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# EFFECT OF WALL JET ON OSCILLATION MODE OF IMPINGING JET

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## ABSTRACT

When an axisymmetric underexpanded jet impinges on a flat plate perpendicularly, the feedback mechanism of the sound waves in the flow field is known to cause the oscillation of jet with strong noise generation. In this paper, we report the effect of the wall jet on the oscillation mode of the impinging jet. The wall jet is modelled as radial jet and it is also underexpanded.. A radial underexpanded jet issuing from a slit nozzle, which consists of two circular tubes, face to face each other, is studied experimentally and numerically. In the experimental shadowgraph picture, it is found that some ring-shaped shocks appear around the nozzle and that the local deformations of the rings occur. Sinusoidal oscillation of jet caused by many vortices is shown and local distortion of shock ring is derived by the phase difference of the oscillation in the circumferential direction. In addition, the density waves moving around the jet and forming the feedback loop are captured by computation and they transmit the information about phase difference toward upstream. As a result, such behaviour of radial jet can be considered to be one of factors of the spiral motion in case of the impinging jet.

**Keywords: Radial Jet, Oscillation, Shock Wave, Vortex, Feedback Mechanism**

## INTRODUCTION

Supersonic jet issuing from a convergent nozzle becomes underexpanded when the nozzle pressure ratio is larger than the critical pressure ratio. The underexpanded jet is often used for many industrial applications such as an assist gas of the laser cutting, (Fieret *et al.*, 1987), a cooling jet in the glass tempering process (Barsom, 1968), and so on.

The impinging jet on a flat plate is a simple model of such flow field and the unsteady characteristics of the supersonic impinging jet have been studied by many researchers because the oscillation of jet and the noise generation from jet can be one of the sources of significant problems in the above applications. Powell (1994) reported a well-known feedback mechanism of the sound waves in whole flow field — the pressure disturbances in the jet produce the sound waves when they impinge on the plate, and these waves propagate around the jet toward the nozzle and interact with the jet boundary at the nozzle lip. The pressure disturbances are produced again by such interaction in jet. Sakakibara and Iwamoto (1998) study the above feedback mechanism numerically using TVD-scheme and show that the sound waves

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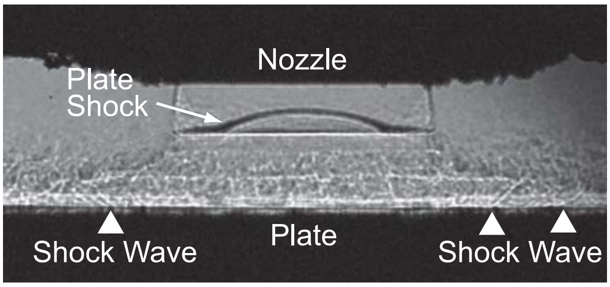
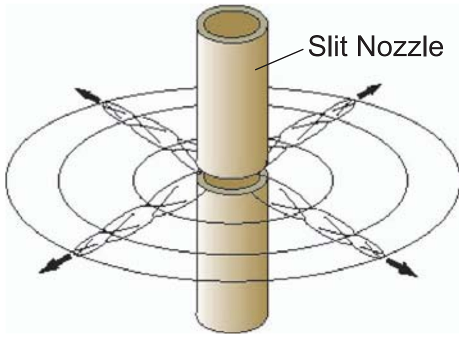



(a) Shadowgraph (Endo *et al.*, 2007)




(b) Radial jet

**Fig. 1. Flow model**

around the jet propagate hemi-spherically from the region of impingement and that the interaction of sound waves with impinging jet occurs over the whole jet boundary.

Although most of the above researchers focus on the relation between the characteristics of the main jet and the feedback mechanism of impinging jet, the unsteady behaviour of the wall jet on the plate should be further studied because, during the oscillation, the sound waves travel surrounding the wall jet as well.

Figure 1(a) shows the shadowgraph picture of the underexpanded impinging jet by Endo *et al.* (2007). There can be seen the shock waves in the wall jet (their positions are represented as ▲) and it is found that the wall jet is also underexpanded because the cell structure is generated by the iteration of reflection of the waves between the jet boundary and the plate. A radial jet issuing from a slit nozzle as shown in Fig. 1(b) can be considered to be a model of such flow field from which the main jet is removed. In this paper, the characteristics of the radial jet are analyzed experimentally and numerically to understand the effect of the wall jet on the feedback loop in the impinging flow field.

## EXPERIMENTAL AND NUMERICAL PROCEDURES

Figure 2 shows the experimental apparatus used in this study. Compressed air passing through an oil mist remover is supplied into a surge tank, and a part of the discharged air which goes through an air dryer and an air cleaner is divided into two high-pressure chambers A and B in a soundproof room. The bypassed air returns to the atmospheric pressure through a silencer in order to control the pressure in the chambers. In this study, the pressure ratio of the stagnation pressure in the chambers to the atmospheric pressure $PR$=3.0 and 4.0.

Two tubes, tube A and B, are fitted to each chamber, their exit surface being face to face each other with very small spacing $w_N$=2mm. The inner diameter of the tube $d$=10mm, and the outer one $d_1$=12mm. The fluids flowing out from these tubes collide each other and change their direction radially. The shape of the inner side of the tube is designed so that the flow velocity reaches sonic speed at the outer lip of the tube (Toriumi *et al.*, 2007).

In this paper, these parts of the tubes are called 'slit nozzle'. Through the slit nozzle, a radial under-expanded jet is formed. The optical system as shown in Fig. 2(b) is arranged in order to visualize such a unique flow field. The light emanated from the spark generator is concentrated by a couple of lenses and focused on the pinhole whose diameter is 1mm. A part of the light from a collimator lens goes across the jet and projects a side view of the flow field on a film, while the other part is reflected by mirror A,

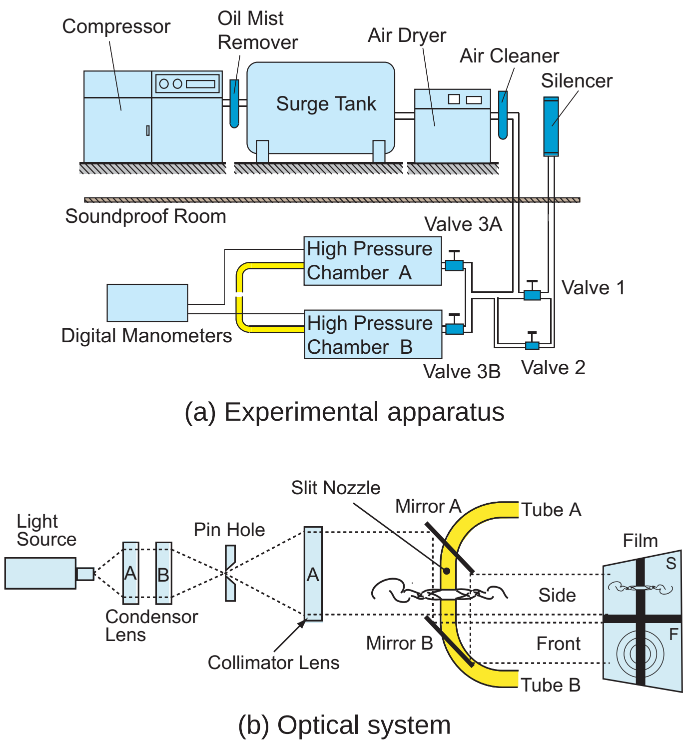



**Fig. 2. Experimental devices**

crosses the jet in a different direction and projects a front view of the field. So, using this optical system, the side view and the front view of the flow field can be printed on a same film simultaneously.

The radial jet is numerically simulated using computational model shown in Fig. 3. Three-dimensional Euler equation system is solved with the second order symmetric TVD scheme (Yee, 1985). The green-colored annular domain between $D_{ci}/D$=0.6 and $D_{co}/D$=3.0 ($D$: the inner diameter of the tube) as shown in the figure is treated as a computational domain and the jet is assumed to be symmetric about the $XZ$ plane at $Y/D$=0.0. For the computation, there are 161 computational grids in radial direction, 74 in circumferential direction and 91 in $Y$-direction, and they are coagulated toward the region near the nozzle exit.

## RESULTS AND DISCUSSION

### Shock Ring

Figures 4 show the shadowgraphs taken by the experiment. Upper halves of Figs. 4(a) and 4(b) are the side view of the flow field and lower halves are the front view. They are projected on a same film simultaneously. In both side views, typical cellular structure of underexpanded jet can be seen near the exit of slit nozzle and is found to oscillate sinusoidally in downstream region. Many vortices, which are generated in the upper and lower side of the jet alternately, cause it like as two dimensional rectangular jet. Because such flow pattern appear surrounding the circular tubes which consist of the slit nozzle in case of the radial jet, shock waves in cellular structure are visualized as ring-shaped shocks. Two or three shock rings can be seen in front views. Comparing the side views in Figs. 4(a) and 4(b), the length of cell becomes larger with higher pressure ratio, and so the diameters of shock ring also become larger.

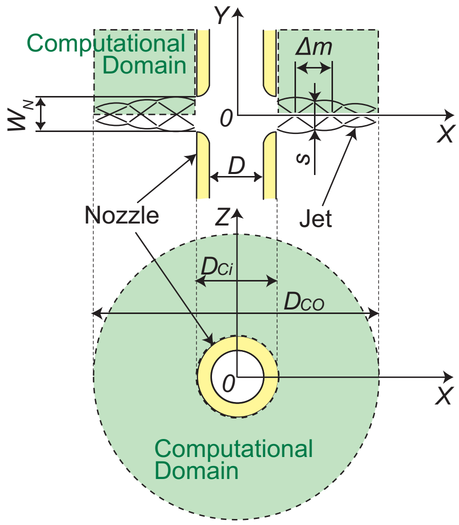



**Fig. 3. Computational model**

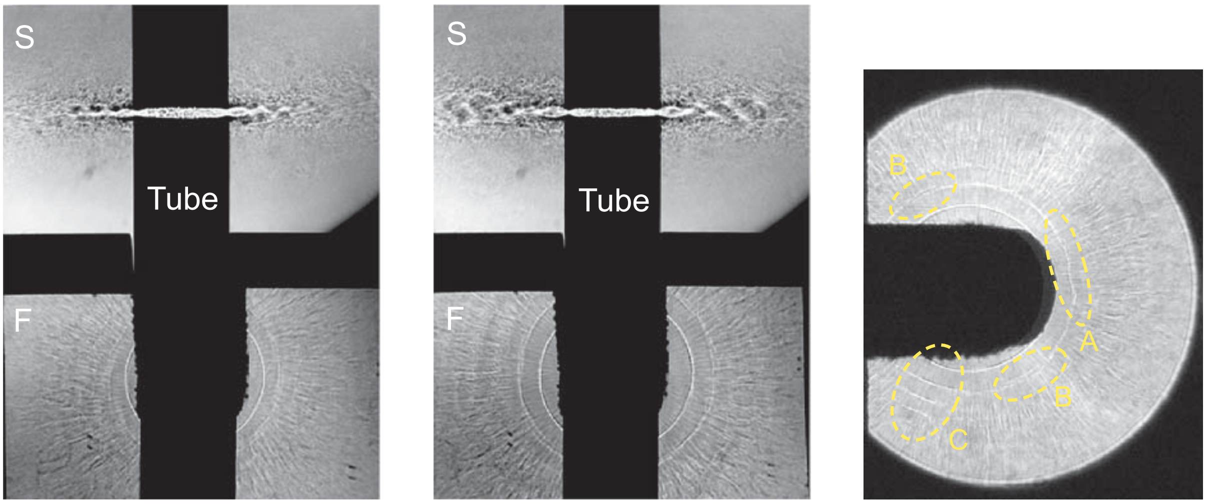
To examine the local distortion of circular shock ring, only the enlarged front view is photographed as shown in Fig. 4(c). *PR* of this jet is 4.0. Although the first shock ring is almost circular, the outer rings are locally deformed as shown in region A. Second ring is branched in regions B and furthermore, four shock rings appear in region C.

Shock rings are also captured by the computation. Figures 5 show the density contours on $XZ$-plane at $Y/D = 0.0$. Red or yellow lines correspond to the shock rings and, although they are almost circular, their strength is locally different. Because the jet is assumed to be symmetric against $XZ$-plane at $Y/D$=0.0, the sinusoidal oscillation is neglected in the computation and the deformation of the shock ring does not appear. The differences of strength are seen to be more clearly in Fig. 5(b) than those in Fig. 5(a), and in addition, contour lines outside of the fourth ring in Fig. 5(b) are found to be spiral distribution.

## Oscillation of Radial Jet

Figure 6 shows the pressure distributions on $XZ$-plane ($Y/D$=0.0) for different $R/D$ ($R$: radial distances from the centre of tube) against the angle from $X$-axis. It is found that the flow field can be divided into 4 regions because 4 cycles of the pressure oscillation are included in 360 degree. $OP_1$ is the position at local minimum pressure in this figure and also shown in Fig. 5(b). A quarter region which corresponds to a period is divided into 10 regions and they are represented as $OP_1$, $OP_2$, $OP_3$, $\cdots$ (see Fig. 5(b)).

The density contours on each $RY$-section at certain instant are shown in Fig. 7(a). The flow field can be seen to consist of the region of the shock cells and that of the vortices. The cellular structure exists in the upstream region and it is found to be collapsed by vortices in the downstream region. These vortices are generated near the nozzle exit and their sizes become larger when they move downstream. The density waves generated around the radial jet are also seen in these figures. There can be found to be two kinds of the waves around the jet—the density waves of which position changes downstream (group B) and of which position changes toward the nozzle upstream (group A) (see in order of $OP_9 \to OP_7 \to OP_5 \cdots$). The former waves are related to the noize from jet and the latter ones form the feedback loop in this flow field. Such movement of density waves can be confirmed by Fig. 7(b). These figures show




(a) $PR$ = 3.0 (b) $PR$ = 4.0 (c) Enlargement ($PR$ = 4.0)

**Fig. 4. Visualization of shock cells**

the density distributions on fixed $RY$-plane ($OP_1$) during one cycle of oscillation. There can be seen two groups of density waves A and B and their motion is similar to that discussed above. Therefore, it is found that the density disturbance generated at certain point in the jet propagates both in circumferential and in radial direction simultaneously. Spiral distribution of density contours in Fig. 5(b) is considered to be formed by such characteristics of the radial jet.

In addition, waves A transmit the informations about changes in the such direction toward upstream. Considering the axisymmetric jet impinging on a plate, the position of the outer surface of tube in case of radial jet corresponds to that of the jet boundary of main jet issuing from nozzle. This means that the disturbances in the main jet caused by the interaction of these waves with the main jet boundary form a new feedback loop and the phase difference in the circamferential direction of radial wall jet causes the helical oscillation of impingin jet.

## CONCLUSIONS

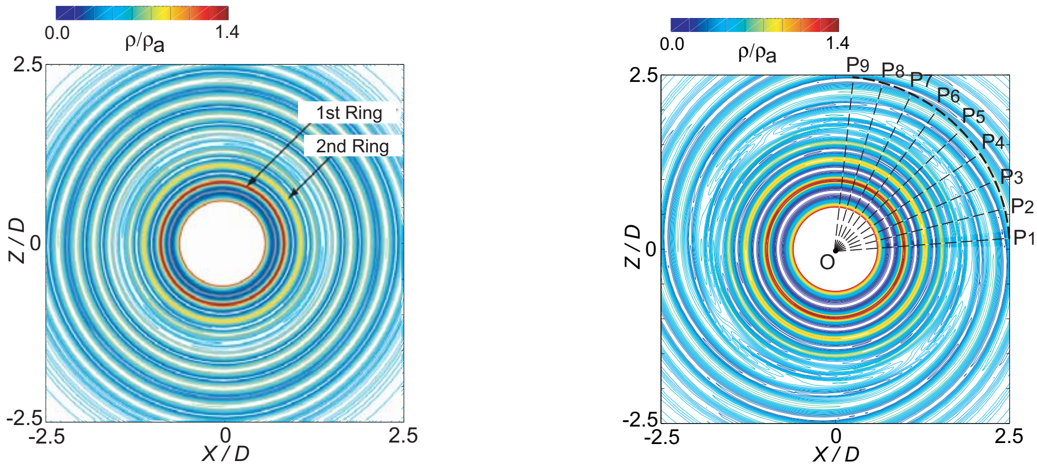
In order to understand the effect of the wall jet on the feedback mechanism in flow field of the impinging jet, its feature is extracted from the wall jet and a radial underexpanded jet issuing from the slit nozzle is studied experimentally and numerically. As a result, the following conclusions are drawn.

(1) Cellular structure of radial underexpanded jet is visualized as shock rings surrounding the slit nozzle.

(2) The shock rings are locally deformed and branched. They are caused by phase difference of the oscillation in the circumferential direction.

(3) The changes of the flow conditions propagate both in circumferential and radial direction simultaneously and the density waves which propagate toward the nozzle transmit the information about phase difference of the oscillation to upstream. They are considered to affect the helical motion of the impinging jet.

So, to analyze the characteristics of the radial jet is important for understanding the effect of the wall jet on the feedback mechanism of the axisymmetric impinging jet.




(a) $PR$=3.0 (b) $PR$=4.0

**Fig. 5. Density contours on XZ-plane ($Y/D$=0)**

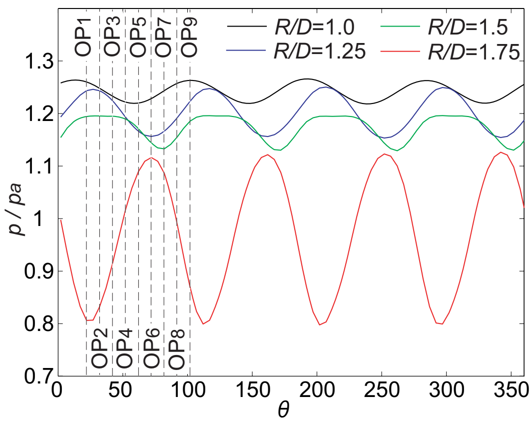



**Fig. 6. Pressure distributions in circumferential direction**

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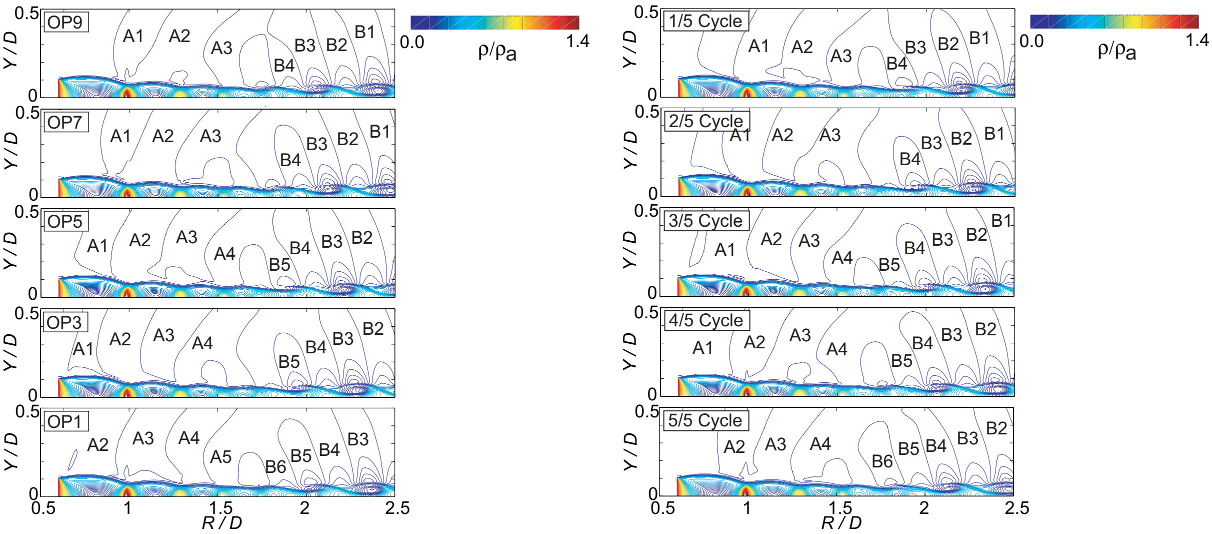

(a) Fixed time

(b) Fixed plane

**Fig. 7. Density contours on $RY$-plane ($PR$=4.0)**

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