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로켓노즐에서 발생하는 횡력변동에 관한 연구

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Study on the Lateral Force Fluctuations in a Rocket Nozzle

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ABSTRACT

Investigation of the lateral force fluctuations in an axisymmetric overexpanded compressed truncated perfect (CTP) nozzle for the shutdown transient is presented. These nozzles experience side-loads during start-up and shut-down operations, because of the flow separation at nozzle walls. Two types of flow separations such as free shock separation (FSS) and restricted shock separation (RSS) shock structure occur. A two-dimensional unsteady numerical simulation has been carried out over an axisymmetric CTP nozzle to simulate the lateral force fluctuations in nozzle during shutdown process. Reynolds Averaged Navier-Stokes equations are numerically solved using a fully implicit finite volume scheme. Governing equations are solved by coupled implicit scheme. Two equation k-ω SST turbulence model is selected. Unsteady pressure is measured at four locations along the nozzle wall. Present pressure variation compared well with the experimental data. During shutdown transient, separation pattern varies from FSS to RSS and finally returns to FSS. Several pressure peaks are observed during the RSS separation pattern. These pressure peaks generate lateral force or side loads in rocket nozzle.

Key Words: Overexpansion Flow(과팽창 유동), FSS(자유박리 충격파), RSS(제한박리 충격파), Lateral Force(횡력)

1. INTRODUCTION

Large scale launch vehicles require nozzle which can produce maximum specific impulse and thrust with reduced nozzle length. Until now, various supersonic nozzles such as Thrust Optimized Contour (TOC), Compressed Truncated Perfect (CTP) contours have been developed to meet such demands. CTP nozzles are currently used with LE-7A engines. CTP nozzle is designed by compressing the truncated perfect (TP) nozzle in axial direction. These engines show large side load during startup and shutdown transient. These problems occur due to a peculiar type of flow

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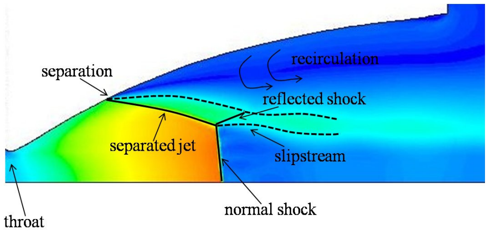

Fig. 1 Free shock separation pattern (Ref. 2)

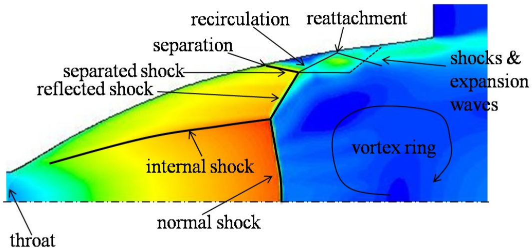

Fig. 2 Restricted shock separation (Ref. 2)

separation under an overexpanded condition during startup and shutdown transient of the engine. Two types of separation pattern such as free shock separation (FSS) and restricted shock separation (RSS) is reported in literature[1]. In FSS, the flow separates fully from the nozzle wall due to an oblique shock that originates from the nozzle wall and is directed towards the nozzle centerline. The separated shear layer continues as a free jet(see Fig. 1). Since no reattachment occurs downstream of the separation location, this separation flow pattern is termed as free shock separation. Downstream of the separation location, a back flow region exists where the ambient air is sucked into the nozzle due to the entrainment effect of the separated jet flow[2]. Nozzle flow fully separates from the wall at a certain ratio of wall to ambient pressure. RSS is a peculiar type of the separation pattern which is observed only in TOC and CTP nozzles at a certain range of pressure ratio. In RSS, the flow separation is restricted over a short axial distance. The separated shear layer reattaches to the nozzle wall generating shocks and expansion waves. Due to the very short separated region, this flow regime is called restricted shock separation(see Fig. 2). This reattached flow results in wall pressures above ambient, which can initiate unsteady side-loads depending upon the asymmetry of the overall flow pattern[3]. Chen et al.[4] have first observed the reattached flow in their numerical simulations, and shown a trapped vortex immediately downstream of the central normal shock. Frey et al.[5-6] have shown the existence of specific cap shock pattern which is a key driver for the transition from FSS to RSS and vice versa. According to Hagemann et al.[7], momentum balance across the cap-shock pattern, with the radial momentum towards the wall generated by the reflected internal shock causes the re-attachment. While, Nasuti et al.[8] have explained that the flow reattachment at the wall depends on the values and kind of upstream pressure gradient, irrespective of the existence of internal shock.

It is important for the rocket nozzles to predict and avoid the flow separation, which cause side-load. The rocket engine transient side-load is a very complicated problem because it is a strongly unstable process. Though, the numerical and experimental studies have been conducted to reveal the actual physics/mechanism behind the FSS/RSS and side-loads, the mechanism and conditions of the occurrence of RSS are not clearly explained. Validation and reproduction of the known mechanisms are essential before taking up the actual work to find the actual cause. In the present study, a computational fluid dynamic analysis of the transient flow during shutdown has been carried out to validate the previous findings with the experiments and numerical results.

2. NUMERICAL PROCEDURE

Reynolds Averaged Navier-Stokes equations are numerically solved using a fully implicit finite volume scheme. Second order accuracy in space is achieved by using upwind method. The k-ω SST two equation turbulence model is employed to close the governing equation systems, which are solved by a coupled implicit scheme. Fig. 3 shows the computational domain with boundary conditions employed. r_i, r_t and r_e are the radius at inlet, throat and exit of nozzle, respectively. Unsteady pressure is measured at four locations such as A, B, C and D along the nozzle wall as shown in fig. 3 Computational grid consists of 450 points in the axial direction(300 points in side the nozzle) and 71 points in radial direction. At inlet boundary, total pressure and temperature are fixed at 100 kPa and 290 K, respectively. Pressure is varied from 1kPa to 10kPa in 0.1 seconds, at outlet boundary. The length of each time step considered is 2.0×10^{-6}second.

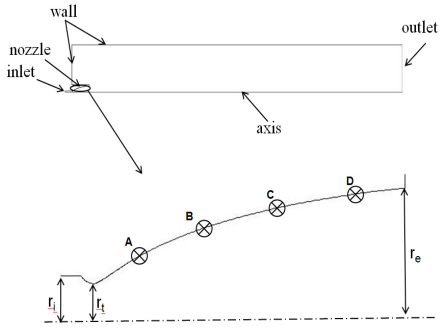

Fig. 3 Computational domain with boundary conditions

Inlet pressure is increased to 100 kPa for startup and then kept for 0.2 seconds. Simulation for shutdown is carried out using this flow field as initial condition.

3. RESULTS AND DISCUSSION

Unsteady wall pressure at location A, B, C and D is computed for the shutdown transient of rocket nozzle. Fig. 4 ~ 7 show the pressure plot for the present computation and experiment[3]. Present results have shown the correct trend for the unsteady pressure at all the locations. Present numerical solution show increase in pressure for high NPR than the observed in experiment and CFD by[3] at location A and B. Whereas, at location C and D, pressure increase closely match with experiment. Pressure peaks are observed at B, C and D point. At the NPR 100, the separation pattern is FSS. At NPR 40, separation pattern has changed into RSS. Present simulation has shown the peak in pressure, but reattachment jet was not strong enough compared to experiment. In experiment, "a" refers to a high pressure region, which is reattachment point. Second high pressure region "b" has appeared near the nozzle exit. "c" is the low pressure region between the separation point.

4. CONCLUSIONS

A numerical investigation of the lateral force fluctuations in an axisymmetric overexpanded compressed truncated perfect (CTP) nozzle for the shutdown transient is performed. Present computational results have shown the correct trend for the static pressure at the selected

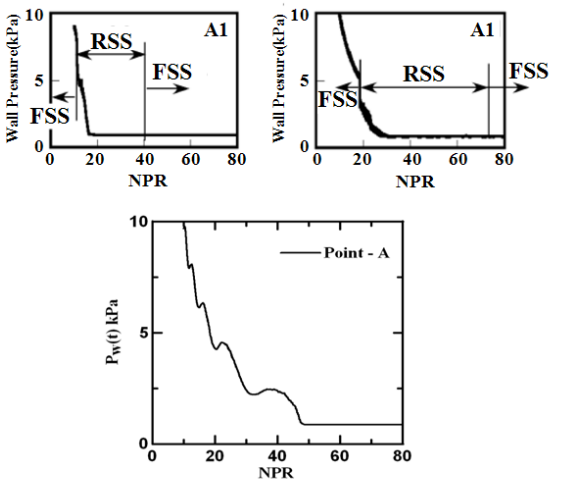

Fig. 4 Comparison of present unsteady wall pressure with experiment and CFD by Ref. [3] at location A

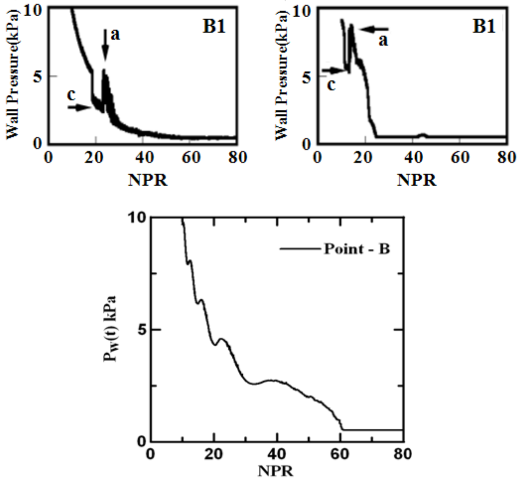

Fig. 5 Comparison of present unsteady wall pressure with experiment and CFD by Ref. [3] at location B

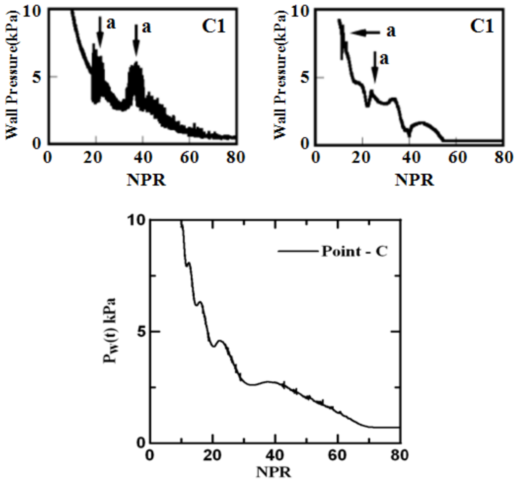

Fig. 6 Comparison of present unsteady wall pressure with experiment and CFD by Ref. [3] at location C

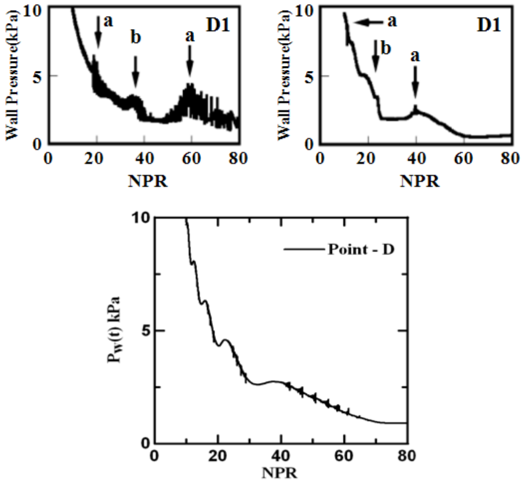

Fig. 7 Comparison of present unsteady wall pressure with experiment and CFD by Ref. [3] at location C

location along the nozzle wall. Pressure peak on the nozzle wall were observed during RSS at the reattachment region. These high pressure peaks result in lateral force, which are the main problems in rocket nozzles. During shutdown transient, the separation pattern varies from FSS to RSS and finally returns to FSS.

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