초음속 제트에 관한 수치해석

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Computational Study on Supersonic Jets

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ABSTRACT

In spite of many researches made on the supersonic jets until now, detailed three-dimensional structures of supersonic jets are not well known. In the current study, the detailed structures of three-dimensional supersonic jets are numerically investigated using a CFD method. The total variation diminishing (TVD) scheme is used to solve the unsteady, three-dimensional, compressible Euler equations. Computational results are visualized to investigate the major features of supersonic jets. The three-dimensional computation results show that the structures of the supersonic jets are significantly different from those of the two-dimensional or axisymmetric supersonic jets.

초 록

현재까지 초음속 제트에 관한 많은 연구들이 수행되어져 왔지만, 초음속 제트의 3차원 구조에 관해서는 상세히 알려져 있지 않다. 본 연구에서는 수치해석을 통하여 초음속 제트의 3차원 구조를 상세히 연구한다. 수치계산에서는 TVD법을 비정상, 3차원, 압축성 오일러 방정식에 적용하였으며, 얻어진 수치해석 결과를 이용하여, 초음속 제트의 유동장을 가시화하였다. 본 수치해석 결과로부터 초음속 제트의 3차원 구조는 2차원적 구조와 매우 다르며, 압력비에 크게 의존한다는 것을 알았다.

1. INTRODUCTION

The supersonic jets have become an increasingly important topic of researches because of their practical applications in aerodynamic control devices of supersonic aircraft, rocket nozzle thrust vectoring devices, fuel injectors for supersonic combustion, supersonic momentum-exchange fluid mechanics, etc.

Until now, many researches have been done experimentally and numerically to reveal the structures of the supersonic jet (1~5). However, most of these studies have been restricted to two-dimensional analysis. To understand the three-dimensional features of the supersonic jets issuing from the supersonic nozzle with various configurations, two-dimensional computational data are not sufficient.

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In recent years, there have been some investigations on the three-dimensional structures of the supersonic jets. Teshima (6) made an experimental investigation about three-dimensional structure of supersonic jets issuing from orifices. Arnette *et al.* (7) reported the streamwise vortices and three-dimensional structure in supersonic axisymmetric jets.

The present study investigates numerically the three-dimensional structures of the supersonic jets issuing from the supersonic circular nozzle. The results obtained from three-dimensional computations were compared with those of two-dimensional computations which were applied to Navier-Stokes equations.

2. COMPUTATIONAL ANALYSIS

In order to investigate the structure of the supersonic jet, computations were performed to solve three-dimensional, inviscid, compressible, Euler equations. Yee's upwind TVD scheme was used to discretize the governing equations.

Figure 1 shows the computational domain and boundary conditions applied in the present study. As boundary conditions of computation, the inflow and outflow conditions were applied to the upstream and downstream boundaries of nozzle exit, respectively. The slip-wall conditions were applied to the nozzle wall.

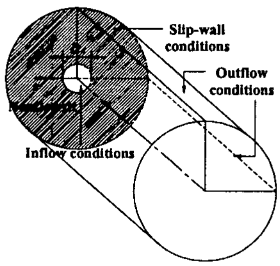
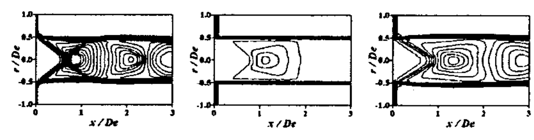


Fig. 1 Schematic of computational flow field and boundary conditions

3. RESULTS AND DISCUSSIONS

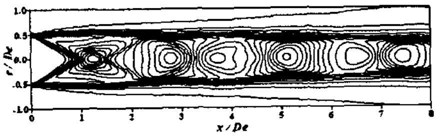
Figure 2 shows the computed density contours for the supersonic jets with three different pressure ratios. Three figures are the results obtained from 3D computations, which were applied to Euler equation. For the over-expanded supersonic jets as shown in Fig.2(a), the weak oblique shock formed from the nozzle lip can be clearly observed and the jet boundary is sunk in first shock cell. For the under-expanded supersonic jet, the jet boundary weakly expands, but the shock structure such as Mach disk can't observed due to a low expand ratio 1.28 (=10/7.8, M_d=2.0), as shown in Fig.2(c).

Figure 3 shows the difference in computed contours between 2-D and 3-D computations for the under-expanded supersonic jet (M_d=2.0 and p_0/p_b=10.0). In the present study, 2-D computations were applied to Navier-Stokes equation with standard κ-ε turbulence model. From Fig.3(a) and (b), the development of the supersonic jet boundary and the decay of supersonic jet core are very well appeared in 2D-NS computation, while 3D-Euler computation is not effective in the prediction of the downstream turbulent mixing region, appearing strongly the viscous effect. The density contours of cross-section perpendicular to flow direction are shown in Fig.3(c). x/D_e=0.0 indicates the exit of nozzle. The supersonic jet has a simple circular cross-section upstream, but the three-dimensional structure of the supersonic jets like the streamwise vortex could not showed.

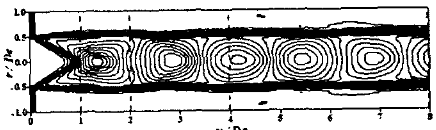


(a) p_0/p_b=6.0 (b) p_0/p_b=7.8 (c) p_0/p_b=10.0

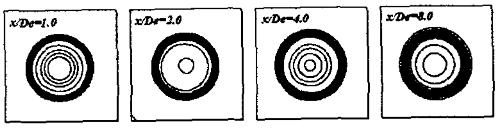
Fig. 2 Computed density contours (M_d=2.0)



(a) 2-D computation (Navier-Stokes)



(b) 3-D computation (Euler)

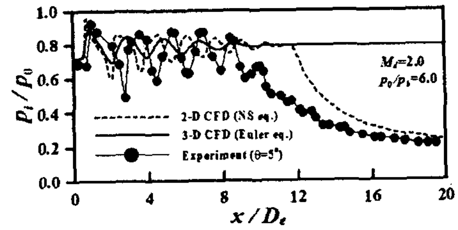


(c) Density contours at different cross-sections

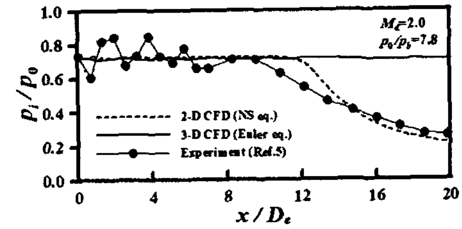
Fig. 3 Computed density contours (M_d=2.0, p_0/p_b=10.0)

Figure 4 shows the impact pressure distributions, where p_i is the impact pressure, p_0 the stagnation pressure of plenum chamber, and p_b the back pressure. For the over-expanded supersonic jet, the impact pressure increases by the oblique shock wave generated from the nozzle lip, while for the under-expanded supersonic jet as shown in Fig.4(c), the impact pressure decreases by the expansion waves. For x/D_e<10.0, the impact pressure distribution fluctuates, but for x/D_e>10.0, it reduce gradually, as shown in Fig.4(a). 2D and 3D computations predict the experimental impact pressure with a little discrepancy for x/D_e<10.0. For x/D_e>10.0 the discrepancy between the 2D and 3D computations is remarkably appeared.

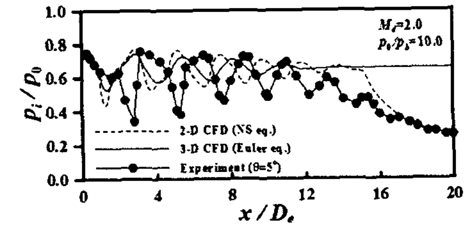
Fig.4(b) represents the impact pressure in the correctly-expanded supersonic jet, where symbol indicates Katanoda et al.' s experimental results (5). As shown in the experimental results (5), although the pressure ratio corresponds to the correctly-expanded supersonic jet, the compression and expansion waves exist at the immediately downstream of the nozzle exit. For a given M_d, the jet core length increases with an increase in the pressure ratio, as shown in Fig.4.



(a) p_0/p_b=6.0

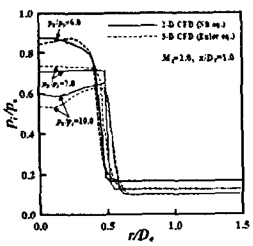


(b) p_0/p_b=7.8

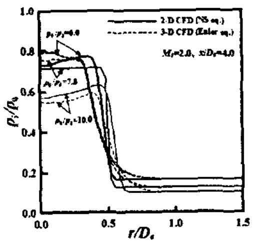


(c) p_0/p_b=10.0

Fig. 4 Impact pressure distributions along the centerline of nozzle (M_d=2.0)

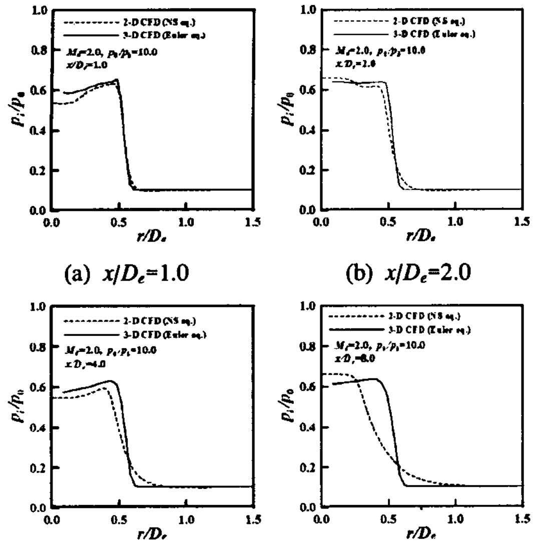


(a) x/D_e=1.0



(b) x/D_e=4.0

Fig. 5 Impact pressure distributions in radial direction (M_d=2.0)



(a) x/D_e=1.0 (b) x/D_e=2.0

(c) x/D_e=4.0 (d) x/D_e=8.0

Fig. 6 Impact pressure distributions in radial direction (M_d=2.0, p_0/p_b=10.0)

Figure 5 shows the impact pressure distributions in radial directions, where r/D_e=0.0 means the nozzle axis. The impact pressure of radial direction decreases with the pressure ratio p_0/p_b, as shown in Fig.5. For the under-expanded supersonic jet, Fig.6 shows the impact pressure distributions in radial direction at various x/D_e. With an increase in x/D_e, the discrepancy between 2D and 3D computational results is to be more remarkable. 3D-Euler computation is not effective in the prediction of the development of supersonic jet boundary.

4. CONCLUSION

The computational results show that the supersonic jet has a circular cross-sectional shape, but it changes to be highly complicated far downstream. The present 3D-Euler CFD can disclose well the structure of the jets at the near-field, but is not effective at the far-field where the flow is governed by turbulent mixing and strong viscous effects. It is also found that 3D-Euler computations unpredict the development of supersonic jet boundary, compared with 2D Navier-Stokes compu -tations.

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