber was closed and there was no secondary flow in the present experiment. The primary stagnation pressure p_{0p} was extremely gradually increased so that the flow might be regarded as quasi-steady. The stagnation pressure in the settling chamber was nearly equal to the atmospheric pressure p_a during the experiments.

The configuration and dimensions of the mixing tube are shown in Fig.2. The widths of the primary nozzle and the mixing tube are constant at 32.5mm. The height of the primary nozzle exit (section 1 in Fig.2) is 30mm. The heights at the inlet and outlet of the mixing tube are 95mm. The primary nozzle is exchangeable and three nozzles whose Mach numbers at the exit M_{1p} are 1.40, 2.05 and 3.05 were used in the present experiment. The height H_2 at the ejector throat (section 2 in Fig.2) was variable and the ratio of the height H_2 at the ejector throat to the height H_p^* at the primary nozzle throat $\Psi \equiv H_2/H_p^*$ ranged from 1.24 to 18.6. Ψ is equivalent to the throat area ratio, since the width of the ejector is constant. The closed circles along the duct axis in Fig. 2 represent the static pressure taps and these pressures were measured by a multi-limb mercury manometer. The stagnation pressures in the primary and secondary stagnation chambers were measured by pressure transducers. The flow was visualized by a schlieren optical system. The Mach number M_{1p} at the exit of the primary nozzle was evaluated from the pressure in the primary stagnation chamber p_{0p} and the static pressure at the nozzle exit p_{1p} , assuming an isentropic flow.

3. Experimental results

3.1 Relation between primary and secondary stagnation pressures

An example of variations of the secondary stagnation pressure p_{0s} and the static pressure p_{1p} at the primary nozzle exit when the primary stagnation pressure p_{0p} increases from the atmospheric pressure p_a is shown in Fig.3, where $M_{1p}=2.05$ and $\Psi=3.70$. Each pressure is nondimensionalized by p_a . The ratio p_{1p}/p_a decreases at first with an increasing p_{0p}/p_a and becomes minimum at a point *b*. This point corresponds to the state that a shock wave generated at the nozzle throat moves downstream and reaches the nozzle exit. After that, p_{1p}/p_a increases in

Fig.2 Configuration of mixing tube

proportion to an increasing p_{0p}/p_a and the shock wave is excluded from the nozzle. On the other hand, p_{0s}/p_a decreases with an increasing p_{0p}/p_a up to the minimum point *c*, and then increases in proportion to an increasing p_{0p}/p_a . In this paper, we define the point *c* as an optimum operating point, since it corresponds to a minimum induced pressure when an ejector is used as a vacuum or exhaust pump. In the following, the properties at this point will be identified by adding the subscript *m*. The variation of p_{1p}/p_a at the point *a* may be caused by a shock-induced separation of the turbulent boundary layer in the nozzle.

3.2 Effect of throat area ratio on performance

An example of the effects of the throat area ratio Ψ on the ejector performance in the case of $M_{1p}=2.05$ is shown in Fig.4, where the solid lines represent the experimental curves for each constant

Fig.3 Performance curve ($M_{1p}=2.05, \Psi=3.70$)

Fig.4 Effect of throat area ratio on ejector performance ($M_{1p}=2.05$)

value of Ψ , and the broken line represents the curve connecting the optimum operating points of each solid line. When $\Psi=5.86$, the ejector is a straight-tube type. As is evident from the figure, when $\Psi<3.70$, the value of p_{op}/p_a at the optimum operating point, $(p_{op}/p_a)_m$, is larger and $(p_{os}/p_a)_m$ is smaller for a larger Ψ . On the other hand, when $\Psi>3.70$, $(p_{op}/p_a)_m$ increases with Ψ and $(p_{os}/p_a)_m$ is held nearly constant and so independent of Ψ . Hence, there exists an optimum throat area ratio Ψ_{opt} where $(p_{os}/p_a)_m$ is minimum and the value of $(p_{op}/p_a)_m$ is also minimum. In Fig.4, $\Psi_{opt}=3.70$. When $\Psi>\Psi_{opt}$, the value of $(p_{op}/p_a)_m$ increases with Ψ , as is evident from Fig.4. The experimental points *a* to *d* shown by closed circles in

(a)

(b)

(c)

(d)

Fig.5 Schlieren photographs [Figs.(a) to (d) correspond to experimental points *a* to *d* in Fig.4, respectively.]

Fig.4 will be explained in the next section.

3.3 Optical observations and axial static pressure distributions

To clarify the physical meanings of the results described above, optical observations of flow and pressure measurements along the duct axis were made. An example is shown in Figs.5 and 6, respectively. Figures (a) to (d) in Fig.5, and the curves (a) to (d) in Fig.6 are schlieren photographs and axial pressure distributions at the points *a* to *d* in Fig.4, respectively. The abscissa in Fig.6 represents the distance from the nozzle exit x , and the ordinate represents the ratio p/p_{op} of the local static pressure p to the primary stagnation pressure p_{op} . The arrows at the right end in Fig.6 show the atmospheric pressure, for reference. Figure 5 (a) shows the flow in the case that $\Psi=2.47<\Psi_{opt}$ ($=3.70$) and p_{op}/p_a is smaller than $(p_{op}/p_a)_m$, and the shock wave generated at the nozzle throat is located just downstream of the nozzle exit. As this shock is a pseudo-shock, as is evident from the curve (a) in Fig.6, the static pressure oscillates in the x -direction just downstream region of the nozzle exit, and then it increases gradually up to the atmospheric pressure at the exit of the mixing tube ($x=1040\text{mm}$). It is evident from the pressure distribution that the flow at the ejector throat is subsonic. Figure 5 (b) shows the flow in the case of the same Ψ as that in Fig.5 (a) and p_{op}/p_a near the optimum operating point. The divergence angle of the jet downstream of the primary nozzle is a little larger than that in Fig.5 (a), and the pseudo-shock is still located upstream of the ejector throat. The curve (b) in Fig.6 shows that the pressure decreases in the divergent section downstream of the ejector throat and then increases. This pressure distribution means that there exist two shock waves; one upstream and the other downstream of the ejector throat. Therefore, the flow is doubly choked both at the nozzle throat and at the ejector throat.

Fig.6 Wall static pressure distributions along duct axis [Curves (a) to (d) correspond to the experimental points *a* to *d* in Fig.4, respectively.]

It was observed that when p_{0p}/p_a further increases from this state, the flow pattern upstream of the ejector throat does not change and the pseudo-shock wave downstream of the ejector throat moves downstream. Therefore, it may be concluded that the optimum operating point when $\Psi = 2.47$ in Fig. 4 corresponds to the state of the minimum p_{0p}/p_a for which the flow is doubly choked.

Figure 5 (c) and the curve (c) in Fig. 6 show the flow and the pressure distribution, respectively, in the case of the optimum throat area ratio $\Psi_{opt} = 3.70$ for $M_{1p} = 2.05$ and p_{0p}/p_a smaller than $(p_{0p}/p_a)_m$, and they are qualitatively similar to Fig. 5 (a) and the curve (a) in Fig. 6, respectively. However, in Fig. 5 (d) where $\Psi = \Psi_{opt}$ but p_{0p}/p_a is nearly equal to $(p_{0p}/p_a)_m$, the supersonic jet from the primary nozzle fully expands through a lip-shock⁽¹¹⁾, and then it is compressed by an oblique shock. The pseudo-shock is not observed in the figure, since it is located downstream of the ejector throat. The expansion and compression process and the pressure rise by the pseudo-shock described above are clearly observed from the curve (d) in Fig. 6. The flow pattern upstream of the ejector throat shown in Fig. 5 (d) does not change even if p_{0p}/p_a further increases, because the flow throughout this region is supersonic. Therefore, the optimum operating point when $\Psi = 3.70$ in Fig. 4 corresponds to the flow state when the pseudo-shock generated at the nozzle throat just passes through the ejector throat. In this case, a double-choking of flow is not observed.

Based on the facts described above, the flow in ejector is classified into the following two patterns according to Ψ .

(1) In the case that $\Psi < \Psi_{opt}$, when p_{0p}/p_a increases, the flow is choked not only at the nozzle throat but also at the ejector throat at a certain value of p_{0p}/p_a (double-choking phenomenon). The optimum operating point corresponds to this state, and even if p_{0p}/p_a increases further, the position of the shock wave generated at the nozzle throat is fixed at a certain point upstream of the ejector throat.

(2) In the case that $\Psi \geq \Psi_{opt}$, the double-choking does not occur and the shock wave generated at the nozzle throat passes through the ejector throat at a certain value of p_{0p}/p_a when p_{0p}/p_a increases. This moment corresponds to the optimum operating point, and the supersonic jet from the nozzle expands fully in the region upstream of the ejector throat.

From the facts described above, it may be concluded that the optimum throat area ratio Ψ_{opt} is the minimum value of Ψ for which the flow is not doubly choked. The descriptions above refer to the case of $M_{1p} = 2.05$, and the same phenomena were observed in the case of $M_{1p} = 1.40$ and 3.05, in which cases $\Psi_{opt} = 2.65$ and 7.84, respectively. It was observed that, in the case that Ψ is a little smaller than Ψ_{opt} , even

if the flow is doubly choked, the pseudo-shock upstream of the ejector throat passes through the throat when p_{0p}/p_a increases extremely. The same phenomenon was observed in the starting process of a supersonic wind tunnel⁽¹²⁾. However, since the vacuum performance of the ejector is poor in this case, it is not discussed here.

3.4 Relations among flow variables at optimum operating point

Variations of $(p_{0p}/p_a)_m$ and $(p_{0s}/p_a)_m$ with Ψ are shown in Fig. 7 taking the nozzle exit Mach number M_{1p} as a parameter, and the value of Ψ_{opt} is also indicated in the figure. $(p_{0p}/p_a)_m$ increases with an increasing Ψ and it is independent of M_{1p} . The relation is represented as follows.

$$(p_{0p}/p_a)_m = \Psi + 1 \quad (1)$$

The reason why $(p_{0p}/p_a)_m$ depends only on Ψ may be due to the fact that the maximum Mach number of the supersonic jet in the mixing tube is determined only by Ψ . On the other hand, $(p_{0s}/p_a)_m$ decreases steeply with Ψ when $\Psi < \Psi_{opt}$ and it is held constant when $\Psi \geq \Psi_{opt}$ for each case of M_{1p} .

Next, the relation between the optimum throat area ratio Ψ_{opt} and M_{1p} is shown in Fig. 8. Ψ_{opt} increases monotonically with M_{1p} .

Fig. 7 Variations of p_{0s}/p_a and p_{0p}/p_a with Ψ and M_{1p} at optimum operating point

Fig. 8 Relation between Ψ_{opt} and M_{1p}

onously with M_{1p} and a double-choking of flow occurs in the hatched region. The broken line in the figure will be explained later.

The experimental values of $(p_{0p}/p_a)_m$, $(p_{0s}/p_a)_m$ and the base pressure ratio $(p_{0s}/p_{1p})_m$ at the optimum operating point in the case of Ψ_{opt} are shown against M_{1p} in Fig. 9. $(p_{0p}/p_a)_m$ and $(p_{0s}/p_{1p})_m$ increase monotonously with M_{1p} , while $(p_{0s}/p_a)_m$ decreases monotonously with M_{1p} . The broken, dash-dotted and dash-two-dotted lines in the figure will be explained later.

4. Flow model

In order to explain the variation of $(p_{0s}/p_a)_m$ with Ψ described above, let us consider the following relation:

$$\left(\frac{p_{0s}}{p_a}\right)_m = \left(\frac{p_{0s}}{p_{1p}}\right)_m \left(\frac{p_{1p}}{p_{0p}}\right)_m \left(\frac{p_{0p}}{p_a}\right)_m \quad (2)$$

The pressure ratio $(p_{1p}/p_{0p})_m$ in the above relation is a function of only M_{1p} and it is expressed as follows.

$$\left(\frac{p_{1p}}{p_{0p}}\right)_m = \left(1 + \frac{\gamma-1}{2} M_{1p}^2\right)^{-\gamma/(\gamma-1)} \quad (3)$$

where γ is the ratio of specific heats. Next, the physical meaning of $(p_{0p}/p_a)_m$ in Eq. (2) was described in the previous chapter. At present, it is difficult to estimate the value of $(p_{0p}/p_a)_m$ theoretically, because the total pressure loss across a pseudo-shock wave in a jet is not known, and so we use Eq. (1), which was obtained experimentally. Further, the value of $(p_{0s}/p_{1p})_m$ in Eq. (2) cannot be calculated theoretically when $\Psi < \Psi_{opt}$, either, because a pseudo-shock wave exists in the upstream and downstream regions of the ejector throat. But, when $\Psi \geq \Psi_{opt}$, the value of $(p_{0s}/p_{1p})_m$ can be calculated as follows. When $\Psi \geq \Psi_{opt}$, a high vacuum performance is attained as mentioned before.

Figure 10 (a) shows a flow model of a

Fig. 9 Relation between pressure ratio and M_{1p} at optimum operating point in the case of Ψ_{opt}

two-dimensional second-throat ejector. The flow model was constructed by modifying the method of calculation for base pressure of a straight-tube ejector presented by Addy and Chow⁽¹⁴⁾. We assume that the velocity distribution of the primary flow is uniform at the nozzle exit and that the centered expansion wave just downstream of the exit is reflected from the jet boundary ab as compression wave. Assuming the value of $(p_{0s}/p_{1p})_m$ for given M_{1p} , $(p_{1p}/p_{0p})_m$ and the geometric configuration, the flow field is calculated by the method of characteristics⁽¹³⁾. Thus the location of the point b and the flow properties (the Mach number M_{bp} , the pressure ratios p_{bp}/p_{1p} and p_{ep}/p_{1p}) upstream and downstream of the oblique shock wave from the point b are determined.

The validity of the assumed value of $(p_{0s}/p_{1p})_m$ can be checked by the criterion that the total pressure of the jet boundary ab must be equal to the static pressure p_{ep} just downstream of the oblique shock. In this calculation, we consider the shear layer on the jet boundary ab , in the same way as Addy and Chow⁽¹⁴⁾. Figure 10 (b) shows the flow in the vicinity of the point b . The curve ab represents the jet boundary calculated by the method of characteristics and the curve ab' represents the jet boundary when the shear stress on the boundary is taken into consideration. That is, the total pressure of the curve ab' is equal to the static pressure p_{ep} just downstream of the oblique shock, and the flow under the streamline ab' moves upstream, since its total pressure is smaller than p_{ep} . Based on this criterion, the correct value of $(p_{0s}/p_{1p})_m$ will be determined as follows. Taking x -axis along ab from the point a and y -axis perpendicular to the x -axis at

(a) Flow model

(b) Detail flow pattern in the vicinity of the point b

Fig. 10 Flow model for base pressure ratio

an arbitrary point on the x -axis, and denoting the velocity in the x -direction at a sufficiently large point of y by u_{bp} , the velocity distribution in the x -direction may be described as follows⁽⁴⁾, if the wall W_1W_2 does not exist.

$$\varphi(\eta) \equiv \frac{u}{u_{bp}} = \frac{1}{2} \left(1 + \frac{2}{\pi^{1/2}} \int_0^\eta e^{-\xi^2} d\xi \right) \quad (4)$$

where $\eta \equiv \sigma(y/x)$ and σ is a similarity parameter⁽⁴⁾. Assuming that the stagnation temperature is constant throughout the flow field and representing the Mach number corresponding to u_{bp} and u as M_{bp} and M , respectively, u/u_{bp} in Eq.(4) is expressed as a function of the Mach numbers as follows:

$$\frac{u}{u_{bp}} = \frac{M}{M_{bp}} \left(\frac{1 + \frac{\gamma-1}{2} M_{bp}^2}{1 + \frac{\gamma-1}{2} M^2} \right)^{\frac{1}{2}} \quad (5)$$

Next, the steady continuity equation between the primary nozzle exit in Fig.10 (a) and the point b (and b') in Fig.10 (b) is given as follows.

$$\rho_{1p} u_{1p} \frac{H_{1p}}{2} = \rho_{bp} u_{bp} y_{bp} = \int_{y_j}^{y_{bp}} \rho u dy$$

where ρ is density, and y_{bp} and y_j are shown in the figure. Substituting Eq.(4) into the right hand side of the above equation, the following relation may be obtained

$$\eta_{bp} = \int_{\eta_j}^{\eta_{bp}} \frac{(1 - c_{bp}^2) \varphi}{1 - c_{bp}^2 \varphi^2} d\eta \quad (6)$$

where $\eta_j \equiv \sigma(y_j/x_b)$, $\eta_{bp} \equiv \sigma(y_{bp}/x_b)$

$$c_{bp} \equiv \left(1 + \frac{2}{\gamma+1} \frac{1}{M_{bp}^2} \right)^{-\frac{1}{2}} \quad (7)$$

Since M_{bp} , x_b and y_{bp} are known from the solution of the method of characteristics, only η_j is unknown in Eq.(6), and η_j is determined by substituting Eq.(4) into Eq.(6). Further, u_j and M_j at a point j are determined by substituting η_j into Eq.(4) and u_j into Eq.(5), respectively. The pressure ratio p_{0j}/p_{1p} of the total pressure p_{0j} to p_{1p} is determined by the following equation.

$$\frac{p_{0j}}{p_{1p}} = \frac{p_{bp}}{p_{1p}} \frac{p_{0j}}{p_{bp}} = \left(\frac{1 + \frac{\gamma-1}{2} M_{1p}^2}{1 + \frac{\gamma-1}{2} M_{bp}^2} \right)^{\frac{\gamma}{\gamma-1}} \left(1 + \frac{\gamma-1}{2} M_j^2 \right)^{\frac{\gamma}{\gamma-1}} \quad (8)$$

As shown in Fig.10 (b), since the jet boundary ab makes the angle ζ with the duct axis at the point b and the inclined angle of the wall is $\alpha \equiv \tan^{-1}[(H_1 - H_2)/2L]$, the total turning angle of the streamline is equal to $\alpha + \zeta$. Therefore, representing

the shock angle by β , the relations among p_{ep}/p_{1p} , $\alpha + \zeta$, β and M_{bp} are expressed by using the oblique shock relations⁽¹³⁾ as follows:

$$\frac{p_{ep}}{p_{1p}} = \frac{p_{bp}}{p_{1p}} \frac{p_{ep}}{p_{bp}} = \left(\frac{1 + \frac{\gamma-1}{2} M_{1p}^2}{1 + \frac{\gamma-1}{2} M_{bp}^2} \right)^{\frac{1}{\gamma-1}} \times \left(\frac{2}{\gamma+1} M_{bp}^2 \sin^2 \beta - \frac{\gamma-1}{\gamma+1} \right) \quad (9)$$

$$\tan(\alpha + \zeta) = \frac{2 \cot \beta (M_{bp}^2 \sin^2 \beta - 1)}{M_{bp}^2 (\gamma + \cos 2\beta) + 2} \quad (10)$$

As mentioned before, p_{ep}/p_{1p} in Eq.(9) must be equal to p_{0j}/p_{1p} in Eq.(8). The correct value of $(p_{0s}/p_{1p})_m$ is determined by this condition.

Figure 11 shows a flow chart of calculation of the present model. In the present calculation, an assumed value of $(p_{0s}/p_{1p})_m$ was regarded as correct if the absolute value of the difference between p_{0j}/p_{1p} obtained from Eq.(8) and p_{ep}/p_{1p} obtained from Eqs.(9) and (10) becomes less than 10^{-4} , and then $(p_{0s}/p_a)_m$ was determined from Eq.(2).

5. Comparison between calculated and experimental results

Each pressure ratio in Eq.(2) calculated by the method described above is shown by the solid lines against the throat area ratio Ψ in Fig.12. Two broken lines in the region of $\Psi < \Psi_{opt}$ represent the experimental lines. The experimental values of $(p_{1p}/p_{0p})_m$ agree well with the calculated values by Eq.(3). As mentioned previously, $(p_{0p}/p_a)_m$ increases nearly linearly with Ψ and the relation can be approximately represented by Eq.(1). The

Fig.11 Flow chart of calculation

calculated values of the base pressure ratio $(p_{0s}/p_{1p})_m$ when $\Psi \geq \Psi_{opt}$ agree fairly well with the experimental values. This fact means that the present model is reasonable. When $\Psi < \Psi_{opt}$, $(p_{0s}/p_{1p})_m$ decreases steeply with an increasing Ψ . This may be due to the fact that the pseudo-shock located upstream of the ejector throat moves downstream with an increasing Ψ and the flow just downstream of the nozzle exit expands, as shown in Fig.5 (b). The calculated values of $(p_{0s}/p_a)_m$ when $\Psi \geq \Psi_{opt}$ agree fairly well with the experimental results and $(p_{0s}/p_a)_m$ is independent of Ψ , since the increase in $(p_{0p}/p_a)_m$ is cancelled by the decrease in $(p_{0s}/p_{1p})_m$. Similarly, $(p_{0s}/p_a)_m$ decreases with an increasing Ψ when $\Psi < \Psi_{opt}$, since the decrease in $(p_{0s}/p_{1p})_m$ is larger than the increase in $(p_{0p}/p_a)_m$.

Next, consider the optimum operating condition when $\Psi = \Psi_{opt}$, and assume a normal shock at a reattachment point b in Fig.10 (b), then the ratio A_2^*/A_p^* of the choked flow area at the ejector throat A_2^* to the throat area of the primary nozzle A_p^* is expressed as follows.

$$\frac{A_2^*}{A_p^*} = \left[\frac{(\gamma-1)M_{bp}^2 + 2}{(\gamma+1)M_{bp}^2} \right]^{\frac{\gamma}{\gamma-1}} \left[\frac{2\gamma M_{bp}^2 - (\gamma-1)}{\gamma+1} \right]^{\frac{1}{\gamma-1}} \quad (11)$$

The calculated values by Eq.(11) are shown by the broken line in Fig.8. Equation (11) means that A_2^*/A_p^* is equal to the total pressure ratio across the normal shock for the Mach number M_{bp} at the reattachment point, and the calculated values are smaller than the experimental results. This means that the total pressure loss in the actual flow is larger than that of the normal shock wave, and the analytical estimation is left to a future study.

The calculated results of $(p_{0s}/p_{1p})_m$ and $(p_{0s}/p_a)_m$ by the present model at the optimum operating point and $\Psi = \Psi_{opt}$ are indicated by the broken and the dash-two-dotted lines in Fig.9, respectively. $(p_{0s}/p_{1p})_m$ increases with M_{1p} and the calculated results agree well with the experimental values except in the case that $M_{1p} = 3.05$. The calculated value when $M_{1p} = 3.05$ is smaller than the experimental re-

sult. This may be due to the fact that the strength of a lip shock wave⁽¹¹⁾ which is not considered in the present model becomes larger. The dash-dotted line in the figure shows the values of $(p_{0s}/p_{1p})_m$ calculated by the method of calculation of the base pressure for an external flow presented by Korst⁽¹⁴⁾, and it shows an opposite tendency to the experimental results, since the reflected waves from the duct-axis are neglected. When M_{1p} is comparatively large ($M_{1p} = 3.05$), the present calculated value agrees with that by Korst. This may be due to the fact that the slope of the expansion wave in Fig.10(a) becomes larger and the reflection waves do not affect the flow field upstream of the ejector throat. The pressure ratio $(p_{0s}/p_a)_m$ decreases with an increasing M_{1p} and the calculated values agree well with the experimental results. Therefore, it may be said that the present model is reasonable.

6. Conclusions

The vacuum performance and the internal flow of a supersonic air ejector of second-throat type were experimentally studied in the case of zero-secondary flow. Furthermore, modifying the method in Ref. (4), the internal flow was calculated, and the results were compared with the experimental values. The results obtained are summarized as follows.

(1) When the ratio p_{0p}/p_a of the primary stagnation pressure p_{0p} to the atmospheric pressure p_a increases, an optimum operating point of p_{0p}/p_a exists where the ratio p_{0s}/p_a of the secondary stagnation pressure p_{0s} to p_a becomes minimum. The values of p_{0p}/p_a and p_{0s}/p_a at that point, $(p_{0p}/p_a)_m$ and $(p_{0s}/p_a)_m$, respectively, depend on the throat area ratio Ψ of the ejector throat to the primary nozzle throat, and there exists an optimum throat area ratio Ψ_{opt} for which $(p_{0p}/p_a)_m$ and $(p_{0s}/p_a)_m$ become minimum.

(2) When $\Psi < \Psi_{opt}$, the flow is doubly choked both at the nozzle throat and at the ejector throat if p_{0p}/p_a is larger than a certain value, and the optimum operating point corresponds to this state. When $\Psi < \Psi_{opt}$, $(p_{0p}/p_a)_m$ increases and $(p_{0s}/p_a)_m$ decreases with Ψ . On the other hand, when $\Psi > \Psi_{opt}$, the flow is not doubly choked and the shock wave generated at the nozzle throat passes through the ejector throat when p_{0p}/p_a is larger than a certain value, and the optimum operating point corresponds to this state. Therefore, Ψ_{opt} is the minimum throat area ratio for which the flow is not doubly choked. When $\Psi \geq \Psi_{opt}$, $(p_{0p}/p_a)_m$ increases with Ψ , and $(p_{0s}/p_a)_m$ is held nearly constant and independent of Ψ .

(3) The pressure ratio $(p_{0p}/p_a)_m$ is independent of the primary nozzle Mach number and increases nearly linearly with Ψ . The experimental formula between $(p_{0p}/p_a)_m$ and Ψ was obtained [Eq.(1) in this paper].

Fig.12 Variation of each pressure ratio in Eq.(2) with Ψ ($M_{1p} = 2.05$)

(4) A flow model for calculating the ratio $(P_{0s}/P_{1p})_m$ of P_{0s} to the static pressure P_{1p} at the primary nozzle exit was presented in the case that $\Psi \geq \Psi_{opt}$ and at the optimum operating point. The calculated results agree well with the experimental values. Using the calculated results by the present model, the effects of Ψ and M_{1p} on $(P_{0s}/P_{1p})_m$ were clarified.

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