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LES를 이용한 Pseudo-Shock Waves의 가시화

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Numerical Visualization of the Pseudo-Shock Waves using LES

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Abstract. The interaction between a normal shock wave and a boundary layer along a wall surface in internal compressible flows causes a very complicated flow. This interaction region containing shock train and mixing region is called as pseudo-shock waves. Pseudo-shock waves in the divergent part of a rectangular nozzle have been investigated by using large-eddy simulation (LES). LES studies have been done for the complex flow phenomena of three-dimensional pseudo-shock waves. The LES results have been validated against experimental wall-pressure measurements. The LES results are in good agreement with experimental results. Pseudo-shock length and corner separation have been studied in three-dimensional LES model. Comparison of centerline pressure measurement and 3D visualization measurement has been discussed for the corner separation position. It has been concluded that the pseudo-shock length should be measured by using 3D visualization measurement.

Key Words : Pseudo-Shock Waves (의사충격파), Rectangular Nozzle (사각 노즐), LES Simulation (LES 해석), Corner Flow (모서리 유동), 3D Visualization (3차원 가시화)

1. Introduction

Shock wave-boundary layer interaction in combination with flow separation is a key phenomenon in many fluid dynamical applications. This phenomenon plays a major role in the design of supersonic air-breathing engine inlets and internal diffusers. The interaction between normal shock wave and boundary layer along wall surface in internal compressible flows causes a very complicated flow. When the shock is strong enough to separate the boundary layer, the shock is bifurcated and one or more shocks appear downstream of the bifurcated shock. The pseudo-shock waves are generally a sequence of oblique shocks and expansion waves interacting with the boundary layers at the nozzle walls and a subsequent mixing zone.

According to previous studies, much work was done to understand the flow behavior of pseudo-shock waves. The effect of pseudo-shock waves on the performance of facilities in many fields of engineering was put into a comprehensive overview by Matsuo et al [1]. Two-dimensional CFD study was conducted in a cold flow isolator with inflow Mach numbers of 1.8 and 3 at different back pressures [2]. Shock train location and pressure profile inside the shock train as well as flow properties at the isolator exit plane were measured, using wall static pressure and probing at the isolator exit [3]. The analytical method of shock train length measurements were reported in rectangular isolators with

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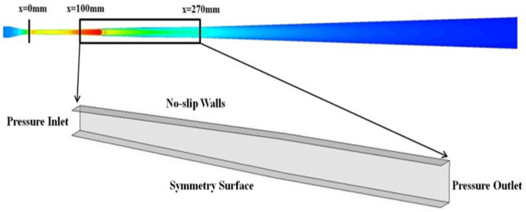


Fig. 1. Geometry and boundary conditions of LES model

incoming Mach numbers of up to 2.5 and duct aspect ratios of 3 and 6 [4]. Although there were several previous experimental studies and numerical studies on measurement of pseudo-shock waves [5-6], the 3D visualization measurement from LES model had been seldom used.

Most of those applications have parallel side walls and rectangular cross-section, therefore, the focus of the presented investigations lies on this topic. The purpose of present study has been to explore the pseudo-shock waves in rectangular nozzle by using LES model. The LES results have been validated against the experimental results. The pseudo-shock length and corner separation have been studied in three-dimensional LES model.

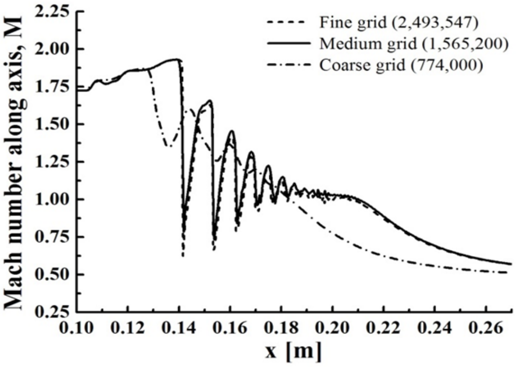


Fig. 2. Grid independence test by using LES model

2. Model Description

2.1 Base model

Geometry of the flow channel as well as operating conditions of this numerical investigation has been adapted to a comprehensive experimental study conducted by Gawehn et al. [6]. The pseudo-shock system is located in the divergent part of the primary nozzle, as shown in Fig. 1. The investigated operation point is characterized by a stagnation pressure of P01=4.8bar and a stagnation temperature of T01=300K. The stagnation pressure ratio is set to P02/P01=0.6. To facilitate such a large-scale simulation, the computational domain is restricted to the pseudo-shock system (0.1m< x <0.27m). The inflow data of LES model at the inlet (x=0.1m) are extracted from a steady-state RANS simulation.

2.2 Numerical modeling

The flow field inside the test section has been numerically simulated using commercially available software FLUENT 14.0. The coupled formulation of density based solver has been used for its applicability in compressible high Mach number flows. Pressure inlet and pressure outlet have been chosen as boundary conditions at inlet and exit of the flow domain. Non-slip walls and symmetry boundary conditions have been imposed at the other regions. The 3D half grid model has been built based on previous experimental model. The ideal gas equation has been employed to predict the working gas density variation and viscosity variation. For the LES simulation, a time step of 10-8s has been implemented for the transient formulation. The LES spans a physical time of approximate 10-3s.

Structured mesh has been used during all regions. The cells of boundary layer must have a low aspect ratio in LES model. A built-in mesh generator enabling adaptive mesh refinement (AMR) has been used for efficiently resolving the channel walls. The applied refinement ratio at block boundaries is set to 2. A grid independence study has been carried out for different grid sizes in the test domain. Mach number variation along the axis at various grid sizes is shown in Fig. 2. It is observed that there is not much difference between medium grid and fine grid. However, depending on the time required for computation, the medium grid has been chosen for the analysis.

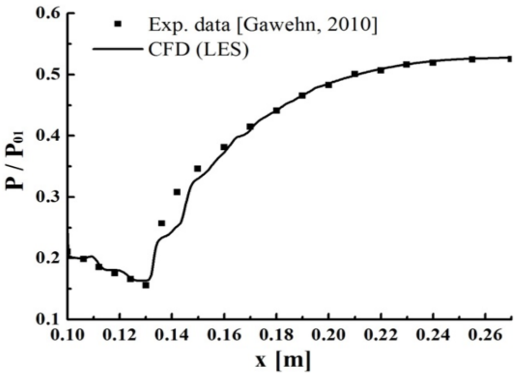


Fig. 3. Comparison between CFD results and experimental results

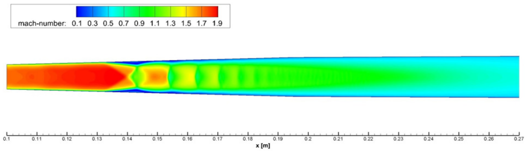


Fig. 4. Mach number contours of symmetry surface

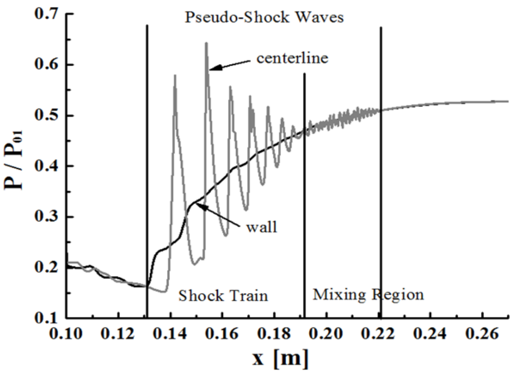


Fig. 5. Static pressure distributions along centerline and wall in symmetry surface

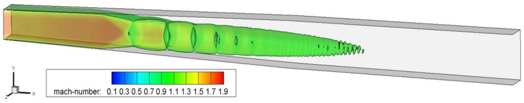


Fig. 6. 3D iso-Mach contours for sonic and supersonic flow

3. Results and Discussion

3.1 Validation

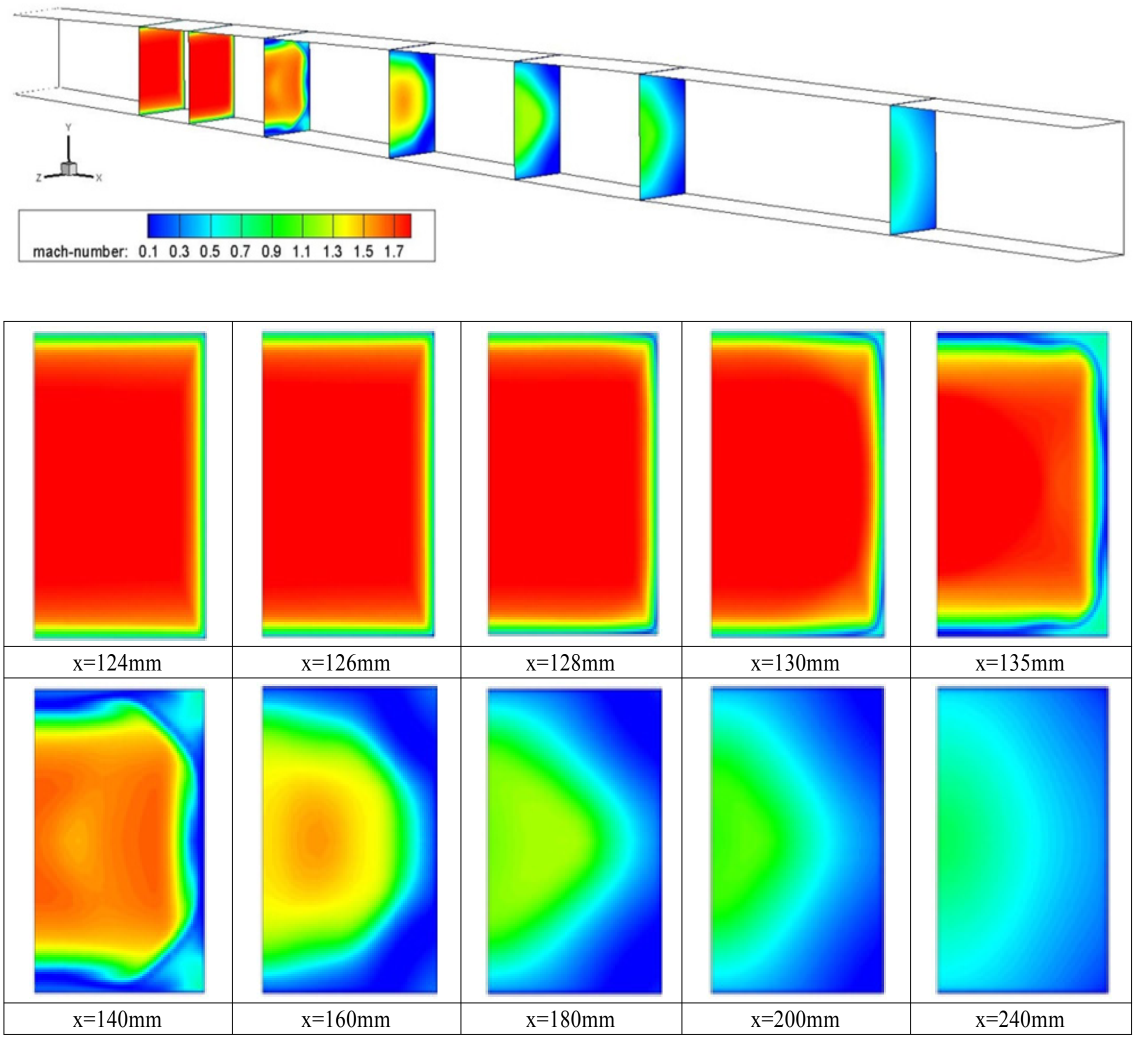
To validate the numerical model, the experimental data of Gawehn et al. [6] is used for comparison. Numerical and experimental static pressure distribution along the center of the upper channel wall is shown in Fig. 3. The pressure distribution is normalized by the stagnation pressure P01. The LES data are in excellent agreement with the experimental pressure data. The first pressure rise is caused by the first shock of shock train. The static pressure along the wall goes up gradually due to the transition between the supersonic flow and subsonic flow.

3.2 Visualization of pseudo-shock waves

Figure 4 shows the Mach number contours of the symmetry surface by LES model. The pseudo-shock waves can be found in this figure. It is clearly separated into two sections, shock train and mixing region. The flow outside the boundary layer remains supersonic throughout the shock train region, but the flow in the core region undergoes successive changes from supersonic to subsonic by the shock train. Fig. 5 shows the static pressure distributions along centerline and wall. As shown in this figure, the pressure increases continuously at the wall, but fluctuates at the centerline. The flow remains mixed supersonic-subsonic downstream of the shock train.

The mixing of a highly non-uniform profile is created in the mixing region. The results show that pseudo-shock waves start from x=131mm and end at x=221mm. According to the centerline pressure measurement, the length of pseudo-shock waves is 90mm.

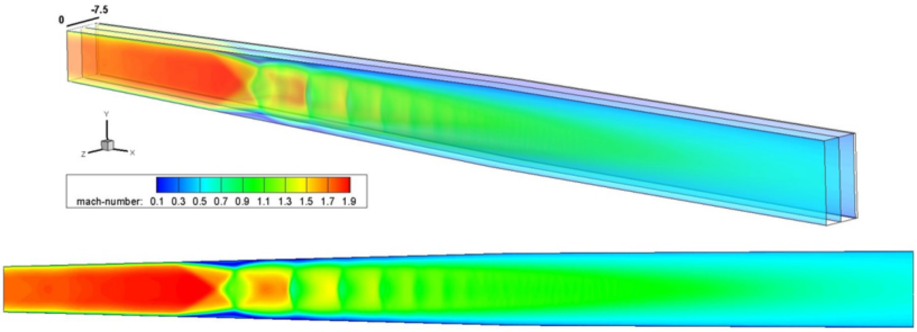
Although centerline pressure measurement may sense the upstream corner flow separation to some extent, more accurate representation of the upstream corner separation is required to obtain a more representative value of total length of pseudo-shock waves. Fig. 6 shows 3D iso-Mach contours based on supersonic and sonic flow. The flow remains mixed supersonic-subsonic at the mixing region. Once the flow reaches the subsonic



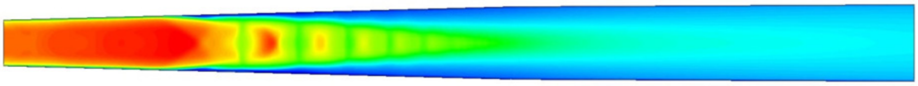
x=124mm x=126mm x=128mm x=130mm x=135mm

x=140mm x=160mm x=180mm x=200mm x=240mm

Fig. 7 Mach number contours of y-z plots at different cross-sections



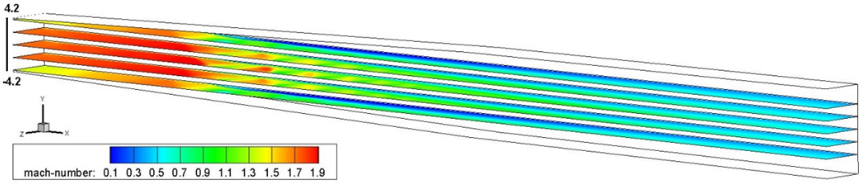
a) z = 0mm

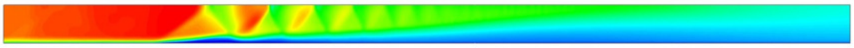


b) z = -3.5mm

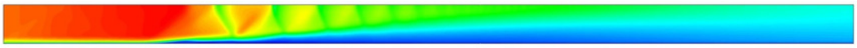
c) z = -7mm

Fig. 8 Mach number contours of x-y plots at different cross-sections

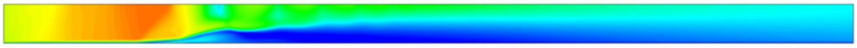




a) y = 0mm



b) y = 2mm



c) y = 4mm

Fig. 9 Mach number contours of x-z plots at different cross-sections

speed fully, the end point of pseudo-shock waves is fixed. The location of the end point is x=221mm. For the end point, the 3D visualization measurement result is same as the centerline pressure measurement.

The starting point in 3D visualization measurement is based on the structure of the corner flow. The corner flow can be captured by different cross-sections very well. Fig. 7-9 show the Mach number contours viewed from different directions. The primary shock leads to flow separation and a recirculation zone that extends over the full channel depth at the diverging section. Large corner separation develops along the channel edges downstream of the primary shock, which extend approximately to the end of the pseudo-shock waves. In Fig. 7, it has been observed that corner separation occurs in the case of x=128mm. The length of pseudo-shock waves is 93mm based on 3D visualization measurement. It has been concluded that the pseudo-shock length should be measured from the 3D visualization measurement due to consideration of corner flow.

4. Conclusions

Numerical approach has been taken in order to investigate the pseudo-shock waves in rectangular nozzle. Fluent 14.0 has been used in order to simulation the flow field of pseudo-shock waves. LES studies have been done for the complex flow phenomena of three-dimensional pseudo-shock waves. The LES results have been validated against experimental wall-pressure measurements. They are in good agreement with experimental results. Comparison of centerline pressure measurement and 3D visualization measurement has been discussed for the length of pseudo-shock waves. The pseudo-shock length should be measured by using 3D visualization measurement due to consideration of corner flow. The length of pseudo-shock waves is 93mm based on 3D visualization measurement. The visualization of corner separation has been studied in three-dimensional LES model.

Acknowledgment

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