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Effects of component geometries and inflow conditions on ejector operational mode †

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Abstract

The ejector system is a useful device for creating high altitude conditions for ground tests of supersonic engines. The ejector performance can be immediately changed by varying the ejector operational mode. The ejector nozzle pressure ratio is well known to have a significant effect of the operational mode of an ejector. However, the effects of the mixing duct length and other geometric design parameters on the ejector mode change have not been clearly determined. In this study, the effects of ejector component geometries and inflow conditions on ejector operational mode are investigated by numerical analysis. By changing the inflow conditions and geometric parameters, twelve test cases are studied. Using the numerical test results, the flow pattern and suction pressure performance of the ejector with a fixed secondary mass flow rate are compared. In the numerical test results, a high primary nozzle stagnation pressure induces a highly underexpanded flow, resulting in the critical operational mode. For the critical operational mode, the mixing duct must be sufficiently long to accommodate the shock train and the choking zone. Primary nozzles with wide angles also induce widely expanded nozzle flows and result in the critical operational mode.

Keywords: Ejector design; Ejector nozzle angle; Ejector operational mode; Fabri-choking; Mixing duct length

1. Introduction

High-altitude tests of the propulsion systems of supersonic air vehicles are important for ensuring system reliability. To accurately estimate the performance of a supersonic engine using wind tunnels, the entire flow field around the engine should be maintained at supersonic speed. For this purpose, an ejector system can be a useful device for providing a low pressure at the exit of the test model and for creating a supersonic flow around the model.

Fig. 1 shows a typical exhaust system using an ejector in a blow-down wind tunnel. As shown in the figure, the wind tunnel provides the fixed amount of the secondary flow. And the primary flow from the ejector nozzle is mixed with the secondary flow and expelled through the diffuser. Due to the entraining effects of the primary flow, the stagnation pressure upstream of the secondary flow, P_{0s}, can be kept low.

Performances of the ejector have long been studied for the application in refrigeration cycles [1-5]. Unlike the cases in supersonic wind tunnels, entrainment ratio and critical back pressure are the main performance parameters in refrigeration cycles. Wu et al. studied the effects of the mixing duct length on the entrainment ratio using numerical simulation [2]. Hakkaki-Fard et al. also performed numerical simulation to study the effects of the ejector geometry on the entrainment ratio using fixed pressure condition in the secondary flow [3]. However, in supersonic wind tunnels, the amount of the secondary flow is fixed and the back pressure is always atmospheric. In particular, the main performance parameter is the pressure of the secondary flow, so it should not be fixed in supersonic wind tunnels.

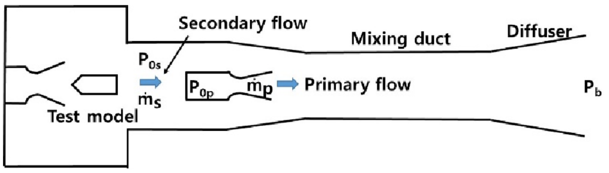

Fig. 1. Schematic of a typical exhaust system using an ejector in a blow-down wind tunnel.

Depending on the operating conditions, ejector regimes can be classified as supersonic, saturated supersonic, and mixed regimes [6]. In the supersonic and saturated supersonic regimes, which can be classified as critical modes, the secondary flow is choked at the aerodynamic throat due to the primary flow in the mixing duct. If the secondary flow is choked,

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the upstream condition of the secondary flow is not influenced by the back pressure of the wind tunnel, resulting in stable suction performance. However, in the mixed regime, which is classified as a subcritical mode, the secondary flow is not choked in the mixing duct, and the flow can be influenced by the back pressure of the wind tunnel.

The ejector performance can be immediately changed by varying the ejector operational mode [7]. Under fixed primary flow conditions, an ejector in critical mode can provide a larger entrainment ratio or lower suction pressure than an ejector in subcritical mode. Furthermore, the flow patterns of the critical mode are less complicated than those of the subcritical mode and can be accurately predicted by simple one-dimensional analysis. In contrast, using one-dimensional analysis, predictions of ejector performance in the subcritical mode are not sufficiently accurate [8, 9]. Therefore, an ejector in the critical mode can be simply designed by a one-dimensional approach and can provide better performance than that in the subcritical mode.

The pressure ratio P_b/P_{0p} is well known to have a significant effect of the operational mode of an ejector [6, 9, 10]. However, for the application in supersonic wind tunnels, the effects of the mixing duct length and other geometric design parameters on the ejector mode change have not been clearly determined. Information regarding the effects of inflow conditions and geometric parameters on the ejector mode and performance can be useful for obtaining an efficient ejector design, especially when the primary flow capacity or the construction space is limited.

In this study, numerical analysis is used to study the effects of the primary nozzle inflow conditions and geometric design parameters on ejector performance.

2. Numerical method

The performance of the ejector is studied using an axisymmetric two-dimensional numerical simulation. Computations are performed using the commercial code Fluent^{TM}, along with a density-based solver. Menter's shear stress transport (SST) *k-ω* model is used to consider turbulence effects. For two-stream mixing cases, *k-ω* SST model is known for its accurate prediction of flow structures in ejector systems [1, 11-13].

Fig. 2 shows the configuration and computational domain of a typical ejector model (case 1) for numerical analysis. As shown in the figure, the geometry of the ejector is assumed to be axisymmetric for simplicity. Approximately 125000 grid points were used in the mesh of the computational domain for case 1. In a grid resolution study, doubling the number of grid points did not significantly affect the results. In previous research, this numerical method was validated by comparing the numerical prediction results and experimental data from an ejector system [14].

In the different numerical test cases, the boundary conditions are varied. However, a fixed stagnation pressure under

Table 1. Numerical test conditions for cases 1-4.

Conditions / Case No.	θ_n (deg)	L_m/D_h	$\dot{m}_p$ (kg/s)	P_{0p} (kPa)	$\dot{m}_s$ (kg/s)
Case 1	16.4	11.5	15.5	4000	8.25
Case 2			19.4	5000	
Case 3			23.3	6000	
Case 4			31.1	8000	

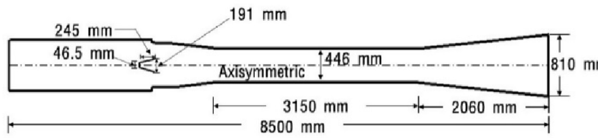


Fig. 2. Computational domain of the ejector for case 1.

sonic speed conditions is typically applied at the primary nozzle inlet. Additionally, the stagnation temperature of the primary nozzle flow is fixed at 300 K. Since most wind tunnels provide a constant mass flow rate during a test, a fixed mass flow rate condition is used for the secondary inflow, and the stagnation temperature of the secondary flow is fixed at 573 K. The outlet pressure is fixed at 101.3 kPa, and all walls are assumed to be adiabatic. More details of the conditions for various test cases are provided in the following sections.

3. Numerical test results

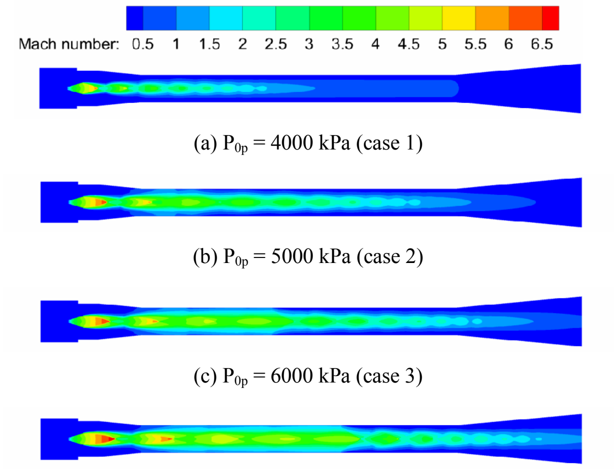
The characteristics of the operational mode and the ejector performance are investigated using numerical tests with various conditions. By changing the inflow conditions and geometric parameters, twelve test cases are studied. Using the numerical test results, the flow pattern and suction pressure performance of the ejector with a fixed secondary mass flow rate are compared.

3.1 Effects of the stagnation pressure of the primary flow

The pressure ratio P_b/P_{0p} is well known to have a significant effect on the operational mode of an ejector [10, 15]. An underexpanded primary nozzle flow generates an aerodynamic throat for the secondary flow in the mixing duct. Therefore, a high P_{0p} is preferable to obtain the critical mode. However, a higher P_{0p} does not necessarily provide a lower suction pressure.

In Table 1, the test conditions for four cases are summarized. As shown in the table, the mass flow rate of the secondary flow is fixed at 8.25 kg/s. For cases 1-4, P_{0p} is increased from 4000 kPa to 8000 kPa. Due to the fixed primary nozzle geometry, the mass flow rate of the primary flow also increases with P_{0p}. The other geometric parameters are fixed at constant values, as shown in the table.

Fig. 3 shows the Mach number distributions within the ejector for cases 1-4. As shown in the figure, the primary nozzle



(a) P_{0p} = 4000 kPa (case 1)

(b) P_{0p} = 5000 kPa (case 2)

(c) P_{0p} = 6000 kPa (case 3)

(d) P_{0p} = 8000 kPa (case 4)

Fig. 3. Mach number distributions within the ejector for cases 1-4.

flow expands and mixes with the secondary flow downstream in the mixing duct. Additionally, a higher P_{0p} induces a wider expansion of the primary nozzle flow, as shown in the figure. Because a higher P_{0p} results in a higher static pressure at the primary nozzle exit, the nozzle flow becomes highly underexpanded and widely expanded downstream of the nozzle. The highly underexpanded primary nozzle flow can generate an aerodynamic throat for the secondary flow in the mixing duct. Therefore, as shown in the figures for the high-P_{0p} cases (cases 2-4), the sonic speed contour lines contacted the wall; thus, the ejector is operated in the critical mode. However, in the low-P_{0p} case (case 1), the secondary flow does not reach sonic speeds; thus, the ejector is operated in the subcritical mode.

However, a higher P_{0p} does not necessarily provide a lower suction pressure. The suction pressures for cases 1-4 are represented in Fig. 4. As shown in the figure, case 1 shows the highest suction pressure among the four cases due to its subcritical mode operation. However, among the critical modes, a higher P_{0p} results in a higher suction pressure. As a result, case 2 shows the lowest suction pressure among the cases.

The reason for this phenomenon can be explained by the choking relation of the secondary flow. According to compressible flow theory, the stagnation pressure of the choked secondary flow can be calculated as follows:

$$p_{0s} = \frac{1}{A^*}\frac{\dot{m}_s\sqrt{RT_{0s}}}{\sqrt{\gamma}\left(\frac{\gamma+1}{2}\right)^{(\gamma+1)/(2-2\gamma)}}. \quad (1)$$

As shown in the equation, the stagnation pressure of the choked flow is inversely proportional to the aerodynamic throat area. As illustrated in Fig. 3, a higher P_{0p} results in a smaller aerodynamic throat area due to a highly underexpanded nozzle flow. Therefore, once the critical mode is achieved, the suction pressure P_{0s} increases with P_{0p} if the mass flow rate remains constant.

Table 2. Numerical test conditions for cases 5-8.

Conditions / Case No.	θ_n (deg)	L_m/D_h	$\dot{m}_p$ (kg/s)	P_{0p} (kPa)	$\dot{m}_s$ (kg/s)
Case 5	16.4	7.1	23.3	6000	3
Case 6		9.3			
Case 7		11.5			
Case 8		13.5			

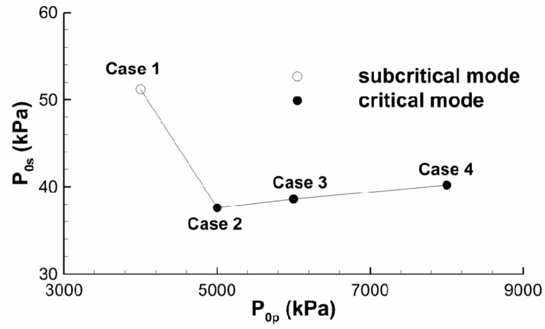


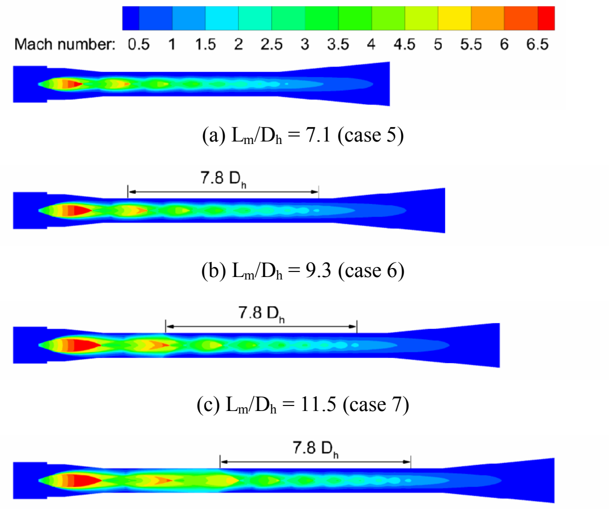
Fig. 4. Suction pressure performance of the ejector for cases 1-4.

3.2 Effects of the mixing duct length

The major operating principle of the ejector is the momentum exchange between the primary flow and the secondary flow by mixing. Therefore, the length of the mixing duct should be sufficiently long to provide enough space for mixing between the primary flow and the secondary flow. Dutton and Carroll demonstrated that the mixing duct length-to-hydraulic diameter ratio should be in the range of $8 < L_m/D_h < 12$ [16]. However, depending on the operating conditions, an L_m/D_h value of 10 may not be sufficient for the diffusion process to be completed [17]. The mixing duct length can be a critical parameter for the ejector design, especially when the construction space for the ejector is limited. However, the effects of the mixing duct length on the ejector operational mode have not been clearly determined.

In this section, the effects of the mixing duct length on the ejector performance was studied via numerical tests. In Table 2, the test conditions for four cases are summarized. As shown in the table, L_m/D_h is increased from 7.1 to 13.5 for cases 5-8. The other parameters are fixed at constant values, as shown in the table.

Fig. 5 shows the Mach number distributions within the ejector for cases 5-8. As shown in the figure, the underexpanded primary nozzle flow generates a shock train in the mixing duct. Through the shock train, the back pressure has an influence upstream in the mixing duct. Therefore, to obtain the critical mode in the ejector, the mixing duct should be long enough to accommodate the shock train and provide space for the secondary flow to be choked. As shown in Figs. 5(c) and (d), the sonic speed lines contact the wall; thus, the ejector is operated in the critical mode for cases 7 and 8. Furthermore, for these two cases, the lengths of the shock trains behind the choking zones are both 7.8 D_h. In both cases, the choking zones are



(a) L_m/D_h = 7.1 (case 5)

(b) L_m/D_h = 9.3 (case 6)

(c) L_m/D_h = 11.5 (case 7)

(d) L_m/D_h = 13.5 (case 8)

Fig. 5. Mach number distributions within the ejector for cases 5-8.

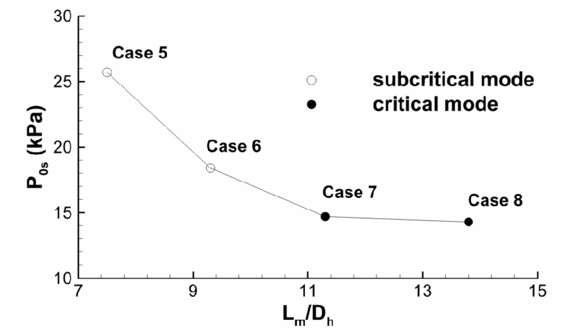


Fig. 6. Suction pressure performance of the ejector for cases 5-8.

located upstream of the shock train. However, as shown in Figs. 5(a) and (b), the mixing duct is not long enough to accommodate the shock train and the choking zone; thus, the ejector is operated in the subcritical mode. As shown in Table 2, the mixing duct for case 5 is shorter than 7.8 D_h; thus, it cannot accommodate the shock train. As shown in Fig. 5(b), the mixing duct for case 6 is longer than 7.8 D_h but does not provide enough space for the choking zone. Therefore, for the critical operational mode with the conditions provided in Table 2, L_m/D_h should be greater than approximately 11 to accommodate the shock train and to provide space for the secondary flow to be choked. The suction pressure performances for cases 5-8 are represented in Fig. 6. As shown in the figure, a longer mixing duct results in a lower suction pressure. However, if the mixing duct is sufficiently long to accommodate the shock train and the choking zone, the further reduction in suction pressure is not substantial.

3.3 Effects of the primary nozzle angle

As described in Sec. 3.1, the highly underexpanded primary nozzle flow expanded in the mixing duct and generated an aerodynamic throat for the secondary flow. A primary flow expansion can also be induced by using a wide-angle primary nozzle. In this section, the effects of the primary nozzle angle on the ejector performance are studied via numerical tests.

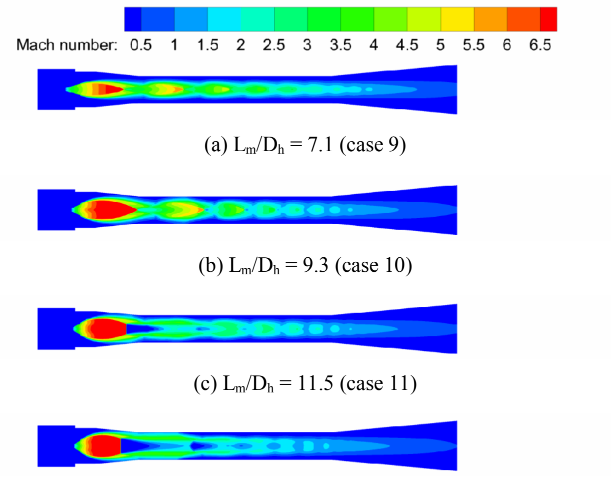
In Table 3, the test conditions for four cases are summarized. As shown in the table, the primary nozzle angle varies from 16.4° to 34.5° for cases 9-12. For consistency in the numerical tests, the expansion ratio of the nozzle is kept constant. The other parameters are fixed at constant values, as shown in the table.

Fig. 7 shows the Mach number distributions within the ejector for cases 9-12. As shown in the figure, the nozzles with wider angles induce more widely expanded nozzle flows. Furthermore, as shown in Figs. 7(b)-(d), the sonic speed contour lines contact the wall; thus, the ejector is operated in the critical mode for cases 10-12, which have nozzles with wider angles.

However, the nozzles with wider angles do not necessarily provide lower suction pressures. The suction pressures for cases 9-12 are shown in Fig. 8. As shown in the figure, case 9 shows the highest suction pressure among the four cases due to its subcritical mode operation. However, among the critical modes, the nozzles with wider angles result in higher suction pressures. As a result, case 10 shows the lowest suction pressure among the cases. As mentioned in Sec. 3.1, the stagnation pressure of the choked flow is inversely proportional to the aerodynamic throat area. The nozzles with wider angles result

Table 3. Numerical test conditions for cases 9-12.

Conditions / Case No.	θ_n (deg)	L_m/D_h	$\dot{m}_p$ (kg/s)	P_{0p} (kPa)	$\dot{m}_s$ (kg/s)
Case 9	16.4	7.1	27.2	7000	3
Case 10	26				
Case 11	30				
Case 12	34.5				



(a) L_m/D_h = 7.1 (case 9)

(b) L_m/D_h = 9.3 (case 10)

(c) L_m/D_h = 11.5 (case 11)

(d) L_m/D_h = 13.5 (case 12)

Fig. 7. Mach number distributions within the ejector for cases 9-12.

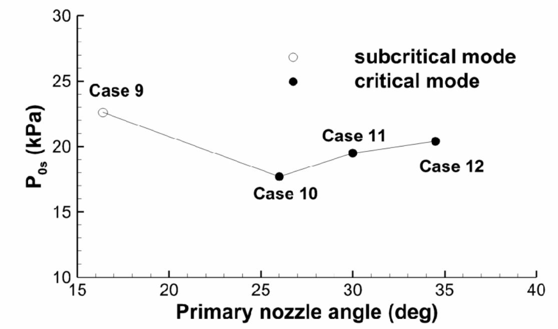


Fig. 8. Suction pressure performance of the ejector for cases 9-12.

in a smaller aerodynamic throat due to the enhanced primary flow expansion. Therefore, once the critical mode is obtained, the suction pressure increases with the nozzle angle when the mass flow rate remains constant.

4. Conclusions

In this study, the effects of primary nozzle inflow conditions and geometric design parameters on ejector performance were investigated by numerical analysis. According to the numerical test results, a high primary nozzle stagnation pressure induces a highly underexpanded flow, resulting in the critical operational mode. However, if the critical mode is obtained, the suction pressure increases with the nozzle stagnation pressure due to the reduced aerodynamic throat area for the secondary flow. For the critical operational mode, the mixing duct must be sufficiently long to accommodate the shock train and the choking zone. Primary nozzles with wide angles also induce widely expanded nozzle flows and result in the critical operational mode. However, if the ejector is operated in the critical mode, the suction pressure increases with the nozzle angle due to the reduced aerodynamic throat area for the secondary flow.

In general, wider primary nozzle angle can reduce the minimum mixing duct length, but it is expected that the suction pressure would relatively be increased due to the reduced throat area. Therefore, considering the construction space for the exhaust system and the required suction pressure, the geometry of the ejector system should be carefully chosen.

Various shapes of the primary nozzles or a two-stage ejector can enhance the performances of the exhaust system in supersonic wind tunnels [18-20]. For future work, investigation of design optimization of an ejector with those parts can be useful to improve the performance of the supersonic wind tunnel.

Nomenclature

A^* : Aerodynamic throat area for the secondary flow
D_h : Hydraulic diameter of the mixing duct
L_m : Mixing duct length
$\dot{m}_p$: Mass flow rate of the primary flow
$\dot{m}_s$: Mass flow rate of the secondary flow
P_{0p} : Stagnation pressure of the primary flow
P_{0s} : Stagnation pressure of the secondary flow
P_b : Back pressure of the ejector
R : Gas constant
T_{0s} : Stagnation temperature of the secondary flow
γ : Specific heat ratio
θ_n : Primary nozzle angle

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