Study on the Off-design Performance on a Plug Nozzle with Variable Throat Area

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Abstract

In the present study were examined numerically and experimentally the off-design performance characteristics on an axisymmetric plug nozzle with variable throat area. In this nozzle concept, its throat area can be changed by translating the plug into the axial direction.

First, a mixed-expansion plug nozzle, in which two expansion parts are arranged both inside and outside, was designed by means of the method of characteristics. Second, the CFD analysis was verified by the cold-flow wind tunnel test. Third, its performance characteristics were evaluated over a wide range of pressure ratio from half to double throat area through the design point, using the CFD code verified by the wind tunnel tests.

It was made clear from the study that not so critical thrust efficiency losses were found and the maximum thrust efficiency loss was at most approximately 5 % under off-design conditions without external flow. This result shows that a plug nozzle can give the altitude compensation even under off-design geometry operations. However, shock waves were observed in the inner expansion part under the doubled throat area operation and thus some thermal problems may be caused on the plug surface.

Furthermore, collapse of cell structure on the plug surface was observed with external flow (around Mach number 2.0) as it became lower pressure ratio below the design point and the fact may result in big efficiency loss regardless of geometrical configuration.

Introduction

Fully re-usable two-stage-to-orbit (TSTO) spaceplanes have been receiving increasing attention as a candidate for next-generation space transportation system (STS) with safety and economical efficiency. R&D of an air turbo ramjet (ATREX) engine have been actively done for an accelerator of the first stage of TSTO. Plug nozzles or aerospike nozzles are a promising candidate as a nozzle for engines of next-generation STS including ATREX engine.

Unlike a bell-shaped nozzle, the nozzle flow is not fixed by a wall but instead, the exhausted jet is bounded by the external flow. The plug nozzle is considered to have better performance globally because the jet boundary adjusts its shape to an ambient pressure and the jet expands optimally for the entire condition (e.q. altitude).

In previous studies, plug nozzles were designed by a certain design method at certain design pressure ratio and operated over wide range of pressure ratio (PR = total pressure in chamber Ptc / static pressure of external flow Pa) to prove altitude compensation[1-3].

However, with air breathing engines, it is necessary to change throat area widely according to mass flow rate of combustor, which compels plug nozzles to operate under off-design geometrical configuration in almost all flight conditions.

This research especially estimated performance at geometrically off-design configurations of a plug nozzle having variable throat area mechanism into axial direction using typical axisymmetric plug nozzle designed at a certain pressure ratio. Moreover, the influence of the external flow on the performance was also investigated.

Geometry of The Plug Nozzle

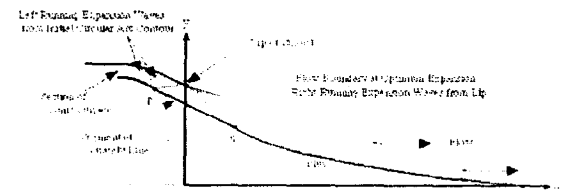

Fig. 1 Plug nozzle design method

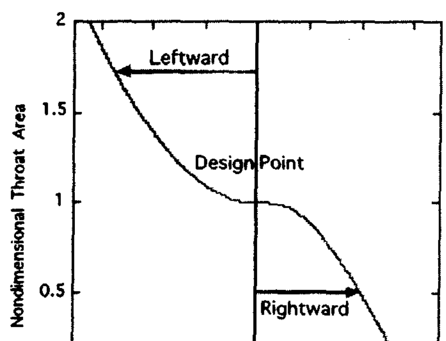

Fig. 2 Throat area fluctuation

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The mixed-expansion plug nozzle having a vertical throat in the inner nozzle was designed based on the method of characteristics[4]. The area ratio for the inner nozzle part and the whole nozzle are 1.7 and 6.5, respectively. Optimum expansion is achieved at the pressure ratio 71 under the assumption that the flow is isentropic (Fig.1). The inner side was designed so that the throat area would decrease and increase, as shown in Fig.2, when the plug is translated to right and left, respectively. Herein, translating the plug rightward, that is the direction where the throat area decrease is defined as positive. The length is nondimensionalized by the radius at the exit of the inner nozzle.

Numerical Analysis

Computational Scheme

The basic equations are axisymmetric compressible Navier-Stokes equations. The convective terms are evaluated by Roe's Flux Difference Splitting scheme. High-order space accuracy is obtained using MUSCL, the primitive variable interpolation. The viscous terms are evaluated by the central differencing and the eddy viscosity is modeled by the Baldwin-Lomax turbulence model. Only the steady-state solutions are considered, and the LU-ADI factorization time integration algorithm is used.

Computational Grids

H-type computational grid is used. Computations are carried out in the inner and outer region, alternately, and two regions are combined on downstream from the cowl lip. Computational grids for one region consist of 249 nodes in the streamwise direction and 50 nodes in the vertical direction, therefore, all grids consist of $249\times50\times2$=24900 grids. Fig.3 shows the grid distribution near the exit of the inner nozzle.

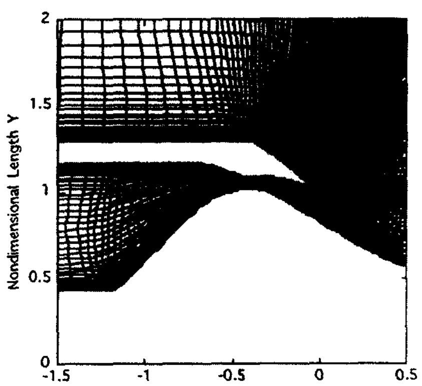

Fig. 3 Grids around inner nozzle

Boundary Conditions

The total pressure (Ptc) and the total temperature (To) of the inner nozzle flow are adjusted by giving its density (ρ) and Mach number (M1) as inflow conditions BC1 for the inner flow (Fig.4). External inflow conditions are given as BC2, after assuming the existence of the object of the same shape as the experiment model ahead of the plug and developing a boundary layer, when the external flow have to be taken into account. Supersonic outflow conditions are given as outflow conditions BC3.

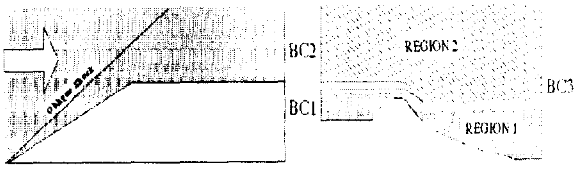

Fig. 4 Boundary conditions

Computational Conditions

To compare CFD results with the wind tunnel test, wind tunnel conditions are given as computational conditions, that is the Reynolds number (Re) = 1.73×10^5 at external flow Mach number (M2) = 3.5, Re = 3.25×10^5 at M2 = 2.5.

In the CFD for performance evaluation, it calculated about following three cases (as shown in Table 1), designed geometrical configuration, doubled and half throat area.

The pressure ratio is changed from 5 to 500. The external flow is set as two cases of M2 = 0.0 and 2.0. M2 = 0.0 is for investigation of the effect of geometrical change to the thrust efficiency coefficient, M2 = 2.0 is for the effect of the external flow. The Reynolds number is set to Re = 3.92×10^6 for M2 = 0.0 and Re = 1.01×10^6 for M2 = 2.0 based on the length between the plug axis and cowl lip and on the external flow conditions.

Table 1. Variables of nozzle configurations at calculated geometries

Throat Area*	Area Ratio	Design Expansion Ratio**
1.0 (Designed)	6.5	71
0.5 (Off-design)	13.0	202
2.0 (Off-design)	3.25	24

* Throat area is nondimensionalized by the throat area of the design configuration

** Design expansion is derived from isentropic relation

Wind Tunnel Test

The wind tunnel test was carried out using ISAS/JAXA supersonic wind tunnel facility. The plug nozzle wind tunnel test model is shown in Fig.5, and the enlargement of its nozzle part is in Fig.6. Nozzle exhaust jet is drawn from the model upper part, and supplied to the nozzle part of the model through inside of its strut.

Possible maximum total pressure of supplied inner flow is approximately 0.9MPa. Run the wind tunnel reduces static pressure of the nozzle external flow and realize maximum of PR = 100.

A load cell installed ahead and inside of the test model can measure the net thrust applied to the nozzle part. Pressure is measured at seven points on the plug surface and two points on the boat tail part.

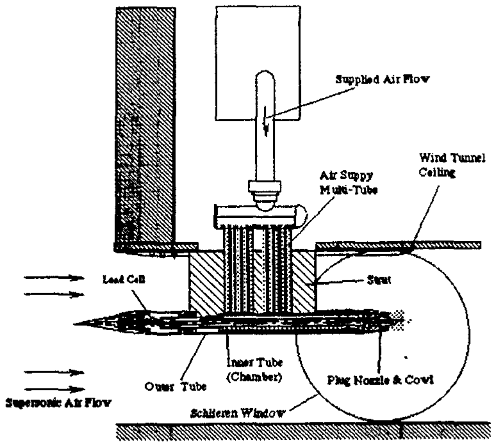

Fig. 5 Plug Nozzle Wind Tunnel Test Model

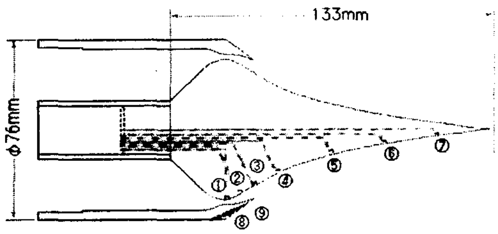

Fig. 6 Plug Nozzle and Cowl

The Analysis Method

Thrust Coefficient and Thrust Coefficient Efficiency

Generally, the performance of a nozzle is expressed using the thrust coefficient CF and the thrust coefficient efficiency η.

CF is expressed with the following equation.

$$C_F = \frac{F}{P_{tc} \cdot A_t} \qquad (1)$$

where Ptc and At means total pressure in the chamber and the throat area, respectively. Putting the gross thrust Fgross, net thrust Fnet and ideal thrust Fideal into (1), CFgross, CFnet and CFideal can be derived, respectively. The control surface and each thrust components are shown in Fig.7.

$$F gross = (Momentum) + (Pressure) + (Ramp) \qquad (2)$$

$$F net = F gross - (Boattail\ Drag) \qquad (3)$$

Fideal is ideal thrust obtained when nozzle exhaust flows isentropically, and is expressed with the following equation.

$$F_{Ideal} = \dot{m}_t \sqrt{\frac{2\gamma}{\gamma - 1} R T_{tc} \left[1 - \left(\frac{P_{tc}}{P_a} \right)^{\frac{\gamma-1}{\gamma}} \right]} \qquad (4)$$

where m means mass flow rate at nozzle throat.

Each thrust coefficient efficiency can be derived from following equations.

$$\eta_{gross} = \frac{C_{F_{gross}}}{C_{F_{ideal}}} = \frac{F_{gross}}{F_{ideal}} \qquad (5)$$

$$\eta_{net} = \frac{C_{F_{net}}}{C_{F_{ideal}}} = \frac{F_{net}}{F_{ideal}} \qquad (6)$$

Subsequent chapters discuss the performance using the thrust coef. efficiency derived from Fgross.

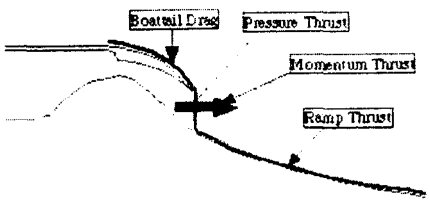

Fig. 7 Thrust components and control surface

Results and Discussions

Comparison between CFD and Experimental Results

Schlieren photographs (above) from the wind tunnel test and Mach number distribution (below) from CFD at design configuration and pressure ratio are shown in Fig.8.

The mainstream Mach number of wind tunnel is Mach 3.5. In both cases, since the external flow expands around the boat tail part and it is re-compressed after that, where a re-compressed shock wave occurs. Furthermore, as this is the operation at the design pressure ratio, the shear layer which is the boundary between internal and external flow is formed almost parallel to the axial direction.

The static pressure distribution along the control surface is shown in Fig.9. The exit of inner nozzle is defined as X=0.0.

The experiment value is lower than the CFD and the theoretical value near the plug tip and the theoretical value is higher than those of CFD and experiment at the exit of the inner nozzle. However, good coincidence is shown

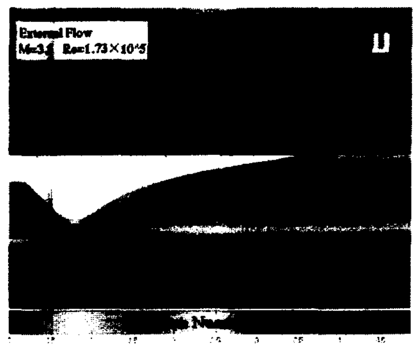

Fig. 8 Schlieren photographs (above) and Mach-Number-Distoribution (below)

among results of the wind tunnel, the CFD, and the one-dimensional theory except for a few points. The difference near the plug tip can be presumed to be the influence of the axial gap in the experiment and at the exit of inner nozzle to be the effect of contraction of inner flow by the boundary layer around the throat region.

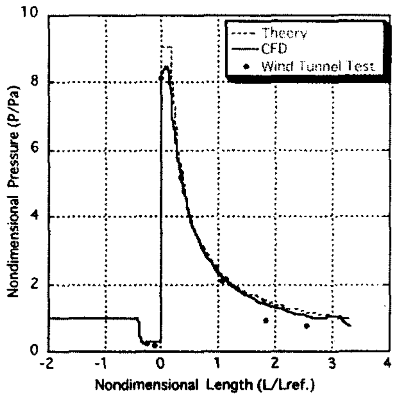

Fig. 9 Pressure distribution along the control surface

Performance Analysis by CFD

External Flow Mach Number = 0.0 (Without Flow)

The relation between PR and η gross in three configurations is shown in Fig.10. The dashed line shows the ideal efficiency when assuming that ideal expansion is achieved with a bell-shaped nozzle having same design pressure ratios.

In design configuration, almost same efficiency as the theoretical performance of a bell-shaped nozzle is attained in pressure ratios higher than the design pressure ratio (PR=71). This can be explained from the same loss factor that the bell-shaped nozzle or the plug nozzle cannot receive the pressure where the flow spread outside in higher pressure ratios. In lower pressure ratio than the design pressure ratio, the exhaust flow is forced on the plug surface and cell structure is formed (Fig.11). Consequently, since the ramp thrust is maintained, high efficiency is realizable.

In the case that the throat area is made into a half, η gross = 0.958 near the design pressure ratio. This value is approximately 3% lower than the efficiency of designed configuration at the design pressure ratio. Since the nozzle is in geometrically off-design operation even in the design pressure ratio, the flow does not be exhausted parallel to the axial direction but spreads outside, which result in the thrust loss. Also in higher pressure ratio, the efficiency decreases by the same reason.

When the pressure ratio is lower than the design pressure ratio, even if the flow comes to be exhausted parallelly to the axial direction, it separates on the plug surface by over expansion after the exit of the inner nozzle (Fig.12). As the cell structure is collapsed by the separation and the ramp thrust is lost, the efficiency becomes the lowest. However, if the pressure decrease lower, the flow comes to be forced on the plug surface to recover the ramp thrust by cell structure forming. In this case, the high efficiency can be maintained.

When the throat area is doubled, in higher pressure ratios than design pressure ratios, the values of efficiency are approximately 3% lower than the theoretical efficiency of a bell-shaped nozzle. In lower pressure ratios, its efficiency decreases as the pressure ratio becomes low. By translating the plug inside, the expansion ratio of the inner nozzle becomes large to separate the flow by over expansion in the inner expansion region at low pressure ratio. However, since the cell structure maintains the ramp thrust to some extent without its collapse completely even when the flow separates, it is still more efficient than a bell-shaped nozzle. It can be seen from experimental and CFD results that the shock waves occurre in the inner nozzle at all calculated pressure ratios.

Although the generation of these shock waves does not affect the efficiency loss greatly, it can produce an additional problem such as local heating on the plug surface.

Numerical analysis was performed in the pressure ratio of 5~500 about three configurations. In all cases, the efficiency of the designed geometrical form is always the highest. However, in the other off-design configurations, the efficiency loss is at most approximately 5% compared to that of the design configuration and much higher efficiency is maintained than that of the bell-shaped nozzle also in low pressure ratios.

Therefore, it turns out that a plug nozzle has advanced altitude compensation even in the off-design configurations.

External Flow Mach Number = 2.0

The relation between the PR and η gross with M2 = 2.0 is shown in Fig.14. In this case, configurations and pressure ratios are taken as same conditions as those of no external flow.

In three forms, η gross is in good agreement with that of no external flow in higher pressure ratios than each design pressure ratios. However, the lower pressure ratio is, the larger efficiency loss is in every form.

This is because the exhaust flow is deflected a little outside, affected by the expansion of external flow around the boat tail region, to cause flow separation on the plug surface and the cell structure, which plays an important role as thrust in low pressure ratio, is collapsed. Therefore, the ramp thrust is lost under the existence of external flow. As the exhaust flow spreads outside in the higher pressure ratios than each design pressure ratio, the exhaust flow near the plug surface is not affected by the external flow.

Conclusion

The geometrically off-design performance of the axisymmetric mixed-expansion plug nozzle was evaluated by CFD which is verified by the wind tunnel test.

It was made clear from the result that critical losses of thrust efficiency were not found and the maximum thrust efficiency loss was at most approximately 5 % under off-design conditions without external flow. Thus, a plug nozzle can give the altitude compensation even under off-design geometry operations.

However, with external flow, the external flow causes serious efficiency losses under the low pressure ratio operation.

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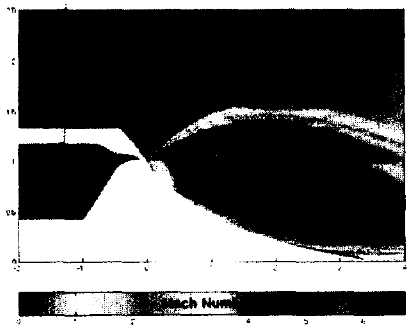

Fig. 12 A half throat area configuration (PR=200)

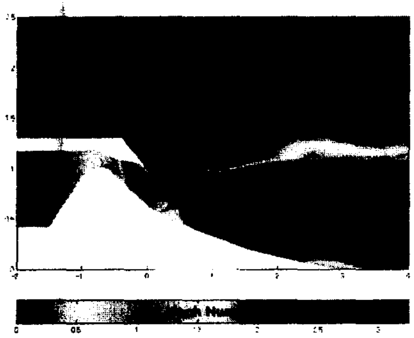

Fig. 13 Doubled throat area configuration (PR=24)

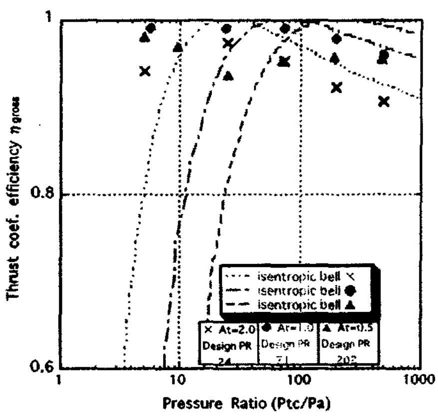

Fig. 10 Thrust coef. efficiency without external flow

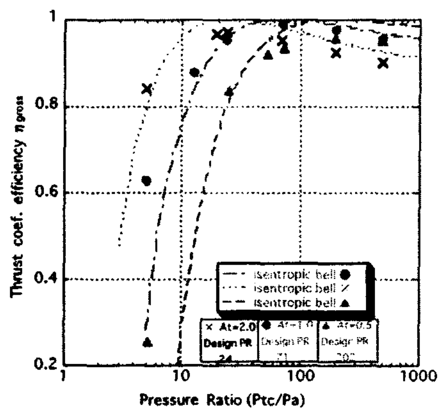

Fig. 14 Thrust coef. efficiency with external flow (M2=2.0)

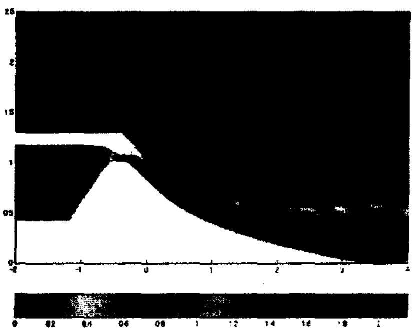

Fig. 11 Design configuration (PR=5)