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Experimental Studies of a Radial Turbulent Jet (4th Report, Flow at and after an Attaching Point of Attaching Jet Flow)*

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A study has been made of a flow at and after an attaching point of a radial attaching jet flow on an adjacent offset disc plate. Mean velocity, turbulent velocity and static pressure distributions were measured. The effects of the diameter and width of nozzles, and also of the distance of nozzle center from an offset plate on flow pattern were investigated.

A flow field has been divided into three regions : recirculating flow region formed near a nozzle outlet, transitional region where jet center velocity increases downward, and wall jet flow region where jet center velocity decreases with distance. Changes of jet center velocity, thickness of inner layer and jet half width in the wall jet flow region along the flow were measured, and it was found that these results agreed well with those for the radial wall jet flow.

1. Introduction

When a jet issuing from a nozzle attaches to an adjacent offset plate, a negative pressure region is formed between the wall and the jet before the attaching point, which will probably be due to the entrainment of fluid by the jet. There have been many studies concerning the flow before the attaching point of the two-dimensional attaching jet flow^{(1)~(5)}. The flow after the attaching point of the two-dimensional attaching jet flow has also been studied to some extent⁽⁵⁾⁽⁶⁾, and it has been shown that this flow has nearly the same characteristics as the two-dimensional wall jet flow. An axisymmetric circular jet or a radial attaching jet flow has been studied by only a few investigators.

This paper concerns the radial attaching jet flow at and after the attaching point. Mean velocity, turbulent velocity and static pressure distributions in the jet were measured, and the results were compared with those for the radial wall jet flows⁽⁷⁾⁽⁸⁾. Both the present results and those in the previous report⁽⁹⁾ will give a sufficient knowledge on the radial attaching jet flow.

Nomenclature

$\sqrt{A}$: equivalent nozzle width = $\sqrt{\pi D_0 L}$

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b : half width of a jet (for the flow before the attaching point, half distance between the points of $u/U_m = 0.5$ in lateral distribution, and for the flow after the attaching point, distance from a wall surface to the point of $u/U_m = 0.5$ in lateral distribution)

D_0 : nozzle diameter

H : step height (distance of nozzle center plane from wall surface)

L : width of slot nozzle

p : static pressure (gauge)

p_0 : wall pressure (gauge)

p_{0m} : maximum value of wall pressure p_0

r : radial distance from cylindrical nozzle axis

u : mean velocity component in r -direction

u' : root-mean-square value of the longitudinal turbulent velocity

u'_1 : value of u' at the maximum jet velocity

U_0 : discharge velocity from slot nozzle

U_m : maximum value of u measured in lateral direction

U_1 : maximum value of U_m measured in longitudinal direction

U_2 : minimum value of U_m measured in longitudinal direction

x : radial distance measured from nozzle outlet

x_0 : radial distance of the nozzle outlet measured from virtual origin of a jet

x_s : value of x at the position of jet attaching point

x^* : radial distance measured from virtual origin of a jet

y : normal distance measured from wall surface

δ_m : thickness of inner layer of flow after the attaching point

η : dimensionless expression of y , $= y/b$

2. Experimental equipment and procedure

The apparatus used for this experiment is almost the same as those in the previous reports⁽⁷⁾⁽⁹⁾⁽¹⁰⁾. Details of the nozzle section and the experimental arrangements are shown in Fig.1. The experiment was performed for the nozzle discharge velocity $U_0 = 40$ m/s, which was proved to be suitable in the previous studies.

Mean and turbulent velocities were measured with a hot-wire anemometer of the constant temperature type with linearized output. Static pressure distribution on wall surface was measured by means of a pitot static tube (0.5mm inside diameter) traversed along the wall surface. This value was also compared with that obtained from static pressure openings ($\phi 0.5$ mm) on the solid wall. Another disc type probe (outside diameter is 20 mm, and hole diameter is 0.5 mm)⁽¹¹⁾ was used to measure the pressure within the flow. All static pressures were led to the pressure pick-up of strain gauge type and the outputs were recorded automatically.

3. Experimental results and discussion

3.1 Deflection and attachment of jet

3.1.1 Distributions of velocities, turbulences and static pressures

Figure 2 shows the distributions of the velocities u/U_0 , the turbulences $(u'/U_0)^2$ and the static pressures $p/(1/2)\rho U_0^2$ across the sections situating at various distances from the nozzle, $x/L = 1/6, 5, 9$, under the conditions of $D_0/L = 15$ and $H/L = 6$. For the range of $x/L \leq 11$, jet center axis (maximum point of u/U_0) tends toward the wall as x/L increases, and the jet attaches to it completely at the sections of $x/L \geq 15$. Within the range of $x/L < 15$, a reversed flow is formed near the wall by entrained fluid around the jet. The flow in this region has been studied

Fig.1 Nozzle section and nomenclature

in the previous report⁽⁹⁾, so that this report deals with the flows at and after the attaching point.

Intensity of turbulence $(u'/U_0)^2$ takes a maximum value near the wall surface and also another maximum value at about the outer boundary of the jet, showing the same tendency as the radial wall jet flow.

Static pressures $p/(1/2)\rho U_0^2$ remain almost negative in the regions before the attaching point, and become approximately an atmospheric pressure after the attaching point.

3.1.2 Distributions of jet center velocities, turbulences, jet half widths and wall pressures

Figure 3 shows the changes of the jet center velocities U_m/U_0 , the turbulences u_1'/U_0 and u_1'/U_m along the x -axis for the height of steps of $H/L = 2 \sim 12$. Results for a radial wall jet flow⁽⁷⁾ are also compared in this figure.

Fig.2 Lateral distributions of velocities, turbulences and static pressures

Although the center velocity U_m/U_0 in the radial wall jet flow decreases gradually, U_m/U_0 in the radial attaching jet flow decreases abruptly near the nozzle outlet and takes a minimum value at the attaching point. This fact may be due to the increases of static pressure and turbulence near the attaching point, and due to the decreases of them after the attaching point. With an increasing step height H/L , the positions of the maximum and the minimum center velocity points move downstream. In this case, the minimum values of U_m/U_0 , U_2/U_0 , and the maximum values of U_m/U_0 , U_1/U_0 reduce with an increasing step height H/L . In the regions after the maximum value of jet center velocity, U_m/U_0 decreases gradually at nearly the same rate as the radial wall jet flow as shown by the dotted line in Fig.3.

Distributions of the turbulences at the jet center velocity points, u_1'/U_0 , take the maximum values at the sections of $x/L = 8 \sim 15$. After these sections u_1'/U_0 decreases gradually and approaches the values for the radial wall jet flow, when $H/L \geq 6$. Turbulent intensities u_1'/U_m increase near the nozzle outlet section as the jet center velocity U_m/U_0 decreases, and take the maximum values at the position of the minimum value of U_m/U_0 (position of jet attaching point). The value

Fig.3 Changes of jet center velocities and turbulences at velocity maxima along the x-axis

of u_1'/U_m , however, decreases in the regions where U_m/U_0 increases (accelerating flow region), and becomes minimum at the position of the maximum value of U_m/U_0 , after which u_1'/U_m increases gradually at nearly the same rate as in the radial wall jet flow.

Figure 4 shows the changes of jet center velocities U_m/U_0 and jet half widths b/H along the x-axis for various values of L and H/L . In the cases of a small step height $H/L \leq 4$, the position of the minimum value of U_m/U_0 , U_2/U_0 , moves to the small value of x/H as H/L increases, since the flow pattern is not proportional to the step height H for the small value of H/L ⁽⁹⁾. In the cases of a large step height $H/L \geq 6.5$, the position of U_2/U_0 remains unchanged ($x/H = 2.10$) as shown by the dotted line in Fig.4. This position corresponds to the jet attaching point, where jet half width b/H becomes maximum. The region of $2.10 < x/H < 3.10$ is a transitional region, in which the jet center velocity U_m/U_0 increases and the jet half width b/H decreases in the downstream direction. After the transitional region, the jet contracts to the minimum width at the position of $x/H = 3.10$ shown by the broken line for $H/L \geq 6.5$ in Fig.4, where U_m/U_0 becomes maximum and b/H minimum. In the region of $x/H > 3.10$, U_m/U_0 decreases gradually and b/H increases linearly.

Figure 5 shows the changes of wall pressures $p_0/(1/2)\rho U_0^2$ along the x-axis for various values of H/L . Near the nozzle outlet the pressures $p_0/(1/2)\rho U_0^2$ are negative and have the minimum values. After that $p_0/(1/2)\rho U_0^2$ increases suddenly from a negative value to a positive one, showing a maximum value at the jet attaching point. The position of the maximum wall pressure moves asymptotically to the small value of x/H as H/L increases, and in the region of a large step height $H/L \geq 6$, it

Fig.4 Changes of jet center velocities and half widths of jet along the x-axis

can be considered to be constant ($x/H = 2.10$) as shown by the dotted line in Fig. 5. This position corresponds to the co-ordinate x defined by the minimum value of jet center velocity as mentioned previously. In the region of $2.10 < x/H < 3.10$ (transitional region), an abrupt pressure reduction due to the acceleration of flow (U_m/U_0 increases shown in Fig. 4) can be seen. In the further downstream regions ($x/H > 3.10$), the wall pressure is almost same as the atmospheric pressure.

From the above results it can be concluded that for the large step height $H/L \geq 6$, U_m/U_0 becomes maximum, b/H minimum and $p_0/(1/2)\rho U_0^2$ maximum at the position of jet attaching point, $x/H = 2.10$, and U_m/U_0 reaches maximum and b/H minimum at the position of the contracted point, $x/H = 3.10$.

Flow fields can be divided into the following three regions:

(a) Recirculating flow region ($x/H < 2.10$), in which U_m/U_0 decreases and b/H increases in the downstream direction. Wall pressure $p_0/(1/2)\rho U_0^2$ increases from a negative value to a positive one.

(b) Transitional region ($2.10 < x/H < 3.10$), in which the flow is accelerated as x/H increases, and U_m/U_0 increases and b/H decreases as well. Wall pressure $p_0/(1/2)\rho U_0^2$ decreases to the atmospheric pressure.

(c) Wall jet flow region ($x/H > 3.10$), in which U_m/U_0 decreases and b/H increases with an increase of x/H , and $p_0/(1/2)\rho U_0^2$ is substantially equal to the atmospheric pressure.

Detailed discussion will be given for the regions (b) and (c) except the region (a) as it was done in the previous study⁽⁹⁾.

3.2 Flow at the position of jet attaching point

As mentioned above, the wall pressure takes the maximum value and the jet center velocity becomes minimum at the position

Fig. 5 Changes of wall pressures along the x -axis

of the jet attaching point. The velocity and the pressure will be discussed in relation to the step height H/L .

Values of the maximum wall pressure $p_{0m}/(1/2)\rho U_0^2$ (the wall pressure at the jet attaching point) are plotted against the step height H/L in Fig. 6 for various nozzle shapes D_0/L . The values of $p_{0m}/(1/2)\rho U_0^2$ change with D_0/L , but they have nearly the same tendency for large values of H/L , where $p_{0m}/(1/2)\rho U_0^2$ varies proportionally to $(H/L)^{-2}$. As a reference, the value of $p_{0m}/(1/2)\rho U_0^2$ proposed by Sawyer⁽²⁾ for the two-dimensional attaching jet flow is shown by the dotted line in Fig. 6, showing a linear relationship of $(H/L)^{-1}$ for large values of H/L .

Rearranging the results of Fig. 6 using the equivalent nozzle width, $\sqrt{A}$, values of $p_{0m}/(1/2)\rho U_0^2$ for different nozzle openings can be plotted in a single curve as shown in Fig. 7, from which the following expression can be derived for $H/\sqrt{A} \geq 0.8$,

$$p_{0m}/(1/2)\rho U_0^2 = 0.75(H/\sqrt{A})^{-2.0} \dots\dots\dots (1)$$

Fig. 6 Maximum value of wall pressure

Fig. 7 Maximum value of wall pressure

Making use of Figs.3 and 4, the relationships between the minimum values of U_m/U_0 , U_2/U_0 (the jet center velocity at the jet attaching point), and the maximum values of U_m/U_0 , U_1/U_0 (the jet center velocity at the contracted point) for different step heights H/L can be plotted as shown in Fig.8. The critical values of U_1/U_0 and U_2/U_0 change with D_0/L , but have nearly a similar tendency for the range of large values of H/L , varying proportionally to $(H/L)^{-1}$. As a reference, the minimum values of jet center velocity, U_2/U_0 , for two-dimensional parallel jets⁽¹¹⁾ are shown by the dotted line, changing in proportion with $(H/L)^{-1/2}$, in Fig.8. The jet center velocity U_m/U_0 of a two-dimensional free jet changes in proportion to $1/\sqrt{x}$, whereas that for a radial free jet is in proportion to $1/x$, hence, the minimum value of U_m/U_0 of a radial attaching jet flow is smaller than that of a two-dimensional attaching jet flow.

Rearranging the results of Fig.8 using the equivalent nozzle width, $\sqrt{A}$, values of U_1/U_0 and U_2/U_0 for different nozzle openings can be plotted in a single curve as shown in Fig.9, from which the following expressions can be derived for $H/\sqrt{A} \geq 0.8$,

$$U_1/U_0 = 0.35(H/\sqrt{A})^{-1.0} \quad (2)$$

$$U_2/U_0 = 0.23(H/\sqrt{A})^{-1.0} \quad (3)$$

Fig.8 Maximum and minimum values of jet center velocity

Fig.9 Maximum and minimum values of jet center velocity

Equations (1) to (3) are the results for the nozzle dimensions of $9.0 \leq D_0/L \leq 30.0$, and they are considered to be valid for $6.0 \leq D_0/L \leq 60.0$.

3.3 Flow after the attaching point

3.3.1 Velocity and turbulence profiles

In Fig.10 velocities of the flow after the jet attaching point, u/U_m , are plotted against the dimensionless distance $\eta = y/b$ for the cases of $H/L = 6$ and 8. The velocity profiles for different lateral sections x/L and step height H/L are almost identical. These results are in good agreement with that of a radial wall jet flow proposed by Glauert⁽⁸⁾ shown by a solid line ① or the experimental results of the radial wall jet flow⁽⁷⁾ (symbol ●). The velocity profile may be divided into two regions at the point of maximum jet velocity shown by the dotted line ($\eta \approx 0.170$); the inner layer near the wall and the outer layer away from the wall surface.

The distribution of turbulences $(u'/U_m)^2$ is shown in Fig.11. The turbulence at the outlet section of nozzles is derived to be $(u'/U_0)^2 \approx 0.035$ from Fig.2 for $H/L = 6$. The turbulence $(u'/U_m)^2$ after the attaching point increases with an increase of x/L as shown in Fig.11, and its distribution curves have nearly similar profiles, but are not identical with the velocity profiles in Fig.10. The degree of the turbulent intensity is nearly the same as that of the radial wall jet flow shown in the same figure (symbol ●). The values of $(u'/U_m)^2$ take a maximum value for each curve at the position of $\eta \approx 0.10$ near the wall and also another maximum value at about $\eta \approx 0.75$ near the outer boundary of the jet. The values of $(u'/U_m)^2$, however, become minimum at about the position of velocity maxima, $\eta \approx 0.170$.

The results of Figs.11 and 12 correspond to the particular cases for a nozzle of $D_0/L = 15$ and step heights of $H/L = 6$ and 8, and they will be available for the other nozzle shapes and step heights.

Fig.10 Velocity profiles of flow after jet attaching point

3.3.2 Virtual origin of flow after the attaching point

In general a virtual origin of the flow from which the jet can be supposed to be discharged does not correspond to the nozzle outlet section, but its position varies with the nozzle shape. Therefore, the virtual origin of the jet flows after the attaching point has to be derived for comparison of the flows with a radial wall jet flow. As mentioned in the previous report⁽¹⁰⁾, the virtual origin of the jet can be given by x_0 , the ordinate of a point, at which the lines for each value of dimensionless velocity u/U_m cross.

In Fig.12, the virtual origin of the jet x_0/L (upstream direction of nozzle outlet section) is shown against the step height H/L for various nozzle widths L . The values of x_0/L for different values of L are plotted in a single curve, the inclination of which changes for the value of $H/L = 6$. From these results the following expressions are obtained,

$$x_0/L = 0.94(H/L)^{3/4} \quad (2 < H/L < 6) \quad \dots\dots(4)$$

$$x_0/L = 0.60(H/L) \quad (H/L \geq 6) \quad \dots\dots(5)$$

In the previous report⁽⁸⁾ the position of the jet attaching point, x_s/L , was found to be expressed by the following formulas for various values of D_0/L ,

$$x_s/L = 3.15(H/L)^{3/4} \quad (1.5 < H/L < 6)$$

$$x_s/L = 2.10(H/L) \quad (H/L \geq 6)$$

If the step height is smaller than 6, the position of jet attaching point x_s/L is not proportional to the step height H/L , since a deflection of jet occurs in the region of jet potential core. On the other hand, for a large step height $H/L \geq 6$, x_s/L varies proportionally to H/L . The same results are given for the flow after the jet attaching point. Comparing the above equa-

Fig.11 Turbulent velocity profiles of flow after jet attaching point

tions, the ratio of x_0 to x_s is given by

$$x_0/x_s \approx 0.30 \quad \dots\dots(6)$$

From this result, it is seen that the virtual origin of the jet assumed by the flow after the jet attaching point coincides with the jet attaching point itself.

3.3.3 Changes of inner layer thickness and half width of jet

As a measure of the thickness of the flow after the attaching point, the distance from the wall surface to the point of velocity maxima δ_m can be used for the inner layer thickness, and the half width of a jet b from the wall surface to the point of y where $u/U_m = 0.5$ (see Fig.1) for that of the outer layer.

The results in Fig.4 for the jet half width b/H can be rearranged in a more general form with use of the distance from the virtual origin of the jet x^*/L , the results of which are shown in Fig.13. At the position of the jet attaching point, the jet half width b/L takes the maximum value and it decreases rapidly in the downstream direction to the minimum value at the contracted point. Beyond this point, b/L increases almost linearly, the relationship of which can be expressed as

$$b/L = 0.094 (x^*/L)^{0.97} \quad \dots\dots(7)$$

The increasing tendency of b/L from the minimum to the value expressed by Eq. (7) is not constant, but it depends on the step height H/L .

After the jet attaching point, the inner layer grows, the thickness of which δ_m/L is shown in Fig.13. It is seen that δ_m/L increases linearly after the contracted point where b/L is minimum, and is expressed by

$$\delta_m/L = 0.016(x^*/L)^{0.97} \quad \dots\dots(8)$$

From Eqs.(7) and (8), the ratio of δ_m to b (the wall region breadth to the whole jet width) becomes approximately constant and is given by

$$\delta_m/b \approx 0.170 \quad \dots\dots(9)$$

Fig.12 Changes of virtual origin of jet with step height

The relationships of Eqs.(7) to (9) agree well with those for the radial wall jet flow⁽⁷⁾.

3.3.4 Decay of jet center velocities

Making use of the distance from the virtual origin of jet x^*/L , the changes of jet center velocity U_m/U_0 along the x -axis for various values of H/L in Fig.3 can be rearranged as shown in Fig.14. The jet center velocity U_m/U_0 takes the minimum value at the position of the jet attaching point and then increases in the downstream direction, taking the maximum value at the contracted point. Thereafter, U_m/U_0 decreases linearly, the relationship of which can be expressed as follows,

$$U_m/U_0 = 12.1(x^*/L)^{-1.07} \dots \dots \dots (10)$$

The decreasing tendency of U_m/U_0 from the maximum to the value expressed by Eq. (10) is not constant, but it depends on the step height H/L .

Making use of the equivalent nozzle width, $\sqrt{A}$, Eq.(10) becomes as follows,

$$U_m/U_0 = 1.54(x^*/\sqrt{A})^{-1.07} \dots \dots \dots (11)$$

which has almost the same form as the following equation for the radial wall jet flow⁽⁷⁾,

$$U_m/U_0 = 1.52(x^*/\sqrt{A})^{-1.09}$$

3.3.5 Changes of turbulent velocities

Figure 15 shows the turbulent velocities at the velocity maxima, u_1'/U_0 and u_1'/U_m . The turbulent velocity u_1'/U_0 in

which u_1' is divided by the nozzle discharge velocity U_0 takes the maximum value at the position where U_m/U_0 shows the minimum value, and then decreases in the downstream direction. On the other hand, u_1'/U_m in which u_1' is divided by the maximum value of u in each section U_m takes the maximum value at the position of the jet attaching point, and then decreases rapidly, showing the minimum value at the contracted point. Thereafter, u_1'/U_m increases gradually and approaches the following constant value,

$$u_1'/U_m = 0.26 \dots \dots \dots (12)$$

The tendency of the curves to this value is not constant, but it depends on the step height H/L . Equation (12) shows the same form as that for the radial wall jet flow⁽⁷⁾.

The results of Fig.13 to Fig.15 for the nozzle of $D_0/L = 15$ are available for the other nozzles with different values of D_0/L .

Fig.14 Changes of jet center velocities along the x -axis

Fig.13 Changes of inner layer and half width of a jet along the x -axis

Fig.15 Changes of turbulences at velocity maxima along the x -axis

4. Conclusions

The results of the investigation on the flow at and after the attaching point of the radial attaching jet flow can be summarized as follows :

(1) For the large step height $H/L \geq 6$, the flow field can be divided into the following three regions by considering the attaching point ($x/H = 2.10$) and the contracted point ($x/H = 3.10$) ;

$x/H < 2.10$; recirculating flow region

$2.10 < x/H < 3.10$; transitional region

$x/H > 3.10$; wall jet flow region

(2) The jet center velocity and the wall pressure at the jet attaching point can be expressed for $H/\sqrt{A} \geq 0.8$ as follows ;

$$U_z/U_0 = 0.23(H/\sqrt{A})^{-1.0}$$

$$p_{0m}/(1/2)\rho U_0^2 = 0.75(H/\sqrt{A})^{-2.0}$$

(3) Distributions of the velocities u/U_m and the turbulences $(u'/U_m)^2$ of the flow after the jet attaching point are similar to those of the radial wall jet flow.

(4) The virtual origin of the flow after the jet attaching point is expressed by a single curve, the inclination of which changes for the value of $H/L = 6$, and the following expressions can be obtained,

$$x_0/L = 0.94(H/L)^{3/4} \quad (2 < H/L < 6)$$

$$x_0/L = 0.60(H/L) \quad H/L \geq 6$$

(5) The results of the flow after the jet attaching point are given as follows ;

Thickness of inner layer and jet half width :

$$\delta_m/L = 0.016(x^*/L)^{0.97}$$

$$b/L = 0.094(x^*/L)^{0.97}$$

Ratio of the wall region breadth to the whole jet width :

$$\delta_m/b \approx 0.170$$

Jet center velocity :

$$U_m U_0 = 1.54(x^*/\sqrt{A})^{-1.07}$$

These results agree well with those for the radial wall jet flow.

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