Flow characteristics of sub- and supersonic jets issued from orifice and notched orifice nozzles, and application to ejector

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Abstract

The flow characteristics of sub- and supersonic under-expanded jets issued from circular nozzles have been studied well; however, this does not apply to sub- and supersonic jets from an orifice nozzle. In this study, the flow characteristics of sub- and supersonic jets issued from an orifice or notched special orifice nozzle are examined experimentally based on the results of a visualized flow pattern by the Schlieren method and the measurements of velocity distribution by a thin supersonic Pitot tube. That is, the effects of the nozzle shape on the flow characteristics such as the decay of the jet centerline velocity, velocity distribution at the cross section, increment of the jet- width and -flow rate to the downstream are examined experimentally. Results indicate that the jet issued from the notched orifice nozzle with a rectangular notch demonstrates excellent entrainment performance. In addition, to improve the performance of a cylindrical ejector, the application of the results is examined.

Keywords : Sub- and supersonic jet, Orifice jet, Notched orifice jet, Flow visualization, Entrainment, Ejector, Efficiency

1. Introduction

The flow characteristics of sub- and supersonic under-expanded jets issued from circular nozzles have been studied well. For example, Donaldson & Snedeker (1971) classified the flow pattern of sub- and supersonic under-expanded jets issued from a smoothly converged contour nozzle in three depending on the pressure ratio of the supplied pressure p_0 to the ambient pressure p_a . In the ranges of $1.0 < p_0/p_a < 1.89$, $1.89 < p_0/p_a < 3.85$ and $3.85 < p_0/p_a$, the jets are subsonic, moderately under-expanded, and highly under-expanded jets, respectively, as shown in the following figure. Kojima, et al. (1986), and Zapryagaev & Pivovarov (2015) showed the mechanism of shock waves and the pressure and velocity distribution of supersonic jet, Shadow, et al. (1990) showed the compressible spreading rates of supersonic coaxial jets, Katanoda, et al. (1995) showed the effects of divergence angle of nozzle and Mach number on shock cell length, Murakami & Papamoschou (2000) showed the flow characteristics of coaxial supersonic jet, Ikui & Matsuo (2001) showed the theoretical and experimental flow characteristics of supersonic jet, and Otobe (2007) studied the effect of non-equilibrium condensation on supersonic jet. However, the sub- and supersonic jets from an orifice nozzle have not been studied well (Shakouchi et al., 2016).

In this study, the flow characteristics of sub- and supersonic under-expanded jets issued from an orifice or notched orifice nozzle are investigated experimentally using the results of visualized flow pattern by the Schlieren method and the measurements of velocity distribution using a thin supersonic Pitot tube (Shakouchi et al., 2016).

The effects of the nozzle shape (Shakouchi et al., 2016; Zaman, 1999; Chanpagné & Wygnanski, 1971; Shakouchi, 2005; Carletti et al., 1996; Behrouzi et al., 2008; Shakouchi et al., 2001) on the flow characteristics such as the decay of the jet centerline velocity, velocity distribution at the cross section and increments in the jet- width and - flow rate to the downstream are examined. An orifice nozzle with small or large notches was used in addition to circular and orifice nozzles with various contraction area ratios. The notch was used to disturb the flow around the outer edge of the jet and to enhance the entrainment flow rate.

In addition, the application of the notched nozzle to a cylindrical ejector (Jou et al., 2011; Carletti et al., 1995) is examined to improve the entrainment performance.

(1) Subsonic jet ($1.0 < p_0/p_a < 1.89$)

(2) Moderately under-expanded jet
($1.89 < p_0/p_a < 3.85$)

(3) Highly under-expanded jet ($3.85 < p_0/p_a$)

* Sub- and Supersonic jets (by Donaldson & Snedekar, 1971)

2. Experimental apparatus and procedure

Figures 1(1) and (2) show the circular nozzle (Pi-n) and orifice nozzle (Ori-n), respectively. Additionally, Figs. 1(3) and (4) show the Ori-n nozzles with a small triangle notch (Tr-n) and large rectangular notch (Re-n), respectively. The Pi-n nozzle was used as a reference, and the Tr-n and Re-n nozzles were used to enhance the mixing and entrainment by disturbing the flow around the outer edge of the jet.

The nozzle diameters of the Pi-n and Ori-n are the same and $d_0 = 4.0$ [mm]. The Pi-n has a parallel section of $L/d_0 = 4.5$. The contraction area ratio of the orifice is $CR = (d_i/d_0)^2 = 0.64-0.13$. The cross-sectional area of Pi-n, Ori-n with $CR = 0.13$, Tr-n and Re-n nozzles are 12.6, 12.6, 14.6, 17.2 [mm²], respectively, and their wetted perimeter are 12.6, 12.6, 17.1, 15.6 [mm], respectively. The hydraulic diameters of the Tr-n and Re-n are 3.42 and 3.66 mm, respectively. Every nozzle is connected to a pipe of diameter 15.5 [mm] and has a static pressure hole of diameter 0.8 [mm] at the upstream 100 mm from the nozzle exit.

The flow pattern of sub- and supersonic jets was visualized by the Schlieren method (Kato Koken, SS-150, Japan), photographed and recorded.

The flow rate was measured with a hot wire flow meter (Azbil Corp., CMG500C150, Japan, and others) installed upstream far away from the nozzle.

The velocity distribution was calculated with measured pressures by a total and static pressure tubes of diameter 1.0 [mm].

(1) Circular, pipe, nozzle (Pi-n)

(2) Orifice nozzle,
 $CR = 0.13$ (Ori-n)

Fig.1 Experimental apparatus, nozzle

3. Results and discussions

3.1 Flow structure and flow pattern

3.1.1 Effects of supplied pressure, P_0 (Pipe jet and orifice jet)

The effects of supplied pressure, P_0 , on the flow structure and flow pattern for Pi- and Ori-jets issued from Pi-n and Ori-n nozzles with $CR = 0.13$ are shown in Figs. 2(1) and (2), respectively. They are the visualized photographs captured using the Schlieren method. The dotted lines in the figures show the approximate jet boundary where the brightness in the radius direction changes clearly. In the jet flow the white and black coloured areas are the expansion and compression flow regions, respectively.

Fig. 2(1),(a) shows the result for the small supplied pressure of $P_0 = 0.02$ [MPa] of the Pi-jet. The jet spreads in the radius direction almost linearly. However, increasing the supplied pressure as $P_0 > 0.115$ [MPa] causes the jet to expand

Fig.2 Visualized flow pattern of pipe and orifice jets by Schlieren image ($P_0 = 0.02 \sim 0.38$ [MPa])

rapidly immediately after the nozzle exit; subsequently, it flows with an almost constant jet width and maintained in the radius direction, and the length of the shock cell increases.

The supersonic jet of $P_0 = 0.380$ [MPa] shows a clear diamond shock repeating expansion and compression, expands in the radius direction slightly from the nozzle exit, and remained in a constant width after assuming a minimum value at $x/d_0 \approx 2.0$.

The results for the Ori-jet with a contraction area ratio of $CR = 0.13$ are shown in Fig. 2(2). The jet from the orifice nozzle at $P_0 = 0.02$ [MPa] spreads almost linearly; however, it is slightly smaller than that of the Pi-jet because of the contraction flow effect by a sudden contraction nozzle.

Increasing the P_0 as $P_0 > 0.115$ [MPa] causes the jet width to be almost constant after the nozzle exit; subsequently, it becomes larger because of the contraction effect. The flow pattern of the Ori-jet with $CR = 0.13$ is different from that of the Pi-jet.

3.1.2 Effects of contraction area ratio (Orifice-jet)

Fig. 3(1) shows the effect of contraction area ratio CR on the flow pattern of the Ori-jet at $P_0 = 0.115$ [MPa]. At $CR = 0.64$, the jet spreads after exhibiting an almost constant jet width area from the nozzle exit. With increasing CR , the jet spreading after an almost constant jet width area becomes slightly smaller. Fig. 3(2) shows the results at $P_0 = 0.380$ [MPa]. At $P_0 = 0.380$ [MPa], clear shock waves of expansion and compression appear; additionally, with increasing CR , the jet spreading after an almost constant jet width area becomes slightly smaller.

Fig.3 Visualized flow pattern of orifice jet by Schlieren image
($d_0 = 4.0$ mm, $CR = 0.64 \sim 0.13$)

3.1.3 Jet width, b_w/d_0

Fig. 4(1) shows the jet width b_w/d_0 near the nozzle exit at $P_0 = 0.115$ [MPa] of the Ori-jet. The jet width was obtained by the visualized flow pattern. The b_w/d_0 of the Pi-jet is almost constant, but the Ori-jet increases to the downstream. With increasing CR , the b_w/d_0 becomes larger; for example, at $x/d_0 = 4.0$, $CR = 0.64$ is about 1.55 times

that of the Pi-jet.

In Fig. 4(2), the results at $P_0 = 0.380$ [MPa] are shown. The b_w/d_0 at $P_0 = 0.380$ [MPa] is about 1.27 times larger than that of the Pi-jet at $P_0 = 0.115$ [MPa] because of a large flow expansion immediately after the nozzle exit. Additionally, in this case, the Pi-jet in $x/d_0 > 1.0$ does not spread in the radius direction and exhibits an almost similar width. The Pi-jet flows down as if it penetrates almost without entraining the surrounding fluid. However, the b_w/d_0 of the Ori-jet increases to the downstream by a contraction effect of the orifice nozzle and indicates a maximum value at $CR = 0.25$. For example, it is about 1.22 and 1.45 times that of the Pi-jet at $x/d_0 = 6.0$ and 8.0, respectively. The b_w/d_0 of $CR = 0.13$ is a minimum value because it has a large flow resistance at the nozzle by a large contraction.

Fig.4 Jet width, b_w/d_0 , of orifice jet

3.1.4 Jet centreline velocity, u_c

Fig. 5(1) shows the jet centreline velocity u_c at $P_0 = 0.115$ [MPa]. In the visualized photograph [Figs. 2(1)(b),(b') and Fig. 3(1)], shock waves by expansion and compression flows are shown; however, the velocity does not fluctuate because of them. The u_c immediately after the nozzle exit increases as CR decreases because of the flow contraction effect by orifice nozzle and it is almost constant in the range of $x/d_0 < 4.0$. Also in the downstream of $x/d_0 > 8.0$, and the u_c of $CR = 0.13$ indicates the largest value and decreases as a function of the power of (x/d_0) .

Fig. 5(2) shows the jet centreline velocity at $P_0 = 0.380$ [MPa]. The u_c after the nozzle exit fluctuates primarily following the shock waves shown in Figs. 2(1)(d),(d') and Fig. 3(2). In the down-stream, the u_c of the Pi-jet indicate the largest value and decreases as a function of the power of (x/d_0) . For example, the u_c of the Pi-jet at $x/d_0 = 14$ is about 3.6 times that of the $CR = 0.13$ because of the low flow pressure loss of the Pi-n nozzle.

Fig.5 Jet centerline velocity, u_c

3.1.5 Velocity distribution, u , at cross section

Fig. 6(1) shows the effect of nozzle shape on the velocity distributions u at the cross section of the Pi-jet and Ori-jet with $CR = 0.13$ at $P_0 = 0.02$ [MPa]. The flow patterns are shown in Figs. 3(1)(a) and (2)(a'), respectively. The jet

(1) Effect of nozzle shape at $P_0 = 0.02$ [MPa] (Pi- and Ori-jets)

(2) Effect of nozzle shape at $P_0 = 0.380$ [MPa] (Pi- and Ori-jets)

(3) Effect of CR of Ori-jet ($P_0 = 0.380$ [MPa])

Fig.6 Velocity distribution, u , at cross section

boundaries obtained by the visualized flow pattern are shown in the figure, as well. Near the nozzle exit at $x/d_0 = 2.1$, a core region exists in the jet center area; further, the profiles are almost the same the Goertler profile. The velocity in the jet center area of the Pi-jet up to $x/d_0 = 5.4$ is larger than that of the Ori-jet because of the large flow resistance of the Ori-n nozzle; however, at the downstream of $x/d_0 = 8.3$, they exhibited almost the same value. The jet boundary obtained by the visualized flow pattern expresses the practical one well and is at $u/u_c = 0.1 - 0.2$.

Fig. 6(2) shows the effect of nozzle shape on velocity distribution u for a large supplied pressure of $P_0 = 0.380$ [MPa]. The flow patterns are shown in Figs. 2(1)(d) and (2)(d'). The velocity distribution is different primarily owing to the small supplied pressure of $P_0 = 0.02$ [MPa], and the Pi-jet exhibits a distinguished minimum velocity at the jet center because it is in the expansion region of the shock cell (Kojima et al., 1986) and recovers to the downstream. The minimum velocity of the Ori-jet is not so small; however, it disappears at the downstream of $x/d_0 = 5.4$ it disappears. The jet width of the Ori-jet is larger than that of the Pi-jet at the downstream.

Fig. 6(3) shows the effect of contraction area ratio CR of the Ori-jet at $P_0 = 0.38$ [MPa]. The Ori-jet with $CR = 0.13$ decreases quickly to the downstream because of its CR that is smaller than that of the $CR = 0.64$ and a large spread.

As shown in Fig. 10 below, the jet width or entrainment calculated by the velocity distribution u of Ori-jet is not so large comparing with Pi-jet, and then in order to have a large entrainment Ori-n nozzle with large notches were used.

3.1.6 Jet flow from notched orifice nozzle

To improve the entrainment characteristics, Ori-n nozzles with two types of notches [see Figs. 1(3), (4), Shakouchi, et al., 2001, 2016, Kaushik, et al., 2006] were used.

Figs. 7(a), (b) show the visualized flow patterns of the Re-n jet at $P_0 = 0.02$ [MPa] at the cross section of major axis "a" and minor axis "b". The jets at the both axes spread primarily from the nozzle exit and the jet width at the axis "a" becomes smaller than that at "b". This is because of so-called jet switching in which the major axis and the minor axis

Fig.7 Visualized flow pattern, Re-n ($P_0 = 0.02, 0.18$ and 0.38 [MPa])

are interchanged.

In Figs. 7(c), (d), the results at $P_0=0.180$ [MPa] are shown. In this case, a barrel shock as that shown for $P_0=0.380$ [MPa] appeared; however, the jet width and shock cell length became smaller. The jet width at the cross section “a” was almost constant; at “b”, it first decreases slightly and subsequently remains constant after taking assuming a minimum value at $x/d_0 \approx 2.0$. Both widths are smaller than that shown for $P_0=0.380$ [MPa].

Figs. 7(e), (f) show the results at $P_0=0.38$ [MPa]. At both cross sections “a” and “b”, the jets spread slightly in the radius direction and exhibit minimum values at $x/d_0 \approx 2.5$ and 1.5, respectively, and subsequently exhibit an almost constant width. The jet flow immediately after the nozzle exit resembles a twisted flow pattern; subsequently, jet switching occurred.

3.2 Velocity distribution

Fig. 8 shows the jet centerline velocity u_c/u_0 (u_0 : nozzle exit maximum velocity) for $P_0=0.020$ [MPa]. The Pi-n jet has a constant maximum velocity in the range of $x/d_0 > 4$ and a developed region of $u_c/u_0 \propto (x/d_0)^{-1}$ in $x/d_0 > 6$. The u_c of the Ori-n and Re-n jets in the developed region are slightly larger than that of the Pi-n jet. The nozzle exit maximum velocity at $P_0=0.020$ [MPa] of the Pi-, Ori-, and Re-n jets were the almost same and $u_0=184.1$, 180.6, and 185.7 [m/s], respectively.

Fig.8 Jet centerline velocity, u_c/u_0 ($P_0=0.02$ [MPa])

Fig. 9 shows the velocity distribution at $P_0=0.020$ [MPa] at the cross section of the Pi- and Ori-jets. The two-dot chain lines in the figure indicate the jet edge of $u/u_c=0.1$. The velocity profiles of both are almost the same. But, The jet widths at $x/d_0=2.1, 4.2$ of the Ori-jet are slightly smaller and the center line velocity in $x/d_0 < 5.4$ of the Ori-jet is larger than that of the Pi-n jet because of the flow contraction of the Ori-jet near the nozzle exit.

3.3 Spread of jet

Fig. 10(a) shows the jet width b_w/d_0 for $P_0=0.380$ [MPa] in the range of $x/d_0 < 4.5$. The jet width was obtained from the jet edge where the brightness in the radius direction in the visualized flow photograph changed clearly. The jet width of the Pi-jet is almost constant and is larger than those of the others, and the Ori-jet increases to the downstream after experiencing the effect of flow contraction. In this case, it appears that the so-called switching phenomenon had occurred, in which the major and minor axes at the cross section of jet is exchanged.

Fig. 10(b) shows the jet width for $P_0=0.020$ [MPa]. Both the jet widths of Pi- and Ori-jets increase with x/d_0 , and the Pi-jet is larger. For the Re-n jet, the minor axis is larger than the major axis. Additionally, it appears that switching has occurred.

Fig.9 Velocity distribution, u , at cross section, Re-n ($P_0 = 0.02$ [MPa]) Fig.10 Jet width, b_w/d_0 (by Schlieren method)

3.4 Entrainment flow rate, Q

Fig. 11 shows the flow rate Q [Nm^3] at the cross section, which was obtained by the integration of the velocity distribution. The Q of the Re-n jet was obtained approximately using the mean value at the sections of “a” and “b”. The Q of the Ori-jet is smaller than that of the Pi-jet in the range of $x/d_0 < 4.2$ because of the flow contraction, and subsequently increases and becomes almost the same with that of the Pi-jet. The Q of the Re-n jet in the range of $x/d_0 = 2.1 - 8.3$ is larger than those of the others and the change is almost the same with the Ori-jet. For example, the Q of the Re-n jet at $x/d_0 = 5.4$ is about 1.55 times that of the Pi-jet. The increase of wet perimeter of notched nozzle exit and the longitudinal vortex and disturbance generated by the notches will enhance the mixing between the jet flow and ambient and increase the amount of entrainment.

3.5 Entrainment efficiency, η , of air cylindrical ejector

In general, a circular nozzle is used as a driving nozzle of an ejector. As described above, the Re-n jet exhibits an excellent entrainment performance at $P_0=0.020$ [MPa]. In this section the application of these results to an air ejector (Jou et al., 2011; Carletti et al., 1995) is examined.

Fig. 12 shows the schematic diagram of a test cylindrical ejector. The driving nozzle can be Ori-n, Tr-n, or Re-n nozzles. The inner diameter of the cylinder is 30.0 [mm].

Fig. 13 shows the entrainment efficiency η of each nozzle as the ratio of the Pi-jet, η/η_{pipe} . We defined the suction efficiency η as the suction flow rate per unit operation power by the following equation.

$$\eta = Q_e / Q_0 (P_0 - P_a) \quad [\text{m}^3/\text{kW} \cdot \text{s}] \quad (1)$$

where, Q_0 : nozzle exit flow rate, Q_e : suction flow rate

The η of the Ori-jet is slightly higher in the range of $P_0 = 0.010 - 0.080$ [MPa] than that of the Pi-jet because of flow contraction immediately after the nozzle exit; for example, it is about 1.19 times that of the Pi-jet at $P_0=0.010$ [MPa]. The η of the Re-n jet is higher in the range of $P_0=0.010$ -0.180 [MPa] compared to the Pi-jet; for example, it is about 1.63 times that of the Pi-jet at $P_0=0.020$ [MPa]. This is due to the enhanced mixing of the jet with the surrounding of the jet edge by the flow fluctuation caused by the notch of the Re-n nozzle.

However, at a larger pressure of $P_0 > 0.10$ [MPa] the efficiency η of each nozzle was almost the same. It is considered that the high-speed jet will flow to penetrate through without an adequate entrainment of the surrounding still air.

Fig.11 Volumetric flow rate ($P_0=0.02$ [MPa])

Fig.12 Cylindrical ejector

Fig.13 Efficiency of cylindrical ejector, η/η_{pipe}

4. Conclusions

The effects of the notch set on an orifice nozzle on flow characteristics such as flow structure and entrainment flow rate, and their application to the driving nozzle of an ejector for performance improvement were examined. The primary results are as follows.

- (1) The jet width b_w/d_0 of supersonic Ori-jet at $P_0 = 0.380$ [MPa] after the nozzle exit is about 1.27 times larger than that of the Pi-n jet at $P_0 = 0.115$ [MPa] because of a large expansion immediately after the nozzle exit.
The Pi-jet flows down as if it penetrates almost without entraining the surrounding fluid. However, the b_w/d_0 of the Ori-jet increases to the downstream by a contraction effect of the orifice nozzle and indicates a maximum value at $CR = 0.25$. For example, it is about 1.22 and 1.45 times that of the Pi-jet at $x/d_0 = 6.0$ and 8.0 , respectively. The b_w/d_0 of $CR = 0.13$ is a minimum value because it has a large flow resistance at the nozzle by a large contraction.
- (2) The jet issued from the Re-n notched orifice nozzle generated switching immediately after the nozzle exit, in which the major and minor axes at the cross section of the jet was exchanged, and flow patterns such as velocity distribution and spread of jet were primarily different from those of the Pi-jet.
- (3) The Q of the Re-n jet in the range of $x/d_0 = 2.1 - 8.3$ was larger than that of the others and the change was almost the same with that of the Ori-jet. For example, the Q of the Re-n jet at $x/d_0 = 5.4$ was about 1.55 times that of the Pi-jet.
- (4) The efficiency η of the cylindrical ejector using the Re-n jet in the range of $P_0 = 0.010 - 0.180$ [MPa] was higher than that of the Pi-jet; for example, the η was about 1.63 times that of the Pi-jet at $P_0 = 0.020$ [MPa].

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