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Effect of Initial Tangential Velocity Distribution on the Mean Evolution of a Swirling Turbulent Free Jet

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S. Farokhi and R. Taghavi
The University of Kansas
Lawrence, Kansas

and

E.J. Rice
Lewis Research Center
Cleveland, Ohio

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EFFECT OF INITIAL TANGENTIAL VELOCITY DISTRIBUTION ON THE MEAN EVOLUTION OF A SWIRLING TURBULENT FREE JET

S. Farokhi*
Aerospace Engineering Dept., The University of Kansas, Lawrence, Kansas

R. Taghavi**
Center for Research, Inc., The University of Kansas, Lawrence, Kansas

E. J. Rice
National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio

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Abstract

An existing cold-jet facility at NASA-Lewis Research Center was modified to produce swirling flows with controllable initial tangential velocity distribution. Distinctly different swirl velocity profiles were produced, and their effects on jet mixing characteristics were measured downstream of an 11.43 cm (4.5 in.) diameter convergent nozzle. It was experimentally shown that in the near field (i.e. $x/D < 5$) of a swirling turbulent jet, the mean velocity field strongly depends on the initial swirl profile. Two extreme tangential velocity distributions, i.e. one with solid-body rotation and the other predominated by a free-vortex distribution, were produced. The two jets shared approximately the same initial mass flow rate of 0.59 kg/s (1.3 lbs/s), mass-averaged axial Mach number ($M_o = 0.14$) and swirl number ($S = 0.48$). Mean centerline velocity decay characteristics of the solid-body rotation jet flow exhibited classical decay features of a swirling jet with $S = 0.48$ reported in the literature. However, the predominantly free-vortex distribution case (with $S = 0.48$) was on the verge of vortex breakdown, a phenomenon associated with the rotating flows of significantly higher swirl numbers, i.e. $S_{crit} \gtrsim 0.6$. This remarkable result leads to the conclusion that the integrated swirl effect, reflected in the swirl number, is inadequate in describing the mean swirling jet behavior in the near field. The relative size (i.e. diameter) of the vortex core emerging from the nozzle and the corresponding tangential velocity distribution are the controlling parameters influencing the swirling turbulent free jet evolution.

Nomenclature

- A,B,C outer, middle, and inner swirl-generating manifolds, respectively
- c constant
- D nozzle exit diameter
- G degree of swirl $\equiv W_{mo}/U_{mo}$
- G_x axial flux of axial momentum
- G_θ axial flux of angular momentum
- M mean axial Mach number (based on the mass-averaged axial velocity)
- O order of
- p static pressure
- R nozzle exit radius
- S swirl number $\equiv G_\theta/G_x R$
- U,V,W mean axial, radial and tangential velocity components in the jet
- u',v',w' fluctuating axial, radial and tangential velocity components in the jet
- x,r,θ cylindrical polar coordinates in the jet
- ε very small quantity
- ρ fluid density

Subscript

- crit critical
- m maximum
- o initial value, (i.e. condition at x/D = 0.)
- ∞ unperturbed, ambient condition
- x quantity along the jet centerline

Introduction

Turbulent jets with swirl exhibit distinctive characters absent in their non-rotating counterparts. A subsonic swirl-free jet, for example, experiences theoretically no static pressure gradient in the axial or radial direction. Hence, in this case, the mechanism for jet spread is dominated by the turbulent mixing at the interface between the jet and the ambient fluid. A turbulent jet with strong swirl, on the other hand, is primarily driven in the near field ($x/D < 5$) by the static pressure gradients in both axial and radial directions, i.e. mainly an inviscid phenomenon. Turbulent mixing then becomes a dominant factor only when the strong pressure gradients are weakened through rapid initial jet spread (i.e. a jet in near pressure equilibrium). The occurrence of flow reversal in the jet, or what is known as vortex breakdown is a fascinating phenomenon observed in high-intensity swirling flows, which we will briefly discuss in this paper. The absence of a potential core, by definition, in a swirling jet is another feature which distinguishes the rotating from the non-rotating jets.

The non-dimensional parameter describing the integrated swirl strength in a jet is the swirl number S, and is defined as

$$S \equiv G_\theta/G_x R \tag{1}$$

$$\text{where } G_\theta \equiv 2\pi \int_0^\infty \rho U W r^2 dr;\ \text{jet torque,} \tag{2}$$

*Associate Professor
**Research Associate

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$$G_x \equiv 2\pi \int_0^\infty (\rho U^2 + (p-p_\infty))\ rdr;$$

jet axial thrust, (3)

and R is the nozzle exit radius. The inclusion of the turbulent shear and normal stresses, $\rho \overline{u'w'}$ and $\rho \overline{u'^2}$, in the integrands of the jet torque and thrust expressions, i.e. equations (2) and (3) respectively provide for total jet thrust and torque as described in Reference [1]. However, our swirl number definition excludes Reynolds stresses. By definition, the swirl number is an integrated quantity, hence it is possible to generate swirling jets with different initial tangential velocity profiles ranging from solid body rotation (i.e. $W_0(r) \approx c.r$) to near free-vortex flow (i.e. $W_0(r) \approx c/r$) with constant S. Moreover, as the static pressure field is coupled to the tangential velocity distribution, through the momentum equations, and dominates the swirling jet evolution in the near field, vastly different mean jet behavior (e.g. mean centerline velocity decay) should be observable in swirling jets with constant S. To pursue this point further, a unique swirl generator was designed and incorporated in an existing cold jet facility at NASA-Lewis Research Center. The mean flow measurement technique employed five-hole pitot probes which compared favorably with the DC-signal of a hotwire anemometer. The bigger objective of our investigation is, however, to

a) study mixing characteristics of
b) evaluate excitability of (i.e. jet response to aerodynamic excitations) and
c) investigate vortex breakdown in

swirling turbulent free jets with controllable initial tangential velocity distribution, from the incompressible limit to supersonic speeds. The present paper covers the mean, incompressible part of the task (a) while Reference [2] has addressed the swirling free jet excitability question and task (c) is currently under investigation.

Review of Literature

From a large body of experimental and theoretical works on the swirling turbulent flows only a few are selected for the purpose of review in this paper. The bulk of the swirl flow investigations may be categorized, with some interdependence, as follows:

a) swirling turbulent free jet issuing from an orifice into a stationary or moving fluid
b) confined swirling flows in variable-area ducts (e.g. combustion aerodynamics)
c) swirling flow in turbomachinery annuli
d) vortex control and management in external/internal aerodynamics
e) leading-edge vortex breakdown over a high-angle-of-attack delta wing

The present review concentrates on swirling turbulent free jets with a brief look on the pertinent literature in related areas.

As might be expected, the evolution of a subsonic swirling turbulent jet issuing from a nozzle into ambient fluid depends on the method of swirl production. This fact was acknowledged by Chigier and Beer in Reference [3], Pratte and Keffer in Reference [4] and others. The design of swirl generators in practice today use the following principles of swirl production, namely a) adjustable vanes, b) tangential blowing on the wall of a pipe with axial through flow, c) spinning, fully-developed pipe flow emerging from a long rotating tube (~ 100 diameters long) and d) flow through a rotating perforated plate, among others. References [1] and [5] can be consulted on the details of various swirl generator designs and their corresponding limitations and efficiencies.

A number of theoretical studies covering laminar, turbulent, weak and strong swirling jets have been carried out in the past. Görtler [6] performed analytical studies of an incompressible laminar jet in the limit of very weak swirl. In this limit, the radial pressure gradient may be ignored, i.e. $p \approx p(x)$ only; and moreover a linearization of the momentum equations in swirl velocity is admissible. Based on these and the boundary layer approximation of the Navier-Stokes equations, Görtler reduces the evolution of a weakly swirling laminar jet problem to an eigenvalue problem of an ordinary, second-order differential equation. Furthermore, upon finding a suitable transformation for the dependent and independent variables, the governing differential equation is transformed into a Legendre type, for which exact solutions are derived. By replacing the kinematic viscosity with an effective constant eddy viscosity, Görtler generalizes his theory to include turbulent, weakly swirling free jets as well. A theory is proposed by Steiger and Bloom [7] in which incompressible and compressible, axially symmetric laminar free mixing, e.g. wakes and jets, with small, moderate and large swirl can be examined. The tangential and axial velocity components and the stagnation enthalpy are assumed to have polynomial profiles in the radial direction. The assumption of very small radial velocity allowed the use of boundary-layer type formulation in the analysis. The Karman integral method is then applied to the viscous layer, i.e. the wake, of a rotating axisymmetric body with no comparison to experimental data. Shao-Lin Lee [8] has obtained closed-form solutions for an axisymmetric turbulent swirling jet using similarity assumptions for the axial and the tangential velocities. The radial and axial velocities are linked via an entrainment assumption, after G. I. Taylor [9]. The theoretical predictions are compared to the experimental data of Rose [10], where close agreement, in the case of weak swirl, is demonstrated. The experimental data reported by Rose [10] were collected in a swirling turbulent jet issuing from a long rotating tube. Lee's assumptions of the Gaussian axial velocity distribution and the corresponding similar tangential velocity profile were directly deduced from Rose' experiment, where similarity conditions were observed for x/D > 1.5.

Chigier and Chervinski [11,12] have performed theoretical and experimental studies of turbulent swirling jets issuing from a round orifice. They used boundary layer approximations and assumptions of similar profiles to integrate the equations of motion for incompressible turbulent flows. The similarity assumption was experimentally demonstrated to hold in a swirling jet, for weak and moderate swirls, for $x/D > 4$. For strongly swirling flows, where the mean axial velocity distribution shows a central trough, or what is also known as a double hump profile, the similarity was not observed until 10 diameters. For $x/D > 10$, the location of the maximum mean axial velocity shifted back to the jet centerline, from which point the similarity was observed. The measured mean axial velocity and static pressure profiles were described by Gaussian error curves and the mean tangential velocity profile was expressed in terms of third-order polynomials. The empirical constants in the data-fit expressions of Chigier and Chervinsky are functions of the degree of swirl in the jet defined as

$$G \equiv W_{mo}/U_{mo} \qquad (4)$$

the ratio of maximum mean tangential-to-axial velocity at the nozzle exit.

Mattingly and Oates [13] performed an experimental investigation of the mean, incompressible mixing process in confined coannular swirling flows. In this investigation, the swirl was present in the inner stream only, thereby leading to flow conditions unstable in the sense of Rayleigh, i.e. instability ensuing from an outwardly decreasing angular momentum. Enhanced radial mixing was attributed to the Rayleigh instability.

The latest reviews in the field of confined swirling flows [14,15], primarily with combustion, reveal an extensive reference list and activities in this area of research. For a more comprehensive and recent work on the predictions and measurements of the swirling flows in combustor geometries, Reference [16] may be consulted.

Kerrebrock [17] has proposed a general theory for the small disturbance field in strongly swirling flows in turbomachine annuli. He concluded that small amplitude "shear" disturbances are not purely convected but rather propagate slowly in flows stable in the sense of Rayleigh and are unstable in flows approaching free vortex.

Extensive literature exists on the phenomenon of vortex breakdown or flow reversal and vortex instability in strongly swirling flows. References [18, 19, and 20] are among the most fundamental. Despite significant strides, still no comprehensive theoretical description of the phenomena leading to vortex breakdown exists. The various theoretical ideas of hydrodynamic stability and finite transition to a subsequent state, analogous to hydraulic jump, are proposed which provide only partial insight into this complex flow phenomenon. For an exhaustive list of references and critical evaluation of the proposed theories, References [21], [22], and [23] should be consulted. The special problem of the bursting of leading-edge vortices (e.g. over delta wings) is examined in References [24] and [25]. In a recent contribution (Reference [26]) Shi et al. have experimentally investigated the location and control of vortex breakdown over a delta wing of high sweep angle.

Common to all the previous methods of swirl generation in free jets and ducts, as described in the experimental swirl research articles, is the production of near solid body rotation flows. In the following section, design of a unique swirl generator system capable of producing variable initial swirl profiles employing the principles of combined tangential and axial air is briefly described.

Experimental Facility

Swirl Generator

Figure 1 is a schematic diagram of the test set-up. An existing cold jet facility at NASA Lewis Research Center was modified to generate flows at a wide range of swirl numbers. The principle of combining axial and tangential streams is applied for swirl generation. Axial air is introduced through a 20.32 cm (8 in.) pipe at the end of the plenum. Tangential air enters the plenum chamber through 54 elbow nozzles mounted on three concentric circular rings as shown in Figures 1 and 2. Specially designed restrictors and screens are inserted into the elbow nozzles to reduce the orifice noise generation. The nozzle exit plane is of multi-hole design which also contributes to the nozzles' low-noise character. Swirl number can be adjusted by remote control valves which vary the proportion of axial to tangential air. The flow leaving the swirl generator passes through a bellmouth and an excitation section before discharging to the test cell through an 11.43 cm (4.50 in.) diameter nozzle. For more details regarding the swirl generator and test facility see Reference [5].

Mean-Flow Measurements

Three components of time-mean velocity as well as static and total pressures are measured by a 5-hole pitot probe having a diameter of 0.318 cm (0.125 in.). The probe tip has a 45-degree cone angle and the pressure ports are located at the midspan of the conical surface. The 5-hole probe is self-nulling in the yaw angle, while the pitch angle, the time-mean velocity components and the pressures are computed from calibration curves. The calibration Mach number range for the 5-hole probe varied between 0.08 and 0.4.

Results and Discussion

The experimental results presented in this section are time-averaged data gathered from two swirling jets generated separately by the manifolds A and C. The swirl number in both jets was held constant at 0.48 and the mass-averaged, mean axial Mach number at the nozzle exit was ≈ 0.14. The Reynolds' number based on the mean axial velocity and the nozzle diameter was in both cases 375,000. Figure 3 is a definition sketch showing the coordinates and the mean velocity components in the jet.

The two extreme tangential velocity distributions investigated in our facility are

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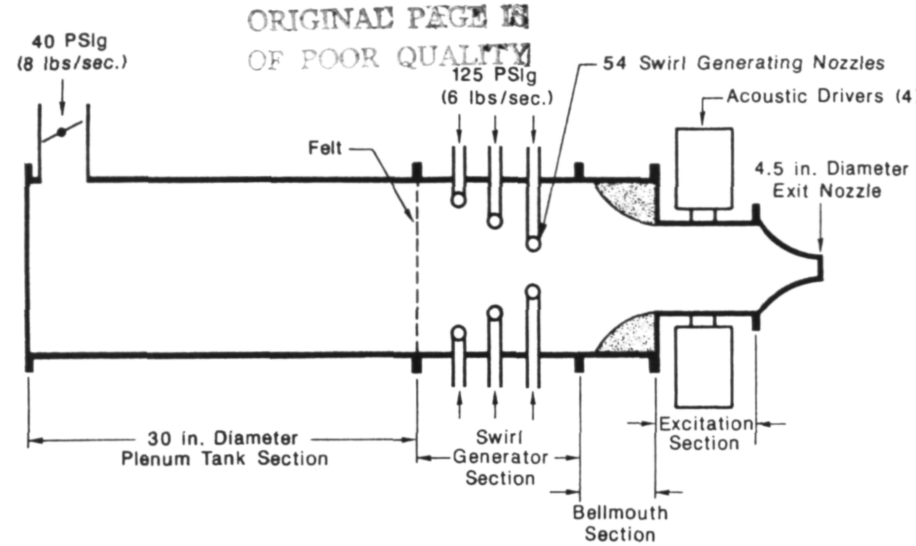

Figure 1. Schematic diagram of the jet facility

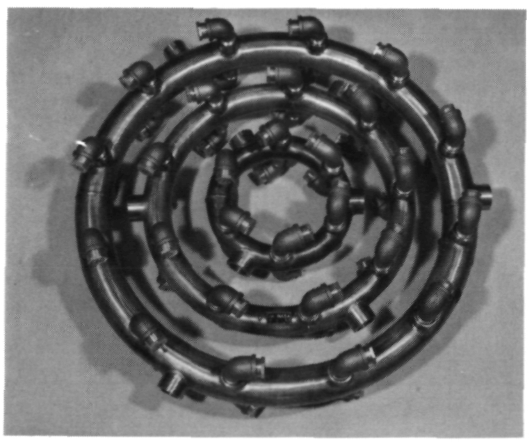

Figure 2. Manifold rings and elbow nozzles (unassembled)

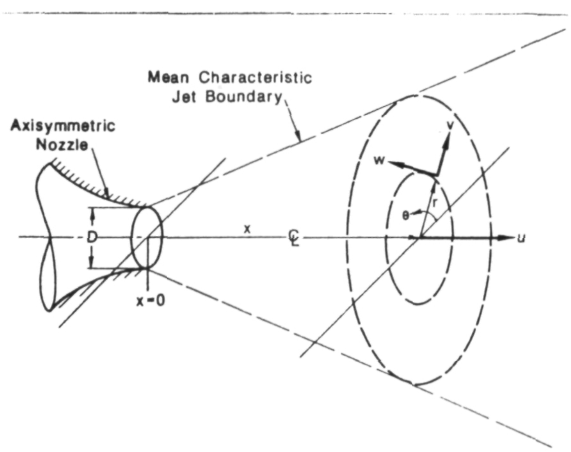

Figure 3. Definition sketch

plotted in Figure 4. The vortex core size generated by the manifold C, at $x/D = 0.06$, is about a quarter of the nozzle exit diameter; while that of the manifold A spans across the

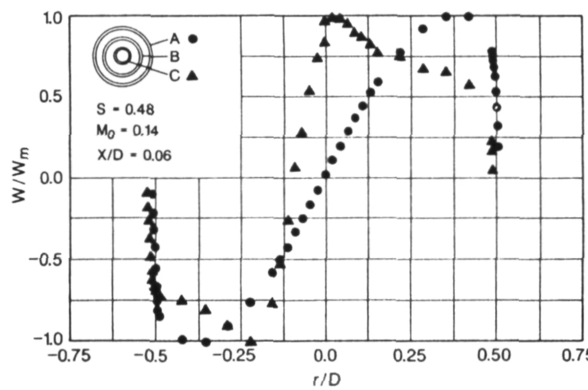

Figure 4. Radial distribution of the mean tangential velocity

full exit plane. It is also noted that the center of the smaller vortex is displaced from the nozzle geometric center by nearly 0.1 D, at $x/D = 0.06$, thereby leading to non-axisymmetric flow conditions. This puzzling behavior was further investigated by allowing the vortical flow to emerge from the nozzles of various lengths. It was noted that the vortex core center described a "helical path" as evidenced by the appearance of the vortex center above, below and to the side of the nozzle axis. A plausible explanation of this behavior may be found in the inviscid flow theory (see for example, Batchelor, Reference [27]) which predicts a spiral motion for an off-centered vortex filament as it passes through a contraction. The condition of axisymmetry for the swirling jet generated by the manifold C is achieved at $x/D \approx 1.0$, as will be discussed later in this section. The forced vortex, i.e. the solid body rotation flow, produced by the manifold A is axisymmetric as it emerges from the nozzle.

The radial distribution of mean axial velocity is shown in Figure 5. It is the nature of vortical flows, in general, which would not

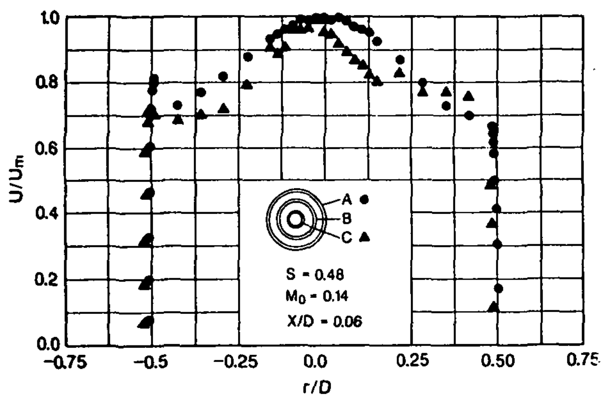

Figure 5. Radial distribution of the mean axial velocity

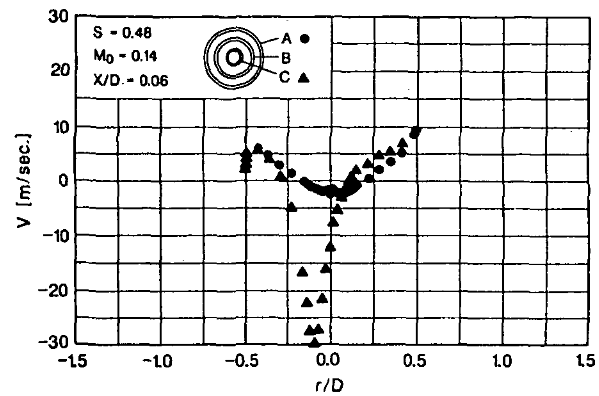

Figure 6. Radial distribution of the mean radial velocity

allow <u>flat top</u> axial velocity profiles to be generated. The differences in the axial flow distributions at the nozzle exit produced by the manifolds A and C, as shown in Figure 5, could be directly related to the size of the vortex cores generated by these manifolds. Furthermore, the condition of near axisymmetry is observed for the swirling jet generated by the manifold A, while that of manifold C is still asymmetric.

An evidence of a very strong inward (i.e. negative) radial flow is revealed in Figure 6 for the manifold-C-generated swirling flow. Further, the magnitude of the radial and axial velocity components are comparable in this case in the near field. Hence, widely accepted boundary layer-type approximation, i.e. $V/U \sim O(\varepsilon)$, made in the theoretical analysis of rotating jets is invalid in the near field of even moderately swirling jets (e.g. with $S = 0.48$). A manifestation of this assumption, i.e. $V/U \sim O(\varepsilon)$, on the radial momentum equation leads to the radial equilibrium condition, i.e.

$$-\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{v^2}{r} \qquad (5)$$

which is also invalid for the rotating free jets of the type generated by the manifold C and depicted in Figure 6. The driving force behind such a large radial inflow is the radial static pressure gradient associated with the core of such concentrated vortex filaments identifying this as a pressure-driven phenomenon. The axial velocity peak observed in the jet center (see Fig. 5) is the continuity-consequence of this radial inflow. The flow generated by the largest manifold, i.e. A, experiences mild radial inflow and is axisymmetric. The rotating flow produced by the smallest manifold, i.e. C, is asymmetric and, as shown in the latter parts of this section, will remain asymmetric up to $x/D \approx 1$.

Figure 7 reveals a static pressure deficit in the core of the swirling jets, produced by the manifolds A and C, at $x/D \approx 0.06$. The depth of the pressure trough for the concentrated vortex flow, i.e. the one generated by the manifold C, is nearly 2.5 times that of the large core vortex, i.e. due to manifold A. We also note the similarity between the radial velocity and the static pressure profiles as plotted in Figures 6

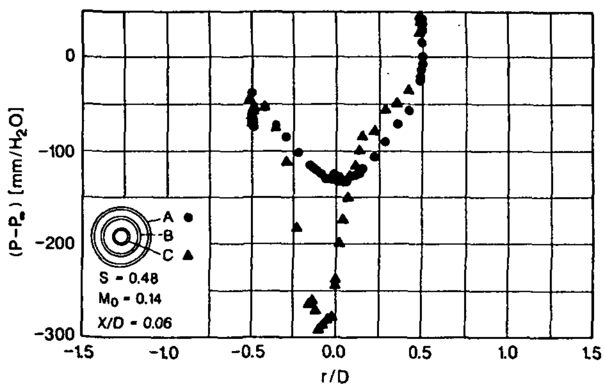

Figure 7. Radial distribution of the mean static pressure deficit

and 7. Again, the symmetry and lack of it could be seen in the A and C-generated flows, respectively.

The axial evolution of the mean tangential velocity is plotted in Figure 8 (a) and (b). In part (a), the manifold A-generated swirling flow is clearly axisymmetric and shows a rapid decay with axial distance. Beyond four diameters, the mean tangential velocity in the jet is so small as to make an accurate measurement with the 5-hole probes questionable. The initial offset between the jet and the nozzle geometric center is clearly visible, in Figure 8 (b), for $x/D < 1.0$. Beyond one nozzle diameter, the two centers coincide. Moving towards the condition of axisymmetry, i.e. the self-centering action of the jet, is a natural tendency we observed in our experiments. Comparison of the parts (a) and (b) of Figure 8 also reveals that the concentrated vortex, i.e. due to manifold C, decays at a slower rate than the solid-body rotation flow induced by the manifold A, up to four nozzle diameter.

Widely different axial evolution of the mean axial velocity profiles, for the two swirling jets generated by the manifolds A and C, is noted from Figure 9 (a) and (b), respectively. The large core-vortex flow, i.e. (a), shows a continuous gradual decay of the mean axial velocity

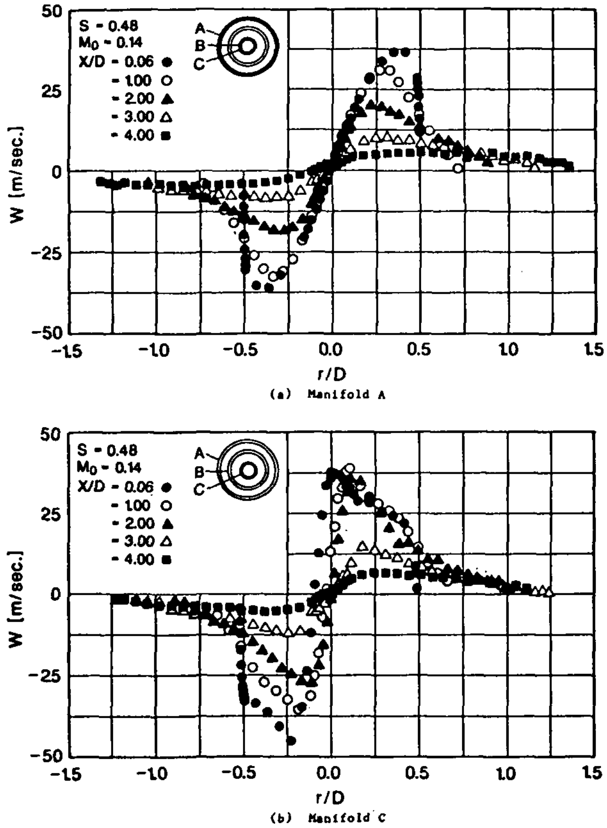

Figure 8. Downstream development of the mean tangential velocity

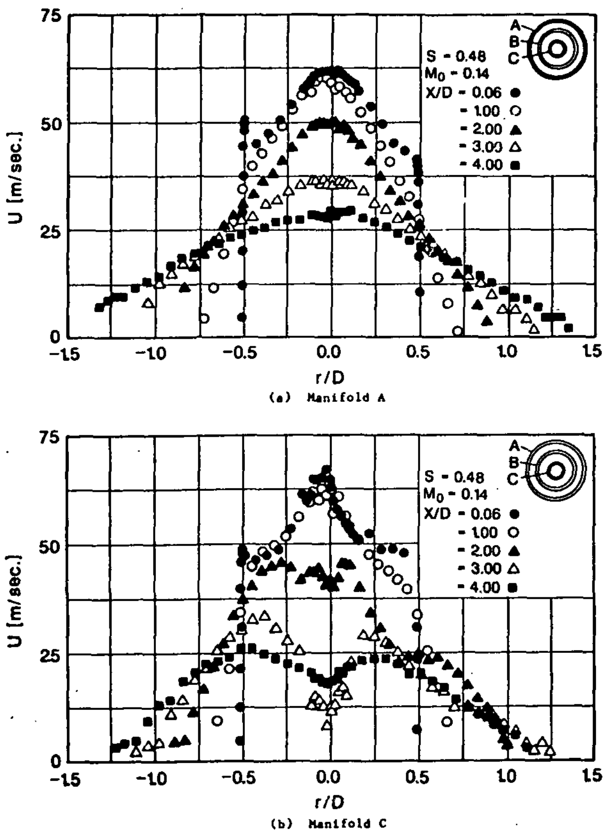

Figure 9. Downstream development of the mean axial velocity

component along the jet. The small core-vortex flow, i.e. (b), demonstrates a central trough or a double-hump profile associated with the swirl numbers higher than 0.48 (namely 0.6). The mean centerline velocity on the jet axis, i.e. r/D = 0, in part (b) shows a rapid initial deceleration followed by an acceleration period which has never been reported for S = 0.48 jets. Upon further examination of the mean axial velocity between three and four diameters, we observed that the small-core-vortex jet with S = 0.48 was on the verge of vortex breakdown, as shown in Figure 10. The forward and rear stagnation points, both very close to the jet axis, exhibited an unsteady behavior, as had been noted in the earlier vortex breakdown experiments. The fact that a swirling jet has been brought to the point of breakdown at a swirl number (i.e. 0.48) significantly lower than the critical value was assumed to be (i.e. $S_{crit} \gtrsim 0.6$) is the most remarkable result of our mean-flow investigation.

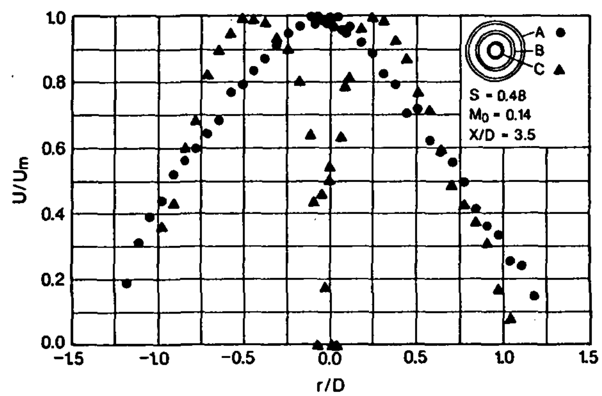

Figure 10. Radial distribution of the mean axial velocity

Downstream development of the mean radial velocity is shown in Figure 11. In part (a), a very minor radial inflow is measured which quickly disappears as the jet evolves in the axial direction. The small core-vortex flow, i.e. (b), due to larger inflow radial velocities, persists longer than (a) and, as shown, decays to nearly zero radial velocity in about five diameters. The mean static pressure deficit in the swirling jet, within the first three diameters of the jet evolution is plotted in Figure 12. The strong adverse pressure gradient along the jet axis, measured for the small core-vortex flow, i.e. part (b), is recognized as the principal contributor to the onset of the vortex breakdown as noted in Figure 10. Finally, the decay of the mean axial velocity along the jet axis is presented in Figure 13. The swirling jet produced by manifold C is on the verge of breakdown, while that of manifold A exhibits classical behavior for this level of swirl number, i.e. 0.48.

Conclusions

The following summarizes the major conclusions of our experimental investigation:

a. Initial development of a subsonic swirling free jet is dominated by the nozzle exit tangential velocity distribution.

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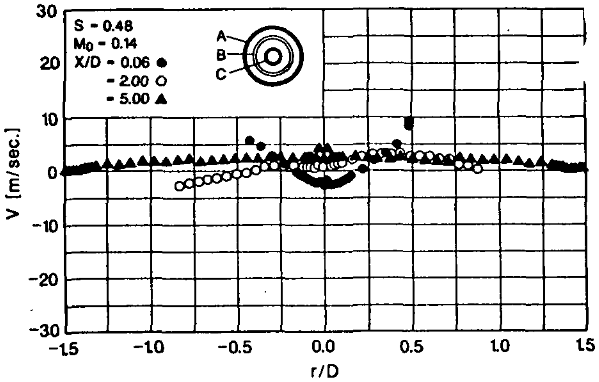
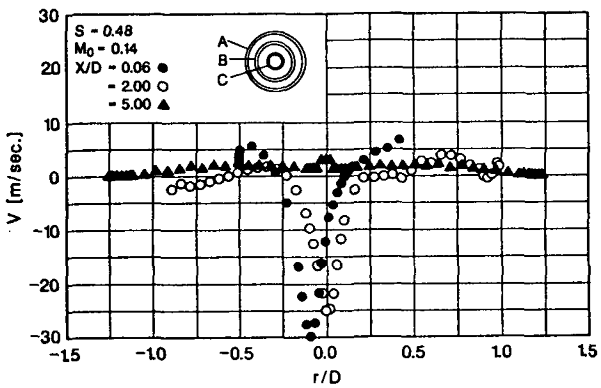
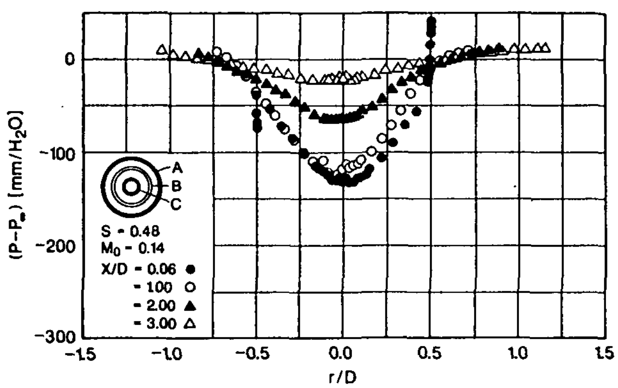


(a) Manifold A

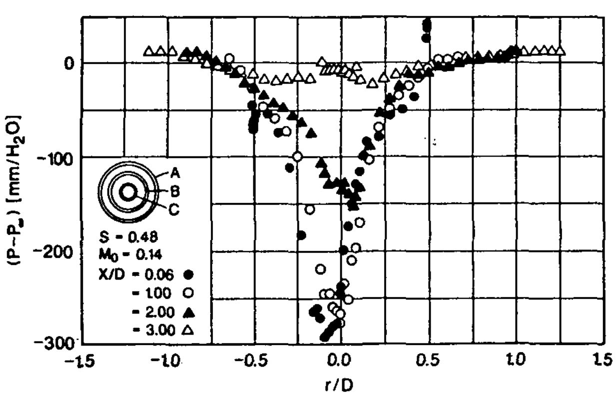


(b) Manifold C

Figure 11. Downstream development of the mean radial velocity



(a) Manifold A



(b) Manifold C

Figure 12. Downstream development of the mean static pressure deficit

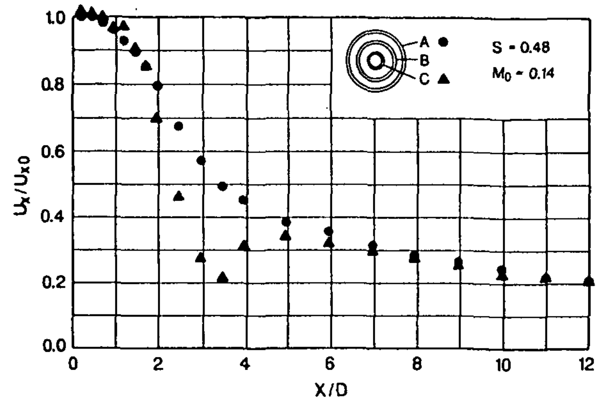


Figure 13. Decay of the mean axial velocity component along the jet axis

b. Vortex breakdown in swirling jets may occur at significantly lower swirl numbers than have previously been reported, i.e. $S_{crit} < 0.6$.

c. Large radial inflows will make a boundary-layer-type approximation, i.e. $V/U \sim O(\varepsilon)$, and its subsequent radial equilibrium condition, invalid in the near field of the jets with moderate to strong swirls.

d. An asymmetric swirling free jet issuing from an axisymmetric nozzle will self center with distance (in our jet, within one nozzle diameter).

e. Reducing the size of the vortex core in a swirling jet creates a higher swirl-number effect on the mean flow.

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16. Abstract

An existing cold-jet facility at NASA-Lewis Research Center was modified to produce swirling flows with controllable initial tangential velocity distribution. Distinctly different swirl velocity profiles were produced, and their effects on jet mixing characteristics were measured downstream of an 11.43 cm (4.5 in.) diameter convergent nozzle. It was experimentally shown that in the near field (i.e., $x/D < 5$) of a swirling turbulent jet, the mean velocity field strongly depends on the initial swirl profile. Two extreme tangential velocity distributions, i.e., one with solid-body rotation and the other predominated by a free-vortex distribution, were produced. The two jets shared approximately the same initial mass flow rate of 0.59 kg/s (1.3 lbs/s), mass-averaged axial Mach number ($M_0 = 0.14$) and swirl number ($S = 0.48$). Mean centerline velocity decay characteristics of the solid-body rotation jet flow exhibited classical decay features of a swirling jet with $S = 0.48$ reported in the literature. However, the predominantly free-vortex distribution case (with $S = 0.48$) was on the verge of vortex breakdown, a phenomenon associated with the rotating flows of significantly higher swirl numbers, i.e., $S_{crit} \gtrsim 0.6$. This remarkable result leads to the conclusion that the integrated swirl effect, reflected in the swirl number, is inadequate in describing the mean swirling jet behavior in the near field. The relative size (i.e., diameter) of the vortex core emerging from the nozzle and the corresponding tangential velocity distribution are the controlling parameters influencing the swirling turbulent free jet evolution.

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