LARGE EDDY SIMULATION OF THE NEAR FIELD OF ROUND JETS WITH VORTEX-GENERATING TABS

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ABSTRACT
Large eddy simulation was used to calculate the effects of vortex-generating tabs on the turbulence structures in the near field of a round jet. Alterations in the shape of the ring-shaped structures were observed. Changes in the rate of flow entrainment were related to the presence of large-scale braid-shaped structures formed as a result of the tabs. These preliminary results demonstrate the potential for using large eddy simulation to aid in design of efficient jet nozzles.

INTRODUCTION
Vortex-generating tabs are used in turbulent round jets to increase mixing and flow entrainment, improve combustion efficiency, and reduce noise. The tabs are small protrusions that extend into the flow from the nozzle wall, often placed at the nozzle exit. They distort the round shape of the exit velocity profile and manipulate the vorticity in the flow field, thereby controlling the evolution of the large-scale turbulence structures.

A relationship between the presence of large-scale structures of vorticity and the rate of entrainment in a turbulent jet flow was observed in the large eddy simulations of McIlwain and Pollard (2000). The structures form due to flow instabilities downstream from the nozzle. The primary Kelvin-Helmholtz instability mechanism causes the shear layer to roll up into vortex rings. Secondary instabilities also develop that create finger-like pairs of streamwise vortex structures that emerge from the region between two vortex rings and stretch around the jet core (Liepmann and Gharib, 1992).

The effect of the shape and tilt (angle of attack) of the tabs, and the combination of several tabs at the nozzle exit, have been previously investigated through experiments. A tab generates a pair of counter-rotating streamwise vortices at the nozzle, largely due to the formation of an upstream "pressure hill" (Zaman *et al.*, 1994). Enhanced mixing within the flow and an increase in the number of small-scale structures has been observed (Huang and Ho, 1990); consequently, an increase in the rate of entrainment of the surrounding fluid is also expected. However, it is not known whether the enhanced mixing in the flow is caused by the increased surface area of the mixing layer that is exposed to the surrounding fluid, or the observed vortex breakdown farther downstream. The effect of a combination of tabs remains controversial: when too many tabs are used, the flow field may settle back into a steadier configuration with a less profound distortion (Zaman *et al.*, 1994; Mi and Nathan, 1999). Zaman (2000) reports that a double-tab configuration produces the best results.

Although tabs do increase mixing by intensifying the interaction between azimuthal and streamwise turbulence structures, they must be used with a good understanding of their mechanisms to obtain a positive and efficient effect (Foss and Zaman, 1996). Therefore, numerical studies of the effects caused by vortex-generating tabs are desirable since the time-dependent evolution of the turbulent structures can be observed. As a first step in this direction, the present study uses Large Eddy Simulation (LES) and flow visualization techniques to investigate the near field effects of two configurations of tabs in a turbulent round jet.

NUMERICAL PROCEDURE
In LES, the smallest turbulence scales are approximated using a subgrid scale model while the larger scales are resolved using the Navier-Stokes equations. Therefore, the velocity and pressure fields in the governing equations must be filtered to remove the subgrid scales of motion. Applying the gradient-diffusion hypothesis and representing filtered quantities using ^, the governing equations of motion are (Ciofalo, 1994):

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$$\frac{\partial \hat{u}_j}{\partial x_j} = 0 \qquad (1)$$

$$\frac{\partial \hat{u}_i}{\partial_t} + \frac{\partial \hat{u}_i \partial \hat{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \hat{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_s)\left(\frac{\partial \hat{u}_i}{\partial x_j} + \frac{\partial \hat{u}_j}{\partial x_i} \right) \right]$$

for i=1,2,3. Here, u_i contains the components of the velocity vector in the x_i direction, t is time, ρ is density, P is a modified pressure quantity, ν is the kinematic viscosity, and ν_s is the subgrid viscosity. The effect of removing the subgrid scales of turbulence is included through ν_s, which must be modelled. In the present research, the dynamic Smagorinsky model, first proposed by Germano *et al.* (1991), is used.

The governing equations were discretized using second-order accurate central differencing, and they were advanced in time using the Kim and Moin (1985) fractional-step method combined with a Runge-Kutta semi-implicit scheme. The code has been verified using the Ethier and Steinman (1994) exact analytical solution to the three-dimensional unsteady Navier-Stokes equations. Complete details can be found in McIlwain (2000).

The round jet computations were performed on a rectangular grid of 73 × 56 × 56 points over a domain size of 4.25D × 3.0D × 3.0D, where D is the jet diameter at the nozzle (Figure 1). The edge of the round nozzle was approximated on a square grid as shown in Figure 2. The jet inlet was prescribed using an analytical time-averaged turbulent velocity profile, upon which was superimposed a small sinusoidal disturbance with a maximum value of 2.8% of the mean jet velocity. The frequency of the disturbance was set to the preferred mode of the jet, as determined from several short test simulations. The standard convective outlet condition was used at the jet outlet:

$$\frac{\partial u_i}{\partial t} + U_{conv}\frac{\partial u_i}{\partial x_1} = 0 \qquad (2)$$

where U_{conv} is the convection velocity. A zero gradient condition was used at all other boundaries. The Reynolds number of the flow based on D and the velocity at the nozzle was 68,000. A previous round jet study of flow at the same Reynolds number using the same grid demonstrated a reasonable level of grid independence (McIlwain and Pollard, 2000). The flow was allowed to develop until the effects of the initial conditions were removed from the solution. Time-averaged statistics were then collected over at least 12 large eddy turnover times or 3000 timesteps.

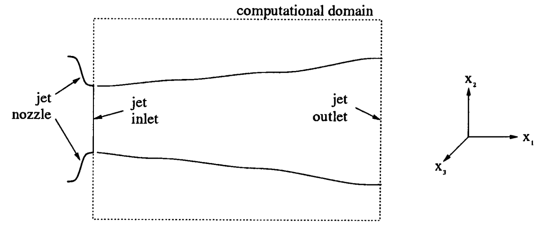

Figure 1: Computational domain of the round jet

The tabs were modelled by blocking off certain control volumes at the inlet, as indicated in Figure 2. The dimension of each tab was chosen to induce a significant perturbation in the jet while maintaining a similar characteristic length scale. Three cases were considered: flow with no tabs, one tab, and four tabs.

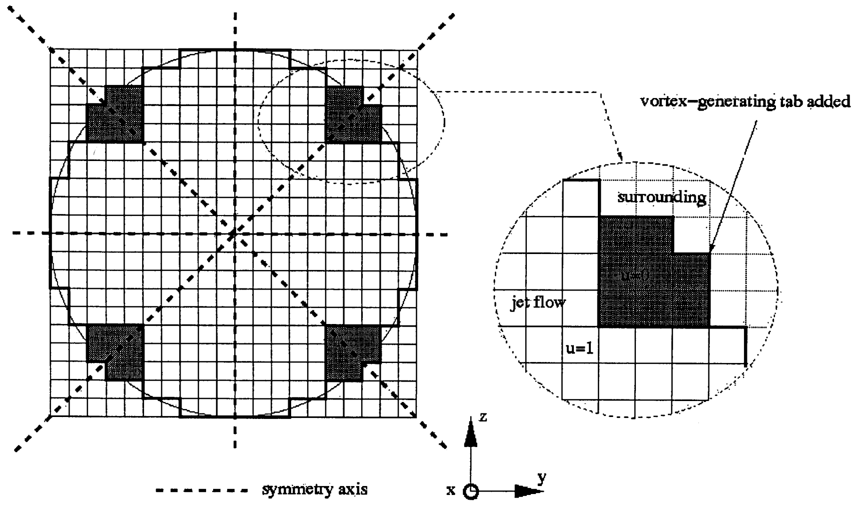

Figure 2: The round jet nozzle with tabs

COHERENT STRUCTURES

Large-scale coherent structures in the flow were identified using plots of instantaneous azimuthal and streamwise vorticity. These are shown in Figures 3-8 at the same instant in time for each of the three flows, and are representative of plots obtained throughout the simulations. Azimuthal vorticity is shaded light grey, and corresponds to flow structures that are aligned with the plane perpendicular to the mean flow. Streamwise vorticity is shaded dark grey. Side, front, and 3D views of each flow are shown. In the side and 3D views, the jet flows from left to right with increasing x. The front view is shown from the nozzle looking downstream at the flow, and the side view is shown looking at the flow from positive y space.

Plots of vorticity in the turbulent round jet without tabs are shown in Figures 3 and 6. Between $0 < x/D < 1.5$, immediately downstream of the nozzle, a shear layer surrounds the jet core. The shear layer develops a Kelvin-Helmholtz instability and rolls up into primary ring-shaped azimuthal structures that are convected downstream. Three such rings are visible at x/D = 1.8, 2.9, and 4.0. The last ring has started to break apart into smaller, less organized turbulence structures, and is no longer complete. The instability mechanism responsible for breaking the rings apart appears to be connected with the appearance of the smaller streamwise vortices downstream of approximately x/D = 1.25. Some isolated pockets of streamwise vorticity are visible in the initial shear layer; however, longer braid-shaped structures tend to form in the wake behind the rings, at points slightly less than the inner ring diameter ($0.25 < r/D < 0.45$, where r/D is the distance from the jet centreline). As the rings are convected downstream, they appear to collide with the braids. The braids are then ejected outwards, become wrapped around the rings, and are reoriented in the direction of the jet flow. Thus the braids transfer fluid from the core to the outer edges of the jet. The interaction between the two components of vorticity eventually tears the rings apart, forming smaller, less organized structures. Streamwise braid structures dominate the flow field downstream of x/D = 2.5. Complete details of the structure interaction can be found in McIlwain and Pollard (2000) and McIlwain (2000).

Large-scale structures in the jet with a single tab are highlighted with plots of vorticity in Figures 4 and 7. In this flow, the tab is located in the nozzle near y/D = -0.35 and z/D = +0.35. The shear layer that forms at the nozzle is bent around the tab, and forms a bulge that extends into the core (see the front and 3D views). Farther downstream, at x/D = 1.0, the bulge disappears and the shear layer becomes circular in shape. However, the rings that form due to the Kelvin-Helmholtz instability are not as regular as those in the round jet without tabs, indicating that the effects of the tab extend farther downstream. The additional instabilities that arise from the tab cause more streamwise vortices to form, even on the opposite side of the jet flow from the tab (see the side view). As a result, the rings are torn apart closer to the nozzle.

Instantaneous vorticity plots of the jet with four tabs are shown in Figures 5 and 8. Here, the tab effects are more apparent. The shear layer bulges into the core at all four tabs, reminiscent of a cruciform-like shape. Unlike the case with a single tab, the shear layer does not become circular before rolling up into rings. Streamwise braid-shaped structures form at the apex of each bulge. These braids pass right through the first ring, which is shown forming at x/D = 1.5; thus, all the rings in this flow are irregularly shaped. Additional braids form in the wake of the rings so that streamwise vorticity dominates the flow field downstream of x/D = 2.0. Some of the braids extend outwards as far as r/D = 1.2 at downstream points in the flow rotated 45° from the location of the tabs. This implies that a greater volume of fluid is influenced by the turbulence structures, and that more flow entrainment occurs compared to the jet without tabs. The rings break apart by x/D = 3.0; the remaining azimuthal structures downstream of this location are disorganized and are not connected to each other.

FLOW ENTRAINMENT

Flow entrainment is used in the present study as an indicator of the effectiveness of the vortex-generating tabs. Entrainment was determined from the increase in the mass flow rate, Q, as a function of distance from the nozzle, x. The flow rate is the integral of the mean velocity across the jet flow,

$$Q(x) = \iint \overline{u}\, dy\, dz \qquad (3)$$

The quantity Q, normalized by the mass flow rate at the nozzle Q_o, is plotted in Figure 9 for each flow. There is little difference in the rate of entrainment between the round jet without tabs and the round jet with one tab. However, the mass flow rate of the round jet with four tabs is 10% greater than either of the other two flows at x/D = 3.0 and 12% greater at x/D = 4.2. Between $0.0 < x/D < 2.5$, the flow rate of all three jets is similar. There is a slight irregularity in the curves between $2.0 < x/D < 3.2$ due to the small number of data points used to calculate the mean flow velocity. However, the error introduced by the small number of data points is less than the difference between the curves at x/D = 3.0.

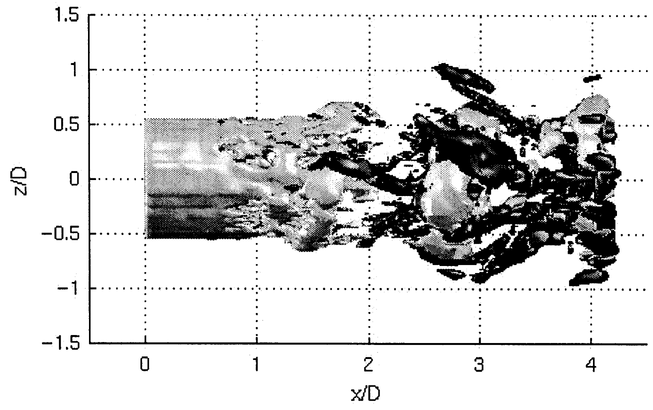

Figure 3: Azimuthal (light grey) and streamwise (dark grey) vorticity in the jet without tabs (side view)

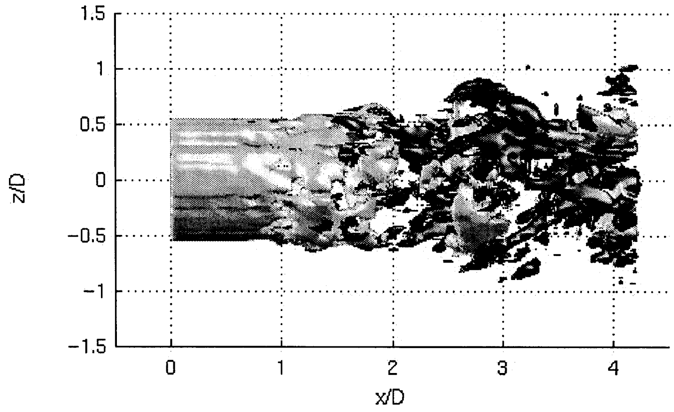

Figure 4: Azimuthal (light grey) and streamwise (dark grey) vorticity in the jet with 1 tab (side view)

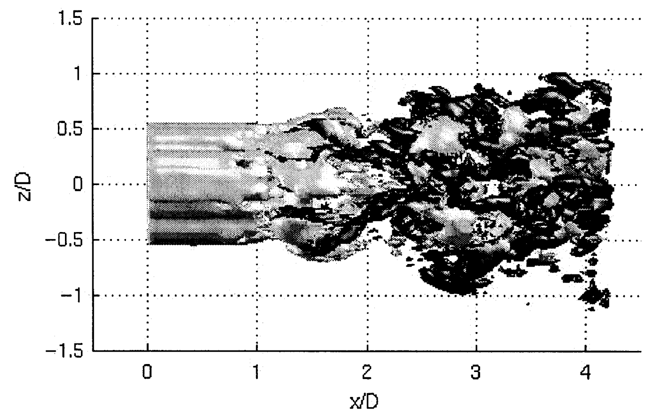

Figure 5: Azimuthal (light grey) and streamwise (dark grey) vorticity in the jet with 4 tabs (side view)

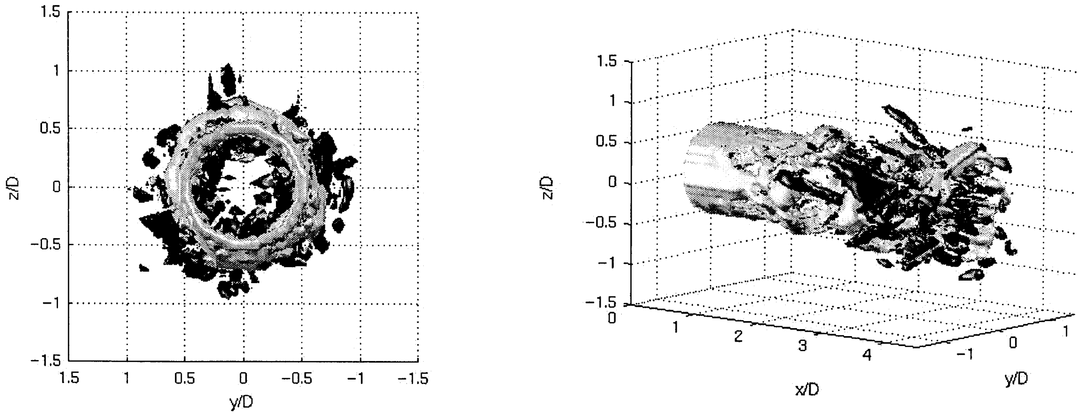

Figure 6: Azimuthal (light grey) and streamwise (dark grey) vorticity in the jet without tabs (front and 3D views)

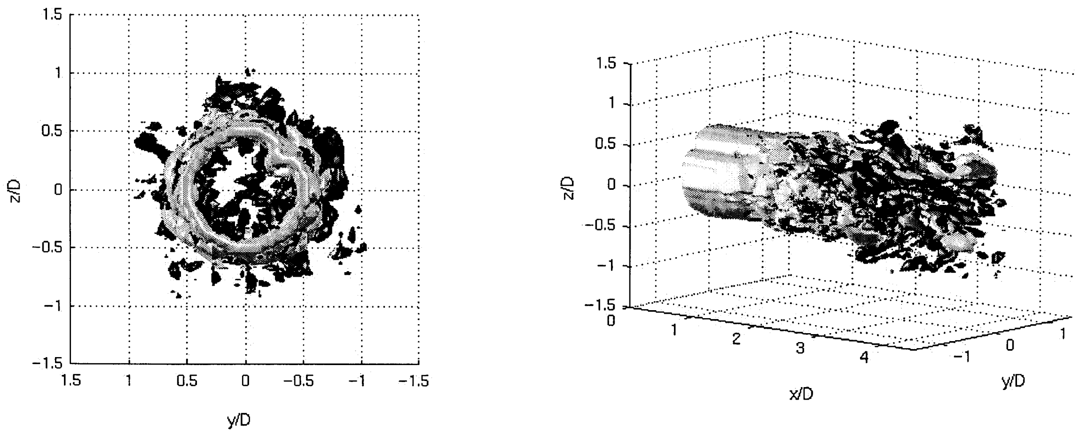

Figure 7: Azimuthal (light grey) and streamwise (dark grey) vorticity in the jet with 1 tab (front and 3D views)

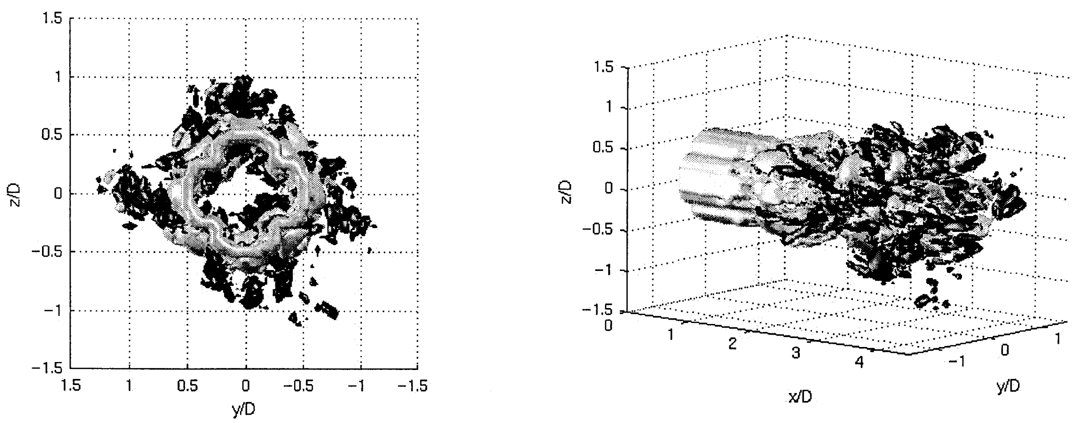

Figure 8: Azimuthal (light grey) and streamwise (dark grey) vorticity in the jet with 1 tab (front and 3D views)

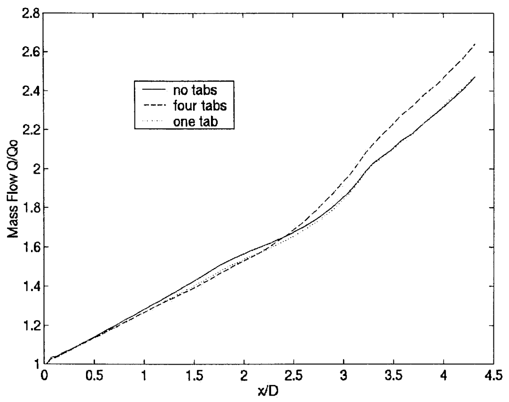

Figure 9: Mass flow rate

The round jet with four tabs entrains approximately 6% more fluid compared to the other two flows. All flows show an increase in the rate of entrainment as the rings are torn apart: at $x/D = 2.5$ for the jet with four tabs, and at $x/D = 3.0$ for the other two flows. This location also corresponds to the point where the braid-shaped structures begin to dominate the flow field. In the jet with four tabs, the braid-shaped structures that form at the apex of each bulge in the shear layer cause the rings to break apart faster, and appear to be responsible for the increased entrainment. This result supports previous findings that the streamwise braid-shaped structures have a greater effect on flow entrainment than the azimuthal ring-shaped structures.

CONCLUSIONS AND FUTURE WORK

Large eddy simulation was used to investigate the effects of vortex-generating tabs in a turbulent round jet. Turbulence structures in the flow field were identified from instantaneous plots of vorticity. A shear layer formed immediately downstream from the nozzle. The introduction of tabs in the nozzle altered the shape of the shear layer, causing it to bulge inwards towards the jet core. When a four-tab configuration was used in the nozzle, the shear layer did not regain a circular shape before it rolled up into rings. In this case, streamwise braids formed in the apex of each bulge at the downstream end of the shear layer. These braids altered the evolution of the rings, causing them to be torn apart by $x/D = 3.0$. A significant increase in entrainment was noted in this flow.

These results represent a first attempt at modelling and visualizing the effects of tabs using large eddy simulation. Additional work is required to study the effects of the size and the configuration of the tabs. Also, the effect of the tabs on the inlet conditions used in the jet model needs to be investigated. However, despite the preliminary nature of these results, this study has demonstrated that large eddy simulation results can be used to illustrate the effects of vortex-generating tabs, and aid in the design of jet nozzles.

Acknowledgements

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References

Ciofalo, M., 1994, ''Large-eddy simulation: a critical survey of models and applications'', *Advances in Heat Transfer, Academic Press, pp. 321-419.*

Ethier, C.R. and Steinman, D.A., 1994, ''Exact fully 3D Navier-Stokes solutions for benchmarking'', *Int. J. Num. Meth. Fluids, Vol. 19, pp. 369-375.*

Foss, J. and Zaman, K.B.M.Q., 1996, "Effect of a delta tab on fine scale mixing in a turbulent two-stream shear layer'', *AIAA Paper 96-0546.*

Germano, M., Piomelli, U., Moin, P. and Cabot, W.H., 1991, ''A dynamic subgrid-scale eddy viscosity model'', *Phys. Fluids, Vol. A3(7), pp. 1760-1765.*

Huang, L. and Ho, C., 1990, "Small scale transition in a plane mixing layer'', *J. Fluid Mech., Vol. 70, pp. 475.*

Kim, J. and Moin, P., 1985, ''Application of a fractional-step method to incompressible Navier-Stokes equations'', *J. Comp. Phys., Vol. 59, pp. 308-323.*

Liepmann, D. and Gharib, M., 1992, ''The role of streamwise vorticity in the near-field entrainment of round jets'', *J. Fluid Mech., Vol. 245, pp. 643-668.*

McIlwain, S., 2000, ''Large Eddy Simulation of the near field of round and co-axial jets with mild swirl'', *Ph.D. Thesis, Queen's University, Kingston, Canada.*

McIlwain, S. and Pollard, A., 2000, ''Large scale turbulence structures in jets with and without swirl'', *Proc. of the 8th Annual Conference of the CFD Society of Canada, Montreal, pp. 413-420.*

Mi, J. and Nathan G., 1999, ''Effect of small vortex-generators on scalar mixing in the developing region of a turbulent jet'', *Int. J. of Heat and Mass Transfer, Vol. 42, pp. 3919-3926.*

Zaman, K.B.M.Q., Reeder, M.F. and Samimy, M., 1994, ''Control of an axisymmetric jet using vortex generators", *Phys. Fluids, Vol. A(6), pp. 778-793.*

Zaman, K.B.M.Q., 2000, ''Spreading characteristics of compressible jets from nozzles of various geometries'', *J. Fluid Mech., Vol. 383, pp. 197-228.*