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TOWARDS FULL FIELD SCALING OF THE CENTERLINE BEHAVIOR FOR INITIALLY TURBULENT AXISYMMETRIC JETS

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ABSTRACT

Recently the authors introduced a length scale for effectively collapsing the near field centerline velocity and mass fraction of constant and variable density axisymmetric jets whose initial conditions correspond to those of fully developed turbulent pipe flow. The new length scale incorporated the initial mass, momentum and turbulence intensity fluxes to capture the Reynolds number dependence of near field development for the velocity and scalar distributions often observed in low Reynolds number turbulent jets. The present paper makes the normalization technique more robust by extending its applicability to the intermediate and far fields using a dynamic length scale based on the local centerline turbulence intensity. The normalized velocity distributions of a constant density jet at several Reynolds numbers collapse over the entire length of jet development when the axial distance is normalized by the proposed length scale, thus achieving Reynolds number independence.

NOMENCLATURE

A	jet cross-sectional area
J_0	initial momentum flux ($= \int_{A_0} \rho U^2(0,r) dA$)
K	centerline decay rate
\dot{m}_0	initial mass flux ($= \int_{A_0} \rho U(0,r) dA$)
r_0	initial jet radius
r_e	effective jet radius (Eq. 2)
r^*	length scale incorporating mass, momentum and turbulence intensity characteristics
R_ρ	density ratio ($= \rho_0 / \rho_\infty$)

Re	Reynolds number ($= 2r_0 U_b \rho_0 / \mu_0$)
t	time
Tu	turbulence intensity ($= U' / \bar{U}$)
U	velocity
z	streamwise distance, measured from jet exit and positive in bulk flow direction
z_0	virtual origin

Greek letters

η	normalized centerline turbulence intensity
μ	dynamic viscosity
ρ	density
τ_0	initial turbulence intensity flux per unit area ($= 1/A_0 \int_{A_0} Tu(0,r) dA$)

Subscripts & Other Notation

0	jet exit plane
0.5	streamwise location where the velocity equals half of the maximum jet velocity at the exit
∞	ambient (surroundings)
b	bulk (average)
l	local field
m	maximum
pc	potential core
u	velocity field
$(\quad)'$	denotes root mean squared (rms) value
(\quad)	denotes time averaged mean value

INTRODUCTION

The push to design improved products and processes for achieving ever increasing optimization has given momentum to the synergistic blend of engineering fundamentals and automation, through computers and control technology. At the same

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time the compactness of modern systems has placed stringent requirements on controlling and coping with variations within a system. Axisymmetric turbulent jets are used in a variety of engineering applications because of their ability to provide high mixing rates in simple and safe configurations. To better control such mixing processes, accurate prediction of jet dynamics is necessary, especially in the early stages of development where important interacting processes, such as, combustion, recirculation and entrainment, are initiated.

There is a considerable volume of information on jets available in the literature (see reviews by: Harsha, 1971; Chen and Rodi, 1980; Gouldin et al., 1986) and it is safe to say that a good understanding exists on jet characteristics and development in the far-field, or self-similar region. In this region of flow the mean and fluctuating centerline velocity of an axisymmetric jet issuing into a still ambient is well described by the following equations:

$$\begin{aligned} \frac{\bar{U}(0,0)}{\bar{U}(z,0)} &= K_u \left(\frac{z-z_{0,u}}{r_e} \right), \\ \frac{U'(z,0)}{\bar{U}(z,0)} &= \text{constant}. \end{aligned} \quad (1)$$

K_u is the centerline decay constant for the velocity, $U(z,r)$. The streamwise distance, z , is measured from the jet exit plane, but to achieve a generic set of equations the introduction of a virtual origin, z_0 , is necessary. This latter term is a displacement along the centerline of the jet representing a correction to the actual origin that yields the location where an idealized point jet-source, having the same mass, momentum and far-field development as the actual jet, would be located. It can thus be regarded as a means of incorporating the effects of non-idealized initial conditions.

The effective radius,

$$r_e = \frac{\dot{m}_0}{(\pi \rho_0 J_0)^{1/2}} \quad (2)$$

introduced in a simpler form first by Thring and Newby (1953) and used in this form by several researchers (Dahm and Dimotakis, 1987; Dowling and Dimotakis, 1990; Pitts, 1991a; Richards and Pitts, 1993) incorporates some initial conditions, primarily the density ratio $R_\rho = \rho_0/\rho_\infty$, but also velocity distribution non-uniformity, through the mass and momentum fluxes at the jet exit plane, \dot{m}_0 and J_0 , respectively. Dahm and Dimotakis (1990) have shown, using dimensional analysis, that the effective radius as defined in Eq. (2) is the appropriate length scale to nondimensionalize the axial coordinate of the jet fluid concentration in the far-field. After a detailed study of variable density jets, Richards and Pitts (1993) concluded that

the final asymptotic state of all momentum-dominated axisymmetric jets depends only on the rate of momentum addition when the streamwise distance is scaled appropriately with r_e . They also showed that, regardless of the initial conditions (fully developed pipe and nozzle flow), axisymmetric turbulent free jets decay at the same rate, spread at the same half-angle, and both the mean and rms mass fraction values collapse in a form consistent with full self-preservation. Nevertheless, the problem of the virtual origin still remains, and is an unknown parameter that needs to be determined specifically for each configuration.

Investigations focusing on the variation of the virtual origin have indicated qualitatively how various initial parameters, such as Reynolds number, profile shape, turbulence intensity and density ratio, affect its location. Some attempts at quantifying the trends observed, especially with respect to Reynolds number, have yielded empirical relations that are merely best fits to specific experimental data (see discussion by Pitts, 1991b). These correlations indicate a downstream displacement of z_0 with increasing Re , reaching an asymptotic value at large Re .

In a recent investigation undertaken by the authors (Papadopoulos and Pitts, 1998) the controlling parameter responsible for the variation of centerline velocity and concentration decay characteristics with Re in the near field of jets whose exit characteristics correspond to those of fully developed turbulent pipe flow was identified to be the initial turbulence intensity flux. The initial turbulence intensity is a significant source of excitation that feeds into the growing shear layer, thus governing directly the growth of turbulence responsible for breaking up the jet potential core and for transitioning the jet into a fully developed self-similar flow. Combining the initial turbulence intensity flux with the definition of the effective radius resulted in a new length scale that captured the near field variation of the velocity and scalar centerline decay with Re , and thus collapsed these distributions for these types of turbulent axisymmetric jets.

The present paper extends the aforementioned work by presenting a similar length scale that is more robust, in that not only it collapses the centerline behavior for turbulent Re cases in the near field, but also in the intermediate and far field as well.

EXPERIMENTAL SETUP AND APPARATUS

Test Configuration

Measurements were performed in a jet produced by a long straight pipe having a sharp-edged exit. The diameter was $6.08 \pm 0.04^{\dagger}$ mm. The gas supply to the pipe passed first into a cylindrical settling chamber (120 mm long and 100 mm in

[†]Reported uncertainties are at 95% confidence.

diameter) and then through a series of pipe fittings before entering the pipe. The fittings provided the necessary initial artificial disturbance to guarantee fully developed turbulent conditions at the exit of the pipe, 103 diameters downstream, for the flow rates considered in the investigation.

Air was the working fluid supplied from an in-house pressurized distribution system. It was filtered to remove oil, moisture, and particulates. A long supply line with several looped copper sections ensured that the issuing jet was in temperature equilibrium with the ambient air. A 100-L/min mass flow controller, accurate to $\pm 1\%$ of full scale and with repeatability of $\pm 0.2\%$ of full scale per manufacturer's specifications, was used to meter the gas. Calibration of the mass flow controller for air was performed using an Optiflow 730 Digital Flowmeter.²² The uncertainty in the mass flow calibration was less than $\pm 1.5\%$. Ambient conditions, temperature and barometric pressure, were recorded at the beginning and end of each complete test for determining the average jet properties. Overall, beginning-to-end ambient variations were small, less than $\pm 0.5^\circ\text{C}$ and $\pm 2\text{ Pa}$. The resulting uncertainty in the bulk flow velocity based on the mass flow controller setting was $\pm 2\%$, which yielded an uncertainty in Re of $\pm 2.2\%$.

Velocity Measurements

A single wire, hot-wire probe was used to measure the velocity at the exit of the pipe and along the centerline of the air jet. The probe was a $2.5\text{-}\mu\text{m}$ diameter tungsten wire with a sensing length of 0.4 mm . It was controlled by a TSI IFA100 anemometer, which incorporated voltage gain and offset capabilities for optimizing the analog output over the voltage range of the Masscomp computer's analog-to-digital converter used to digitize the signal. Calibration of the hot-wire was performed using a TSI Model 1125 Calibrator unit over the velocity range of 2 m/s to 60 m/s . The calibration data was fitted to a general King's law relation, $E^2 = A + BU^n$, where E is the hot-wire voltage output and A , B , n are calibration constants. The absolute error in U was estimated to be no more than 4% . The frequency response of the hot-wire was approximately 25 kHz . Data sampling was performed at 500 Hz and 10 kHz ($0 \leq z/r_0 \leq 21$), $10,000$ and $30,000$ samples respectively, the high sampling rate used to better evaluate velocity dynamics in the near and intermediate fields. The uncertainties associated with determining the mean and rms values were less than 0.2% of the initial centerline velocity at the exit of the jet.

The pipe assembly was fixed horizontally on a lab bench with the jet issuing into the laboratory. Fine meshed screens

²²Certain commercial equipment, instruments or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

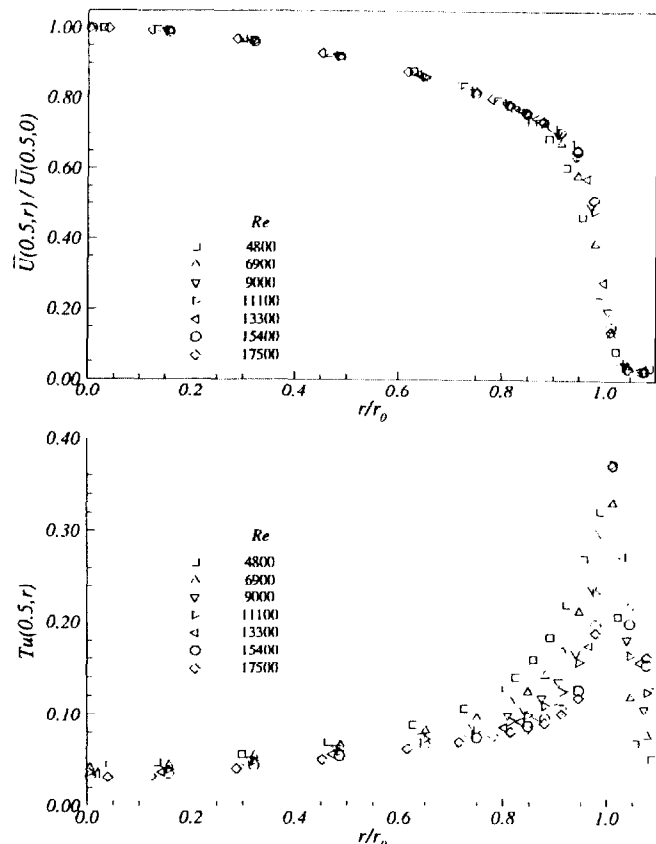


Fig. 1 Normalized mean velocity and turbulence intensity distributions at $z/r_0 = 0.16$.

placed at a standoff distance of about 0.3 m surrounded the jet to limit the effects of cross-currents in the room. A two-dimensional computer-controlled traverse was used to move the hot-wire probe in relation to the jet. For measuring the exit velocity distribution, the wire was centered longitudinally along a jet diameter and traversed perpendicular to it with the wire's longitudinal axis normal to the travel and incoming flow directions. The streamwise location of this measurement was $z = 0.5\text{ mm}$. The local mean velocity (normalized by the centerline value) and the turbulence intensity obtained from these measurements are shown in Fig. 1. Centerline measurements were performed up to a location of $z/r_0 \approx 90$. The error in initially positioning the probe was less than $\pm 0.05\text{ mm}$ and $\pm 0.1\text{ mm}$ in the radial and streamwise directions, respectively. Subsequent positioning was done at a manufacturer's specified accuracy of $\pm 1.6\text{ }\mu\text{m}$ and $\pm 3.2\text{ }\mu\text{m}$, respectively.

RESULTS

Mass, momentum and turbulence intensity distributions at the exit plane influence flow development in the near field of the jet, the latter being a perturbation mechanism that feeds into the growing shear layer. Initial mass and momentum distributions

are already incorporated in the definition of the effective radius, Eq. (2). Since the gas density is constant across the exit of the jet, Eq. (2) may be written as

$$r_e = R_p^{1/2} r_u; \quad r_u = \frac{M_0}{(\pi N_0)^{1/2}} \quad (3)$$

where

$$M_0 = \int_{A_0} U(0,r) dA$$

$$N_0 = \int_{A_0} U^2(0,r) dA \quad (4)$$

The term r_u represents the contribution to the effective radius of the mean velocity distribution at the exit. For a uniform (top-hat) profile $r_u = r_0$, while for a parabolic profile $r_u = \sqrt{3}r_0/2$. For a turbulent velocity profile r_u needs to be determined by integrating the profile at the pipe exit. Doing so for the present data, as well as for other data found in the literature, gives the results shown in Fig. 2. The horizontal lines in the figure show the values one gets if a power law profile is assumed,

$$\frac{\bar{U}(0,r)}{\bar{U}(0,0)} = \left(1 - \frac{r}{r_0}\right)^{1/\kappa} \quad (5)$$

where κ takes on values from 5 to 7 as Re increases

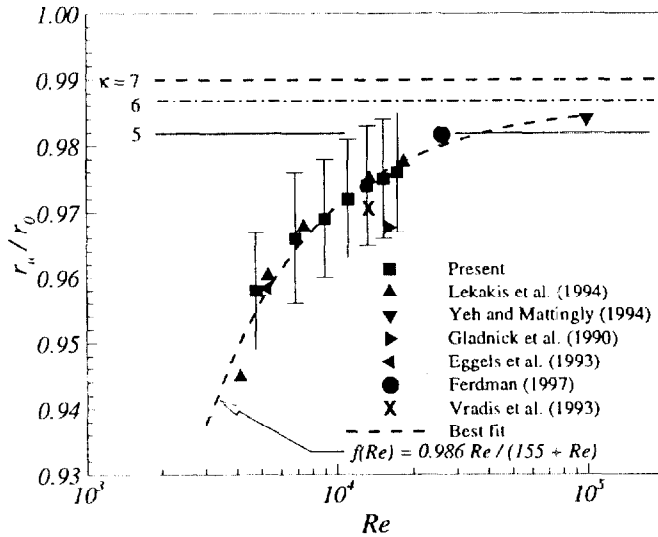


Fig. 2 Contribution to effective radius resulting from exit velocity distribution consideration only.

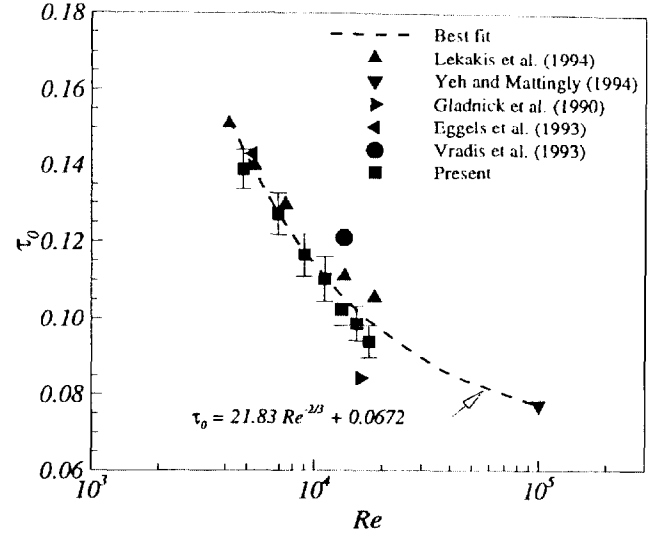


Fig. 3 Initial turbulence intensity flux per unit area.

(Schlichting, 1979).

In the authors' previous work (Papadopoulos and Pitts, 1998) a new length scale was introduced,

$$r_0^* = r_e \tau_0^{-1/2} = \frac{R_p^{1/2} M_0}{(\pi N_0 \tau_0)^{1/2}} \quad (6)$$

which incorporated the jet's initial mass, momentum, and turbulence intensity information, the latter through the turbulence intensity flux per unit area, τ_0 , shown in Fig. 3. Normalization of the axial distance by r_0^* collapsed the near field centerline velocity and mass fraction decay curves. The effectiveness of r_0^* on the present measurements and those of Lee et al. (1996) is realized in Fig. 4 where the mean centerline velocity distribution for several Re is shown. However, since far field similarity requires that the flow be dependent only on the total mass and momentum flux, and not on any specific characteristics of the initial flow, the normalization by r_0^* fails to correlated the data when extended to the far field region, as evident in Fig. 5.

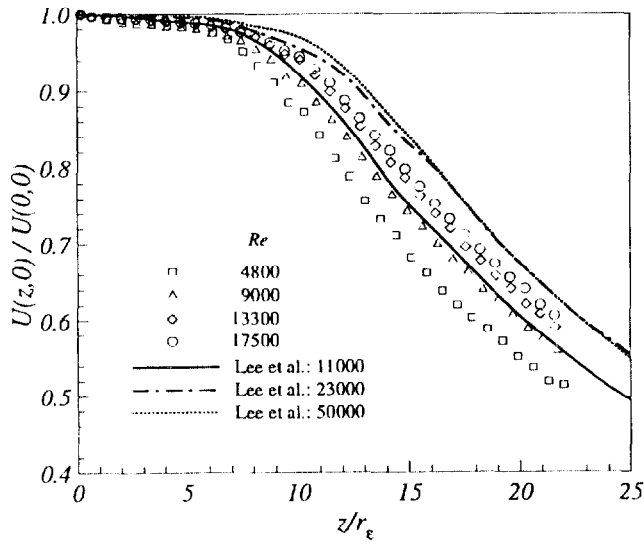
In order to correct the aforementioned shortcoming of r_0^* as a nondimensionalizing length scale, it is clear that a dynamic term replacing the constant τ_0 term is necessary. The effectiveness of r_0^* in the near field implies that this dynamic term be initially equal to τ_0 . On the other hand, far field similarity requires that the effective radius be the proper length scale to nondimensionalize the axial coordinate. Thus, in the far field the dynamic term needs to equal unity. These two bounds may be satisfied by introducing a dynamic term of the form $\tau_0^{\eta/2}$ with $\eta = f(Tu)$ taking on values between one and zero, thus incorporating the expected diminishing effect of the initial turbulence intensity on the growth of the shear layer as the jet

propagates downstream.

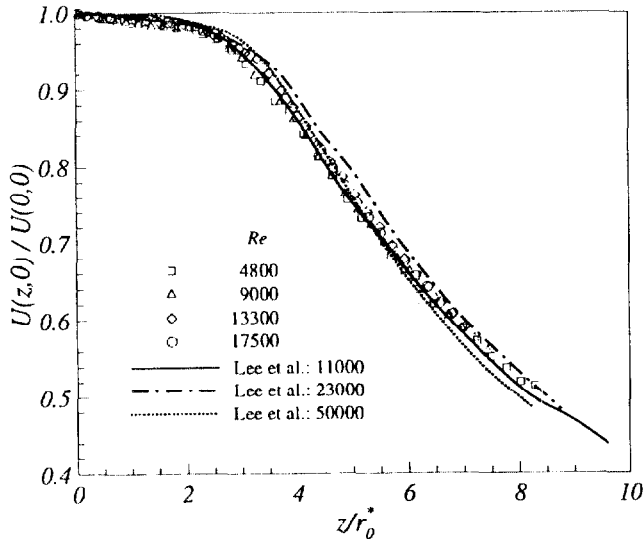
A function for η meeting the aforementioned criteria may be formed by considering the centerline turbulence intensity distribution, normalized to yield a value of one at the jet exit and zero in the far field. The result is

$$\eta = \frac{Tu(\infty,0) - Tu(z,0)}{Tu(\infty,0) - Tu(0,0)} \quad (7)$$

where $Tu(\infty,0)$ is the centerline turbulence intensity measured in the jet far field, which according to Eq. (1) is a constant



(a)



(b)

Fig. 4 Normalized mean centerline velocity decay for several Re : (a) axial distance normalized by effective radius; (b) axial distance normalized by length scale based on initial mass, momentum, and turbulence intensity fluxes.

throughout this self-similar region. Figure 6 shows distributions of η for several Re versus z/r_l^* , where $r_l^* = \tau_0^{-\eta/2} r_e$ is the new dynamic length scale. Recasting the data of Fig. 5 in terms of z/r_l^* yields good results (Fig. 7), implying that a generic curve for the centerline velocity decay of initially turbulent axisymmetric jets can be realized when the streamwise distance variable is normalized using the newly proposed dynamic length scale. Such a generic realization also implies that a single value for the virtual origin exists for jet data plotted in this manner, obtained by linearly fitting the far field velocity data of Fig. 7 ($z/r_l^* > 60$) and extrapolating to $\bar{U}(0,0)/\bar{U}(z,0) = 0$, as indicated by the dashed line. The corresponding number obtained from the figure is $z_0/r_l^* = 6 \pm 1$. Reverting back to absolute coordinates requires the use of Figs. 2, 3 and 6. When this is done a value for z_0/r_0 may be determined for each Reynolds number. Doing so for the data shown in the present paper yields the results shown in Fig. 8. Included in Fig. 8 are the potential core measurements, z_{pc}/r_0 , reported by Lee et al. (1996) and Harsha (1971), and the length to $\bar{U}(z,0)/\bar{U}(0,0) = 0.5$, $z_{0.5}/r_0$, reported by Ebrahimi (1976). Similar lengths can also be extracted from the generic curve, and these are shown in Fig. 8 as well. The trend of the present data compares well, supporting the results of the present investigation that the mean centerline velocity decay distribution for initially turbulent axisymmetric jets may be scaled to attain Reynolds number independence using the proposed length scale, r_l^* .

CONCLUSIONS

Centerline velocity data were presented for a constant density axisymmetric jet having a non-uniform initial velocity distribution that is fully turbulent. The several Reynolds numbers investigated showed distinctly the effect of Re on the

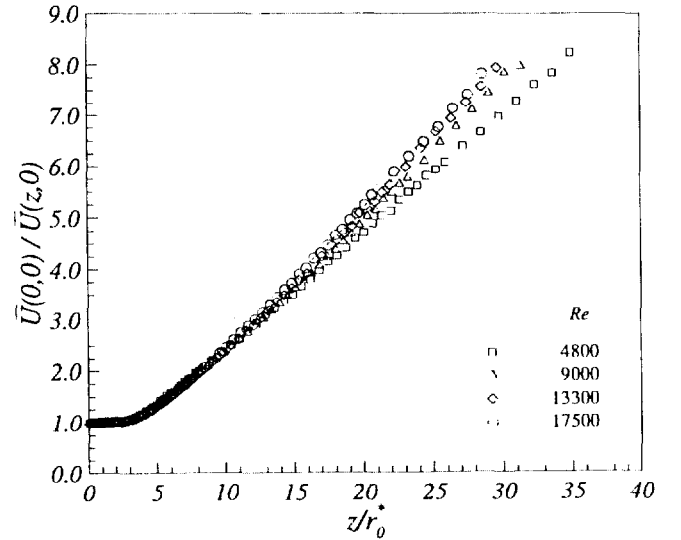


Fig. 5 Inverse decay of mean centerline velocity in the near, intermediate and far fields of the air jet; streamwise distance variable normalized by r_0^* .

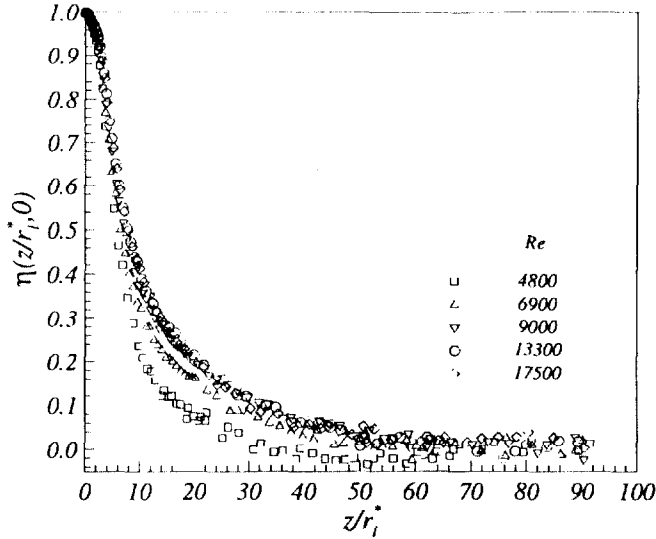


Fig. 6 Normalized centerline turbulence intensity distributions.

development of the jet, specifically the downstream shift of the virtual origin with increasing Reynolds number. This shift of the centerline velocity decay curves was attributed to the initial turbulence intensity distribution, which may be thought of as a natural source of random excitation that disrupts vortex formation and pairing processes responsible for elevated momentum mixing under initially laminar conditions. Thus, it directly governs the changes in the growth of turbulence within the shear layer of the jet (Papadopoulos and Pitts, 1998). The relative magnitude of the initial turbulence intensity may then be used to scale the changes in the growth of the shear layer, and by forming an appropriate length scale render Re independence to the centerline velocity decay distribution when the axial distance is normalized by this length scale. This was achieved in the near field by determining a new length scale that incorporated the initial mass, momentum and turbulence intensity fluxes.

The effectiveness of this length scale, r_0^* , was however limited to the near field of the jet where the influence of initial conditions is greatest. As the jet develops the effects of initial conditions rapidly decay. In the far field or self similar region jet development becomes independent of initial conditions, and only the initial mass and momentum fluxes are important. Hence, to extend the near field scaling over the entire jet development region, the diminishing effect of initial conditions (turbulence intensity) was incorporated into the previously proposed near field length scale by using the local normalized centerline turbulence intensity distribution. This yielded a dynamic radial length scale that effectively captured the virtual origin shift, and resulted in the collapse of the centerline mean velocity distribution curves for initially turbulent axisymmetric jets as identified in the paper. From the generic curve a single value for the virtual origin location was realized, this being

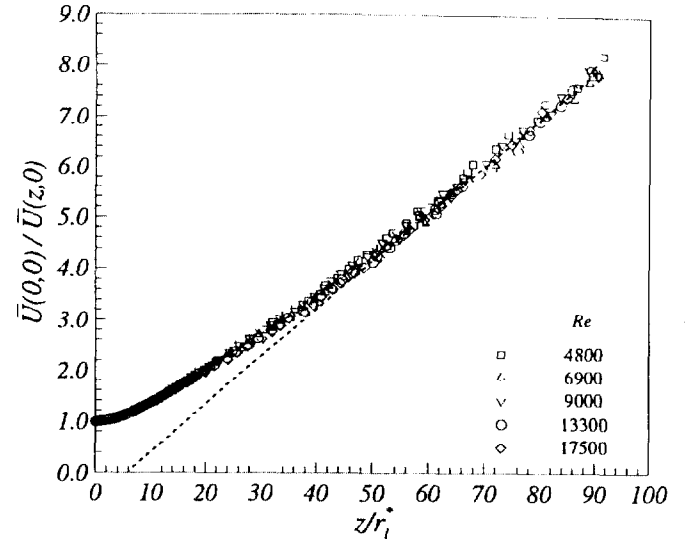


Fig. 7 Inverse decay of mean centerline velocity in the near, intermediate and far fields of the air jet; streamwise distance variable normalized by new dynamic length scale.

$$z_0/r_i^* = 6 \pm 1.$$

The introduction of a local scale to capture the Reynolds number effect goes along with the ideas of Sautet and Stepowski (1995, 1996) who proposed replacing the ambient density with a local average density to better capture the initial density effect on variable density jets. Application of r_i^* to variable density jets is presently under way, as is the extension to other geometries such as flow exiting a contoured nozzle or a square pipe.

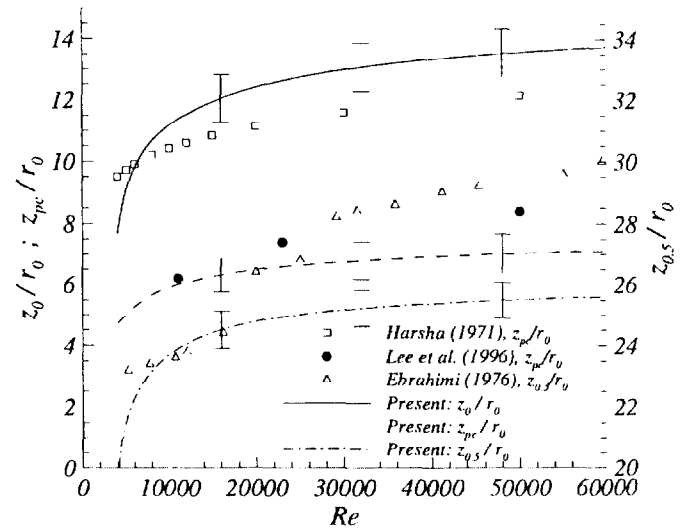


Fig. 8 Comparison of virtual origin, potential core and half-decay lengths obtained from the generic velocity decay curve with potential core and half-decay lengths reported in the literature.

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