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Study of Supersonic Flow Issuing from Annular Nozzle

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In this paper, it aimed to clarify that exit shape of an annular nozzle which is applied in various fields in industry affects a flow field of a supersonic jet flow. The annular nozzles are three kinds of exit shape on the exit point. A small hole is installed in the center part of the annular nozzles and it is clarified that pressure on the exit part of the annular nozzles affects the flow which comes from the small hole. In this report, the flow filed of the annular supersonic flow is clarified by experiment and numerical analysis. In the experiment, it is clarified that the pressure vibrations of the supersonic jet flow issuing from an annular nozzle influences a flow field. In the numerical analysis, they are clarified about the flow situation of the vicinity of the nozzle exit, the position of the separation point of the flow, and the vortex formed on the low-pressure region. Moreover, they are clarified about the change of flows, the movement of separation points, the change of vortex areas according to pressure decrease, and the influence from pressure vibrations to a flow according to changing exit shape of nozzles and stagnation pressure.

Keywords : Shock wave, Numerical analysis, Exhaust silencer, Compressible flow, Separation, Supersonic flow, Unsteady flow, Annular nozzle

1. Introduction

A supersonic jet flow issuing from an annular nozzle is used in various fields of industry 1), 2), but the structure and the behavior have not been clarified clearly. In the already reported paper 3), the unsteady characteristic of the supersonic jet flow issuing from the annular nozzles and the influence from the geometrical shape of the annular nozzles were clarified by authors.

In this study, it aimed to clarify a flow field of a supersonic jet from changing exit shape and protrusion amount of annular nozzles with experiment and numerical analysis. In the experiment, the flow field and the pressure vibrations were examined in the vicinity of exit of a annular nozzle. Moreover, in the numerical analysis, they were analyzed about the flow situation in the vicinity of annular nozzle's exit, the separation position of flows, the clarification of vortex areas formed in the low-pressure, and the condition that cannot be achieved in the experiment.

As a result, they were clarified that the geometrical shape of the annular nozzles and the difference of the stagnation pressure influence velocity vectors, separation position of flows, formation of vortexes, and pressure vibrations.

2. Experiment method and Analysis method

The air, via stagnation tanks, was continuously issued from an annular nozzle to atmosphere. The total pressure vibrations were measured by a micro semiconductor mounted in the point of a total pressure probe.

Nozzle A, which is used in the experiment, has a curve on the corner of nozzle's top. In the experiment, the center axis of nozzles was made as X axis and the vertical cross section was made as Z axis. The total pressure vibrations and the time average total

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pressure distribution were measured in the jetting direction from $X/d=0$ to 7.0 and in the vertical direction from $Z/d=0$ to 0.5. It experimented at pressure ratio Po/Pa, to divide stagnation pressure Po by atmospheric pressure Pa, = 6.0.

In the numerical analysis, primitive equations of flow were established by momentum equation and equation of energy. For dispersing the primitive equation, the simultaneous equations that can be run on computers was set up by Finite Volume Method (FVM).

The nozzles used in the numerical analysis were the above-mentioned nozzle A, nozzle B whose amount of protrusion is increased than nozzle 1 in the already reported paper [3], and nozzle C whose amount of protrusion is increased than nozzle 2 in the already reported paper [3].

In the numerical analysis, it was analyzed at pressure ratio $Po/Pa=3.0$, 6.0, 10.0, and 20.0.

3. Experiment results and Consideration

In the Fig. 1, total pressure vibrations of nozzle A is shown as pressure ratio $Po/Pa=6.0$ and from $X/d=0.1$ to 1.2 in the vicinity of exit of the nozzle. In the position which is $Z/d=0.0$, 0.2 of $X/d=0.1$ and $Z/d=0.0$ of $X/d=0.3$ in the vicinity of exit of the nozzle, remarkable total vibrations could not be seen. It was thought that the separation point of the flow was generated early and the vortex area became larger because the plane part of the nozzle increased. In the vicinity which is $Z/d=0.3$, 0.4 of $X/d=0.1$ and $Z/d=0.2$, 0.3, 0.4 of $X/d=0.3$ and $Z/d=0.2$ of $X/d=0.5$, the total pressure vibrations greatly appeared according to the flow of the boundary layer in the inside of the annular jet. In the vicinity which is $Z/d=0.0$, 0.2 of $X/d=0.8$ and $Z/d=0.0$, 0.2 of $X/d=1.1$, the total pressure vibrations greatly appeared in the vicinity of jet's center axis for the annular jet joining.

In the Fig. 2, total pressure vibrations of nozzle A is shown as pressure ratio $Po/Pa=6.0$ and from $X/d=1.5$ to 7.0 in the vicinity of exit of the nozzle. In the vicinity of $X/d=0.3$, the total pressure vibrations greatly appeared excluding $X/d=0.5$ which was out of the boundary layer of the jet flow. It is understood that it considerably vibrated in the rearward of the downstream than a nozzle having roundness on the point. It is considered that the joining position of the annular jet flow shifted backward.

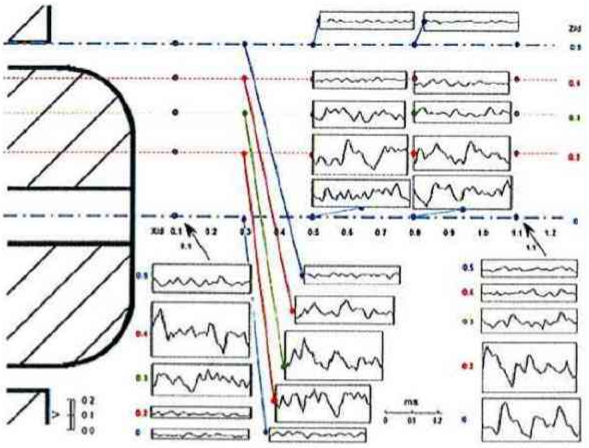


Fig.1 Total pressure vibrations for nozzle A ($Po/Pa=6.0$, $X/d=0.1$~1.2)

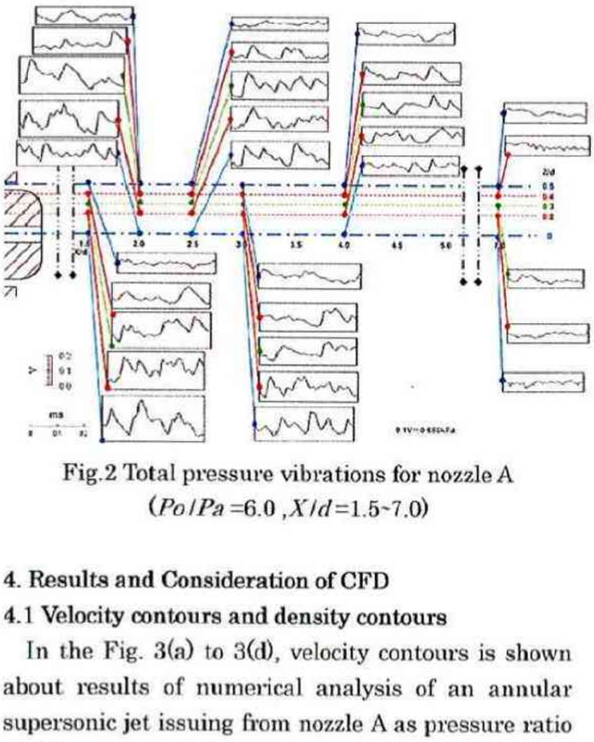


Fig.2 Total pressure vibrations for nozzle A ($Po/Pa=6.0$, $X/d=1.5$~7.0)

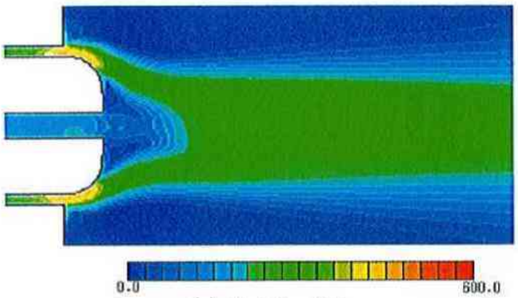
4. Results and Consideration of CFD

4.1 Velocity contours and density contours

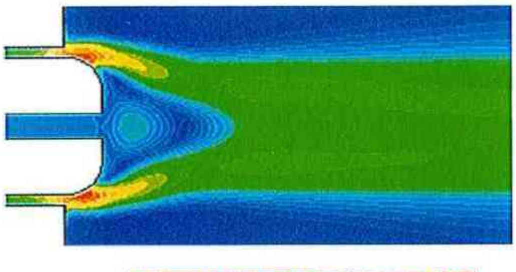
In the Fig. 3(a) to 3(d), velocity contours is shown about results of numerical analysis of an annular supersonic jet issuing from nozzle A as pressure ratio $Po/Pa=3.0$, 6.0, 10.0, 20.0.

In the pressure ratio $Po/Pa=3.0$ shown in the Fig. 3(a), the jet flow was accelerated in the exit part of an annular nozzle and became an attached jet that flowed along the curved surface of the nozzle corner. The flow separated at the position of the nozzle shape becoming plate and formed a pair of vortexes. In the region of the downstream, the flow was invited according to the vortex region, and became a single jet.

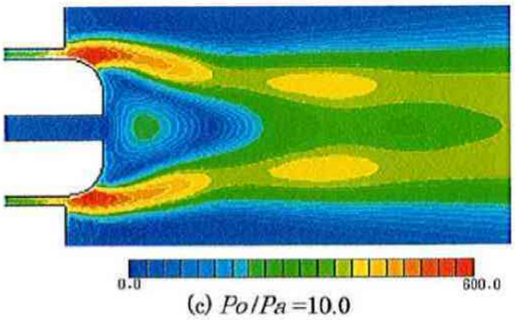
In the pressure ratio $Po/Pa=6.0$ shown in the Fig. 3(b), the swelling of the flow was increased a little than pressure ratio $Po/Pa=3.0$ by rapid expansion in the exit of the nozzle and a supersonic jet could be seen in the exit of the nozzle. The separation point moved to the upstream side of the nozzle corner. Flow velocity in the exit and the downstream quickened considerably and the width of the jet had extended in the downstream, too. The vortex area formed in the nozzle point also showed a tendency to become larger.



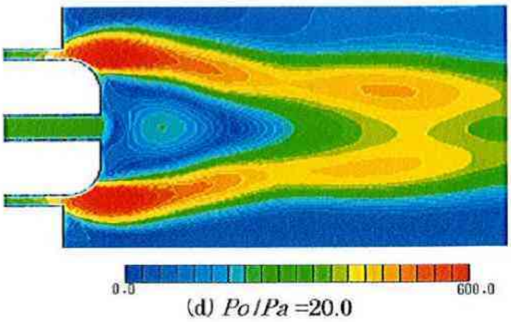
(a) $Po/Pa=3.0$



(b) $Po/Pa=6.0$



(c) $Po/Pa=10.0$



(d) $Po/Pa=20.0$

Fig.3 Velocity contours for nozzle A

In the pressure ratio $Po/Pa=10.0$ shown in the Fig. 3(c), the swelling of the flow was increased further in the exit part of the nozzle than $Po/Pa=3.0$, 6.0 and the velocity of the annular jet became quickly. The annular jet showed a tendency to join in the downstream region while repeating acceleration and deceleration. Moreover, the jet flow issuing from the nozzle flowed out in an outside direction. By the influence, the separation point moved to more upstream side of the nozzle corner. Because the annular jet took air, which was in the vortex area, away to the downstream, the vortex area showed a tendency to grow up further. The velocity of the circulation flow in the vortex area became faster.

In the pressure ratio $Po/Pa=20.0$ shown in the Fig. 3(d), the flow expanded rapidly considerably immediately after the exit of the annular nozzle and became a supersonic jet in a wide area. To receive the influence of a geometrical shape of the annular nozzle, the flow became a flow that extended in an outside direction. The annular jet, which was the same as $Po/Pa=10.0$, showed a tendency to join while repeating acceleration and deceleration. The separation point on the nozzle corner moved to the downstream side. The vortex area, liking a close space, caused according to the annular jet. It became a low pressure further by taking air away, and grew up more. Moreover, the velocity of the circulation flow which was formed in the vortex area also showed a tendency to grow considerably.

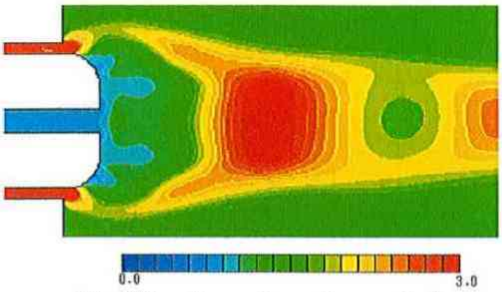


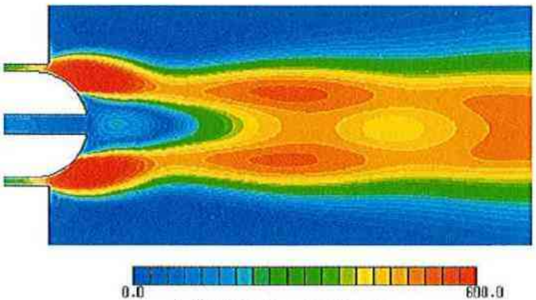
Fig.4 Density contours for nozzle A
($Po/Pa=20.0$)

In the Fig. 4, density contours is shown about a result of numerical analysis of an annular supersonic jet issuing from nozzle A as pressure ratio $Po/Pa=20.0$ in the vicinity of exit of the nozzle. The density reduced in the exit part of the nozzle and it rose in the place where the annular jet joined and collided. In the downstream region, it became a flow whose density was repeated increasing and decreasing. Moreover, the flow of the annular jet repeated expanding and compressing from the point of the nozzle, and it was guessed that it became a pseudo-shock wave in the downstream region.

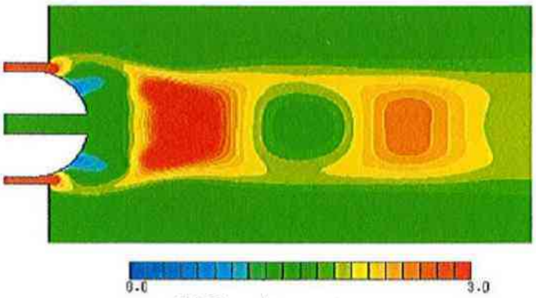
In the Fig. 5(a), 5(d), velocity contours and density contours are shown about results of numerical analysis of an annular supersonic jet issuing from nozzle B as pressure ratio Po/Pa =20.0 in the vicinity of exit of the nozzle.

Showing velocity contours in the Fig. 5(a), the separation point moved to downstream side of the nozzle's curved surface compared with nozzle A. For the reason, the rapid expansion at the nozzle exit was more remarkable than nozzle A, and it became a jet whose shape is a barrel type.

Showing density contours in the Fig. 5(b), the density decreased in the vicinity of a rapid expansion of the nozzle point and increased in the place where the contacting and joining started in the inside of the annular jet. In the downstream region, the density changed according to the increase and decrease of the flow.



(a) Velocity contours



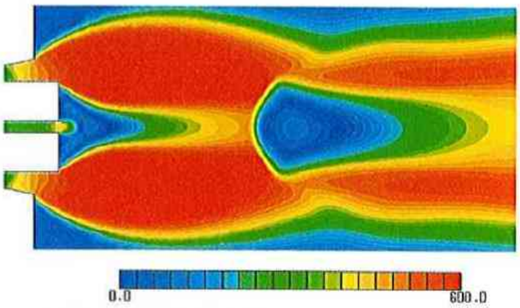
(b) Density contours

Fig.5 Contours for nozzle B, Po/Pa =20.0

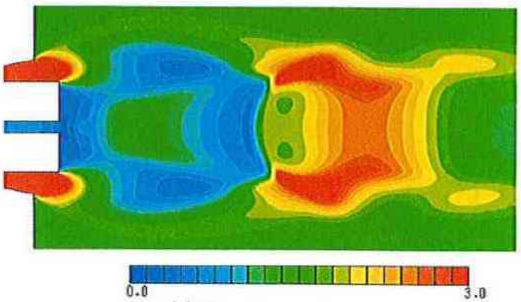
In the Fig. 6(a), 6(d), velocity contours and density contours are shown about results of numerical analysis of an annular supersonic jet issuing from nozzle C as pressure ratio Po/Pa =20.0 in the vicinity of exit of the nozzle.

Showing velocity contours in the Fig. 6(a), the flow expanded rapidly considerably immediately after the exit of the annular nozzle and became a supersonic jet in a wide area. In nozzle C, the flow keeping a supersonic flow generated a shock wave in the vicinity of the jet center where the annular jet joined. Behind it, the subsonic area was formed.

Showing velocity contours in the Fig. 6(b), the increase and decrease of the density is seen corresponding to the flow.



(a) Velocity contours



(b) Density contours

Fig.6 Contours for nozzle C, $Po/Pa = 20.0$

4.2 Velocity vectors and vortex flow

In the Fig. 7(a), 7(b), velocity vectors and vortex flows are shown about results of numerical analysis of an annular supersonic jet issuing from nozzle A as pressure ratio Po/Pa =20.0 in the vicinity of exit of the nozzle.

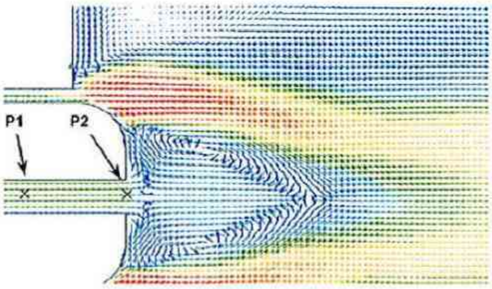
Showing nozzle A in the Fig. 7(a), 7(b), a pair of vortexes had been generated in the point of the nozzle. The Air, from a small hole opened in the center part of the nozzle, became a flow that flowed out from P1 to P2 because the P1 pressure is larger than the P2 pressure.

In the Fig. 8(a), 8(b), velocity vectors and vortex flows are shown about results of numerical analysis of an annular supersonic jet issuing from nozzle B as the pressure ratio Po/Pa =20.0 in the vicinity of exit of the nozzle.

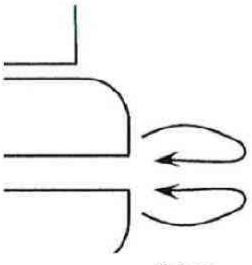
Showing nozzle B in the Fig. 8(a), 8(b), the rapid expansion of the flow in the nozzle exit was more remarkable than nozzle A. In the point of the nozzle, a pair of vortexes had been generated as well as nozzle A. The vortex area in the nozzle point appeared small to compare with nozzle A because the nozzle has a roundness shape in the point. Moreover, the flow that flowed out from P1 to P2 was caused as well as nozzle A.

In the Fig. 9(a), 9(b), velocity vectors and vortex flows are shown about results of numerical analysis of an annular supersonic jet issuing from nozzle C as pressure ratio *Po*/*Pa* =20.0 in the vicinity of exit of the nozzle.

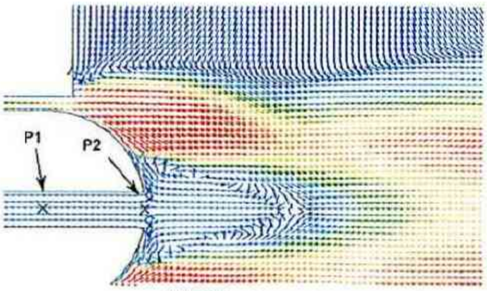
Showing nozzle C in the Fig. 9(a), 9(b), the flow became a supersonic jet that expanded rapidly in the nozzle exit and the pressure in the small hole appeared that P1 was lager than P2. Because the nozzle point was plate, the pressure behind the nozzle became a considerable negative pressure. A high-speed flow that flowed out from the small hole collided with the flow of the low-pressure vortex area. A pair of small vortexes was formed in the exit part of the small hole. For the season, two pairs of the vortexes were formed and the situation was different with the case of nozzle A and nozzle B.



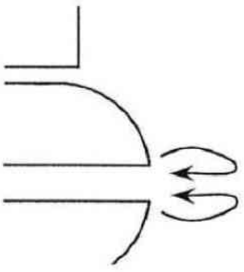
(a) Velocity vector



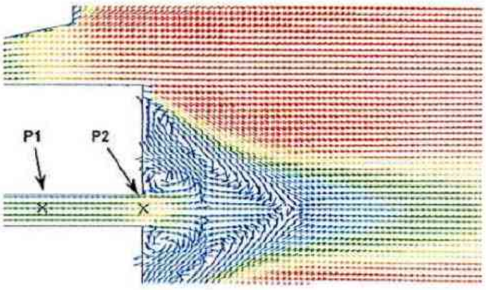
(b) Vortex flow
Fig.7 Exit flow of nozzle A, *Po*/*Pa* =20.0)



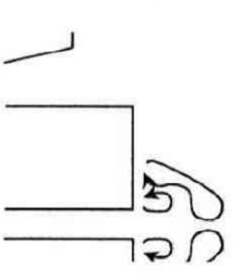
(a) Velocity vector



(b) Vortex flow
Fig.8 Exit flow of nozzle B, *Po*/*Pa* =20.0)



(a) Velocity vector



(b) Vortex flow
Fig.9 Exit flow of nozzle C, *Po*/*Pa* =20.0)

4.3 Pressure about nozzles' point

In the Fig. 10, a relation is shown between differential pressure ΔP, which is in P1 and P2, and pressure ratio *Po* /*Pa*. When the differential pressure ΔP became plus, the air became a flow which flowed out from the small hole, and flowed in the direction from P1 to P2. When the differential pressure ΔP became minus, the air became a flow which entered to the small hole, and flowed in the direction from P2 to P1.

In nozzle A and B, when the pressure ratio was small, the air became a flow that entered in the direction from P2 to P1. There was a tendency that inflow decreases with increase of the pressure ratio, and it becomes a flow that flowed out from the small hole in $Po/Pa = 20.0$.

In nozzle C, the flow flowed out from the small hole and the air flowed in a direction from P1 to P2.

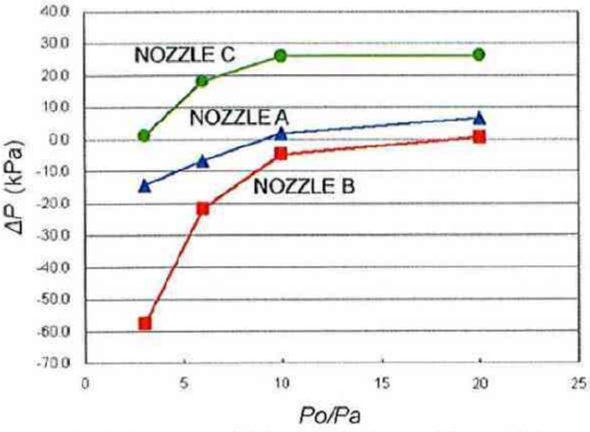


Fig.10 Pressure difference between P1 and P2

5. Conclusion

Using experiment and numerical analysis to understand the influence on a flow field from the difference of annular nozzles' shape and stagnation pressure's amount, the following conclusions are obtained.

(1) Total pressure vibrations greatly appeared in the vicinity of the boundary layer of inside of the annular jet and the joining region of the annular jet.

(2) According to shape of point of nozzles, a great different can be seen in the vortex area formed in exit of nozzles.

(3) Negative pressure of a vortex area of nozzle C having flat on the point became remarkable than nozzle A and nozzle B having a round shape on the point.

(4) According to difference of nozzles' shape and pressure ratio, difference of the flow direction which is in the hole of the center part of nozzles is seen.

(5) In pressure ratio $Po/Pa = 20.0$, a air flows form a hole in which nozzle.

(6) A pair of vortexes formed in the exit part of a nozzle in which nozzle. But in pressure ratio $Po/Pa = 20.0$ of nozzle C, two pairs of vortexes formed in the exit part of the nozzle.

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