Experimental Study of the Supersonic Free Jet Discharging from a Petal Nozzle

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페탈노즐로부터 방출되는 초음속 자유제트에 관한 실험적 연구

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Key Words : Supersonic Free Jet(초음속 자유제트), Petal Nozzle(페탈 노즐), Compressible Flow(압축성 유동), Shock Wave(충격파), Mach Disk(마하 디스크)

Abstract

In general, flow entrainment of surrounding gas into a supersonic jet is caused by the pressure drop inside the jet and the shear actions between the jet and the surrounding gas. In the recent industrial applications, like supersonic ejector system or scramjet engine, the rapid mixing of two different gases is important in that it determines the whole performance of the flow system. However, the mixing performance of the conventional circular jet is very low because the shear actions are not enough. The supersonic jet discharging from a petal nozzle is known to enhance mixing effects with the surrounding gas because it produces strong longitudinal vortices due to the velocity differences from both the major and minor axes of petal nozzle. This study aims to enhance the mixing performance of the jet with surrounding gas by using the lobed petal nozzle. The jet flows from the petal nozzle are compared with those from the conventional circular nozzle. The petal nozzles employed are 4, 6, and 8 lobed shapes with a design Mach number of 1.7 each, and the circular nozzle has the same design Mach number. The pitot impact pressures are measured in detail to specify the jet flows. For flow visualization, the schlieren optical method is used. The experimental results reveal that the petal nozzle reduces the supersonic length of the supersonic jet, and leads to the improved mixing performance compared with the conventional circular jet.

1. Introduction

The characteristic features of a supersonic jet discharging from a supersonic nozzle are specified by the ratios of back pressure to supply pressure. A number of works on supersonic free jets discharging from a circular supersonic nozzle have been conducted, and its characteristics are well known comparatively. Same results revealed that the shock system inside the jet is dependent upon the flow expansion conditions, and the jet flow entrains the surrounding gas causing the jet to spread and resulting in decrease in the jet velocity.

The extent of the surrounding gas entrainment affects the jet attenuation, jet core length, jet width, etc. in supersonic jet(1). Generally, the entrainment of the surrounding gas is obtained by both the pressure drop and the shear actions between the surrounding gas at rest and the high-speed jet. Recently, mixing enhancement is being an important issue to determine the performance of the system in the industrial applications like supersonic ejectors(2,3) or scram jet engine(4,5,6). In supersonic jets, the development of the shear layer is not enough compared with the incompressible subsonic jet(7,8,9,10), and the mixing effect of the supersonic jet with surrounding gas is not so much in itself. In order to enhance the mixing effect of supersonic jet

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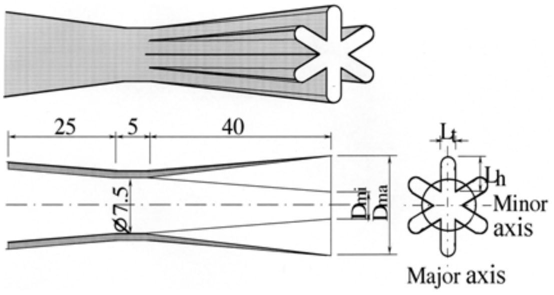
with the surrounding gas, a petal lobed nozzle has been suggested$^{(11,12,13)}$. Supersonic jet discharging from a petal nozzle forms strong longitudinal vortex since the flow characteristic lengths on the major and minor axes of the petal nozzle are different, as shown in Fig. 1. It is thus expected that the petal nozzle would not only increase the entrainment of the surrounding gas but it also enhance the supersonic jet mixing effects. However, to date, there is a little work on the supersonic jets discharging from a petal nozzle.

This study aims at examining how the nozzle exit shape affects the flow characteristics of the supersonic free jet discharging from a petal nozzle. In experiment, 4, 6, and 8-lobed petal nozzles were adopted for the nozzle exit shape variation, and the experimental results are compared with the case of circular nozzle.

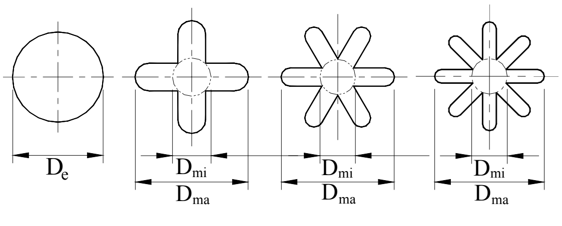
2. Experimental Apparatus

2.1 Nozzles

Fig. 1 and Table 1 represent the detailed shapes and dimensions of nozzles adopted in this study. The nozzle shape variations are circular and 4, 6, and 8 lobed petal lobed nozzles. The petal lobed nozzle consists of converging section, throat, and diverging section, where the sectional shape at the throat is circular, but the shape at the diverging section is lobed petal. That is, the sectional shape, where the diverging section starts is circular, and the diverging sectional shape becomes lobed gradually to downstream. At the petal lobed nozzle exit, the cross sectional line along the longer part and the shorter part are denoted as major axis and minor axis respectively. Therefore, the major axis is longer than the nozzle throat diameter, and the minor axis is shorter than that. In nozzle design, the averaged nozzle exit diameter is 8.67mm, the nozzle throat area ratio is 1.34, and the design Mach number is 1.7 for all nozzles.



(a) schematic view of petal nozzle (6-lobed petal nozzle)



(b) exit configurations of petal lobed nozzle

Fig. 1 Schematics of nozzle geometry

Table 1 Nozzle Geometric Parameters

Nozzle type	Circular	4-Lobed	6-Lobed	8-Lobed
D_e	8.67	-	-	-
D_{ma}	-	12	12	12
D_{mi}	-	4.24	4	3.91
L_t	-	3	2	1.5
L_h	-	3	3.27	3.44
M_e	1.7	1.7	1.7	1.7

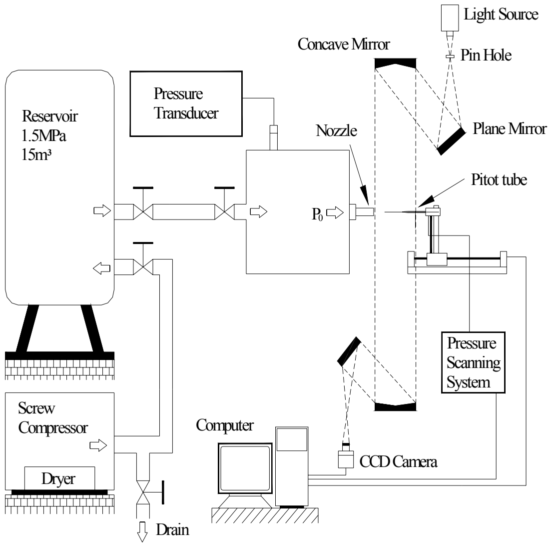


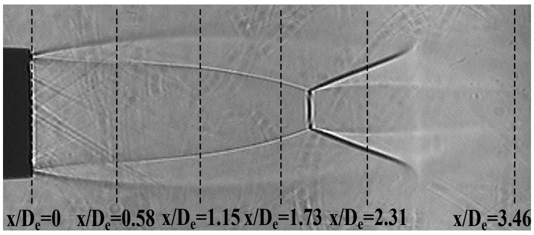
Fig. 2 Schematics of experimental apparatus

2.2 Experimental Setup and Procedures

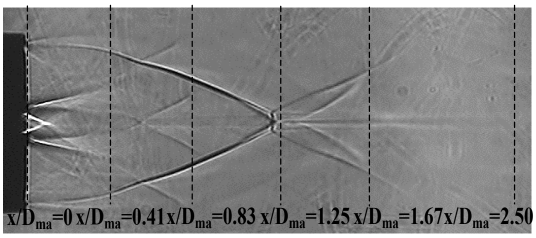
Fig. 2 shows the schematic diagram of the experimental setup for the present study. The apparatus consists of compressor, reservoir, plenum chamber, nozzle, pitot tube, measuring system, and schlieren system. The compressed air at 1.5MPa in the reservoir is induced to the plenum chamber, where the flow is restored to its stagnation conditions, and discharged into the atmosphere through nozzle. In the free jet flow field, detailed measurements of total impact pressures are made using a fine pitot probe with 0.5mm diameter in longitudinal and radial directions operating together with the pressure scanning system. In experiments, the nozzle pressure ratio is changed in the range of p_0/p_a=4.0~10.0, and the transferred distance of the pitot tube is varied in the range of x/D_e=0.0~25.0 normalizing the longitudinal distance with the averaged diameter at nozzle exit. For flow field visualization, a shadow method with a halogen light source was employed, and the taken images were forwarded to the PC through the CCD camera.

3. Experimental Results and Discussions

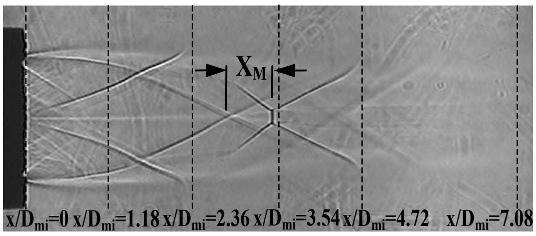
In Fig. 3, jet flow fields for circular nozzle and 4-lobed petal nozzle are visualized when p_0/p_a=10.0. Here, Fig. 3(a) is for the flow field of circular nozzle, and Fig. 3(b) and Fig. 3(c) are for the major and minor axis view of 4-lobed petal nozzle respectively. The supersonic free jet produced from the circular nozzle is in typical under-expanded condition. Thus, a lot of expansion fans are observed at the nozzle exit plane, and the barrel shock and Mach disk are formed resulting from the coalescence of the compression waves.



(a) circular nozzle



(b) 4-lobed petal nozzle(major axis view)



(c) 4-lobed petal nozzle(minor axis view)

Fig. 3 Jet flow fields for circular nozzle and 4-lobed petal nozzle(p_0/p_a=10.0)

However, in the case of the free jet generating from the4-lobed petal nozzle, the inclination of the incident shock increases, the location of the Mach disk shifts to upstream, and the Mach disk diameter also decreases compared to the case of circular nozzle. In the major axis view of Fig. 3(b), the incident shocks generating from both the major and minor axes are crossed at $x/D_{ma} \fallingdotseq 0.54(x/D_{mi} \fallingdotseq 1.54)$, and forms Mach disk at $x/D_{ma} \fallingdotseq 1.21(x/D_{mi} \fallingdotseq 3.41)$. However, in the minor axis view of Fig. 3(c), the incident shocks are intersected at $x/D_{ma} \fallingdotseq 0.98(x/D_{mi} \fallingdotseq 2.77)$, which locates slightly upstream of the Mach disk. That is, the incident shocks generating from the major axis form a Mach disk, and the incident shocks from the minor axis intersect slight upstream of the Mach disk. In Fig. 3(c), the distance between the Mach disk and crossing point is denoted as X_M, and $X_M/D_e \fallingdotseq 0.41$.

To investigate the effects of the petal nozzle exit sectional shape on the Mach disk formation and the incident shock crossing, the correlation among X_M/D_e, D_M/D_e, and nozzle exit sectional shape at p_0/p_a=10.0 in Fig. 4, where X_M and D_M denote the Mach disk distance from the crossing point of the incident shocks and Mach disk diameter

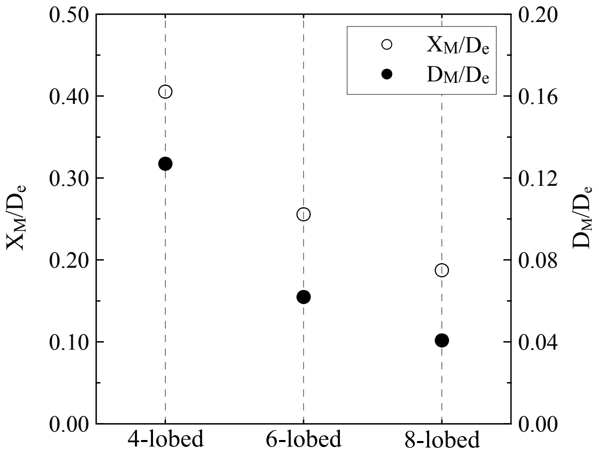
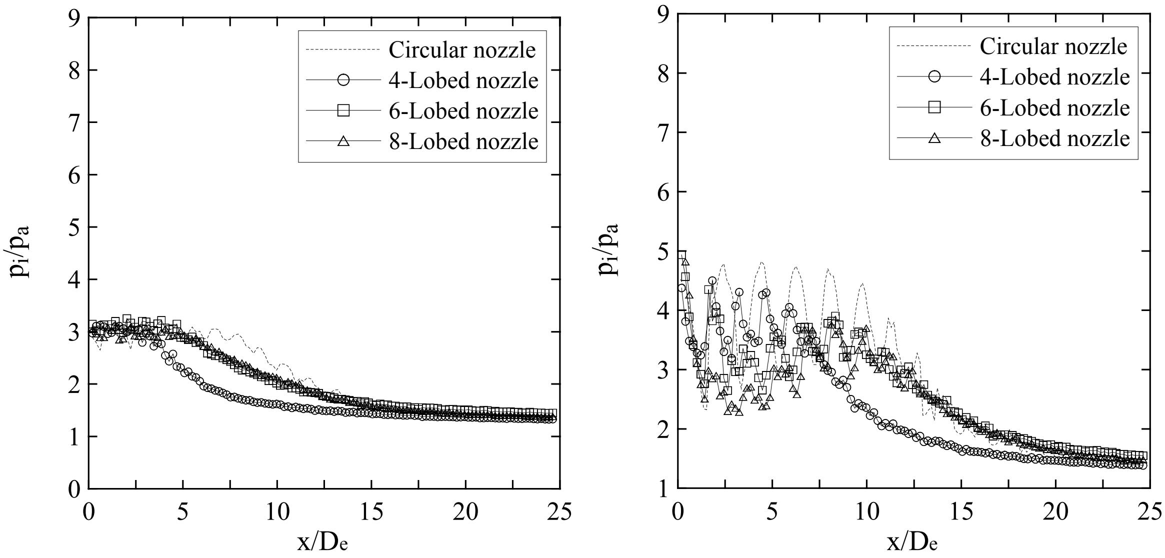
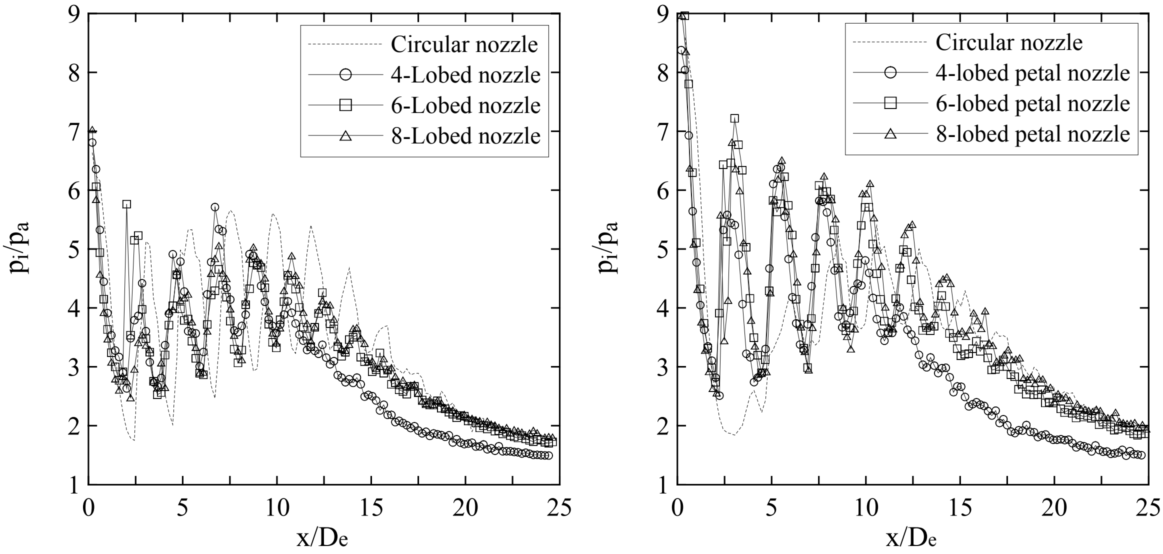


Fig. 4 Correlation among X_M/D_e, D_M/D_e, and nozzle exit shape(p_0/p_a=10.0)



(a) p_0/p_a=4.0 (b) p_0/p_a=6.0



(c) p_0/p_a=8.0 (d) p_0/p_a=10.0

Fig. 5 Pitot impact pressure distributions along the center line of nozzle.

respectively, and normalized by equivalent diameter of the circular nozzle, D_e. In Fig. 4, when the number of lobes increases, X_M/D_e and D_M/D_e decrease. This tendency is considered to be caused by the supersonic length difference between the major axis and minor axis.

The pitot impact pressure distributions along the center line of the circular nozzle and petal lobed nozzles are given in Fig. 5 when p_0/p_a=4.0~10.0. In the plots, the equivalent diameter of the circular nozzle, D_e is used to normalize the axial distance, x in the abscissa, and the pitot impact pressure, p_i is normalized with the back pressure, p_a in the vertical coordinate. The pressure ratio required for correct-

number, M_d1.7 is p_0/p_a≒4.94 theoretically, so the jet is in over-expanded condition for p_0/p_a=4.0, and the others are in under-expanded conditions for p_0/p_a=6.0, 8.0, and 10.0. In the case of p_0/p_a=4.0, the pitot impact pressures are observed to be maintained equal potential core length, and varied accordance with the nozzle type. Namely, the case for 4-lobed nozzle starts to decay quickly, and cases for 6-lobed, 8-lobed, and conical nozzle are followed in sequence slowly. When the jets are in over-expanded conditions, the impact pressures are drastically decreased because of expansion fans, and repeat compression and expansion becoming subsonic condition in downstream. For the jets from the petal lobed nozzles, the ranges and amplitudes of the shock fluctuation seem to be shortened compared to the case of circular nozzle, because the jets producing in the major and minor axes make complicated shock interferences and vortices. Alike the case for p_0/p_a=4.0, the impact pressure for 4-lobed nozzle first starts to be decayed, and the supersonic length is shorten distinctly rather than the cases for 6-lobed, 8-lobed, and conical nozzles. In the plots, the impact pressure distributions for 6-lobed, 8-lobed, and circular nozzles seem to be overlapped in downstream, but the cases for 6-lobed and 8-lobed nozzles precede slightly the case for circular nozzle. That is, the case for 4-lobed nozzle is observed to be the most effective to shorten the supersonic length and potential core for all operating conditions.

4. Conclusion

The characteristics of the jets discharging from petal lobed nozzles are studied experimentally, and their performances are compared with the case of conventional circular nozzle. The pitot impact pressures along the jet axes and the shock structures inside the jets are analyzed. The petal lobed nozzle is considered to be effective for reducing supersonic length and potential core. The effects of the shape of petal lobed nozzle on the jet flow are as follows:

1. Petal lobed nozzle is more effective for reducing the supersonic length and potential core of the jet compared to the case of conventional circular nozzle for all operating conditions. Moreover, there exists optimum design for the petal lobed nozzle for decreasing the supersonic length and potential core of jets, so it is considered that 4-lobed petal nozzle is the most effective, and follows 6-lobed petal nozzle and 8-lobed petal nozzle in sequence from this study.
2. The characteristic lengths from both the major axis and minor axis of the petal lobed nozzle are different, so the incident shocks generating from the major axis form a Mach disk, and the incident shocks from the minor axis intersect slight upstream of the Mach disk. In addition, the distance between the Mach disk and the intersecting point is getting closed, and the Mach disk diameter is decreased when the number of lobes is increased as 4, 6, and 8 in petal shapes in the jets discharging from the petal lobed nozzles.
3. The distance between the Mach disk and the intersecting point represents the characteristic length differences producing from both the major axis and the minor axis in the jets discharging from a petal lobed nozzle, so the supersonic length is effectively shorted when the distance between the Mach disk and the intersecting point is becoming larger for the jet discharging from a petal lobed nozzle.

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