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Experimental Study of a Radial Turbulent Jet (1st Report, Effect of Nozzle Shape on a Free Jet)*

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Mean velocity and turbulence together with pressure distributions in a radial free jet flows were studied. By changing diameter and width of nozzles and discharge velocity, the flow pattern were measured.

The concept of the equivalent nozzle width which contains the diameter and width of the nozzle can be usefully applied to describe both maximum flow velocity decay and growth of the jet half width with distance from a nozzle outlet. The maximum flow velocity decay and the growth of the jet half width lie on a single curve according to this equivalent nozzle width. In the main region at large nozzle Reynolds number, the maximum flow velocity decays following the same rule as in circular jet, and the growth of the jet half width is in good agreement with that in the two-dimensional jet.

1. Introduction

In the past, many theoretical and experimental studies on jet flows have been performed because of their wide applications to the engineering problems. But the investigations were almost limited to the cases of two-dimensional jets or axisymmetric three-dimensional jets^{(1)~(3)}, and details of the problems remain unsolved. Thus, the jet flows are again becoming an attractive subject among many investigators.

Cylindrical jet flows have been studied to some extent, by Tuve⁽⁴⁾, Abramovich⁽⁵⁾ and Heskestad⁽⁶⁾, but the effects of nozzle opening on the flow pattern have not been clarified.

In this paper, mean velocity and turbulence together with pressure distributions of the jet issuing from ring nozzles with various openings were measured. The results were compared with those obtained already for two-dimensional jets or circular jets. Theoretical treatment was given to the flow within the fully developed region of the jet flows.

Nomenclature

$\sqrt{A}$: equivalent nozzle width = $\sqrt{\pi D_0 L/2}$
 b : half width of a jet (half distance between the points of $u/U_m = 0.5$ in lateral Distribution)
 b_1 : half width of uniform velocity region within the initial region
 b_p : half width of a jet in the static

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pressure distribution

D_0 : nozzle diameter

$$J = J_u + J_t + P$$

J_0 : efflux momentum of nozzle outlet = $\rho U_0^2 \pi D_0 L$

$$J_t = 2\pi \rho r \int_{-\infty}^{\infty} u'^2 dy$$

$$J_u = 2\pi \rho r \int_{-\infty}^{\infty} u^2 dy$$

$$K = J_u / \rho$$

l_u : mixing length = $u' / (\partial u / \partial y)$

L : width of nozzle slot

p : static pressure

p_m : minimum value of p measured in lateral direction

$$P = 2\pi r \int_{-\infty}^{\infty} p dy$$

r : radial distance from a nozzle axis

r_0 : nozzle radius = $D_0/2$

R_e : exit Reynolds number based on nozzle slot = $U_0 L / \nu$

R_{eA} : exit Reynolds number based on equivalent nozzle width = $U_0 \sqrt{A} / \nu$

u : mean velocity component in r-direction

u' : root-mean-square value of the longitudinal turbulent velocity = $\sqrt{u'^2}$

u_m' : maximum value of u' measured in lateral direction

U_0 : discharge velocity from nozzle

U_m : maximum value of u measured in lateral direction

v : mean velocity component in y-direction

x : radial distance measured from virtual origin of a jet

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

x_1 : length of potential core

y : normal distance measured from x-axis

ϵ : virtual kinematic viscosity [Eq.(4)]

ϕ : stream function [Eq.(5)]

$$\kappa = \varepsilon / U_m b$$

$$\eta = \sigma y / r$$

σ : parameter of jet expansion

ν : kinematic viscosity of air

ρ : density of air

2. Equation on velocity distribution

Figure 1 shows the co-ordinate system and the main nomenclature of the radial free jet. The free jet discharging from a nozzle to the surrounding rested fluid is generally divided into two regions: the initial region near the nozzle where the maximum jet velocity has not yet begun to decay, and the second region downstream of the initial region where the flow develops fully and the maximum velocity is decreasing continuously.

The present study concerns mainly the fully developed region. In this case, the equations of continuity and motion can be written as ⁽⁶⁾,

$$\partial(ur)/\partial r + \partial(vr)/\partial y = 0 \quad (1)$$

$$u(\partial u/\partial r) + v(\partial u/\partial y) = \varepsilon(\partial^2 u/\partial y^2) \quad (2)$$

The boundary conditions are

$$y=0; u=U_m, v=0, \partial u/\partial y=0,$$

$$y \rightarrow \infty; u=0 \quad (3)$$

The virtual kinematic viscosity is given by

$$\varepsilon = \kappa b U_m \quad (4)$$

Denoting the maximum velocity at section $r = s$ by U_s , the following stream function ψ can be introduced as in the two-dimensional jet ⁽⁷⁾,

$$\psi = \sigma^{-1} U_s r F(\eta), \quad \eta = \sigma y / r \quad (5)$$

and the velocity components are

$$u = \frac{U_s}{r} F'(\eta), \quad v = \frac{U_s}{\sigma r} \{\eta F'(\eta) - F(\eta)\} \quad (6)$$

Substitution of Eqs.(5) and (6) into Eq.(2) yields the following differential equation for $F(\eta)$;

$$F'^2 + F F'' + \frac{\varepsilon \sigma^2}{U_s} F''' = 0 \quad (7)$$

Since the third term of Eq.(7) contains a free constant, it may be allowed that ⁽⁷⁾,

$$\varepsilon \sigma^2 / U_s = 1/2 \quad (8)$$

Fig.1 Co-ordinate system and nomenclature

Substituting Eq.(8) into Eq.(7), and integrating Eq.(7) three times with the boundary conditions given by Eq.(3), the following result can be obtained

$$F(\eta) = \tanh \eta \quad (9)$$

Now, the momentum of jet in the radial direction can be calculated by

$$J_u = \rho K = 2\pi \rho r \int_{-\infty}^{\infty} u^2 dy,$$

and hence the following form can be obtained

$$U_s = \sqrt{3\sigma K/8\pi} \quad (10)$$

Using this result the velocity component u in Eq.(6) is expressed as follows

$$u = \sqrt{3\sigma K/8\pi} \operatorname{sech}^2 \eta / r \quad (11)$$

From Eq.(11), the maximum velocity at $\eta=0$ becomes

$$U_m = \sqrt{3\sigma K/8\pi} / r \quad (12)$$

From the above results the following nondimensional form of the velocity in r -direction can be obtained

$$u/U_m = 1 - \tanh^2 \eta \quad (13)$$

This is exactly the same as Goertler's equation ⁽⁷⁾ found for a two-dimensional jet.

3. Experimental equipment and procedure

3.1 Equipment

Figure 2 shows the apparatus used for this experiment. The flow from the blower (2) is separated equally into two flows by the divided guide vane (4). Each flow passes through the control valve (5), settling chamber (7) and discharge duct (8), and joins again at the cylindrical nozzle (9). Consequently, a jet is issued radially from this cylindrical nozzle (9).

(1) variable motor	(6) duct
(2) turbo blower	(7) settling chamber
(3) air filter	(8) discharge duct
(4) divided guide vane	(9) cylindrical nozzle
(5) flow control valve	(10) automatic traversing equipment

Fig.2 Experimental equipment

3.2 Nozzle

Three types of nozzles as shown in Fig.3 were used in order to find the effects of the nozzle shape on the jet flow. The nozzle tip a) has a circular roundness and the nozzle tip b) has an elliptical roundness at the upstream edge respectively, and each discharge edge has a straight part of 2 mm. Flange type nozzle tip c) has the same roundness as nozzle b), but has a straight part of 17 mm. These nozzles have two static pressure holes (0.5 mm ϕ) at the station of 50 mm upstream from the discharge edge. Flow control valves [Fig.2-(5)] were adjusted to equilibrate the pressure in two pressure holes so that the uniform velocity profile at the nozzle outlet was obtained.

The greatest care was taken to align the axes of two nozzles installed up- and downward.

3.3 Measuring apparatus

Mean and turbulent velocities were measured with a hot-wire anemometer of the constant temperature type with linearized output. The hot-wire which was made of tungsten had a diameter of 5 μ and an active length of 1 mm. Static pressure was measured by a pitot static tube (0.5 mm ϕ inside diameter) and a pressure pick-up of strain gauge type. The hot-wire probe and pitot static tube were moved in the radial direction r and the normal direction y with an automatic traversing equipment [Fig.2-(10)] driven by a servomotor. The traversing speed was changed stepwise

Fig.3 Nozzle

Table 1 Experimental conditions

D_0 mm	60	90	120
L mm	2, 4, 6, 8	2, 3, 4, 5, 6, 8, 10	2, 4, 6, 8, 10
U_0 m/s	20~80	20~80	20~80
Re	2.6×10^3 $\sim 4.3 \times 10^4$	2.6×10^3 $\sim 5.5 \times 10^4$	2.6×10^3 $\sim 5.5 \times 10^4$
Re_A	1.8×10^4 $\sim 1.46 \times 10^5$	2.2×10^4 $\sim 2.01 \times 10^5$	2.6×10^4 $\sim 2.32 \times 10^5$
A mm ²	$60\pi \sim 240\pi$	$90\pi \sim 450\pi$	$120\pi \sim 600\pi$
$\sqrt{A}$ mm	13.7~27.5	16.8~37.6	19.4~43.4

to 5, 15 and 45 mm/min in r direction, and 0.8, 2.4 and 7.2 mm/min in y direction. The speed was selected to accord with the response of the measuring equipment. The outputs of the hot-wire and pressure pick-up were recorded automatically with an electric signal generated by means of a photo-transistor. The distance of the signal was 0.5 mm in r and 0.25 mm in y direction, respectively.

3.4 Experimental conditions

The experiments were carried out under the conditions given in Table 1. Measurements were performed for nozzle mouth velocities of 20 m/s $\sim$ 80 m/s, which correspond to the exit Reynolds numbers $Re = U_0 L / \nu$ of $2.6 \times 10^3 \sim 5.5 \times 10^4$.

The velocities at the nozzle outlet section were reasonably uniform over about 85 % of nozzle width in the case of the nozzles a) and b), and about 70 % in the case of the nozzle c), Fig.3. Symmetry of the flow was checked by measuring the velocities at the nozzle outlet section.

4. Experimental results and discussion

4.1 Lateral distributions of velocities, turbulences and static pressures

Figure 4 shows the distributions of velocities u/U_0 , turbulences $(u'/U_0)^2$ and static pressures $p/(1/2)\rho U_0^2$ across the sections of various values of $x/L = 1/6, 2, 4$, respectively, where x denotes the radial distance from the virtual origin of

Fig.4 Lateral distributions of velocities, turbulences and static pressures

a jet (see Sec.4.2). The turbulence $(u'/U_0)^2$ shows a maximum value at the outer boundary of the jet within section of $x/L = 1/6$. The static pressure $p/(1/2)\rho U_0^2$ has a positive value at the center of the jet near the nozzle.

The changes of velocity, turbulence and static pressure along the x-axis will be discussed later in Sec.4.2.

4.1.1 Size of jet potential core

As is seen in the velocity profile u/U_0 in Fig.4, jet potential core in which the nozzle exit velocity U_0 is maintained exists in the region near the nozzle outlet. Figure 5 a) shows how the width of the jet potential core b_1 changes with the downstream distance. In flange type nozzle of $D_0 = 120$ mm, the boundary layer grows more than in the other two nozzles having small values of D_0 , and hence the tendency of the curves in Fig.5 a) is also changed. In this case, if the ratio of the potential core length x_1 (the value of x at $b_1/L = 0$) to the nozzle width L is taken, then $x_1/L = 3.5 \sim 5.0$. These values are nearly equal to those obtained for the circular jet, namely, $x_1/L = 4.0 \sim 5.0$ ⁽⁵⁾, but considerably smaller than $x_1/L = 6.0 \sim$

8.0 ⁽⁵⁾, or $x_1/L = 6.5$ ⁽⁸⁾ which is obtained for two-dimensional jets.

Using a parameter $x/\sqrt{A}$ ($\sqrt{A} = \sqrt{\pi D_0 L/2}$, see Sec.4.2.1), the above results are rearranged in Fig.5 b), in which all the curves for different values of L and D_0 fall into a single curve. From this result the following relationship can be obtained

$$x_1 = 0.90\sqrt{A} \dots \dots \dots (14)$$

4.1.2 Velocity profiles

In Fig.6 velocities u/U_m in the main region are plotted against the parameter $\eta = y/b$. The velocity profiles for different lateral section x/L are fairly similar regardless of the nozzle diameter D_0 , and the results are in good agreement with Eq. (13) (solid line in figure). The equation for a radial jet proposed by Abramovich⁽⁵⁾ is shown by a dotted line, which deviates from the present data, when $y/b \geq 1.5$.

4.1.3 Turbulent velocity and static pressure profiles

Profiles of turbulences $(u'/U_m)^2$ are shown in Fig.7. The value of $(u'/U_m)^2$ increases with the distance measured downstream from the nozzle outlet. The turbulence of the two-dimensional jet⁽²⁾ is compared in this figure, showing a fairly good coincidence.

Using u_m' , the maximum value of u' in each section, the values of u' in Fig.7 are rearranged in Fig.8. The rearranged profile of turbulence $(u'/u_m')^2$ is seen to be similar within the region of $x/L \geq 20$, and coincides well with that of a two-dimensional jet⁽²⁾.

Fig.5 Size of jet potential core

Fig.6 Velocity profiles in main region

Fig.7 Lateral distribution of turbulent velocities in main region

The results of the static pressure $p/\rho U_m^2$ are shown in Fig.9, in which the effects of nozzle diameters D_0 can be scarcely seen and the profile coincides well with that obtained for a two-dimensional jet⁽²⁾. The pressure at the jet center shows slightly a negative value. The results in Fig.9 are rearranged in Fig.10, where the pressure p is referred to the minimum value p_m and the abscissa to the half width of jet b_p for each section. The experimental points of p/p_m lie on a single curve within the region of $x/L \geq 20$,

Fig.8 Lateral distribution of turbulent velocities in main region

Fig.9 Lateral distribution of static pressures in main region

showing good agreement with Goertler's result⁽⁸⁾ (solid line in Fig.10).

4.2 Changes of velocities, turbulences and static pressures along the x-axis

Changes of velocity U_m/U_0 , turbulence $(u'/U_0)^2$ and static pressure $p_m/(1/2)\rho U_0^2$ measured along the x-axis are shown in Fig. 11. To check the effects of the nozzle exit velocity on the flow, six series of the nozzle exit velocities U_0 between 30 ~ 80 m/s were used. It is found from Fig.11 that there are no effects of the Reynolds number, when $Re \geq 1.64 \times 10^4$.

The length of the potential core is found from Fig.11 a) to be $x_1/L \approx 4$. In this range, both the values of turbulence $(u'/U_0)^2$ and turbulence intensity u'/U_m

Fig.10 Lateral distribution of static pressures in main region

Fig.11 Changes of velocity, turbulence and static pressure along the x-axis

become nearly zero [Fig.11 b)] since in the potential core there is no mixing, and the static pressure $p_m/(1/2)\rho U_0^2$ has a small positive value [Fig.11 c)]. In the transitional region in which the potential core is dying out, the turbulence $(u'/U_0)^2$ increases and reaches a maximum value, while the static pressure $p_m/(1/2)\rho U_0^2$ decreases and takes a minimum value at about $x/L = 10 \sim 15$. For comparison, the changes of the static pressure along the x-axis for the two-dimensional jet⁽²⁾ is also shown in Fig.11 c).

In Fig.12, the values of r and y , for which the dimensionless velocity u/U_m tends to a constant value are plotted for $u/U_m = 9/10, 3/4, 1/2$ and $1/3$. The growth of the jet width and the virtual origin of the jet can be read from these results. Experimental points for the same values of u/U_m lie on a single line, and the inclination of them varies with u/U_m . The lines for each value of u/U_m cross at a special point. The ordinate of the point, x_0 , from the nozzle outlet may be taken to be a virtual origin of the jet within the main region.

Figure 13 shows the effects of the exit Reynolds number Re on the ratio x_0/r_0 . As can be seen in this figure, x_0/r_0 remains constant within the range of $Re \geq 1.4 \times 10^4$, and $x_0/r_0 = 0.10$ regardless of nozzle diameter D_0 . As the virtual origin of the jet, the following values have been found already,

$x_0/L = 1.572^{(2)}, 1.86^{(5)}, 2.25^{(8)}$; two-dimensional jet,
 $x_0/L = 2.20^{(5)}$; circular jet.

In this experiment a rather different value of x_0/r_0 may be obtained, namely,

Fig.12 Equal dimensionless velocity lines

Fig.13 Virtual origin of a jet in main region

from Fig.13, $x_0/r_0 = 0.10$ for the radial jet. This may be written as $x_0/L = 0.10 \times (r_0/L)$, from which $x_0/L = 0.45 \sim 1.50$.

4.2.1 Decay of jet velocities and growth of jet half widths

Figure 14 shows the changes of maximum jet velocity U_m/U_0 and the half width of the jet b/L along the x-axis for various nozzle openings. As mentioned in Sec. 4.1.1, the abscissa x_1 where the maximum velocity begins to decay is changed by the values of L and D_0 . In the main region downstream of the initial region described just above, U_m/U_0 decreases in proportion to $(x/L)^{-1.0}$. On the other hand, the value of b/L lies on a single curve and increases in proportion to x/L regardless of L and D_0 . As a reference, a result of the two-dimensional jet⁽⁸⁾ is shown in Fig.14. In this jet flow the values of U_m/U_0 decrease as $x^{-0.5}$. In spite of this fact, the growth of the half width of the radial jet coincides well with that for the two-dimensional jet.

Abramovich⁽⁵⁾ has used a parameter $\sqrt{\pi D_0 L / 4\pi} = \sqrt{A/2\pi}$

to arrange his experimental results for a radial jet (fan jet). Rearranging the result of Fig.14 with use of the equivalent nozzle width $\sqrt{A}$, Fig.15 can be obtained. The decay of the maximum velocity U_m/U_0 is seen to lie on a single curve. The maximum velocity U_m/U_0 remains constant in the initial region ($x/\sqrt{A} \leq 0.90$), and decreases gradually as $x/\sqrt{A}$ in the transitional region ($0.90 < x/\sqrt{A} < 2.5$).

Fig.14 Changes of maximum velocity, half width of a jet and turbulence intensity along the x-axis

In the main region ($x/\sqrt{A} \geq 2.5$), the maximum velocity decays as follows, when $ReA \geq 9.77 \times 10^4$,

$$U_m/U_0 = 1.61(x/\sqrt{A})^{-1.0} \quad (15)$$

The experimental result by Tuve⁽⁴⁾ and the empirical curve by Abramovich⁽⁵⁾ are also shown in Fig.15. It is found that the curve of Abramovich is considerably lower than that given by Eq.(15). This may be due to the fact that Abramovich's results are arranged with an assumption that the virtual origin of the jet is at the nozzle outlet.

The half width of the jet in the main region ($x/\sqrt{A} \geq 2.5$) grows as follows, when $ReA \geq 9.77 \times 10^4$,

$$b/\sqrt{A} = 0.098(x/\sqrt{A})^{1.0} \quad (16)$$

This is in good agreement with Foerthmann's result⁽⁵⁾ obtained for a two-dimensional jet.

4.2.2 Turbulent velocities along the x-axis

The changes of turbulence u'/U_0 and turbulence intensity u'/U_m along the x-axis are given in Fig.14. The turbulence u'/U_0 changes with the nozzle width L and the diameter D_0 as well as the maximum velocity U_m/U_0 . The turbulence intensity, however, takes a constant value of $u'/U_m \approx 0.30$ when $x/L \geq 40$, irrespective of L and D_0 . The changes of turbulence u'/U_0 and u'/U_m along the x-axis for the two-dimensional jet⁽⁸⁾ are also shown in Fig.14. The turbulence u'/U_0 for the two-dimensional jet is larger than that obtained in the present study, and the turbulence intensity u'/U_m approaches rapidly a constant value in the course of flow. The constant value for the two-dimensional jet is $u'/U_m \approx 0.22$, and this is 25 % smaller than that for the radial jet obtained in this experiment.

4.3 Virtual kinematic viscosity and mixing length

The virtual kinematic viscosity is

Fig.15 Changes of maximum velocity and half width of a jet along the x-axis

expressed from Eqs.(8), (10) and (12) as follows,

$$\varepsilon = U_m r / 2\sigma^2 \quad (17)$$

Within the region sufficiently downstream from the nozzle, it may be assumed that $r \approx x$, and hence Eqs.(4), (16) and (17) give the relation of $\kappa = 1/0.098 \times 2\sigma^2$. From this experiment, the value of σ can be taken to be $\sigma \approx 8.99$, and hence the following result can be obtained,

$$\kappa \approx 0.0631 \quad (18)$$

This is approximately twice the value of $\kappa = 0.037$ ⁽⁷⁾ found in the two-dimensional jet and also of $\kappa = 0.025$ ⁽⁷⁾ in the circular jet. This means that the diffusion of the momentum in the radial jet is more intensive than in the two-dimensional or the circular jet.

This fact may also be confirmed by examining the mixing length $l_u = u' / (\partial u / \partial y)$ found from the measured turbulence intensity u'/U_m . Figure 16 shows the lateral distribution of the mixing length l_u/b obtained from the turbulence profile given in Fig.7. When $\eta \geq 0.5$, the mixing length l_u/b remains roughly constant and $l_u/b = 0.40 \sim 0.45$ for each nozzle. On the other hand, the values for the two-dimensional jet by Abramovich⁽⁵⁾ were 0.24 to 0.26. Thus, the momentum diffusion in the radial jet is more intensive than in the two-dimensional jet. These results confirm the changes of virtual kinematic viscosity explained above.

Fig.16 Mixing length

4.4 Conservation of jet momentum flux

Taking into account the static pressure variation and turbulence intensity, the equation of the momentum at any cross section of the jet is given as follows⁽²⁾,

$$J_u/J_0 + J_t/J_0 + P/J_0 = J/J_0 \dots \dots \dots (19)$$

where

$$J_u = 2\pi\rho r \int_{-\infty}^{\infty} u^2 dy, \quad J_t = 2\pi\rho r \int_{-\infty}^{\infty} u'^2 dy$$

$$P = 2\pi r \int_{-\infty}^{\infty} p dy, \quad J_0 = 2\pi\rho r_0 U_0 L$$

Usually, in the free jet P is of the same order of magnitude as J_t but different in sign, and the two terms cancel out. Then the momentum J_u is conserved⁽⁷⁾.

The changes of J_u , J_t and P with x can be found by the graphical integration of Figs. 6, 7 and 9, respectively, and the results are shown in Fig. 17. The momentum due to turbulence J_t/J_0 and the static pressure P/J_0 are considerably small, being in order 5 % of the velocity momentum J_u/J_0 . Each momentum is preserved approximately in the whole course of flow.

Consequently, the total momentum J/J_0 becomes nearly equal to the velocity one J_u/J_0 , and is conserved as in a two-dimensional jet. The momentum flux in the main region is expressed by the following relation,

$$J/J_0 \doteq J_u/J_0 \doteq K/K_0 = 1.06 \dots \dots \dots (20)$$

This result is shown in Fig. 17.

Fig. 17 Changes of jet momentum

5. Conclusions

The results of the investigation about the effects of the nozzle diameter, nozzle width and nozzle exit velocity on the radial free jet may be summarized as follows:

(1) The velocity profiles in the main region are similar and are in good agreement with the profile obtained by Goertler for a two-dimensional jet. The profiles of turbulence $(u'/U_m)^2$ and the static pressure $p/\rho U_m^2$ are not similar, but the profiles of $(u'/u_m')^2$ and p/p_m are similar and expressed by a single curve.

(2) By arranging the results with the equivalent nozzle width $\sqrt{A} = \sqrt{\pi D_0 L/2}$, decay of the maximum jet velocity and growth of the jet half width can be expressed by a single curve. When $ReA \geq 9.77 \times 10^4$, the flow field is divided into the following three regions,

$x/\sqrt{A} \leq 0.90$: initial region

$0.90 < x/\sqrt{A} < 2.50$: transitional region

$x/\sqrt{A} \geq 2.50$: main region

(3) The maximum velocity in the main region decays following the same rule as in circular jet and is expressed by

$$U_m/U_0 = 1.61(x/\sqrt{A})^{-1.0}$$

(4) Growth of the half width of the jet is in good agreement with that in the two-dimensional jet and is expressed by

$$b/\sqrt{A} = 0.098(x/\sqrt{A})$$

(5) The virtual kinematic viscosity ϵ is found to be $0.0631bU_m$ and the mixing length l_m/b is $0.40 \sim 0.45$. These values are considerably greater than those obtained for a two-dimensional jet.

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