VISUALIZATION OF UNSTEADY BEHAVIOR OF SHOCK WAVES AROUND SUPERSONIC INTAKE INSTALLED IN SHOCK TUNNEL

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Abstract

This paper describes unsteady behavior of shock waves around supersonic intake at Mach 2.5. The experiment carried out by small shock tunnel. Flow visualization was conducted with shadowgraph method and pressure-sensitive paint (PSP). A fast response anodized aluminum pressure-sensitive paint (AA-PSP) was used in the experiment. And to confirm the valid of experimental results, numerical calculation were performed by compressible Navier-Stokes equations with Weighted Average Flux (WAF) method and Adaptive Mesh Refinement (AMR). From the results of shock wave structures and pressure distribution, we confirmed shock waves behavior around the supersonic intake model at subcritical state. It considers occurring buzz.

1 Introduction

A ramjet engine is considered as an engine of a next generation supersonic plane and a space plane. A ramjet engine is an air breathing engine, which compresses air by shock waves, which occurs at supersonic flight. Therefore, a supersonic intake is an important component for engine efficiency.

To keep the stable combustion of a ramjet engine, a supersonic intake should capture enough air and should be a certain level of pressure recovery [1]. When shock wave oscillation (buzz) occurs at a supersonic intake, ideal air mass flow and ideal pressure recovery are difficult to obtain. At worst, buzz leads to structural damages of a ramjet engine [2]. Unknown portion remains in the mechanism of buzz generation. Therefore, it is important to confirm the flow structure and flow characteristics around a supersonic intake, to clarify buzz mechanism.

The purpose of this study is to confirm unsteady behavior of shock waves around the supersonic intake by shock wave structures and pressure distribution. The experiment is carried out by small shock tunnel. Also shock wave structures are obtained by shadowgraph method, and pressure distribution is obtained by a fast response anodized aluminum pressure-sensitive paint (AA-PSP). The experiment results are evaluated with the numerical results calculated with the compressible Navier-Stokes equation.

2 Experimental Setup

2.1 Shock Tunnel

Figure 1 shows a schematic diagram of the small shock tunnel used in this experiment.

The length of high pressure tube is 1000 mm, low pressure tube is 3000 mm, test section is 310 mm and the dump tank is 800 mm. The bore of high pressure tube is 50 mm, the cross section of low pressure tube is 30 mm × 40 mm and the bore of dump tank is 195 mm. Also, reduce enlarging back pressure, an extra dump tank (1000 mm height) is added. High pressure tube and low pressure tube are separated by polyethylene terephthalate diaphragm (TORAY INDUSTRIS, INC., Lumirror). A needle is set

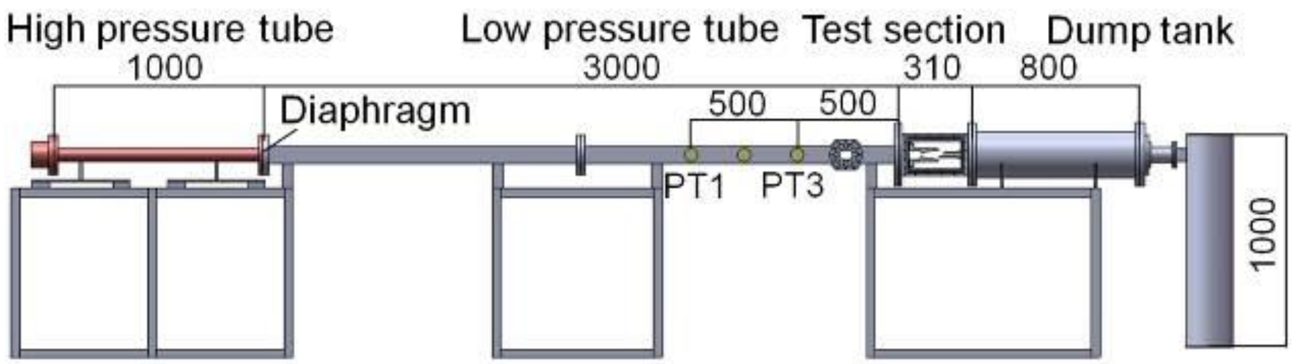


Fig. 1. Shock Tunnel. (unit: mm)

at high pressure tube, which is puncturing a diaphragm. A nitrogen cylinder is connected to the high pressure tube and a vacuum pump is connected to the dump tank. Two pressure ports (PT1 and PT3) are set at the low pressure tube. Fast response piezoelectric pressure transducers (PCB PIEZOTRONNICS INC., 113A20 series) are installed in each pressure ports. Output voltage resulting from pressure transducers are recorded by a digital oscilloscope (Yokogawa Electric Corporation, DL-750). From each pressure results, we measure shock wave arrival time and calculate shock Mach number.

Figure 2 shows a schematic diagram of the test section used in this experiment. The test section has two dimensional Laval nozzle (design Mach number 2.5).

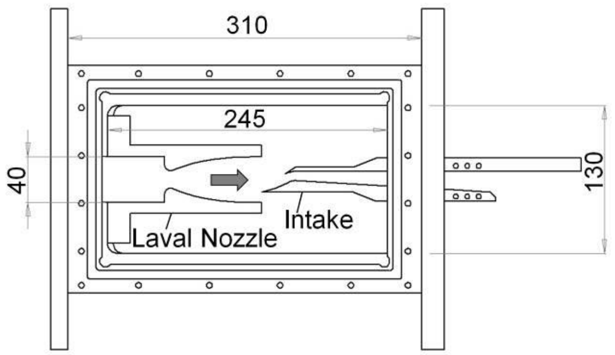


Fig. 2. Test Section. (unit: mm)

2.2 Supersonic Intake Model

Figure 3 shows the external supersonic intake model (design Mach number 2.4) used this experiment. The intake model is consisted of a double-wedge ramp, cowl, subsonic diffuser, and a plug. The plug is set at rear of the intake model and is able to adjust a position of the intake model. The plug, which is able to change back pressure by moving back and forward.

2.3 Measurement Technique

2.3.1 Shadowgraph Method

Figure 4 is schematic diagram of shadowgraph system. Flow visualization is conducted by through digital delay circuit (SUGAWARA Laboratories Inc., FG-310), that trigger signal is from piezoelectric pressure transducers PT1. Flow visualization images are acquired by a digital high speed camera (Vision Research Inc., Phantom V7.1) and a digital still camera (Nikon Corporation, D200; Maximum effective pixels 3872 × 2592 pixels). Metal halide fiber optic illuminator (Dolan-Jenner Industries, MH100) is used for high speed camera light source. Xenon

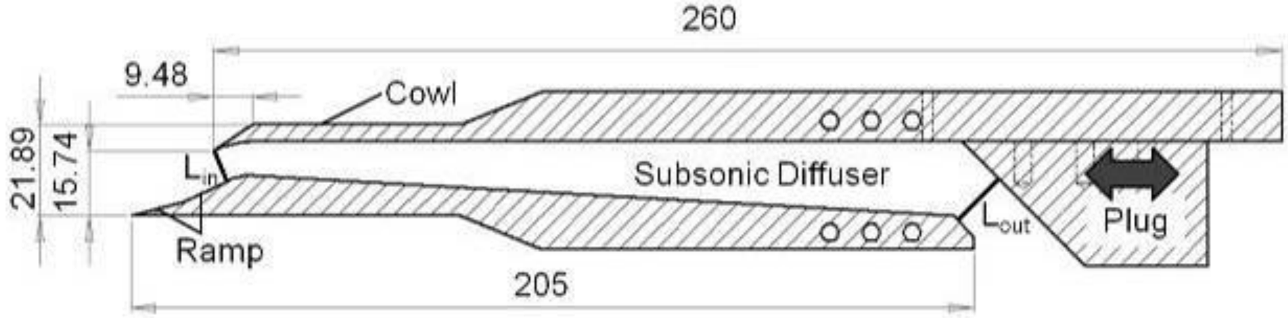


Fig. 3. Supersonic Intake model. (unit: mm)

flash lamp (SUGAWARA Laboratories Inc., NP1-A; Flash duration 180μs) is used for digital still camera light source.

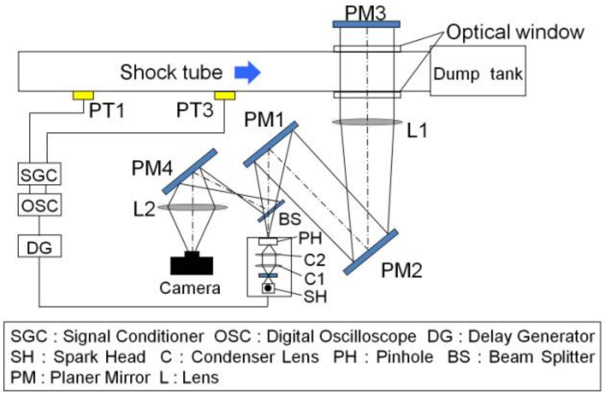


Fig. 4. Schematic diagram of shadowgraph system.

2.3.2 Pressure-Sensitive Paint

The pressure-sensitive paint (PSP) is the molecular sensor, which used oxygen quenching from the organic molecule luminescence. General polymer PSP is insufficient time response for high speed unsteady phenomenon measurement (e.g., measuring buzz). Therefore, a fast response anodized aluminum pressure-sensitive paint (AA-PSP) is used in the experiment [3] [4] [5]. The AA-PSP gives short response, which is suitable for high-speed unstable phenomenon measurement. The AA-PSP is produced anodized coating on aluminum material, and adsorbs the dye on its coating. The AA-PSP has more than 10 kHz time response. In this experiment, dye is Bathophenanthroline Ruthenium ([Ru(ph2-phen)3]Cl2). Figure 5 is Schematic diagram of AA-PSP structure.
Figure 6 shows schematic diagram of PSP system. The Ar^+ laser (Coherent Inc., Innova 70; Wavelength 488.0 nm) is as the illumination light source. Pressure-sensitive images is obtained by a digital high speed camera (Vision Research Inc., Phantom V7.1) and the luminescence filter (HOYA CORPORATION, O-58), which is transmitted only 580 nm or more. The aluminum board (A-5052) which coated the AA-PSP is installed in test section of the supersonic intake model side wall.

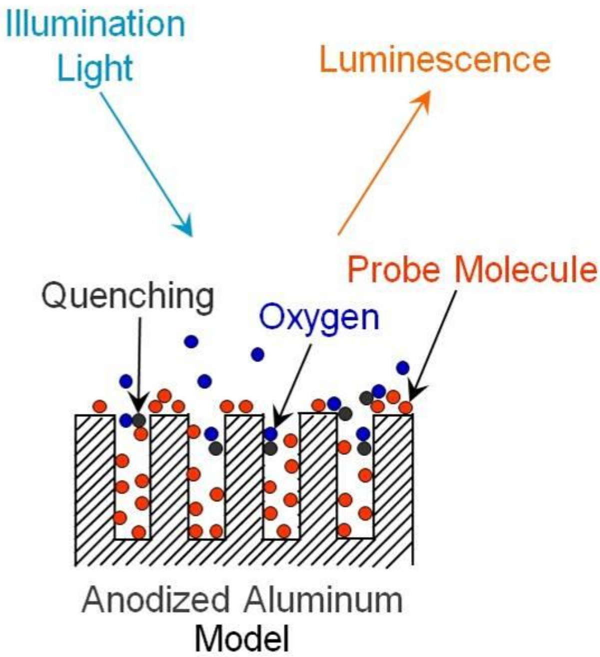


Fig. 5. Schematic diagram of AA-PSP structure.

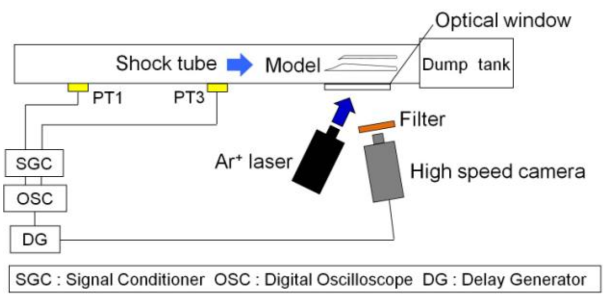


Fig. 6. Schematic diagram of PSP system.

3 Experimental Condition

Table 1 shows experiment condition in this research. Experiments are carried out on three pattern back pressures. Back pressure is adjusted by the plug is moving back and forward, and changing the ratio of the intake exit L_{out} to the intake entrance L_{in}. But at pattern (a), the plug is not installed.
Table 2 shows shock tunnel condition in this experiment. Test flow is about Mach 2.5.

Table. 1. Experimental conditions.

	L_{in} [mm]	L_{out} [mm]	L_{out} / L_{in}
(a)	8.09	—	—
(b)	8.09	8.09	1.00
(c)	8.09	4.05	0.501

Table. 2. Shock tunnel conditions.

	(a) (b)	(c)
Driver Gas	N_2	N_2
Driven Gas	Air	Air
P_1	10 [kPa]	10 [kPa]
P_4	2000 [kPa]	500 [kPa]
P_4/P_1	200	50
Ms	2.45	2.07
Me	2.54	2.50

P_1: Low pressure room
P_4: High pressure room

4 Numerical Calculation

Numerical calculations are performed by compressible Navier-Stokes equations with Weighted Average Flux (WAF) and Adaptive Mesh Refinement (AMR) [6] [7].
Boundary condition is isothermal wall, Prandtl number is Pr = 0.733, and Reynolds number is Re = 7.71×10^4. Reynolds number's diameter is decided by low pressure tube's cross-section height. Another numerical calculation condition is the same as experimental condition.
Figure 7 is schematic diagram of computational domain in this calculation. Its left edge is in flow boundary condition and right edge is out flow boundary condition. Also, a shock wave was generated from the position shown in Fig. 7.

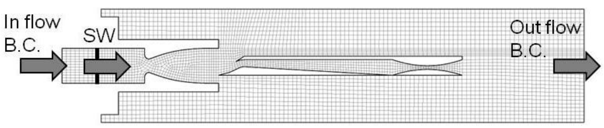


Fig. 7. Computational domain.

5 Results

5.1 Shadowgraph Method

5.1.1 Plug Position Variation

Figure 8 is flow visualization images around supersonic intake by shadowgraph method. These images are acquired by a digital high speed camera.
From pattern (a) result, two oblique shock waves can be confirmed at two ramps. These are concentrated on around the cowl lip. Also, two oblique shock waves can be confirmed in the subsonic diffuser. It can be determined; flow speed in the diffuser is supersonic. Therefore, the supersonic intake is supercritical state.
From pattern (b) result, two oblique shock waves can be confirmed at two ramps. These are concentrated at the cowl lip. Also, a normal shock wave can be confirmed on the cowl lip, and shock waves cannot be confirmed at the diffuser. This is because the plug is adjusted and air is compressed properly. Therefore, it can be determined flow speed in the diffuser is subsonic, and the supersonic intake is critical state.
From pattern (c) result, two oblique shock waves can be confirmed at two ramps. Also, a normal shock wave can be confirmed on the left of the cowl lip. This is because the intake back pressure is increased by the plug adjustment, and shock waves are pushed. And, two oblique shock waves can be confirmed in the diffuser. This is because behind the normal shock wave flow is accelerated at until flow goes into the diffuser. Therefore, it can be determined; the supersonic intake is subcritical state.

5.1.2 Time Variation

Figure 9 is flow visualization images around supersonic intake by shadowgraph method. These images are taken at time change in subcritical state. The acquiring is conducted by a digital still camera. The state of Fig. 8 (c) is set to 0 μs, and a shadowgraph image is taken in 500 μs and 1000 μs.
From results of Fig. 9, a normal shock wave that behind oblique shock waves can be confirmed moving to left at ramps. Also, at 500 μs and 1000 μs, we cannot confirm oblique shock waves at the diffuser. This is because air is leaking from the cowl lip, and air does not flow in the diffuser. Therefore, from results of Fig. 9, moving shock waves to left is considered occurring shock wave oscillations (buzz).

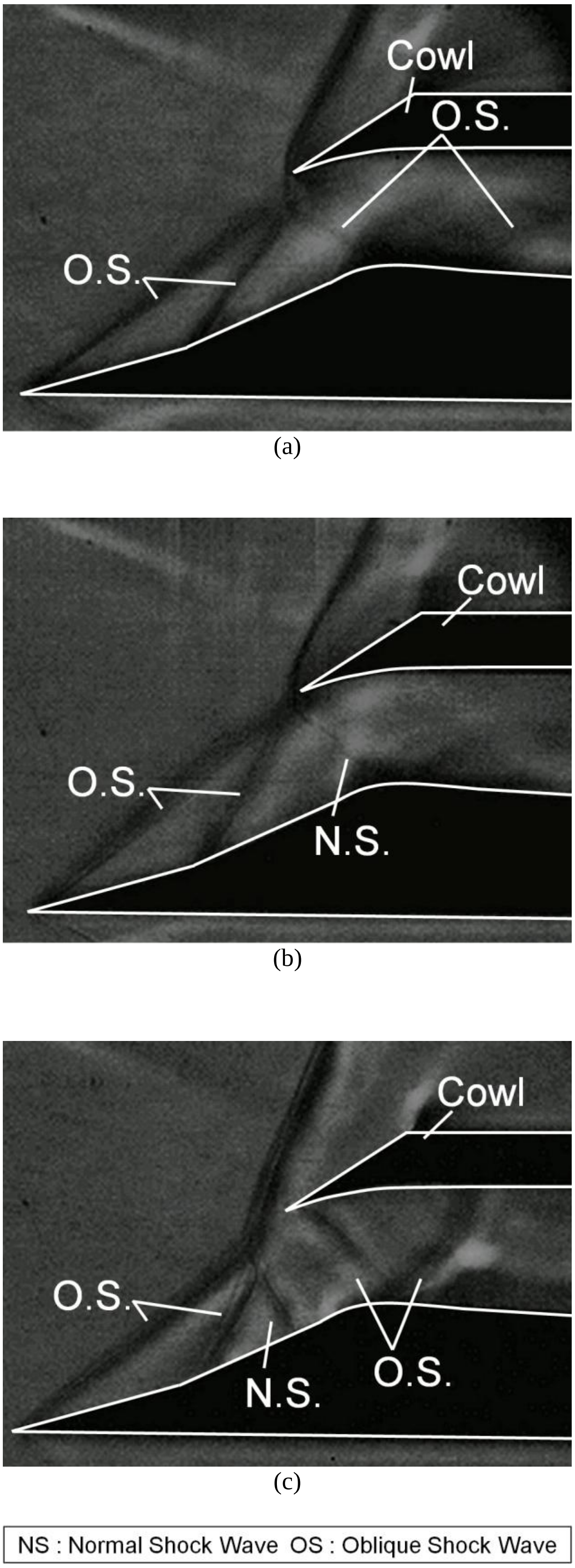


Fig. 8. Visualization Image Results
(plug position variation).

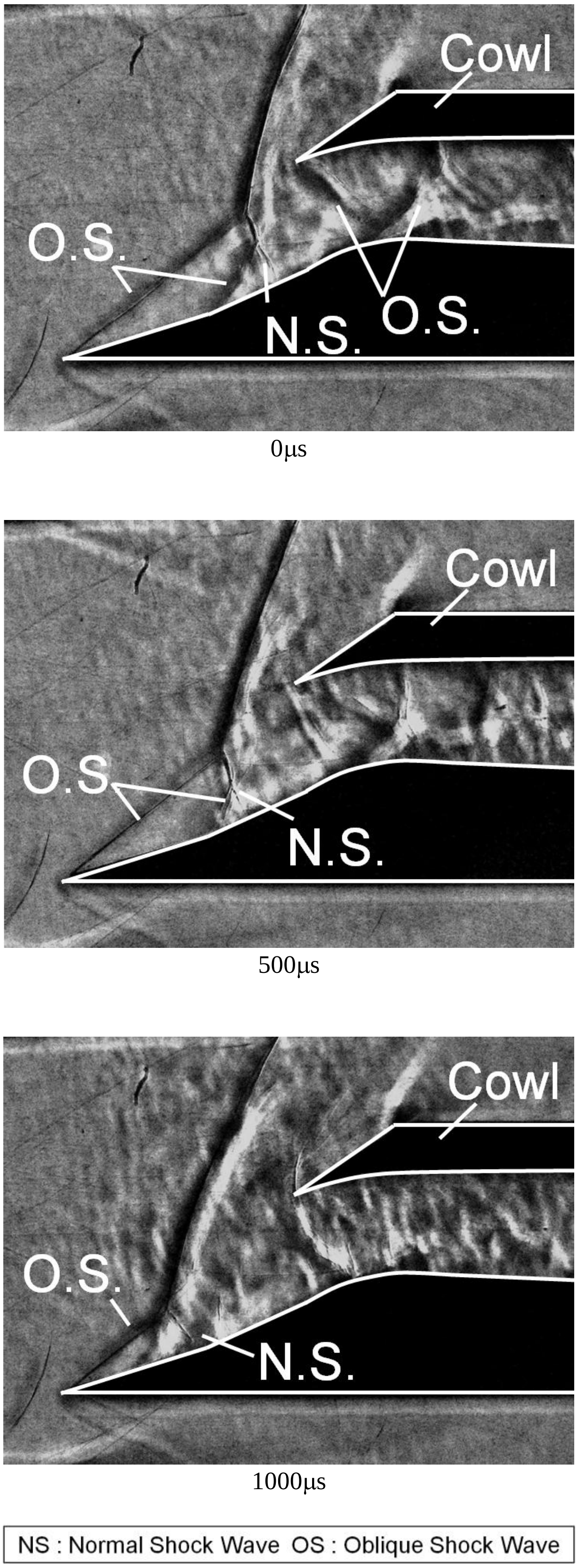
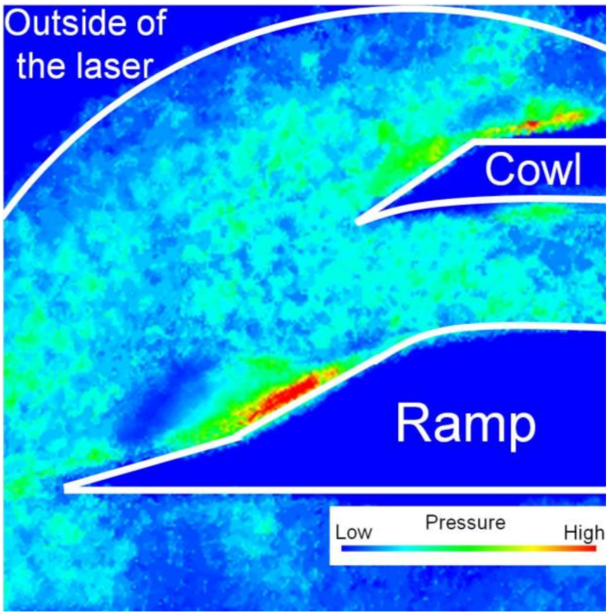


Fig. 9. Visualization Image Results
(time variation).

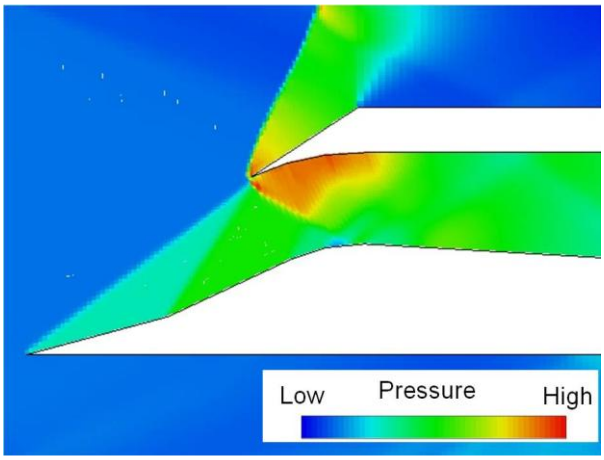
5.2 Pressure-Sensitive Paint

Figure 10 are PSP image (top) and numerical result (bottom) at supercritical state. These results are shown pressure distribution.
From the PSP result, we can be confirmed high pressure area at around the cowl lip. From the numerical result, we can be confirmed same result. But, we cannot confirmed oblique shock waves at ramps, which confirmed by the shadowgraph method and the numerical calculation.

Figure 11 are PSP image (top) and numerical result (bottom) at subcritical state.
From the PSP result, we can be confirmed high pressure area at the subsonic diffuser. From the numerical result, we can be confirmed same result. But, we cannot confirmed detached shock wave at ramps, which confirmed by the shadowgraph method and the numerical calculation.
This is because, camera's exposure time is longer and PSP results are smudged. Therefore, we should obtain more luminance by AA-PSP luminescence.

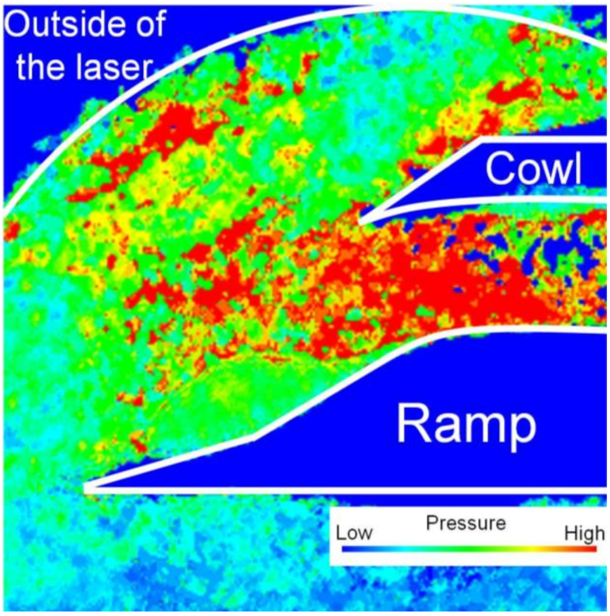


PSP

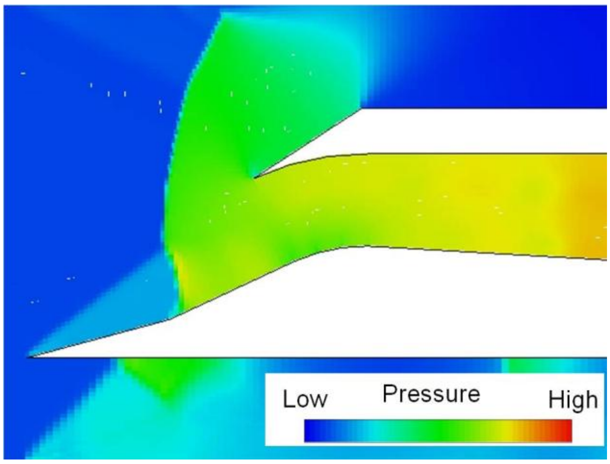


Numerical result (Pressure distribution)

Fig. 10. PSP Image Result and Numerical result (Supercritical state).



PSP



Numerical result (Pressure distribution)

Fig. 11. PSP Image Result and Numerical result (Subcritical state).

6 Conclusions

In this research, we visualized shock wave structures around the external supersonic intake model. Flow visualization was conducted by shadowgraph method and PSP. Also, PSP experiment results were evaluated with the numerical results. The results indicate below.

- We confirmed supercritical state, critical state and subcritical state by experiment.
- Shock wave behaviors can be confirmed at subcritical state. It considers occurring buzz.
- We obtained intake side wall surface pressure by AA-PSP. But some phenomenon, we could not be confirmed.
- From the AA-PSP result, we should obtain more luminance by AA-PSP luminescence.

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