Proceedings of 2004 Korea-Japan Joint Seminar
on Particle Image Velocimetry
POSTECH, Korea, Dec. 9 - 10

Flow Visualization of Flowfield Structures around an Aerospike Nozzle using LIF and PSP

Tomohide NIIMI, Hideo MORI and Mashio TANIGUCHI

Department of Micro-Nano Systems Engineering
Nagoya University,
Furo-cho, Chikusa, Nagoya, 464-8603, Japan
niimi@mech.nagoya-u.ac.jp

Abstract: Aerospike nozzles have been expected to be used for an engine of a reusable space shuttle to respond to growing demand for rocket-launching and its cost reduction. In this study, the flow field structures in any cross sections around clustered linear aerospike nozzles are visualized and analyzed, using laser induced fluorescence (LIF) of nitrogen monoxide seeded in the carrier gas of nitrogen. Since flow field structures are affected mainly by pressure ratio, the clustered linear aerospike nozzle is set inside a vacuum chamber to carry out the experiments in the wide range of pressure ratios from 75 to 200. Flow fields are visualized in several cross-sections, demonstrating the complicated three-dimensional flow field structures. Pressure sensitive paint (PSP) of PtTFPP bound by poly-IBM-co-TFEM is also applied to measurement of the complicated pressure distribution on the spike surface, and to verification of contribution of a truncation plane to the thrust. Finally, to examine the effect of the sidewalls attached to the aerospike nozzle, the flow fields around the nozzle with the sidewalls are compared with those without sidewalls.

Keywords: Aerospike nozzles, LIF, PSP, Flow visualization, Pressure distribution

1. Introduction

In recent years, as demands for rocket-launching of commercial satellites and ISS (International Space Station) grow, the cost reduction of space transportation systems becomes more important. Single-Stage-to-Orbit (SSTO) has been expected to realize the cost reduction, for which aerospike nozzles[1] have been proposed instead of conventional bell-type nozzles. Unlike bell-type nozzles causing a big thrust loss due to over-expansion at low altitudes, since aerospike nozzles expand the combustion gases equilibrating with ambient pressure, the nominal expansion ratio is adjusted automatically to the suitable one at any altitude. Therefore, aerospike nozzles have high performances from the low to high altitudes. Though aerospike nozzles are longer than conventional bell-type nozzles, they can be truncated with negligibly small thrust loss because of the additional thrust produced by a pressure increase on the base (truncation plane) [1] [2].

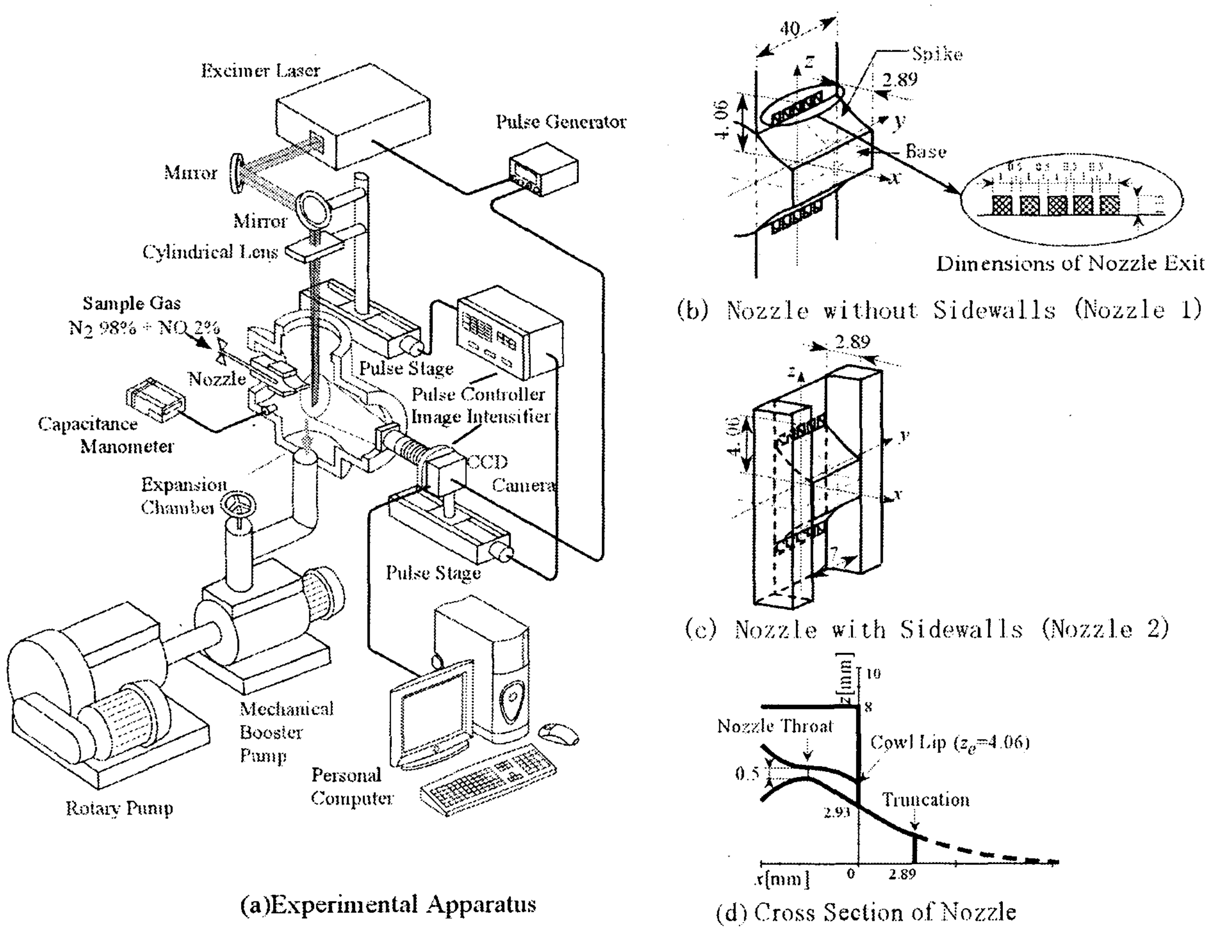
In this study, NO-LIF (Laser Induced Fluorescence), one of a non-intrusive measurement techniques, is used to visualize and analyze the flow field structures around clustered linear aerospike nozzles at any cross-sections. We also apply PSP (Pressure Sensitive Paint) to measure the complicated pressure distribution on the spike surface. Since the flow field structures are affected mainly by pressure ratios (P_s/P_a, P_s: the source pressure, P_a: the ambient pressure), we set the nozzle into a vacuum chamber to carry out the experiments in the wide range of pressure ratios.

The linear aerospike nozzle used in this study is designed and developed assuming a two-dimensional flow. However, the undesirable lateral expansion out of the nozzle occurs actually, and it may cause a thrust loss. To suppress the lateral expansion, sidewalls can be attached to the nozzle. To demonstrate the effect of sidewalls suppressing the undesired lateral expansion, the flow fields around the nozzle with the sidewalls are compared with those around the nozzle without the sidewalls.

2. Experimental Apparatus

Figure1(a) shows a schematic diagram of the experimental apparatus used for visualization of flow fields around the clustered linear aerospike nozzles by NO-LIF. The nozzles are set into a vacuum chamber evacuated by a mechanical booster pump (ULVAC PMB-006C) and a rotary pump (ULVAC VS2401) to achieve larger pressure ratios. A gas mixture of NO2% + N_2 98% expands through rectangular nozzle orifices into the vacuum chamber. A broadband ArF excimer laser (Lambda Physik LPX 105E; wavelength 193 nm, FWHM 0.5 nm) is used as an excitation source, and the laser beam is focused on the flow fields by a cylindrical lens (SIGMA Koki; f=400mm, size 30×30mm). The flow fields are imaged onto an image-intensified CCD camera (Hamamatsu C7300-10) with a camera lens (Nikon UV-NIKKOR; F(0.5)) set perpendicular to the laser sheet. A UG5 filter is placed in front of the camera lens to eliminate elastically scattered laser light and to pass the broadband NO fluorescence. The CCD camera is synchronized with each laser pulse.

We apply PSP of PtTFPP/poly-IBM-co-TFEM[3][4] to measurement of pressure distribution on the nozzle surfaces. In these experiments, pure oxygen gas is supplied to increase the pressure sensitivity. A xenon-arc lamp (Ushio UXL-500SX) with a band-pass filter (400±10nm) is used as an excitation light source. The luminescence of PSP is filtered by a long pass filter (600nm) to eliminate the light of the xenon-arc lamp, and detected by the CCD camera.



(a)Experimental Apparatus

(b) Nozzle without Sidewalls (Nozzle 1)

(c) Nozzle with Sidewalls (Nozzle 2)

(d) Cross Section of Nozzle

Figure 1. Experimental apparatus

Figure 1(b) and 1(c) depict the clustered linear aerospike nozzle without the sidewalls (nozzle 1) and the nozzle with the sidewalls (nozzle 2), respectively, used in this study along with the coordinate. The nozzle 1 has five rectangular nozzle orifices in both sides of the spike and is truncated at 20% (2.89mm) of the entire length of the spike. The nozzle 2 has the same cross section as the nozzle 1, but the width of the spike is equal to the sum of the width of the five orifices and the four gaps (The width and height of each orifice are 1mm and 1.13mm, respectively, and the width of the gap is 0.5mm. see Fig.1(b)). The length of the sidewalls is equal to that of the spike (2.89mm) and the height of the sidewalls is much larger than that of the cowl lips. Figure 1(c) illustrates the cross section of the nozzle on the *xz*-plane. The nozzles are composed of the internal expansion region from a reservoir to the cowl lip and the external expansion region from the cowl lip to the tip of the nozzle. The nozzle contour is designed by the method of characteristics so that the jet boundary forms parallel to the nozzle center axis (*x*-axis) at the designed pressure ratio (P_s/P_a =100 in this study)[5]. The height of the nozzle throat is 0.5mm. Linear dimensions are normalized by the height of the cowl lip z_e (4.06mm) in this study.

3. Results and discussion

3.1 Analyses of Jet Structure around Clustered Linear Aerospike Nozzle without Sidewalls

It has been reported for annular aerospike nozzles that the thrust loss caused by truncation of the spike is negligible, because the base pressure compensates for the thrust loss[2]. For linear aerospike nozzles, we investigate the compensation for the thrust loss experimentally, considering the base pressure measured by PSP.

Figure 2(a) and (b) show the flow field images visualized by NO-LIF around the nozzle 1 on the *xz*-plane at P_s/P_a=200 and 75, respectively. The schematic flow field structure on the *xz*-plane for P_s/P_a=200 (Fig. 2(a)) is illustrated in Fig.3. The jets issued from the nozzle orifices expand at the cowl lips B and B' and form the barrel shock waves BC and B'C' originating from the cowl lips. Since the jets also expand at the spike edges A and A', the barrel shock waves AF and A'F originate from the spike edges. For a relatively high pressure ratio (P_s/P_a=200), the barrel shock waves AF and A'F interact with each other at the point F, causing an increase in pressure at the point F. As the pressure at the interacting point F becomes higher than that of the base, the back-flow emanates from the point F toward the base surface and impinges on it, leading to an increase in pressure on the base. This is the reason why the pressure increase on the base surface compensates for the thrust loss.

Pressure distributions measured by PSP on the base at P_s/P_a=200 and 75 are presented in Figs. 4(a) and (b), respectively, in which a dark region corresponds to high pressure. As shown in Fig. 4(a), for P_s/P_a=200, there appear two high pressure regions on the base, which are caused by the back-flow as mentioned above. On the contrary, for P_s/P_a=75, there are no high pressure regions on the base as shown in Fig. 4(b) and it is also found from Fig. 2(b) that the barrel shock waves do not interact behind the base because the jets expand weakly. These mean that no back-flow is generated toward the base, resulting in no pressure increase on the base and no compensation for the thrust loss.

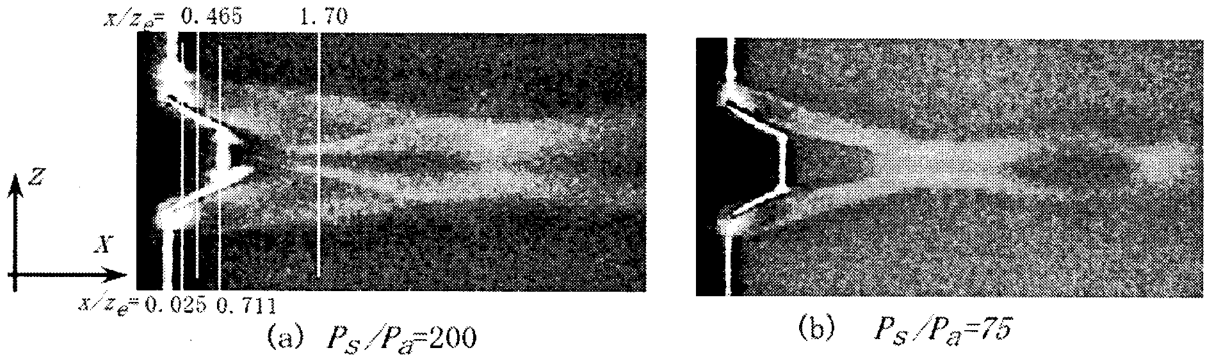


Figure 2 LIF images on xz-plane (Nozzle 1)

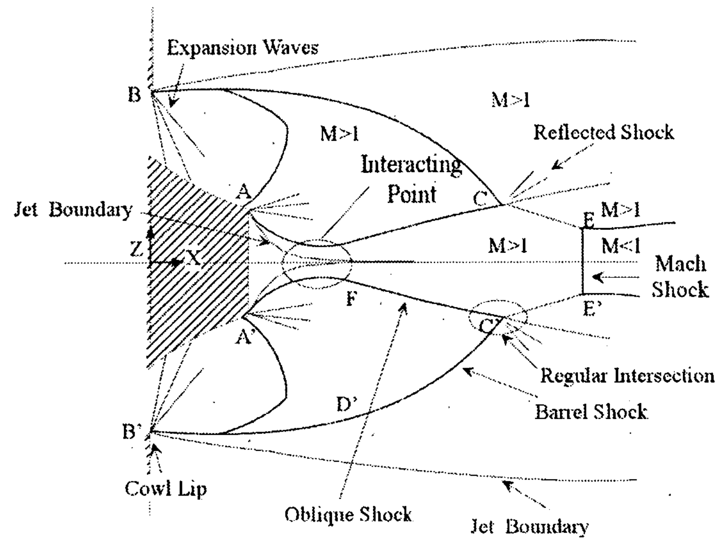


Figure 3 Schematic Jet Structure on *yz*-plane *Ps/Pa=200*

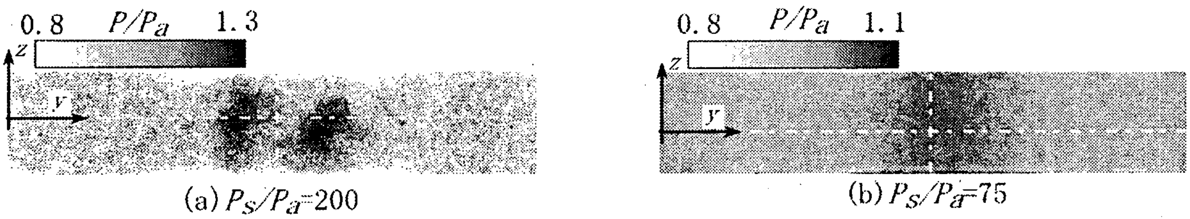


Figure 4 Pressure distributions on the base surface (Nozzle 1)

Figures 5 show the visualized images on the cross sections parallel to the *yz*-plane at P_s/P_a=200. These figures are taken at the cross sections, x/z_e=0.025, 0.465, 0.711 and 1.70, indicated by white lines in Fig. 2(a). The pressure distribution on the spike surface measured by PSP is presented in Fig. 6(a), and the flow field structure along the spike surface, deduced from Figs. 5 and 6(a) and Ref. [6], is depicted in Fig. 6(b). At x/z_e=0.025, there appear five bright regions in both sides of the spike as shown in Fig. 5(a), corresponding to high pressure and high density regions just behind the nozzle orifices. In Fig. 6(a), the five high pressure regions are also observed just behind the orifices. At x/z_e=0.465, four bright regions can be found, which indicate the high pressure regions caused by the interaction of the adjacent barrel shock waves at the points a and a' in Fig. 6(b), which can also be confirmed as four high pressure regions in Fig. 6(a). At x/z_e=0.711 (the base plane), we can find three bright regions, which correspond to the high pressure regions caused by the regular intersection of the barrel shock waves ab and a'b at the point b. At x/z_e=1.70 (behind the base), it is found clearly that the jets from the both sides of the spike interact with each other and expand toward the *y*-direction (lateral expansion) as well as the *z*-direction.

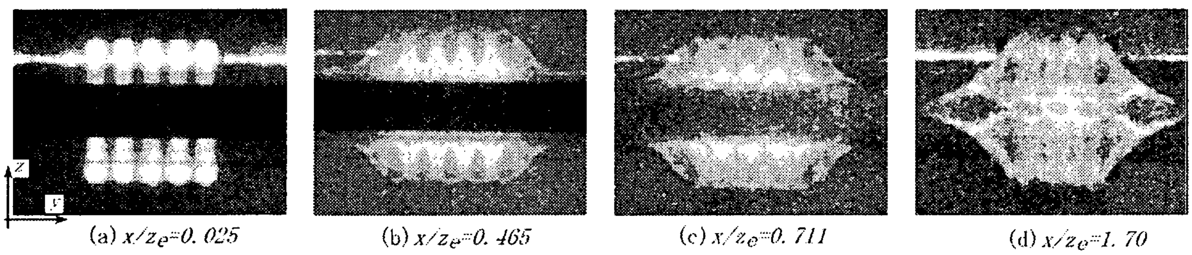


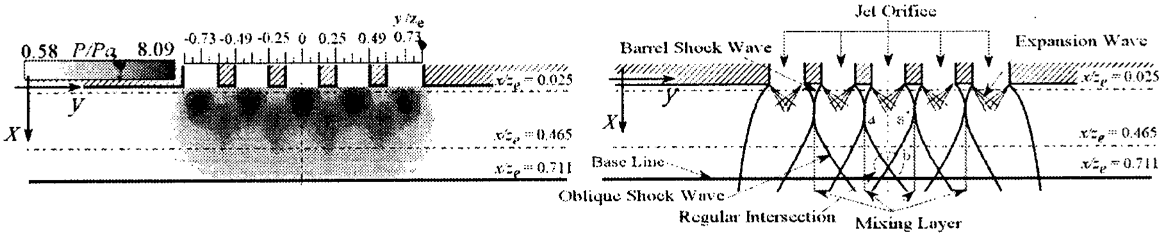
Figure 5 Visualized images parallel to the *yz*-plane at P_s/P_a = 200 (Nozzle 1)

3.2 Comparison between Clustered Linear Aerospike Nozzle with and without Sidewalls

As mentioned in the previous section, the jets around the clustered linear aerospike nozzle demonstrate the lateral expansion especially behind the base. To clarify the effect of sidewalls suppressing the undesired lateral expansion, the flow fields around the nozzle 2 with sidewalls are compared with those around the nozzle 1 without the sidewalls. Figures 7(a) and (b) show visualized images for the nozzle 2 on the *xz*-plane by NO-LIF, which are taken at P_s/P_a=200 and 75, respectively. Comparing Fig. 7 with Fig. 2, the expansion toward the *z*-direction for the nozzle 2 is wider than that for the nozzle 1. For P_s/P_a=200, the cross sections on the *yz*-plane visualized at x/z_e=0.711 and 1.70 are demonstrated in Figs. 8(a) and (b), respectively. Figures 8(c) and (d) show the images for P_s/P_a=75 at x/z_e=0.711 and 1.70, respectively. From these figures, in the both case of P_s/P_a=200 and 75, it is found that the sidewalls prevent the jets from expanding toward the *y*-direction at x/z_e=0.711 (the base plane). Moreover, it is also clarified that the expansion toward the *y*-direction is still prevented at x/z_e =1.70 (behind the base), although the length of the sidewalls is the same as the spike (x/z_e=0.711).

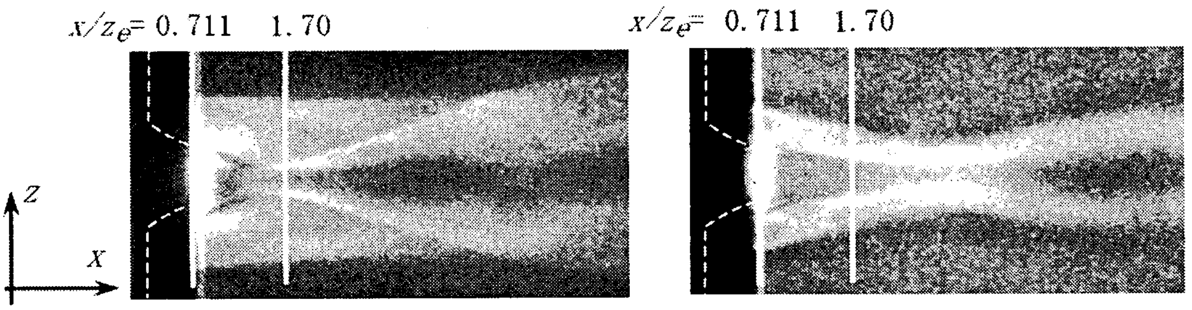
Fig. 9(a) indicates the pressure distribution on the spike of the nozzle 2 measured by PSP for P_s/P_a=200. Pressure distributions on the base of the nozzle 2 for P_s/P_a=200 and 75 are shown in Figs. 9(b) and (c), respectively. The pressure distribution on the spike of the nozzle 2 (Fig. 9(a)) is relativity higher than that of the nozzle 1 shown in Fig. 6(a), resulting in higher thrust. Since the base pressure of the nozzle 2 is higher than the ambient pressure P_a in the most regions as shown in Fig. 9(b), it can produce the additional thrust to compensate for the thrust loss by truncating the spike. For low pressure ratio (P_s/P_a=75), however, the high pressure regions on the base of the nozzle 2 cannot be observed clearly as shown in Fig. 9(c), because the jets in both sides of the spike expand weakly and do not interact with each other, regardless of the existence of the sidewalls.

From the results it is clarified that the lateral expansions of linear aerospike nozzles can be suppressed by applying sidewalls, resulting in the probable increase in the thrust. Moreover, the sidewalls also give rise to the higher thrust on the base surface for high pressure ratio, which causes the more effective compensation of the thrust loss caused by truncating the nozzle.



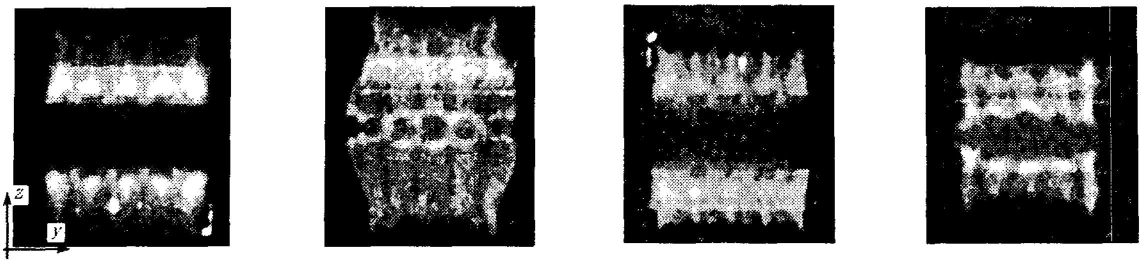
(a)Pressure Distribution on Spike Surface (b)Jet Structure along Spike Surface

Figure 6 Pressure distributions on the spike surface at P_s/P_a = 200



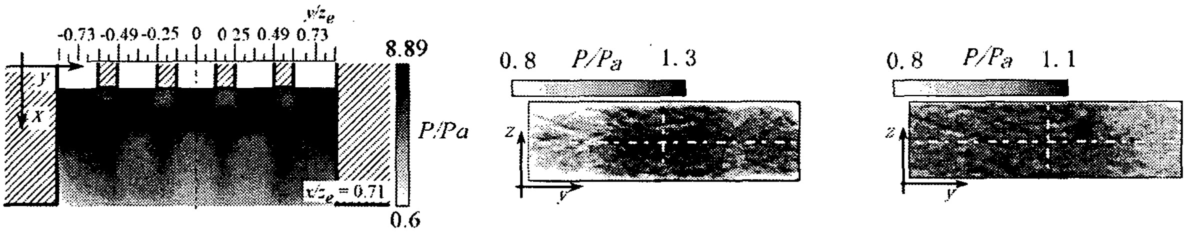
(a) P_s/P_a=200 (b) P_s/P_a=75

Figure 7 LIF images on xz-plane (Nozzle 2)



(a) P_s/P_a=200, x/z_e=0.711 (b) P_s/P_a=200, x/z_e=1.70 (c) P_s/P_a=75, x/z_e=0.711 (d) P_s/P_a=75, x/z_e=1.70

Figure 8 Visualized images parallel to the *yz*-plane (Nozzle 2)



(a) Spike Surface (P_s/P_a =200) (b) Base Surface (P_s/P_a =200) (c) Base Surface (P_s/P_a =75)

Figure 9 Pressure distributions on the spike and base surfaces (Nozzle 2)

4. Conclusion

We have applied NO-LIF and PSP to measurement of the flow field structures around the clustered linear aerospike nozzles and the pressure distribution on the spike and the base surfaces, respectively. Concluding remarks are obtained as follows.

1. The complicated jet structures around the nozzle are clarified by using NO-LIF, such as the interactions of the jets issued from the adjacent nozzle orifices and of the jets from both side of the spike. For the relatively high pressure ratio (P_s/P_a =200), the barrel shock waves originating from the both spike edges interact with each other just behind the base surface, and the pressure on the base increases due to the back-flow from the interacting region, leading to the compensation for the thrust loss. On the other hand, for the relatively lower pressure ratio (P_s/P_a=75), the jets interact weakly and the back-flow does not occur.
2. It is clarified that the undesirable lateral expansions of linear aerospike nozzles can be suppressed by applying sidewalls, resulting in the probable increase in the thrust. Moreover, for the relatively high pressure ratio (P_s/P_a = 200), the pressure on the base surface of the nozzle with sidewalls is higher than that without sidewalls, causing the higher additional thrust.

Acknowledgments

The present work was supported by a grant-in-aid for Scientific Research of Ministry of Education, Culture, Sports, Science and Technology. The authors would like to thank Mr.Yukihiro Nakanishi, a technical assistant of Nagoya University, for producing the aerospike nozzles used in this study.

References

[1] Rao,G.V.R., "Spike Nozzle Contour for Optimum Thrust", Ballistic Missile and Space Technology, Vol.2, Pergamon Press, 92-101, (1961)

[2] T. Ito, K. Fujii and A. K. Hayashi, "Computations of Axisymmetric Plug Nozzle Flow Fields", AIAA Paper 99-3211, (1999)

[3] H. Mori, et al.,"Application of PSP to Low Density Gas Flows", Jurnal of Visualization, Vol.7, No.1, 55-62, (2004)

[4] Y.Amao, et al., Polymer Journal, Vol.31, No.12, 1267-1269, (1999)

[5] C. Lee and D. Thompson, "Fortran Program for Plug Nozzle Design", NASA TM X-53019, (1964)

[6] F. Nasuti, et al., Journal of Propulsion and Power, Vol.15, No.4, 554-551, (1999)