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Technical Notes

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A Starting Procedure of Supersonic Ejector to Minimize Primary Pressure Load

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Nomenclature

D	=	mixing tube diameter, mm
d	=	secondary inlet diameter, mm
L	=	length
P	=	pressure, atm
R	=	radius
X	=	x coordinates from secondary inlet

Subscripts

a	=	ambient
D	=	diffuser
exit	=	ejector exit
m	=	mixing chamber
max	=	outer boundary of primary nozzle exit
p	=	primary flow
s	=	secondary flow
st	=	starting condition
T	=	ejector system total part
throat	=	primary nozzle throat
unst	=	unstarting condition
0	=	stagnation state
2	=	mixing tube

I. Introduction

AN EJECTOR is a flow device in which the momentum of the primary flow is transferred to the secondary flow. The momentum transfer takes place as the primary flow is injected into the secondary flow that is stagnant or moving. Ejectors are classified as subsonic, transonic, and supersonic depending on the flow speed at the exit of the primary nozzle. Typically the flow channel of an ejector is axis symmetric. Depending on the configuration of the primary flow inlet, the ejectors are either a central injection type or an annular injection type. Primary flow is injected either annularly or centrally based on the nature of the secondary flow. Ejectors have many advantages over other devices in pumping fluids [1–9]. Although ejectors with central injection primary flow are widely used, annular injection of primary flow is indispensable to certain applications: pumping chemical lasers and high speed/high altitude test facilities. To pump a high power chemical laser, central injection of primary flow cannot be used, as the supply tubing of the primary flow is exposed in the stream of high temperature secondary flow [10]. For a test facility to simulate a high speed/high altitude environment, the central injection with protrusion of the primary supply into the secondary flow would cause significant loss in the momentum of the secondary flow. The starting behavior of a supersonic ejector with annular injection of primary flow is different from one with central injection [11,12]. In the present study, the starting behavior of a supersonic ejector with an annular injection of primary flow was investigated. To recover stagnation pressure, supersonic ejectors are generally equipped with a mixing tube downstream of the injection of the primary flow. A sequence of the starting operation of such a supersonic ejector with annular injection of primary flow is illustrated in Fig. 1.

The plot begins at a point where both primary stagnation pressure and secondary static pressure are equal to ambient pressure. As the stagnation pressure of the primary flow injection increases, the secondary flow accelerates from a stagnant ambient state and its static pressure decreases as shown in region (1) of Fig. 1. In this region, the flow is supersonic only within the primary nozzle. The whole flowfield outside of the primary nozzle is still subsonic. As the primary pressure further increases, the shock wave moves out of the primary nozzle to form an oblique shock as in region (2) of Fig. 1. When the primary pressure increases beyond the starting point, the oblique shock wave is abruptly swallowed by the mixing tube and the whole flowfield inside the ejector becomes supersonic; the ejector is started and the static pressure of the secondary flow drops abruptly in region (3). Once the ejector is started, the static pressure of the secondary flow is not sensitive to the variation of the stagnation pressure of the primary flow. The ejector maintains supersonic operation, even when the stagnation pressure of the primary flow decreases below the value at which the ejector started. The unstarting of the ejector occurs when the stagnation pressure of the primary flow is noticeably less than the starting pressure. The discrepancy between the starting and unstarting stagnation pressures of the primary flow is due to the hysteresis of the ejector operation. To take advantage of this hysteresis, the stagnation pressure of the primary flow is lowered to a value that is slightly higher than the unstarting pressure, once the ejector enters the supersonic operation mode [13,14]. In this way, the design requirement on the primary flow that drives the ejector can be reduced. In the present study, a new procedure to start a supersonic ejector is proposed to reduce the burden on the stagnation pressure of the primary flow further. The new starting procedure was tested and validated by varying the secondary inlet condition. It was discovered that a significantly less primary mass flow rate was required to start a supersonic ejector when the new starting procedure was used.

II. Experimental Apparatus

A. Test Facility

Figure 2 shows a schematic view of the axisymmetric annular injection ejector examined in this study. The supersonic primary flow is injected along the side wall. The primary flow is deflected by a

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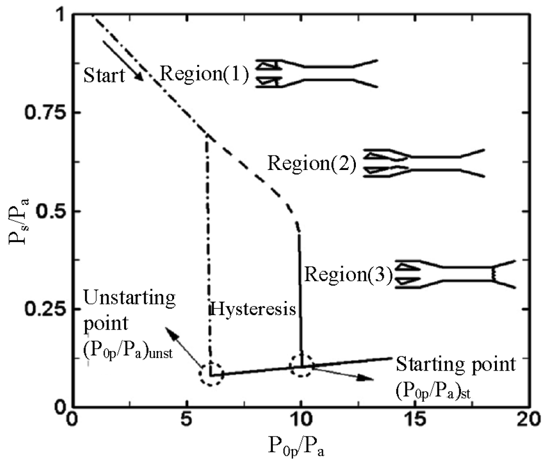

Fig. 1 Performance curve of a typical annular injection supersonic ejector.

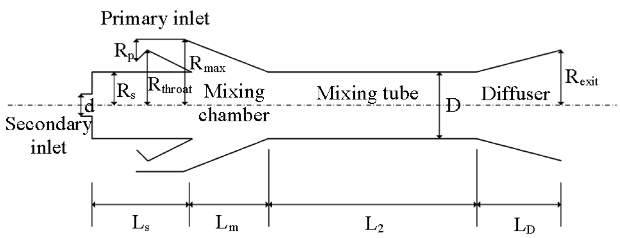

Fig. 2 Axisymmetric supersonic ejector.

contraction angle and mixed with the secondary flow in a mixing chamber. The combined flow enters the mixing tube downstream of the mixing chamber. The flow further recovers pressure by a subsonic diffuser attached to the mixing tube. The geometric data of the ejector are listed in Table 1. At a fixed primary mass flow rate and mixing tube diameter, the secondary mass flow rate directly affects the performance of the ejector by producing a low pressure region in the mixing chamber. So in this study, the starting behavior of the ejector is investigated by varying the secondary inlet mass flow rate. Mixing tube diameter D is fixed and secondary inlet diameter d is changed in experiments. An increase of d/D means an increase of the secondary mass flow rate.

The primary flow is supplied from a compressed air reservoir. The primary nozzle area ratio was 15 and the design Mach number at this condition was 4.38. At the primary stagnation pressure 17 atm, the flow rate was 1.35 kg/s.

B. Measurements

Pressure was measured at seven locations, from the inlet of the secondary flow to the inlet of the subsonic diffuser as shown in Fig. 3. In addition to the static pressure of the secondary flow (P_s) and the stagnation pressure of the primary flow (P_{0p}), static pressures at the inlet of the mixing chamber (P_{m1}) and at the vicinity of its exit, 50 and 290 mm from the exit of the primary nozzle were measured, respectively. Pressures at two locations inside the extended throat were measured: 50 mm from the inlet (P_{21}) and 50 mm upstream of the throat exit (P_{22}). A piezopressure transducer with an operating range of 1–31 bar and accuracy of 0.08% was used for the stagnation pressure of the primary flow, while a transducer with a range of

Table 1 Ejector configurations in units of mm

R_s	56.57	R_{throat}	68.19
R_{max}	68.94	R_p	41.72
R_{exit}	72.34	L_2	666.0
L_m	389.26	L_s	100.0
L_D	350.0	D	83.44

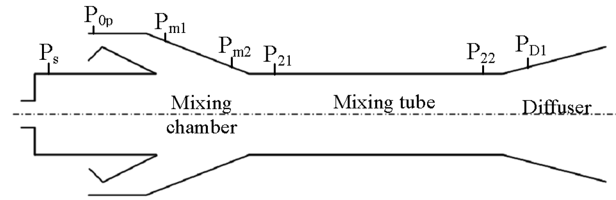

Fig. 3 Location of pressure sensor and its label.

0–2.2 bar and accuracy of 0.06% was used for measurement of the static pressure of the other points. The data rates of all pressure measurements were 1000 Hz.

III. Experiment Results and Discussion

A. Flow Characteristics of the Ejector

Figure 4 shows the performance curves obtained by the pressure measurement of the secondary flow and primary flow. Pressure distribution along the axial distance is displayed in Fig. 5. When the ratio of the secondary inlet diameter to the mixing tube diameter, d/D, is 0.264, the ejector starts at the primary stagnation pressure of 18 atm. In this state, the ejector starts and the supersonic ejector is in operation until the primary pressure drops to 13 atm. While the ejector is in supersonic operation, the static pressure of the secondary flow remains nearly constant at 0.05 atm. Oscillation of the pressure measured downstream of the mixing tube also confirms this as shown by the error bars in Fig. 5 for P_{22} and P_{D1}. When d/D is increased to 0.356, the ejector fails to start supersonic operation for a given range of the primary stagnation pressure. A much higher primary stagnation pressure or primary mass flow rate is needed for this value

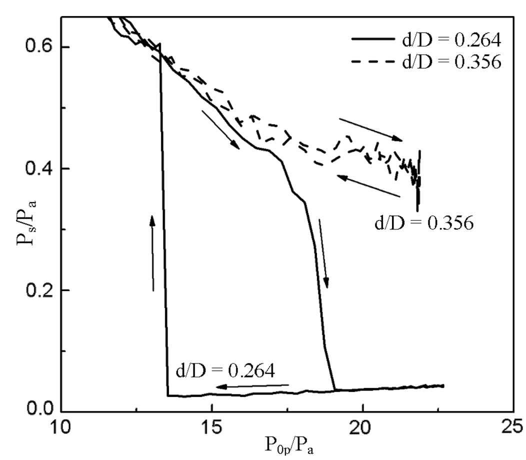

Fig. 4 Performance curves with respect to d/D.

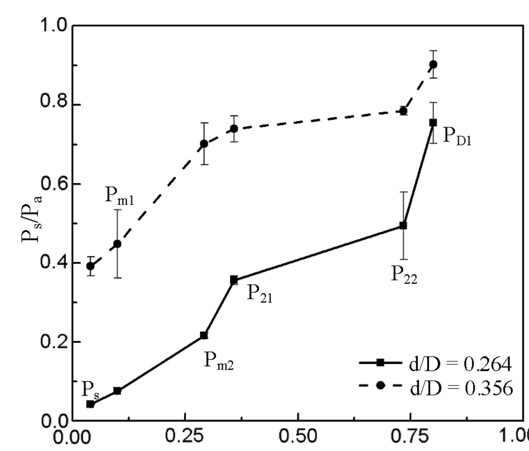

Fig. 5 Wall pressures distribution with respect to d/D ($P_{0p} = 22$ atm).

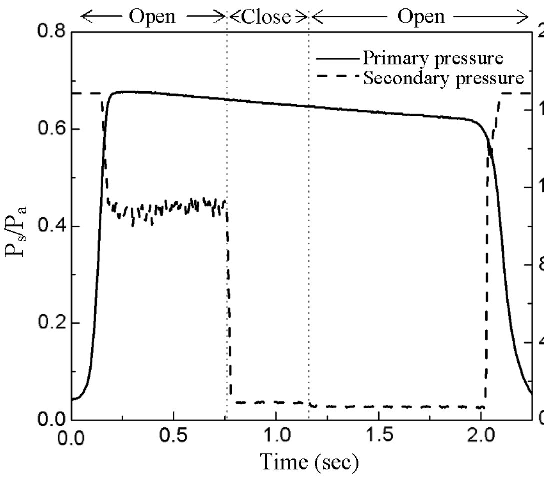

Fig. 6 Wall pressure history ($d/D = 0.306$).

of d/D. The static pressure of the secondary flow is relatively high throughout the axial length of the ejector as shown in Fig. 5. The secondary flow remains mainly subsonic. Therefore, an oblique shock stands in the mixing region [15]. This is confirmed by the large error bars of the pressure measurement inside the mixing chamber.

B. Close–Open Mode Hysteresis

The starting behavior of the supersonic ejector was investigated by varying the secondary flow conditions. Figure 6 shows the time history of the secondary static pressure and primary stagnation pressure for an ejector with $d/D = 0.306$. At this d/D value, the ejector did not start normally. When the primary flow is turned on, a subsonic secondary flow is induced from the ambient stagnation state and the static pressure of the secondary flow decreases to 0.4 atm. Now the inlet of the secondary flow is abruptly closed. The static pressure of the secondary flow drops to 0.03 atm, although the secondary flow becomes stagnant due to the inlet closure. As a result of the inlet closing, the exit pressure of the primary nozzle prevails over the whole flow region inside the ejector and the oblique shock that was standing inside the mixing chamber is swallowed by the mixing tube. The inlet of the secondary flow is uncovered, after the low static pressure is established. Interestingly, the low static pressure of the secondary flow persists even after the ambient air is allowed to flow into the inlet because of operating pressure hysteresis as shown Fig. 1; the characteristic of the supersonic ejector equipped with a mixing tube maintains its starting condition below starting pressure once the ejector is started. By taking this procedure, a supersonic ejector can be started at a primary stagnation pressure that is much lower than a pressure that would have started its operation otherwise.

Figure 7 shows a comparison of ejector performance curves at normal starting procedure and the close–open procedure that is proposed in the present study. Both of the measurements were carried out on the same ejector with $d/D = 0.306$. At state 1, the supersonic operation of the ejector is started normally by the action of the primary flow. In the normal operation, therefore, the ejector would not have been started at state 2, as the primary stagnation pressure is too low.

However, the inlet of the secondary flow is uncovered after closing at state 3, the close–open starting procedure of the present study started the ejector, and the static pressure of the secondary pressure drops abruptly.

C. Ejector Starting with Close–Open Mode Hysteresis

The verification of a supersonic ejector starting below normal starting pressure by the close–open mode hysteresis was studied. The authors conducted ejector starting tests at various primary stagnation pressures with the secondary inlet closed. Before the close–open

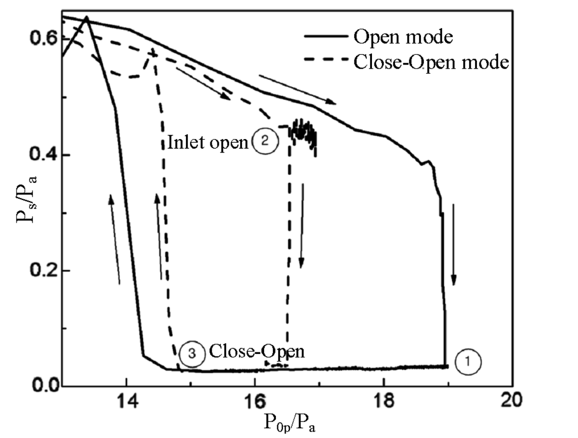

Fig. 7 Open and close–open mode performance curve comparison ($d/D = 0.306$).

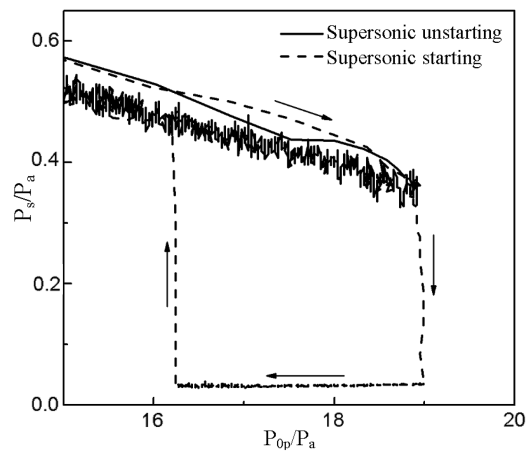

Fig. 8 Ejector performance curves ($d/D = 0.311$).

mode procedure test, an ejector starting with a normal open mode procedure was tested.

Figure 8 shows the performance curves for an ejector with the diameter ratio $d/D = 0.311$ under normal starting procedure. The starting pressure was approximately 19 atm and unstarting pressure is about 16.2 atm. In comparison of the two performance curves in the figure, it is found that the ejector starts at a narrow pressure margin from 19 atm, the limit starting pressure at diameter ratio $d/D = 0.311$.

Figure 9 shows three performance curves of the close–open mode procedure test with the primary stagnation pressure as a parameter. In

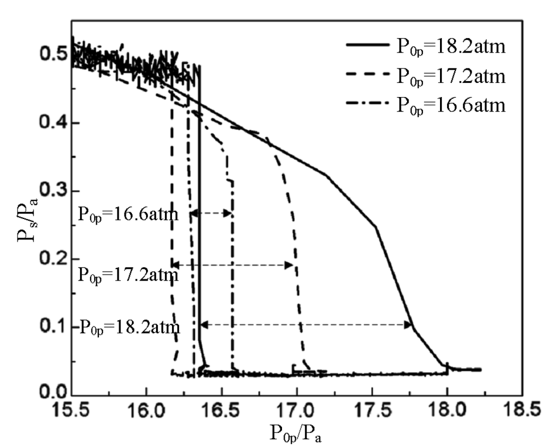

Fig. 9 Close–open mode performance curves with respect to various primary stagnation pressures ($d/D = 0.311$).

all cases, the primary stagnation pressures were lower than normal starting pressure, 19 atm and the ejector started with the secondary inlet closed. Once the ejector was started, the inlet of the secondary flow was uncovered. As shown in Fig. 9, all the experiments of the startup using the close–open procedure succeeded in supersonic starting at a primary stagnation pressure below the normal starting pressure. In some of the tested condition, the starting primary pressure was slightly higher than the unstart pressure.

IV. Conclusions

A starting procedure of an annular injection supersonic ejector equipped with a mixing tube was investigated experimentally by varying the secondary inlet condition. In our experiments, we measured the pressure which provides essential information necessary for the prediction of flow phenomena during ejector operation. For a given ratio of the secondary inlet diameter to the mixing tube, the ejector starts at a fixed stagnation pressure of the primary flow for a given ejector configuration. When the diameter ratio increases, the starting primary pressure also increases. In the present study, the primary flow is injected, while the inlet of the secondary flow is closed. Throughout the passage of the secondary flow, a very low static pressure state is established. This low static pressure persists even after the secondary flow is allowed from the ambient, implying the ejector is started. This new starting procedure can reduce the load to the primary flow that is needed to start the supersonic ejector. In view of the results so far achieved in this study, it is expected that the close–open mode procedure will be helpful in a variety of ejector applications.

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