Passive flow control of jets

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Abstract
One of the major purposes of fluid mechanics and engineering is to reduce the flow resistance caused by flow friction, flow separation, vortex generation, and other factors. To reduce or eliminate flow resistance, in general, flow control is performed either passively or actively. Passive flow control is performed by changing the flow channel or object shape a little and reducing the total flow resistance. On the contrary, active flow control uses a device requiring power, but it can perform various complex flow controls. In this paper, the passive flow control of jets is examined with flow characteristics, control methods, and some applications because jet flows include the essence of fluid dynamics, such as, boundary layer flow, turbulent flow, shear flow, and flow mixing. In particular, the effects of the nozzle shape, the tab, rib and vortex generator, and the orifice or notched orifice on the flow characteristics of sub- and supersonic jets are examined. Furthermore, the control and suppression of high speed jet noise by a chevron nozzle, some examples of active flow control, and other areas are examined. Globular formation of fine solid particles by flow control, lift control of airplane wings, and the flow control of a NOTAR helicopter without tail rotor are also addressed.

Keywords: Flow control, Passive flow control, Jets, Orifice jet, Application of jet control

1. Introduction

Usually, flow control is carried out by a passive or an active method in order to reduce or increase the flow resistance depending on the need. For example, it is whether changing the shape of an object in the flow by putting a tab or rib, passive flow control, or using actuator that needs some energy, active flow control, in order to suppress or eliminate the flow separation from the solid wall. In addition, flow separation causes the degradation in the element performance due to the flow not being along the surface of the object. One of the major methods of active flow control is feedback flow control using an actuator, in a desired flowing state based on the data regarding the flow condition of the controlled object. For example, Parekh (Kral, 2000) showed that for an active flow control triad there are three important subjects: flow phenomena, controls and sensors, and actuators. Now, it is desirable to improve the feed-forward control by AI and establish the control method by combining it and the feedback control.

Jets, wakes, and separated flows are major research subjects in the fields of fluid mechanics and engineering because they include the essence of fluid mechanics, such as boundary layer, turbulence, shear flow, and separated flow, and their flows appear in many practical applications.

In this paper, the flow control of jets is examined with the flow characteristics, control methods, and some examples of practical applications. In particular, the effects of the nozzle shape (Fiedler, 1998), the tab, rib, and vortex generator (Samimy et al., 1993, Carletti et al., 1996, Zaman et al., 1999, Miyakoshi et al., 2003, Ito et al., 2018), and the orifice or notched nozzle (Shakouchi et al., 2008, 2009, 2011, 2019), on the characteristics of jet flows including supersonic jet, and suppression of the high speed jet noise by the chevron nozzle (Gutmark, 2006, Munday et al., 2013) are examined. Furthermore, some examples of active flow control (Kral, 2000), for example, using an intelligent nozzle (Suzuki et al., 2004, Kasagi, 2006) are also examined.

Globular formation of fine solid particles by flow control (Nakamura, 2006), lift control of airplane wings (US-2, 2017), and the flow control of a NOTAR helicopter without tail rotor (NOTAR, 2017) are also touched upon.
2. Classification of Flow Control

Flow control can be classified into two types: passive control and active control (Fig. 1). Passive control of the flow in and around an object is fabricated by a small change in the flow path geometry. It can be achieved by the fitting of a tab, rib, vortex generator, among others.

There are two types of active flow control, predetermined and interactive methods. Interactive method is classified into two types: feedback- and feed forward-control. By the way, in the past, active flow control was mainly performed by feedback control. However, now it is important to improve the feed-forward control method using AI technology and establish the control method combining it and feedback control.

Parekh (Kral, 2000) showed the active flow control triad as shown in Fig. 2. This is shown for reference. When controlling various flow phenomena, available control methods, sensors and actuators are shown.

3. Passive jet flow control by nozzle shape

The flow characteristics of the jet flow are highly influenced by the nozzle configuration. In other words, they can be controlled passively by the configuration.

In this section, the jet flow is controlled and examined using various kinds of nozzle configurations.

3.1 Noncircular nozzle

The jets issued from noncircular nozzles exhibit different flow patterns. Fiedler (1998) showed the flow pattern, and vortex ring for the jets from oval, rectangular, and triangular nozzles. Figure 3 is the sketch of the variation of their vortex rings to the downstream. The jet issued from a rectangular or triangular nozzle flows downstream while deforming by longitudinal vortices of the Prandtl’s secondary flow of second kind generated at the corners as shown in Fig. 3. Gutmark et al. (1999) examined the jet flow control by noncircular nozzle.

![vortex ring diagram](image-url)
3.2 Turbulence promoter: Tab, rib, and vortex generator

Jet flow control using a tab, rib and a notch set at and around the nozzle exit has been studied by many researchers.

For example, Carletti et al. (1996) studied passive jet mixing enhancement by vortex generators, tabs, and deflector plates as shown in Fig. 4. They measured the velocity profiles for various positions of the vortex generator, the tab, and the deflector plates, and concluded that the maximum average vorticity of a single tab and a single half delta-wing vortex generator at the downstream of twice the nozzle diameter is 20 - 25% higher than that of the axisymmetric jet without the generator. Ito et al. (2018) examined the enhancement and suppression of the mixing and diffusion in an axisymmetric jet by half delta-wing tabs.

Samimy et al. (1993) showed the effect of tabs on the flow and noise field of axisymmetric transonic- and supersonic jets, and the flow field was visualized by the Schlieren method and the smoke injection method. They concluded that the mass flow rate and noise level, SPL, can be increased and decreased by tabs, respectively, and the vortex structure also can be controlled. Furthermore, Zaman (1999) showed the characteristics of the distribution of compressible jets from nozzles with various geometries, and the flow pattern was visualized by the Schlieren method. Circular or rectangular nozzles with and without tabs, ellipse nozzles, and lobed nozzles were used. He concluded that the mass flow rate can be increased by tabs and the noise level, SPL, can be decreased.

Miyakoshi et al. (2003) showed a two-dimensional jet flow control by a small object set in the nozzle, as shown in Fig. 5. Where, Reynolds number is $Re = u_m h / \nu = 2508$ ($u_m$: mean velocity at the nozzle exit, $\nu$: kinematic viscosity of the fluid). The shedding vortex from the semi-circular cylinder set in the nozzle excites the jet fluctuation after the nozzle exit and consequently the jet spreads widely in the direction perpendicular to the jet axis. This can enhance the jet entrainment.

![Fig. 4](image1.png)

(a) Nozzle design
(b) Vortex generator parameters

Fig. 4 Tab, delta tab, and half delta-wing vortex generator (by Carletti et al., 1996)

![Fig. 5](image2.png)

Fig. 5 Passive jet flow control by small object, $h = 15.0$ mm, $Re = 2508$ (by Miyakoshi et al., 2003)

3.3 Orifice nozzle

The jet issued from an orifice nozzle has a special flow pattern with the flow contracting just after exiting the nozzle. The flow contracts suddenly at the nozzle exit and the velocity vector heads inward. The flow characteristics of a circular jet can be controlled by an orifice nozzle with a contraction area ratio (Shakouchi et al., 2008) or notched orifice nozzle (Shakouchi at al., 2009, 2011, 2019).

3.3.1 Effect of contraction area ratio

Figure 6 shows the velocity distribution, $u/u_m$ and $u'/u_m$, of the jet issued from an orifice nozzle measured by hot...
wire anemometry. Since the profiles were axisymmetric, only the half of the region in the direction of the radius is shown. Here, $u_m$ is the mean velocity and $u'$ is the RMS of the fluctuating velocity in the x-direction. The orifice nozzle is shown in Fig. 7 with a quadrant nozzle that has a gradual and smooth contraction. All nozzles have a diameter of $d_o = 10.0 \text{ mm}$, and a contraction area ratio $(CR) = 0.11 - 0.69$. The figure shows a pipe nozzle with a length of $L/d_o = 50.0$.

The mean velocity profile of the pipe nozzle $(CR = 1.00)$ matched the seventh power law for a fully developed turbulent pipe flow.

On the contrary, the $CR$ had a considerable effect on the exit velocity profile. When $CR = 0.69$, the profile was nearly a top-hat profile and a stronger effect of contraction was observed as the $CR$ decreased. The orifice jets had saddle-shaped profiles due to the vena contracta effect and the smaller $CR$ had a thinner shear layer. The exit velocity of the quadrant nozzle also had a thin shear layer. However, the flow is distributed uniformly over the nozzle exit and is wider than the orifice jets because there is no vena contracta effect. It is, therefore, not surprising that the quadrant jet centerline velocity $u_c/u_m$ is smaller than the others. The orifice jet velocity at the center is $u_c/u_m \approx 1.3$ for all the orifices. The smaller $CR$ causes a smaller orifice jet width, reflecting a maximum velocity value.

The maximum fluctuating velocities were observed at the largest velocity gradients. The value of the turbulent intensity at the jet center decreased from 4.3% to 0.2% with a decreasing $CR$.

Figure 8 shows the visualized flow pattern at the center section of $r-x$ plane. The vortex structures of the submerged orifice water jet were visualized by the tracer method and the laser light sheet method. The effects of $CR$ on them were examined. The results in the middle plane are shown in the figure for different $CR$ values at the nozzle Reynolds numbers $Re = u_m d_o / \nu = 1000$ and 3000. The flow pattern clearly shows a dependency of the jet width at the nozzle exit on the $CR$. The orifice nozzle with $CR = 0.11$ yielded a narrow jet width at the nozzle exit due to strong contraction. All of the flows were initially laminar and eventually became turbulent following the transition process.

There is no clear vortex in the pipe jet flow in Fig. 3(a), even at $Re = 3000$, except at the extreme downstream shown in Fig. 8(b). In contrast, outstandingly large coherent vortexes were observed in Fig. 8(c)-(h). Although it was not so clear at $Re = 3000$, the large vortex structure of the orifice jets could be observed as they are accentuated with arrow lines showing the flow direction roughly. Detailed observations of videos of the orifice’s jets revealed the production process of the large vortexes. At first, many vortex rings were produced at the exit of the nozzle due to instability at the edge. A rapid decay in velocity downstream prevented the vortex rings, which yielded a large vortex structure. The contraction ratio $CR$ caused significant changes in the formation of vortices. These changes are related to the development of the shear layer instability at the exit.

The vortex rings in Fig. 8(c) are not as clear as those in Fig. 8(e). The coherent vortex rings in Fig. 8(c) seem too weak to affect the flow inside the jet, while those in Fig. 8(e) are large enough to affect the core of the jet and retard the flow. The flow issuing from $CR = 0.11$ spread wider and mixed with the ambient fluid faster in the downstream region than that from $CR = 0.69$. The mean velocity for $CR = 0.11$ increased and decayed more quickly than that for $CR = 0.69$, as will be explained in the next section. This may be the reason for the difference in the vortex size. A coherent vortex structure yields high mixing and heat transfer rates. Therefore, changing the orifice nozzle contraction ratio, and thereby controlling the coherent structure, would offer a better performance with respect to the flow and heat transfer characteristics.

\[ \text{Fig. 6 } u'/u_m \text{ and } u'/u_m \text{ at nozzle exit of } x/d_o = 0.2 \]

\[ (d_o = 10.0 \text{ mm}, \ Re = 1.5 \times 10^4, \ CR = 1.0 - 0.11) \]
Figure 8(g) also shows clear coherent vortexes produced by a quadrant nozzle due to instability at the edge of the nozzle exit, reflecting a thin shear layer, as shown in Fig. 6.

The large vortexes expanded and appeared in the downstream region as compared to the jet from the orifice nozzle having the same $CR = 0.11$, as shown in Fig. 8(e). It should also be mentioned that the jet from the quadrant nozzle did not grow as wide as those from the orifice nozzles. The flow when $CR = 0.11$ apparently spread wider and faster than the others. Therefore, the visualized images demonstrated that a smaller $CR$ enhanced the mixing rate more.

Figure 9 shows the jet centerline velocity $u_c/u_m$ for various $CR$ values with a quadrant nozzle at $Re = 1.5 \times 10^4$. The centerline velocity increased from the nozzle exit and reached the maximum at $x/d_o = 2.0$ for all of the orifice nozzles due to the vena contracta effect, while the velocity was almost constant from the nozzle exit up to $x/d_o \equiv 4.0$ and 5.0 for the jets with $CR = 1.00$ for the pipe nozzle and the quadrant nozzle, respectively. Thereafter the velocity decayed at the rate of $u_c/u_m \propto (x/d_o)^{-1.0}$ in the fully developed region. The velocity growth from the exit increased with a decreasing $CR$.

The centerline maximum velocities for different value of $CR$ at $x/d_o = 2.0$ are summarized in Fig. 10. The centerline maximum velocity $u_c/u_m$ can be expressed

$$u_c / u_m = 1.9CR^3 - 3.55CR^2 + 1.38CR + 1.53 \quad (for \ 0.1 < CR < 1.0)$$

which has a maximum value of 1.7 at $CR = 0.27$. Velocity vectors towards the centerline produced by a strong contraction at the orifice nozzle exit contributed to the increase in the centerline velocity, which had a maximum at $CR = 0.27$.

Figure 11 shows the cross sectional mean velocity at $Re = 1.5 \times 10^4$. Since the profile was axisymmetric, only the results in the half region of $r$ is shown. Even though the effects of the vena contracta were moderated at $x/d_o = 1.0$, the maximum velocity at the jet center was higher for a fully developed turbulent pipe flow than for the pipe jet at the...
nozzle exit. A steeper velocity gradient was observed at the edge of the jet for a smaller CR, producing a higher turbulence due to the strong shear force. In addition, we found that every cross-sectional velocity profile matched Tollmien’s theoretical solution for \( x/d_o > 5.0 \). Therefore, the exit velocity profile had negligible impact on the distance from the nozzle exit to the fully developed region.

The jet and half widths are plotted in Fig. 12. The jet width was determined from the location where the velocity ratio was \( u/u_m = 0.1 \). Both the widths varied with CR at \( x/d_o < 5 \). A larger CR provided larger widths corresponding to the shear layer thickness. However, the jets for a smaller CR grew so fast that both the widths in all the cases matched for \( x/d_o > 5 \). This rapid growth poses the increase in entrainment flow rate. In addition, the half jet width can be expressed by the function of \( x/d_o, b_{1/2}/d_o = F(x/d_o) \).

The measured ratios of entrainment flow rate to the exit flow rate are plotted in Fig. 13 along with the equation given by Boguslawski and Popiel (1979) for the pipe jet data. The flow rate at location \( x, Q_x \), was determined by

\[
Q_x = 2\pi \int_0^\delta urdr
\]

where \( \delta \) is the radial location at \( u/u_m = 0.01 \) and \( Q_0 \) is the flow rate at the nozzle exit.

A satisfactory agreement could be observed between the present pipe jet data and the line in the form of \( (Q_x - Q_0)/Q_0 = 0.183(x/d_o) \), as suggested by Boguslawski and Popiel (1979). In the case of the quadrant jet, the entrainment growth seemed slightly different from the pipe jet and was found to be expressed by \( (Q_x - Q_0)/Q_0 = 0.201(x/d_o) \). A sudden increase in the entrainment flow rate due to the thin shear layer, whose instability promoted the entrainment of the ambient fluid, was observed in the near field \( x/d_o < 1 \), as shown in Fig. 6. The entrainment flow rate increased linearly from \( x/d_o > 3 \) onwards with a decreasing CR. This relationship, in terms of the non-dimensional distance from the exit may be expressed from the present data by the function of \( x/d_o, (Q_x - Q_0)/Q_0 = F(x/d_o) \).

These results indicate that the CR affected the entrainment rate, making the jets from the smaller CR entrain ambient fluid more in the far field, \( x/d_o > 3 \).
3.3.2 Effect of notched orifice

It is conceivable to control the flow characteristics of the orifice jet with a notched turbulence promoter (Shakouchi et al., 2009, 2011).

Figure 14 shows the shape of a notched orifice nozzle. The notched orifice has 4- or 8-triangular shaped notches as shown in Fig. 14(c), (d). The nozzle exit diameter is \( d_o = 10.0 \) mm, the pipe inner diameter is \( d_i = 19.23 \) mm, and \( CR = (d_o/d_i)^2 = 0.27 \).

Figure 15 shows some examples of the visualized flow pattern of a submerged orifice or a notched orifice water jet at \( Re = 1000 \). The flow visualization was carried out by the laser-light-sheet technique. Ring-shaped vortex formations in the shear layer of the orifice free jet can be clearly seen in Fig. 15(a).

Figure 15(b) shows the flow pattern of the submerged orifice impinging water jet on the impingement plate. This was taken from the backside of the transparent acrylic resin plate which was set at the downstream of \( x/d_o = 2.0 \) and \( Re = 1000 \). The ring-shaped vortices impinge on the plate intermittently. The interval between ring-shaped patterns corresponds to the vortex shedding frequency.

Figures 15(c) and (d) show the orifice free and impinging jets with 8-notches, respectively. It is clearly observed that the presence of the notches strongly affects the flow patterns. The fluctuations at the nozzle edge produce large vortex structures in the downstream that intermittently impinge on the plate as observed in the orifice impinging jet. However, the large vortex structures of the notched orifice jets are distorted by small notches. Diamond-shaped and 8-pointed-star patterns are seen corresponding to the number of small notches located at the orifice nozzle exit.

The vortex shedding frequency of 4-notched and 8-notched orifice jets was higher and lower, respectively, than that of the orifice free jet.
Figure 16(a) shows the mean and fluctuating velocity distributions in the A-A’ section at the nozzle exit of $x/d_o = 0.2$ for the orifice, the notched orifice, and the pipe jets under the same operation power. The mean exit velocity, $u_{lum}$, is plotted on the left half of the figure and the fluctuating velocity, $u'/u_{lum}$ (RMS), is on the right half because they were axisymmetric. The results in the direction of B-B’ at the nozzle exit are plotted in Fig. 16(b) in the same manner. The saddle-backed profile is observed for the orifice jet, which is caused by the vena contracta effect. The maximum fluctuating velocity of the orifice jet occurs at the jet edge, and is attributed to the exit velocity vector inside the nozzle toward, the center because of the orifice nozzle contraction.

A similar profile can be seen for the notched orifice jets, especially in Fig. 16 (b). The jet widths of the orifice jets increase because of the notches in the A-A’ plane, while the vena contracta effects appear in the B-B’ plane. The differences between the profiles in the A-A’ plane and B-B’ plane become less significant when the number of notches increase. This might be attributed to the interference of vortices produced by the notches. The fluctuating velocity of the notched orifice jets increases in the A-A’ plane. The fluctuating velocity reflecting the steep velocity gradient near the center of the jet is higher than that of the notched orifice jets that are discharged toward the center of the jet and accelerated.
Figure 17 shows the jet center line velocity $u_c$ under the same operation power of the pipe jet. $u_c$ of the orifice jet increases from the nozzle exit because of the vena contracta effect and keeps nearly constant in a potential core region and subsequently reaches the fully developed stage. Similar trends of development are also observed for the notched orifice jets. The potential core length of the 4-notched jet is shorter than that of the others because there is a large mixing between the A-A' and B-B' sections with significant different velocity profiles.

The turbulence intensity of the 4-notched jet along the jet center line was larger than that of the others by approximately 47.2% at $x/d_o = 3.5$.

Figure 18 shows the jet spreading by jet width $b/d_o$ and half width $b_{1/2}/d_o$. They were obtained from the cross-sectional velocity measurements under the same operation power. The jet edge was defined as the position of radius direction $r$ where the velocity was $u/u_c = 0.1$. The both widths of the 8-notched jet are larger than those of the pipe and orifice jets not only because of the large nozzle exit width with notches but also because of the higher mixing performance with ambient fluid due to an axis-switching phenomenon, which can be seen in the range of $0.2 < r/d_o < 1.0$.

Figure 19 shows the visualized flow pattern of an 8-notched jet using the Schlieren method. The white colored line marks the half jet width. The jet at $Re = 1.5 \times 10^4$ was heated to 40 degrees above the ambient temperature to have a clear photo. The half width in the A-A' section is initially larger than that in the B-B' section because of the notches. However, the width becomes smaller in the range of $0.2 < x/d_o < 1.0$.

Figure 20 shows the equi-velocity profiles of the half jet width of 8-notched jet. The notches are located on the axes in Fig. 20. The pointed positions of the equi-velocity profile at the nozzle exit are flattened at $x/d_o = 1.0$ and the other positions are protruded, as shown by the arrows in Fig. 20. The axis-switching phenomenon (Shakouchi, 2011), in which the major axis and minor axis of the jet cross section are interchange, may be caused by longitudinal vortex flows produced at the edge of the notches, which causes the jet to accelerate and decelerate, distorting the vortex ring.

Figure 21 shows the volumetric flow rate of the 8-notched jet under the same operational power. The flow rate of the orifice jet is compared with the others. The cross-sectional flow rate, $Q_x$, was obtained by summing all the flow rates in the range of $\theta = 2\pi/16$ [rad], calculated from the cross-sectional velocity measurements by the following equation.
\[ Q_i = \int_{0}^{\frac{b}{a}} \int_{0}^{2\pi} u r \, dr \, d\theta \]  

where \( u \) is the mean velocity in the A-A’ and B-B’ sections.

The flow rate of the 8-notched jet at the nozzle exit of \( x/d_o = 0.2 \) increased by 10.9 % (9.7 % for the 4-notched jet) compared to the orifice jet under the same operational power.

### 3.3.3 Supersonic orifice jet

#### (a) Effect of contraction area ratio

The flow characteristics of a supersonic under-expanded free jet issued from a circular (Murakami, et al., 2000) or orifice nozzle (Shakouchi et al., 2019), especially the effect of the contraction area ratio, was examined.

Figure 22 shows the orifice nozzle (Ori-n) with a contraction area ratio \( CR = (d_o/d_i)^2 = 0.13 \). The nozzle exit diameter is \( d_o = 4.0 \, \text{mm} \), and is constant, and the \( CR \) can be changed by changing the pipe diameter \( d_i \).

![Orifice nozzle (Ori-n), CR = 0.13](image)

Figure 23(a) shows the effect of the \( CR \) on the flow pattern of the orifice jet (issued from Ori-n, Ori-jet) at \( P_o = 0.115 \, \text{[MPa]} \). At \( CR = 0.64 \), the jet spreads after exhibiting an almost constant jet width area from the nozzle exit. With a decreasing \( CR \), the spread of the jet, after an almost constant jet width area, becomes slightly smaller. Fig. 23(b) shows the results at \( P_o = 0.380 \, \text{[MPa]} \). At \( P_o = 0.38 \, \text{[MPa]} \), clear shock waves of expansion and compression appear; additionally, with an increasing \( CR \), the jet spread after an almost constant jet width area, becomes smaller expecting \( CR = 0.13 \).

Figure 24(a) shows the jet width of the Ori-jet, \( b/d_o \), near the nozzle exit at \( P_o = 0.115 \, \text{[MPa]} \). The jet width was obtained by the visualized flow pattern. The \( b/d_o \) of the Pi-jet is almost constant, but the Ori-jet increases to the downstream. With an increasing \( CR \), the \( b/d_o \) becomes larger; for example, at \( x/d_o = 4.0, CR = 0.64 \) is about 1.55 times that of the pipe jet (Pi-jet).

In Fig. 24(b), the results at \( P_o = 0.380 \, \text{[MPa]} \) are shown. The \( b/d_o \) at \( P_o = 0.380 \, \text{[MPa]} \) is about 1.27 times larger than that at \( P_o = 0.115 \, \text{[MPa]} \) because of a large flow expansion immediately after the nozzle exit. Additionally, in this
case, the Pi-jet, for \(x/d_o > 1.0\), does not spread in the radius direction and exhibits an almost similar width. The Pi-jet flows down as if penetrating almost without entraining the surrounding fluid. However, the \(b/d_o\) of the Ori-jet increases to the downstream because of the contraction effect of the orifice nozzle and indicates a maximum value at \(CR = 0.25\). For example, it is approximately 1.22 and 1.45 times that of the Pi-jet at \(x/d_o = 6.0\) and 8.0, respectively. The \(b/d_o\) of \(CR = 0.13\) is a minimum value because it has a large flow resistance at the nozzle, caused by a large contraction.

![Image](image_url)

**Fig. 23** Visualized flow pattern of orifice-jet by Schlieren image (\(d_o = 4.0\) mm, \(CR = 0.64\) - 0.13)

**Fig. 24** Jet width, \(b/d_o\), of orifice jet

Figure 25(a) shows the jet centre line velocity, \(u_c\), at \(P_o = 0.115\) [MPa]. In the visualized photograph [Fig. 23(a)], the shock waves caused by expansion and compression flows are shown; however, the velocity does not fluctuate because of them. The \(u_c\) increases immediately after the nozzle exit as the \(CR\) decreases, because of the flow contraction effect by the orifice nozzle and it is almost constant in the range of \(x/d_o < 4.0\). Also, in the downstream of \(x/d_o > 8.0\), \(u_c\) of \(CR = 0.13\) indicates the largest value and decreases as a function of the power of \((x/d_o)\).

Figure 25(b) shows the jet center line velocity at \(P_o = 0.380\) [MPa]. The \(u_c\) after the nozzle exit fluctuates primarily following the shock waves, as shown in Fig. 23(b). In the down-stream, the \(u_c\) of the pipe-jet indicates the largest value and decreases as a function of the power of \((x/d_o)\). For example, the \(u_c\) of the pipe-jet at \(x/d_o = 14\) is about 3.6 times that of the \(CR = 0.13\) because of the low flow pressure loss of the pipe-nozzle.
(b) Effect of notch

To improve the entrainment properties of the orifice jet, orifice nozzles with two types of notches, triangle (TR-n) and rectangle (Re-n), were used as shown in Fig. 26. They have small triangle or rectangular notches in four places around the circumference of the orifice nozzle.

Figure 27(a) shows the jet width for $P_o=0.020$ [MPa]. Both the jet widths of the pipe nozzle (Pi-n) and the orifice nozzle (Ori-n) increase with $x/d_o$, and the Pi-n jet is larger. For the Re-n jet, the minor axis is larger than the major axis. Additionally, it appears that switching has occurred.

Figure 27(b) shows the jet width, $b/d_o$, for $P_o=0.380$ [MPa] in the range of $x/d_o<4.5$. The jet width was obtained from the jet edge, where the brightness in the radius direction, in the photograph of the visualized flow, changed clearly. The jet width of the Pi-n jet was almost constant and was larger than that of the others, and the Ori-n jet increased in the downstream after experiencing the effect of flow contraction. In this case, it appears that the so-called switching phenomenon, in which the major and minor axes at the cross section of jet swap, had occurred.
Figure 28 shows the flow rate \( Q \) [Nm\(^3\)] at each cross section from \( x/d_o = 2.1 - 8.3 \), which was obtained by integrating the velocity distribution. The \( Q \) of the Re-n jet was obtained using the mean value sections of “a” and “b”. The \( Q \) of the Ori-n jet was smaller than that of the Pi-n jet in the range of \( x/d_o < 4.2 \) because of the flow contraction, and subsequently increased and became almost the same as that of the Pi-n jet. The \( Q \) of the Re-n jet in the range of \( x/d_o = 2.1 - 8.3 \) was larger than that of the others and the change was almost the same as the Ori-n jet. For example, the \( Q \) of the Re-n jet at \( x/d_o = 5.4 \) is approximately 1.55 times that of the Pi-n jet.

![Fig. 28 Volumetric flow rate \((P_o = 0.02 \text{ [MPa]})\)](image)

By applying this notched nozzle to a cylindrical ejector, its entrainment performance and efficiency, \( \eta \) could be enhanced approximately 1.63 times as compared to a circular pipe nozzle, i.e., \( \eta/\eta_{pipe} = 1.63 \), at the supplied pressure \( P_o = 0.02 - 0.04 \) [MPa]. However, at a higher supplied pressure of \( P_o > 0.08 \) [MPa] the entrainment efficiency did not improve because the flow resistance of the nozzle increased and the entrainment did not increase as much. Here, the entrainment efficiency is defined by

\[
\eta = \frac{Q_e}{Q_o} \cdot \frac{(P_o - P_a)}{\text{[m}^3/\text{kW} \cdot \text{s}]}
\]

where, \( Q_e \) is entrainment, suction, flow rate, \( Q_o \) is nozzle exit flow rate, and \( P_a \) is ambient pressure.

### 3.4 Chevron nozzle, noise reduction of high-speed jet

We can see the wave-shaped exit of the jet engine, as shown in Fig.29. This is called “Chevron nozzle”, and is used to reduce the jet noise (Gutmark et al., 2006, Munday et al., 2013). Gutmark et al. (2006) examined the effect of the chevron nozzle on noise reduction.

Figure 30 shows the separate flow exhaust model with primary and secondary exit areas of 23.23 cm\(^2\) and 80.65 cm\(^2\), respectively. One conical and three chevron nozzles with 8 and 12 lobe chevrons were used (Fig. 31). The chevron nozzle of which the level of penetration of the chevrons into the flow was equal to the boundary layer thickness and twice was used. They are marked as LP and HP in Fig. 31. Their acoustic studies identified that nozzle with a higher penetration provides a superior low frequency benefit. However, nozzle with a nominal penetration provides an inferior high frequency. The chevron penetration controls the strength of the mixing, and stronger mixing makes the jet

![Fig. 29 Boeing 787, jet engine with chevron nozzle](image)

https://www.quora.com/Why-does-the-Boeing-787-have-a-curved-engine
potential core length shorter, which leads to an additional noise reduction of lower frequency. However, this strong mixing generates an additional high frequency noise. To get an optimum benefit, it is important to tailor this design parameter.

There are many other studies on the chevron nozzle, and they concluded that the sound pressure level (SPL), can be controlled and reduced by the chevron nozzle. Furthermore, the chevron nozzle is used practically to reduce the jet noise from jet engine (Fig. 29).

4. Active jet flow control

In the above section, passive control of jet flows, especially an orifice jet, was discussed. Here, some examples of active flow controls of jets, wakes, and separated flows are shown simply.

There are many active flow control methods, but the following are interesting.

* active flow control by acoustic excitation:
  It is carried out basically by acoustic excitation of the natural vortex shedding frequency of gas jet. Crow and Champagne (1971) showed that the turbulent jets have a large scale coherent structure, and the flow characteristics of the coherent structure and their control by acoustic excitation to enhance the entrainment have been examined by many researches (Hussain et al., 1980, 1981, Gutmark et al. 1983, Ho et al., (1984).

* active flow control by sub jet, micro jet, synthetic jet, and plasma jet:
  By sub or micro jets (Freund et al., 2000, Ibrahim et al., 2002, Nakamura et al., 2006, Behrouzi et al., 2008, Saiki et al., 2016):
  The flow characteristics of the main jet can be controlled through the sub or micro jet injection. Behrouzi et al. (2008) demonstrated the active flow control of jet mixing using steady and pulsed fluid tabs by injectioning the flow into the jet core region at the nozzle exit. Nakamura et al. (2006) showed a new globular formation system of fine solid resin particles made by jet milling method of several µm to tens of µm using a hot gas jet of about 200°C. The performance was greatly improved by controlling the flying path of the particles in a hot gas by the jets issued from triple concentric nozzle.

By synthetic jet (Smith et al., 1998, Caruana et al., 2009, Tan et al., 2015):
  The synthetic jet with zero net mass flux generated by the alternate movement of a diaphragm is used for the flow control. Caruana et al. (2009) used the plasma jet as a synthetic jet, and Tan et al. (2015) showed the heat transfer enhancement of impinging jet by a synthetic jet.

By plasma jet (Touchard, 2008, Hasebe et al., 2011, Caruana et al., 2013):
  The Dielectric-Barrier-Discharge Plasma Actuator, DBD-PA, has two electrodes separated by a dielectric

![Dielectric-Barrier-Discharge Plasma Actuator, DBD-PA](fig32.png)
subject, as shown in Fig. 32. Applying a high voltage alternating current between two electrodes causes the air near the exposed electrode to be ionized, and the ions accelerate the surrounding air, and induce a flow. The induced flow can be used to control the main flow.

* active flow control by intelligent nozzle:

Suzuki et al. (2004), Kurimoto et al. (2004) and Kasagi (2006) demonstrated the active jet flow control by an intelligent nozzle with 18 electromagnetic flap actuators as shown in Fig. 33(a). These flap actuators are cantilever and their one end can be moved inward of the nozzle, and their movements can be controlled arbitrarily. By controlling the movement of each flap arbitrary, various kinds of flow patterns can be realized. One example can be seen in Fig. 33(b). This shows the flow pattern of jet bifurcation induced by the actuation of alternate modes at the Strouhal number, \( St = 0.25 \).

* active flow control by Coanda attached flow:

By Coanda jet flow:

NOTAR helicopter, MD500 (NOTAR Technology, 2017), without tail rotor uses anti-torque system with no moving part. The downward flow by main rotor flows around the tail boom. To produce the thrust against the torque action by the main rotor the downward flow around the tail boom is controlled by the thin blowing jet from the slit nozzle set on one side and along the length direction of the tail boom. The attached flow on the tail boom by the Coanda effect is accelerated by the thin blowing jet flow, and consequently the lift force is generated. This lift force is used as anti-torque force. To prevent the flow separation on the wing surface at a large attack angle and enhance the lift force, a blowing jets from small holes or thin slits and a Coanda attached flow are used (US-2, 2017).

5. Concluding remarks

In this paper, the passive flow control of jet flows was mainly examined and reviewed, with the flow characteristics, control methods and some examples, because jet flows include the essence of fluid dynamics, such as boundary layer flow, turbulent flow, shear flow, separated flow, and flow mixing. In particular, the effects of nozzle shape, the tab, rib, and vortex generator, and the orifice or notched nozzle on the flow characteristics of jet flows including supersonic flow, flow control, and suppression of high-speed jet noise by chevron nozzle, and others were examined. Furthermore, some methods of active flow control, for example, using an intelligent nozzle were also examined.

Globular formation of fine solid particles by flow control, lift control of airplane wings, flow control of NOTAR helicopter without tail rotor, and others were also examined briefly.

Passive flow control is effective and economical control method, however it is important to know the flow characteristics well and use it because the flow situation changes largely with a slight change in the shape of flow.
passage.

As mentioned above, in this paper, passive flow control of jets flows were mainly examined, however, active flow control is also very important because passive flow control method is useful but its effectiveness is limited.

Now, it seems desirable to improve the feed forward control using advanced sensing, data collection and organization, IT and AI technologies and establish the control method by combining it and the feedback control.

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