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Study on Boundary Layer Control of Jet Issued from Divergent Nozzle

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This report has aimed to control the boundary layer of jet flow. Especially, the research on the control of the separation point of the jet flow was done about the jet flow issued from the divergent nozzle in the region from subsonic jet flow to supersonic jet flow. The boundary layer of the jet flow was controlled by the control flow. And the position of the separation point was controlled by this method. Moreover, the frequency analysis of total pressures was done by the experiment.

Furthermore, the numerical analysis was done to examine the separation point of the flow issued from the divergent nozzle. Consequently, an unsteady characteristic of the flow was clarified. And, it was clarified that the boundary layer control influenced the total pressure. As a result of the numerical analysis, it was found that the control flow influenced the separation of the flow, and the position of the separation point was different according to the stagnation pressure.

Keywords : Compressible flow, Separation, Boundary layer, Numerical analysis, Divergent nozzle

1. Introduction

In this study, separation control of a jet flow was researched about issuing from a divergent nozzle and the jet flow was continuously issuing to the atmosphere from supersonic speed to subsonic speed. Especially, the separation control of the divergent part was done by the inhalation and the exhalation of the control flow from the holes installed in the divergent part. By above way, it is clarified that the separation control influences the boundary layer. Moreover, it is clear that the boundary layer control influences self-excited vibration. In addition, to analysis the frequency of the pressure vibration coming from the self-excited vibration, it is clarified about the unsteady characteristic of the jet flow.

Furthermore, by the numerical analysis, the influence to the separation of the divergent part was examined about the presence of the control flow, and a confirmation was done about the control flow influencing the main flow.

As the result, it is clarified that the position of the separation is different form the presence of the control flow and the difference of the stagnation pressure, and the separation of the flow influences the boundary layer.

2. Experiment method and Analysis method

Shape of nozzles used in the experiment is shown in Figure 1. Two kinds of nozzles were used in this experiment. Model 1 s internal diameter was 9.2mm and divergent angle was 20 degrees, and model 2 is the same size and was installed holes in the divergent part for controlling flow. In the model 2, internal diameter 1.2mm of each 8 holes for controlling flow were installed from the point of the nozzle 8mm and 15mm. In this time, the experiment was done when

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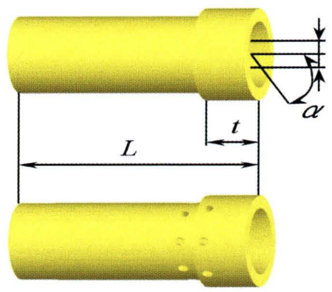
holes closed from the point of the nozzle 15mm and holes freed from the point of the nozzle 8mm.



Symbol	L (mm)	d(mm)	t (mm)	(
TP9SA20L	46	9.2	10	20

Fig. 1 Configuration of Divergent nozzle

In the experiment, it was made with pressure ratio *Po/Pa* = from 0.05 to 5.0. The pressure ratio *Po/Pa* was that stagnation pressure Po was divided by atmospheric pressure Pa. The jet flow was continuously issuing from the nozzles to atmosphere. On measuring total pressure vibration, a micro semiconductor pressure transducer was installed on the point of the total pressure probe. And total pressure vibration was taken by FFT analyzer.

In the numerical analysis, it was made with pressure ratio *Po/Pa* = 3.0 and 6.0 about velocity vectors, velocity contours, density contours and pressure contours. It was analyzed with momentum equation, equation of energy and Finite Volume Method (FVM).

3. Unsteady characteristic of Jet flow

3.1 Unsteady characteristic of Subsonic jet flow

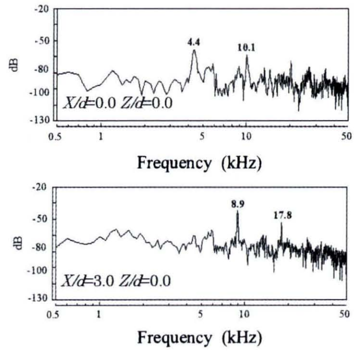
The frequency analysis of the total pressure as *Po/Pa* = 0.33 for model 1 and model 2 are shown in Figure 2(a) and Figure 2(b).

In model 1 shown in Figure 2(a), the discrete frequency distribution having peak was seen at the central axis of the jet flow *X/d* = from 0.0 to 3.0. Because the pressure was low, it was thought that the separation of the flow happened near the divergent part of the nozzle and the unstable separation point vibrated intensely. In this time, the frequency analysis of the noise did not appear here, but it was similar with the frequency analysis of the total pressure. And the intense noise above 124dB has been generated.

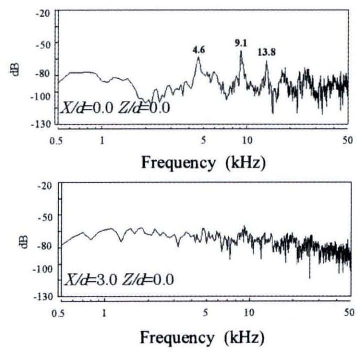
At *X/d* = 0.0, the first peak was assumed to be fundamental blade frequency and was generated at 4.4 kHz. The second peak was generated at the position of multiple of fundamental blade frequency. At *X/d* = 3.0, the position of the peaks moved to the radio frequency side. It is guessed that the fluid was vibrated by separation and diffusion. The diffusion was rolled up by the stream at the downstream side, and the position was behind the exit.

In model 2 shown in Figure 2(b), at *X/d* = 0.0, a peak was assumed to be fundamental blade frequency and was generated at 4.6 kHz. Three peaks were seen at the position of multiple of fundamental blade frequency.

At *X/d* = 3.0, the peak could not be seen, but it is thought that the influence was from the inhalation of the control flow.



(a) Model 1



(b) Model 2

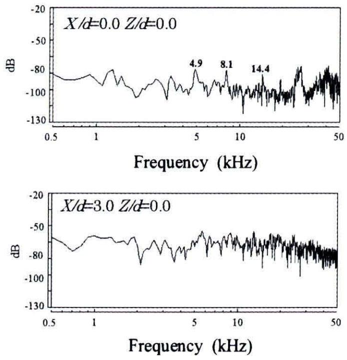
Fig.2 Frequency analysis of total pressures as *Po/Pa* = 0.33

3.2 Unsteady characteristic of Supersonic jet flow

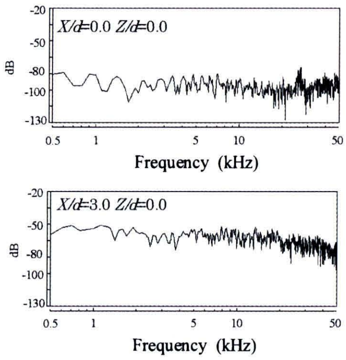
The frequency analysis of the total pressure as *Po/Pa* = 3.31 for model 1 and model 2 are shown in Figure 2(a) and Figure 2(b). It is thought that the jet flow became a supersonic jet flow in the nozzle exit.

In model 1 shown in Figure 3(a), at *X/d* = 0.0, small peaks appeared, but the peaks did not generate after *X/d* = 3.0.

In model 2 shown in Figure 3(b), the peak has not been generated at all of the measuring point according to the influence of the inhalation of the control flow.



(a) Model 1



(b) Model 2

Fig.3 Frequency analysis of total pressures as *Po/Pa* = 3.31

4. CFD results and Consideration

4.1 CFD results of Subsonic jet flow

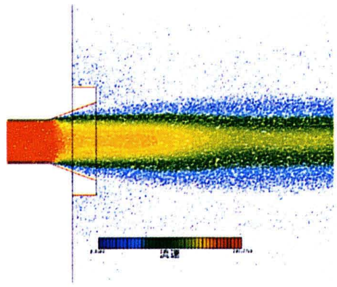
The velocity vectors as *Po/Pa* = 0.33 for model 1 and model 2 are shown in Figure 4(a) and Figure 4(b). The velocity contours are shown in Figure 5.

As showing in Figure 4, two models generated separation near by the divergent part of the inside of the nozzle.

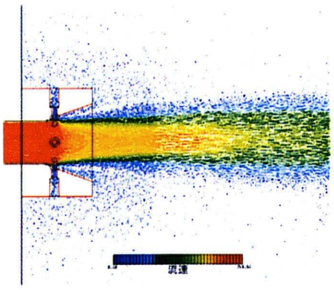
In model 1 shown in Figure 4(a), the separation was generated immediately after the flow passed the divergent part. In model 2 shown in Figure 4(b), according to the influence of the inhalation of the control flow, the separation was generated at the divergent part and the separation point moved to the upstream side a little.

As the velocity contours shown in Figure 5(a), in case of no control flow, there is a tendency that the jet flow expanded after the separation. When there was the inhalation of the control flow shown in Figure 5(b), the expansion of the jet flow was controlled after the separation, and the region where speed is fast became narrow until to the downstream with the same velocity. Therefore, there is a tendency that the velocity attenuated difficultly by the inhalation of the control flow.

Moreover, as showing in Figure 2(a), the position of the peaks moved to the radio frequency side at *X/d* = 3.0. As showing in Figure 4(a) and Figure 5(a), it is thought that the jet flow vibrated in the downstream.

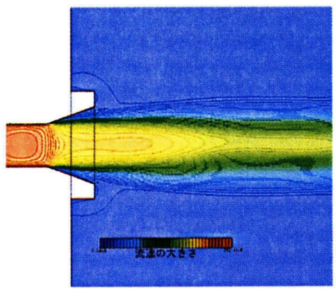


(a) Model 1

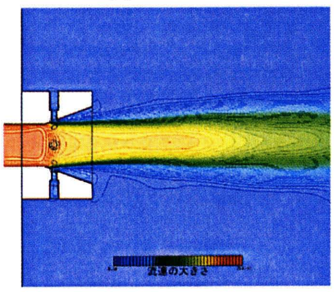


(b) Model 2

Fig.4 Velocity vector for *Po/Pa*=0.33



(a) Model 1



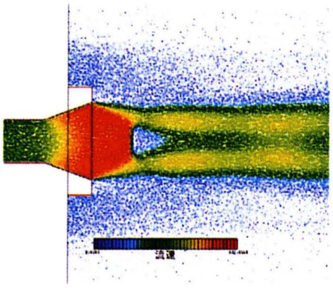
(b) Model 2

Fig.5 Velocity contours for *Po/Pa*=0.33

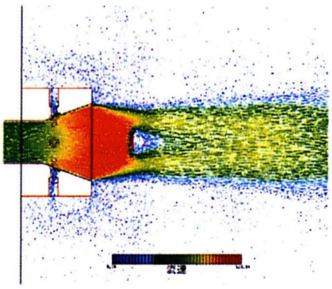
4.2 CFD results of Supersonic jet flow

The velocity vectors, the velocity contours, the density contours and the pressure contours as *Po/Pa* = 6.0 for model 1, model 2 are shown in from Figure 6(a), Figure 6(b) to Figure 9(a), Figure 9(b).

As the velocity vectors shown in Figure 6, the jet flow was the same speed in the straight part of the nozzle, but it became a supersonic jet flow after accelerating rapidly in the divergent part. The Mach disk was generated after the oblique shock wave which was generated in the end of the nozzle. Then slipping side was seen in the rear and it became a subsonic jet flow. The slipping side of model 1 was generated until to the downstream. The difference was not seen in the shape of the jet flow with model 1 and model 2.



(a) Model 1

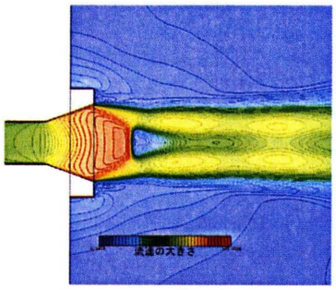


(b) Model 2

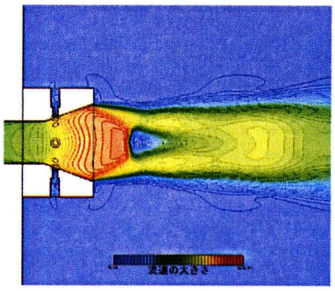
Fig.6 Velocity vectors for *Po/Pa*=6.0

As the velocity contours shown in Figure 7, it was known that the slipping side was generated until to the downstream in the model 1. Moreover, the interference of the shock wave was repeatedly generated in the slipping side and the boundary layer, and it was seen that the increase and decrease of the velocity. Above the phenomenon, the model 1 was remarkable.

As the density contours shown in Figure 8, it became high density in the straight of the nozzle and it was in compressional state. The remarkable shock wave with a circular arc was generated in the end of the straight part of the nozzle, in a word, in the starting of the divergent part of the nozzle. The density decreased in the divergent part, and the Mach disk was generated by compression because the pressure of the surrounding atmosphere was high in the end of the nozzle. There was a region of high pressure that the reflected shock waves were seen in top and bottom both sides behind the Mach disk.

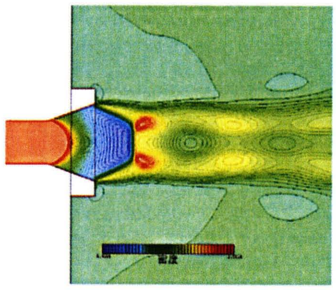


(a) Model 1

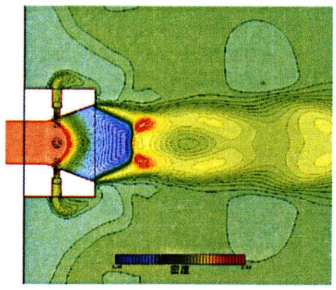


(b) Model 2

Fig.7 Velocity contours for *Po/Pa*=6.0



(a) Model 1

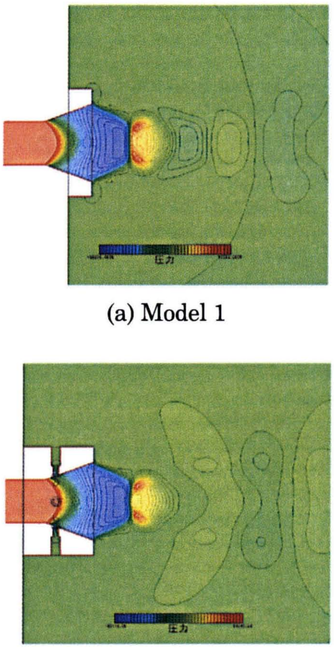


(b) Model 2

Fig.8 Density contours for *Po/Pa*=6.0

As mentioned above, it is guessed that the shock waves were reflected by the interference with the slipping side and the boundary layer of the jet flow.

As the pressure contours shown in Figure 9, the same thing was guessed as mentioned above.



(a) Model 1

(b) Model 2

Fig.9 Pressure contours for *Po/Pa*=6.0

4.3 Influence on jet flow by control flow

The comparison of the pressure near by the divergent part of the nozzle as *Po/Pa* = 6.0 with model 1 and model 2 is shown in Figure 10.

As measuring position shown in Figure 10, the point 1, point 2 and point 3 were located 8 mm, 6 mm and 4 mm from the point of the nozzle and offseted 0.5 mm from the inside of the divergent part of the nozzle.

There was not a big difference in pressure with model 1 and model 2, and the pressure decreased almost straightly forward the exit of the nozzle in order of point 1, point 2 and point 3.

In the subsonic jet flow, the separation point moved by the control flow gives influence to the main flow. In the supersonic jet flow, the influence to the main flow by the control flow is small because the separation point is generated in the exit of the nozzle.

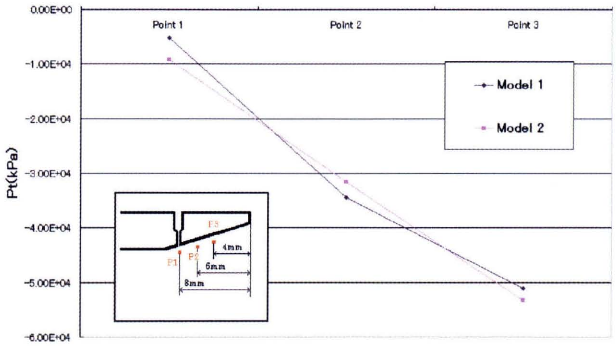


Fig.10 Pressure distribution

5. Conclusion

(1) It influents self-excited vibration of control flow that a supersonic jet is bigger than a subsonic jet.

(2) In the subsonic jet, its swelling is suppressed by control flow, and it becomes a jet with a little vibration and a little diffusion to the downstream region.

(3) In the supersonic jet, it forms a Mach disk, and it forms a slipping side and becomes a jet with a little diffusion to the downstream region when there is no control flows.

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