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진공 이젝터 시스템의 유동 컨트롤

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Flow Control in the Vacuum-Ejector System

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ABSTRACT

Supersonic ejectors are simple mechanical components, which generally perform mixing and/or recompression of two fluid streams. Ejectors have found many applications in engineering. In aerospace engineering, they are used for altitude testing of a propulsion system by reducing the pressure of a test chamber. It is composed of three major sections: a vacuum test chamber, a propulsive nozzle, and a supersonic exhaust diffuser. This paper aims at the improvement of ejector-diffuser performance by focusing attention on reducing exhaust back flow into the test chamber, since alteration of the backflow or recirculation pattern appears as one of the potential means of significantly improving low supersonic ejector-diffuser performance. The simplest backflow-reduction device was an orifice plate at the duct inlet, which would pass the jet and entrained fluid but impede the movement of fluid upstream along the wall. Results clearly showed that the performance of ejector-diffuser system was improved for certain a range of system pressure ratios, whereas the orifice plate was detrimental to the ejector performance for higher pressure ratios. It is also found that there is no change in the performance of diffuser with orifice at its inlet, in terms of its pressure recovery. Hence an appropriately sized orifice system should produce considerable improvement in the ejector-diffuser performance in the intended range of pressure ratios.

Key Words: Compressible Flow (압축성 유동), Internal Flow (내부 유동), Ejector (이젝터), Mach Number(마하수)

1. INTRODUCTION

Supersonic ejectors are simple mechanical components, which generally perform mixing and/or recompression of two fluid streams. Ejectors have found many applications in engineering. In aerospace engineering, they are used for altitude testing of a propulsion system by reducing the pressure of a test chamber. It is composed of three major sections: a vacuum test chamber, a propulsive nozzle, and a supersonic exhaust diffuser. The

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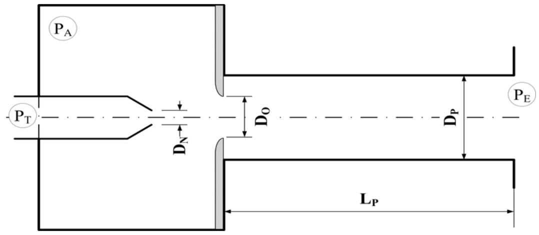

Fig. 1 Schematic of vacuum ejector with inlet orifice

fluid with highest total energy is the primary stream, while the other, with the lowest total energy is the secondary stream . The ejector system entrains the secondary flow through a shear action generated by the primary jet. When it is used to create high-vacuum levels in the secondary chamber, such as those required in high-altitude simulation tests, this is done by dragging mass from a finite secondary chamber often called as zero-secondary flow ejector (fig.1). The efficiency of such an ejector system is relatively very low, compared to other fluid transport devices driven mainly by normal forces [2]. However, its major advantage is in a simple structure with no moving parts, and it can not only compress and transport a large amount of fluid with a small driving energy, but also needs little maintenance. For these reasons, the ejector system has been extensively utilized for the thrust augmentation of V/STOL [3-4], high-altitude simulation facility [5], combustion facility [6], refrigeration system [7], natural gas generation [8], fuel cells [9], noise-control facility [10], etc. This paper aims at the improvement of ejector-diffuser performance by focusing attention on reducing exhaust back flow into the test chamber, since alteration of the backflow or recirculation pattern appears as one of the potential means of significantly improving low supersonic ejector-diffuser performance. The simplest backflow-reduction device was an orifice plate at the duct inlet, which would pass the jet and entrained fluid but impede the movement of fluid upstream along the wall.

2. Orifice Plate Installation

The axial position of the orifice plate from the nozzle exit was estimated by assuming Prandtl-Meyer expansion from the nozzle. The orifice plate should pass completely the supersonic primary jet and entrained fluid while isolating the altitude chamber from the downstream conditions (fig.2). Owing to such shielding effect, the evacuation process is no longer affected by the ambient state, and hence the performance of the vacuum ejector system can be increased. The primary jet and the entrained secondary jet should pass through the orifice. For the ejector with orifice system to be effective the orifice in no way should obstruct the flow of primary jet. The orifice is expected to be effective until the expanding primary jet just touches the orifice plate tip. Hence, axial position of orifice plate is a governing parameter as well as orifice size. For the present analysis, the axial position is estimated by using PM-expansion theory for an established NPR and orifice size. Although many different axial positions of orifice are possible for different NPR values, the orifice plate was placed close to the primary nozzle (using a higher NPR) with the sole intension of avoiding taking into consideration the jet curvature and hence closely follows the PM theory. Mach number at the nozzle exit is found by assuming a nozzle pressure ratio (NPR).

$$NPR = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

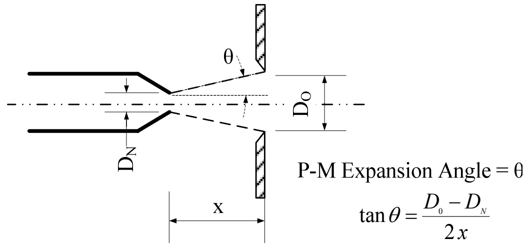

Fig. 2 Prandtl-Meyer expansion at nozzle exit

The axial position, x was estimated to be 6mm from the primary nozzle exit for NPR=17.0, D_o/D_N = 1.56 with PM expansion angle (θ) of 40°, which is calculated using the relation.

$$\theta = \left(\frac{\gamma+1}{\gamma-1}\right)^{1/2} \tan^{-1}\left[\frac{\gamma-1}{\gamma+1}\left(M^2-1\right)\right]^{1/2} - \tan^{-1}\left[\left(M^2-1\right)\right]^{1/2}$$

This θ is the angle, measured from the flow direction where M = 1(primary nozzle throat), through which the flow has been turned (by an isentropic process) to reach the Mach number at the nozzle exit position. Good agreements were found between the PM expansion angle and the actual jet turning angle, suggesting that the under-expanded axi-symmetric free-jet from the nozzle was essentially inviscid. The flows are purely laminar with no turbulence practically, inside the altitude chamber. But downstream of the nozzle choice of the turbulence model plays an important role for correctly predicting the turbulent internal flows under zero-pumping conditions.

3. COMPUTATIONAL METHODOLOGY

The governing equations are discretized using a control volume technique. Sst-kω turbulence model is best suited to predict the shock phase, strength and the mean line of pressure recovery; also it has further shown better performance in term of stream mixing. Axi-symmetric coupled implicit solver is chosen with sst-kω turbulence model for the steady simulations. Simulations were done with a single convergent nozzle of diameter 19mm with Duct-to-nozzle area ratios of 5.5 and duct length-to-diameter ratios of 5.4 with orifice plate of diameter 28mm placed at an axial distance of 6mm from nozzle exit. Schematic of vacuum ejector system with orifice plate along with the boundary conditions are shown in fig. 3.

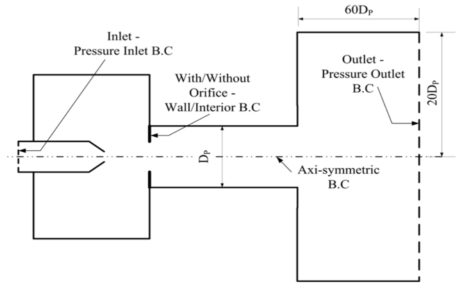

Fig. 3 Schematic of vacuum ejector with boundary conditions.

4. Results and Discussion

Figure 4 shows the improvement of vacuum-ejector for different orifices placed at an axial distance x of 29 mm from NXP. For larger orifice both the primary and entrained secondary jet are passed by the orifice, hence no improvement in performance was seen. It can be seen that ejector performance is increased for an optimum orifice diameter of D_o/D_N=1.74. In this case, the expanding primary jet just touches the orifice lip, thus isolating the vacuum chamber from downstream conditions. No recirculation into the vacuum chamber is possible since there is no flow passage area available for the recirculation flow to enter the vacuum chamber. Effect of orifice size on the performance of ejector is shown in Fig. 5 For SPR higher than 4.0 the orifice plate was

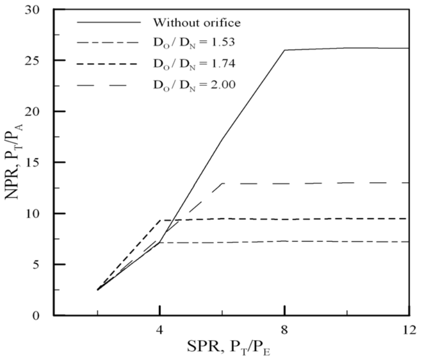

Fig. 4 Improvement in performance of ejector

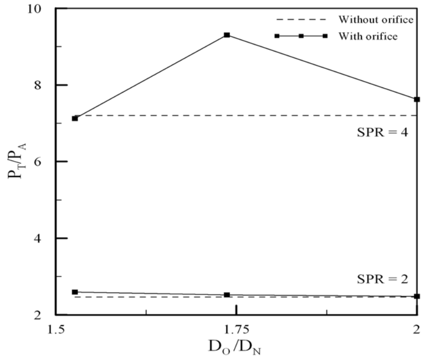

Fig. 5 Effect of orifice size on the performance of ejector

detrimental to the performance of ejector, as the primary jet interfere with the orifice, preventing the jet expansion. For any performance improvement to be feasible there should not be any orifice-jet interaction. The vacuum ejector can fail (drastic increase in vacuum chamber pressure) due to severe interactions with orifice plate at higher-pressure ratio. Hence it can be concluded that for a given position of orifice plate (x), there exists an optimum size (D_0/D_N) and suitable pressure ratio (SPR) in order to see an improvement in the vacuum performance. Mach number distribution along the ejector axis for an optimum orifice is shown in fig.6. It appears that the orifice plate significantly alters the shock pattern inside the constant area diffuser. Placing an orifice at the diffuser inlet in no way affects the pressure recovery of the existing diffuser can be used. Diffuser, as can be seen from Fig. 7, hence No design changes are needed to accommodate a properly designed orifice system to improve the performance. Fig. 8

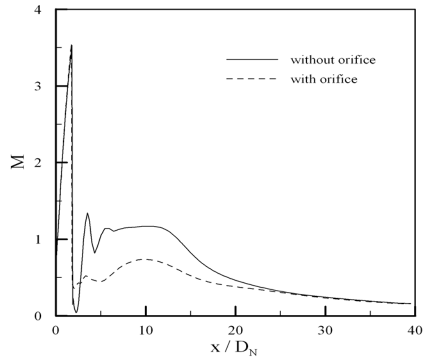

Fig. 6 Centerline Mach number variation (D_o/D_N=1.74,SPR=4)

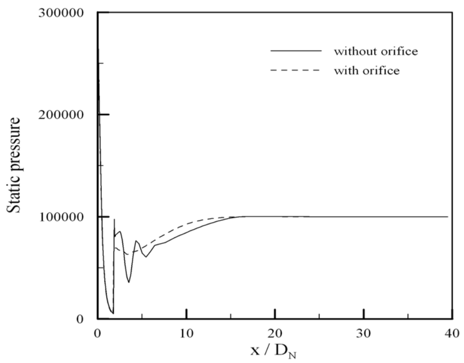

Fig. 7 Static pressure along axis(D_o/D_N= 1.74, SPR=4)

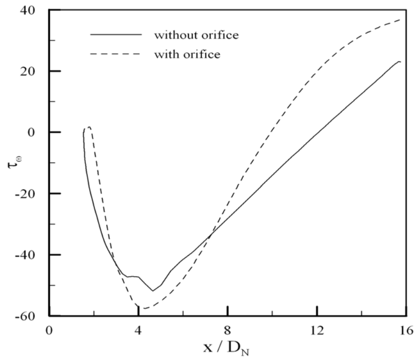

Fig. 8 Axial wall shear stress along diffuser wall (D_o/D_N=1.74,SPR=4)

shows the axial wall shear stress along diffuser wall with and without orifice. Recirculation is present along the whole length of diffuser (unstarted) as can be seen from the below zero values of wall shear stress. With the placement of an orifice at the diffusr inlet, recirculation area increases, which indicates that the orifice plate is preventing the movement of the recirculation zone into the upstream vacuum chamber, hence increasing its performance.

5. CONCLUSIONS

A simple and low cost way to improve the performance of an existing vacuum-ejector system is presented. Results clearly showed that the performance of a vacuum-ejector system was improved for certain a range of system pressure ratios, and the orifice plate was detrimental to the ejector performance for higher pressure ratios. Also shown that, the introduction of an orifice plate at the diffuser inlet in no way affected the diffuser performance in terms of pressure recovery. Hence an appropriately sized orifice system should produce considerable improvement in the vacuum-ejector performance in the intended range of pressure ratios.

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