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Effects of Tangential Blowing on High-Speed Jets

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Velocity measurements have been performed to survey the effect of tangential blowing to enhance the mixing of jets. Mixing enhancement was expected to result from the creation of streamwise vorticity and from the effect of centrifugal forces. The velocity field in the plume of Mach 0.8 and 1.5 jets was measured with a Pitot rake. In the subsonic case, tangential blowing from two diametrically opposite ports enhances the jet mixing and reduces by 67% the length of the potential core. This requires an actuation mass flow rate less than 1 percent of that of the main jet. Significant deformation of the plume cross section is observed which suggests the induction of streamwise vortices entraining and mixing ambient air. Flow visualization techniques can reveal this phenomenon. Centrifugal forces seem to play a minor role since the tangential blowing induces a mild swirl in the jet. Tangential blowing was less effective in the supersonic case, possibly the result of inducing a striction of the jet potential core in the axial direction.

Nomenclature

A = nozzle cross-sectional area
C_μ = tangential blowing to main-jet momentum ratio
D = nozzle exit diameter
$\dot{m}$ = mass flow rate
M = fully-expanded Mach number
r = radial location
u = local horizontal component of jet velocity
U = fully-expanded velocity
x = stream-wise location
ρ = density

Subscripts
j = main jet
t = tangential blowing

I. Introduction

PHYSICALLY, the key parameter governing the effect of compressibility on turbulent mixing is the convective Mach number, that is the Mach number in a coordinate system convecting with the velocity of the structures of the shear layer[1]. It is known that compressible mixing layers also extract less energy from the main flow when compared to incompressible cases with reduced turbulence and growth rates[2,3]. Flow visualization studies reveals that with increasing compressibility effects the mixing layer change from organized spanwise-oriented two-dimensional structure to highly irregular three-dimensional structures[4,5]. The formation of streamwise vortical structures would mix and entrain fluid, and extract energy from the main flow even under highly compressible conditions[6]. However, where compressibility is important, Papamoschou and Roshko have suggested that naturally occurring three-dimensional structures containing streamwise components cause the turbulent mixing layer growth rate to asymptote to a value approximately 20% of the corresponding incompressible case[1]. This implies that the adverse effect of compressibility on growth rate would be reduced by adding more three-dimensionality into the

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flow. For an axisymmetric jet, helical structures would potentially enhance mixing as the flow would locally experience lower effective convective Mach numbers.

One obvious method of creating a streamwise component of vorticity is the addition of a tangential-velocity component to an axisymmetric jet. The concept of swirl-enhanced mixing is not new. A widespread application is the mixing of fuel and oxidizer to promote efficient burning and pollutants reduction. To this aim, much work has focused on optimizing the mixing of liquid and gas streams in fuel injectors[7-12]. In most cases this involves the use of a van-type swirler to bulk-swirl the entire jet. Clearly this approach is not applicable to jet engines as significant propulsive energy would be lost to the swirling effect. Selective introduction of swirl in the jet should be used instead. Previous experimental studies of mixing enhancement by introducing swirl to axisymmetric jets demonstrates that the mixing-layer growth rates are significantly increased compared to non-swirling jets. Swithenbank and Chigier[13] postulated that the cause for increased mixing of low speed and transonic swirling flows may be similar for higher speed compressible flow. Using secondary swirling jets injected in a co-flowing non-swirling supersonic stream do not appear to enhance the mixing[14,15]. A more recent study by Cutler et al. indicates that swirl can significantly enhance compressible Mach 2.2 swirling free jet[16]. The study reveals that the growth rates increased with the degree of swirl and can be increased by threefold that of the non-swirling jet.

In the present study micro jets are injected tangentially to the main jet to create a swirl and add three-dimensionality to the flow. This differs from previous works where the micro jet or jets are introduced radially towards the main jet[17,18]. The aim here is to explore a new flow-control device involving microjets blowing tangentially and switchable so as to control the level of swirl and hence mixing. In contrast to vanes as swirling devices the present approach should incur less pressure losses. A similar study by Faivre and Poinsot shows improved mixing performance by using actuation jets located close to the exit but still within the nozzle and oriented to provide maximum swirl[19]. In our study the micro jets are introduced on the jet external to the nozzle. A variable number of micro jets from 1 to 4 is investigated to examine the actuation mode. The underlying idea is to add angular momentum to the jet mixing layer thus increasing its ability to expand due to centrifugal forces. In some ways this study parallels that of Cheng et al.[12] except that we consider a case where gas is used in both the primary jet and the tangential flow. More precisely, we studied the effects of three different blowing configurations on a subsonic and a supersonic jet by comparing the velocity fields of the forced and baseline cases. The findings indicate that the high-speed core of a subsonic jet can be shortened and jet mixing enhanced. These effects can be attributed to the presence and interaction of both centrifugal forces and Kelvin-Helmholtz instabilities. These results are encouraging and suggest that the technique can benefit the jet mixing in several practical applications.

The remainder of the article is organized in two main sections. The experimental setup, instrumentation, and procedures are introduced first followed by the discussion of the results.

II. Experiments

All the experiments were conducted in the Temasek Laboratories of the National University of Singapore by using the following equipment and diagnostics.

A. Nozzles and Flow Conditions

High-speed air jets issued from nozzles with exit diameter D = 12.7 mm (0.5 in). A convergent type of nozzle was used to produce subsonic jets at Mach 0.8. Experiments at supersonic speed were conducted using a convergent-divergent nozzle designed with the method of characteristics for nominal exit Mach number 1.5. In Table 1 these jets are coded M08 and M15 respectively. Air is supplied to the nozzles through a plenum. A pressure transducer (Setra Model 208E) connected to the plenum allows control of the stagnation pressure within ±1% of the nominal values. The nozzle pressure ratio (NPR) and the fully-expanded Mach number, velocity, and Reynolds number of the jets (based on their diameter) are given in Table 1.

Tangential blowing is provided by four 1-mm diameter stainless-steel pipes mounted at the jet exit, Fig. 1. The pipes are solidly inserted in a support ring connected to the nozzle and reach close to the jet exit diameter without protruding into the stream, Fig. 1. A separate plenum supplies air to the tangential pipes through a valving system that allows independent operation of each pipe. A pressure transducer similar to jet plenum allows control of the blowing stagnation pressure within ±1% of the nominal value. In this study tangential blowing was achieved at NPR=1.2. Accounting for the minor pressure losses occurring in the small size tubing between the plenum and the pipe exhausts, the tangential jets issued at Mach 0.5, with velocity of 170 m/s. In these conditions the mass flow rate of each tangential jet is $1.6 \cdot 10^{-4}$ kg/s. The Reynolds number, based on the diameter, is about 10^4.

For each jet Mach number we tested four different configurations, Fig. 2. The baseline case (B) is the jet without tangential blowing. Blowing cases comprise use of a single tangential pipe (T1), of two diametrically opposite tangential pipes (T2), and of four tangential pipes (T4). The tangential blowing to main-jet mass flow ratio is provided in Table 1 for each flow configuration. The same table provides also the tangential blowing to main-jet momentum ratio $C_\mu = \rho_t A_t U_t^2 / \rho_j A_j U_j^2$, which represents a measure of the actuation effort.

B. Mean Velocity Measurements

A Pitot rake was used to survey the mean velocity in the jets. The rake consists of five stainless steel tubes, each 76.2mm (3in) long, supported by an airfoil-shaped holder. The tubes are mounted 12.5 mm apart and their inner diameter is 1.0 mm. The rake is mounted on a carriage with motorized motion in the x-direction (longitudinal) and in the y- and z-directions (spanwise and vertical directions), Fig. 3. The first from the top probe is the reference probe, and it is initially positioned on the jet axis at the nozzle exit. The five probes of the rake are individually connected to five pressure transducers (Setra Model 208E) mounted close to the traverse assembly in order to minimize the length of the tubing between each probe and transducer. Mach number and velocity were computed from the Pitot pressure by assuming constant total temperature (equal to the ambient temperature) and uniform static pressure. Control of the three-axis carriage allowed incremental-step motion in each direction. 1000 samples from each probe were acquired at each rake location through a National Instrument 6014 board installed on a Dell Optilex GX270 personal computer.

Streamwise velocity profiles were obtained in the x-z plane. For each case 20 uniformly spaced x-locations were surveyed downstream of the plug tip, with x/D spanning a distance from 1 to 20. For each location 60 measurements were taken in the vertical (radial) direction separated by Δz=1.04mm, Fig. 3 .The jet cross section was surveyed at distances of x/D=4, 6, and 8. The sampling grid is centered with the jet axis and consists of 30 points in each direction separated by 2.08mm, i.e., one fifth of the probe spacing. Thus the size of square area covered is 62.4mm corresponding to almost 5 jet diameters.

III. Results

Figures 4 to 11 provide the longitudinal and the cross-sectional contours of the jet velocity normalized by the corresponding fully-expanded jet velocity U_j .

The velocity isocontours of the baseline Mach 0.80 jet are presented in Fig. 4. The high-speed region (defined here as $U/U_j > 0.9$) of the axisymmetric jet extends to about 8 diameters downstream of the nozzle. Cross sectional measurements confirm that the jet is round and well centered. Figure 5 shows the effect of blowing with one jet. Even though the blowing jet was meant to graze tangentially the mixing layer of the main jet, it is evident that it “kinks” and deforms the jet cross-section close to the nozzle exit. Further downstream the jet tends to recover a more axisymmetric shape. In the process the jet also acquires a moderate axial spin in the blowing direction. It is possible that the blowing jet induces a streamwise vortex pair in the main jet, but we could not verify this with the current setup. In any case, the net effect is a growth of the jet cross section compared to the baseline, a clear indication of increased mixing. Furthermore, both the cross-stream and the longitudinal profiles indicate that the high-speed region of the jet has been shortened by two diameters. The effect of two tangential jets is illustrated in Fig. 6. Similar to the previous case the cross-section of the jet is distorted by the pounding action of the tangential jets. Centrifugal effects induced by the blowing are either very small or masked by the distorted geometry. The surface of the cross-section is further increased, a fact not revealed by the longitudinal profile due to the rotation angle of the largest cross-sectional dimension. The high-speed region of the jet has additionally shrunk by more than one diameter thus achieving an overall reduction of 42% compared to the baseline. Application of blowing at four tangential points produces the results shown in Fig. 7. The cross section close to the nozzle is nicely deformed to a 4-lobed shape which likely promotes the entrainment and mixing of the ambient air. Further downstream the cross section evolves to a squarish shape with an undetectable spin in the blowing direction. The high-speed region of the jet has virtually the same extension as in the previous case.

We repeated these measurements on Mach 1.5 jets. At the conclusion of our experiments we determined that at nominal NPR=1.5 conditions these jets were actually slightly underexpanded. As a result, the initial jet boundary barely touches the tip of the tangential pipes just past the nozzle exit. This produces the same effects observed in jets with tabs[20], which in our case is the creation of very small streamwise vortex pairs that grow further downstream, Fig. 8. As a result, this jet spreads more than expected, and in fact more than the subsonic baseline, by entraining and mixing ambient air. Its high-speed region is also shorter and contains of expansions-compression waves in the potential core. The cross section does not rotate moving downstream and past x/D=4 it shows a slight preferential growth towards in the vertical direction. A more representative baseline could be obtained by lowering the NPR until the jet matches the ambient pressure at the nozzle exit. Similar to the subsonic case, application of tangential blowing induces distortion and a rotation of the jet plume. This is clearly visible when one tangential blowing jet is applied, Fig. 9. Interestingly, in this case the cross section does not tend to recover a circular shape while moving downstream. On the contrary, it evolves to a more triangular shape. This, in conjunction with the rotation in the blowing direction, produces a somewhat warped longitudinal profile. The high-speed region is not reduced compared to the baseline case and the cross-sectional areas of the two cases are comparable. The effect of blowing with two jets is illustrated in Fig. 10. The cross section is initially distorted to an almost hexagonal shape that evolves to a more square shape while rotating counterclockwise. Compared to the non-actuated jet, the area of the cross-section becomes actually slightly smaller at x/D=4 and beyond, and the high-speed region is actually stretched by 12%. Four-point tangential blowing distorts the cross section to an almost square shape, Fig. 11. Similar to the corresponding subsonic case, the cross section does not appear to rotate. Also, the area of the cross section for $x/D >$ 4 is smaller than those of the other supersonic cases and the jet high-speed region has been stretched by about 26% relative to the baseline.

Figure 12 presents the axial distribution of the maximum velocity of all the jets. This parameter substantially coincides with the centerline velocity and summarizes the impact of actuation in reducing the jet velocity. It is also very useful to identify the potential core of the jet and its decay as the velocity in the core region is about uniform and produces a nearly flat profile. The core of the subsonic baseline case extends about 6 diameters past the nozzle, Fig. 12a. Application of tangential blowing promotes the velocity decay and lowers the jet speed. This effectively amounts to a shift of the whole velocity profile closer to the nozzle. Tangential blowing with one jet shifts the profile upstream by two jet diameters, whereas blowing with two and four jets further shifts the profile upstream by two additional jet diameters. Thus the potential core of these jets extends only two diameters past the nozzle. The behavior of the supersonic cases is quite different, Fig. 12b. First, close to the nozzle we can observe the effect of the expansion and compression waves. Tangential blowing from one point offers a very modest jet velocity reduction. Increasing the number of blowing points stretches by 2 diameters the jet potential core and the train of expansion-compression waves. It also decreases the velocity decay further downstream. In this respect, tangential blowing from multiple points appears to worsen the jet performance.

From our results it appears that tangential blowing is more effective in the cases revealing larger deformation of the cross sectional profiles, a condition typically associated to streamwise vortices. Different studies have shown that such vortices are very effective in promoting the entrainment and the mixing of ambient air[20-23]. Laser flow visualization and PIV measurements can be used to clearly reveal the presence and the effect of such vortices. Thus tangential blowing may be a useful technique to enhance on demand the jet mixing by promoting the formation of streamwise vortices. On the other hand the effect of centrifugal forces may be modest given the relatively low spin induced in the jet by the tangential blowing. In fact with four-sided blowing no appreciable spin was observed. The slight underexpansion of our supersonic jets complicates a clean assessment of the effect of tangential blowing in these cases. We attribute the unfavorable performance obtained by using two and four blowing ports to a side-effect of these configurations which can induce a striction of the jet potential core in the axial direction. Additional measurements using single-point blowing with same momentum as the T2 and T4 cases are required to assess this conjecture.

IV. Conclusion

The effect of tangential blowing on the velocity field of high-speed subsonic and a supersonic round jets has been investigated. Three forcing schemes have been considered that encompass blowing with one, two and four tangential jets distributed on the periphery of the main jet. Comparison between the baseline and the forced cases reveal that tangential blowing distorts the jet cross section to shapes that promote the entrainment and mixing of ambient air. This can be exploited in practical applications to enhance on demand the mixing of jets. The effects need to be further investigated by using flow visualization and PIV techniques. As expected, the cross sections rotate while moving downstream, but the spin rate is quite small. Therefore the influence of centrifugal forces can be minor and is easily masked by other phenomena. Forcing generally shortens the potential core of the jet as a result of the increased entrainment. In the subsonic case the tangential blowing from two points reduces the length of the potential core by about 67% with an actuation mass-flow-rate which is less than one percent of the main stream. The effect of tangential blowing on supersonic jets is less clear. Two and four-points blowing seems to reduce the mixing and lengthens the potential core. We speculate this is caused by a striction of the core in the axial direction with these configurations.

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References

1. Papamoschou, D. and Roshko, A. R., “The compressible turbulent shear layer: an experimental study,” *Journal of Fluid Mechanics*, Vol. 197, 1988 , pp. 453-477.
2. Elliot, G. and Samimy, M., “Compressibility effects in free shear layers,” AIAA Paper 90-0705.
3. Goebel, S. G. and Dutton, J. C., “Experimental study of compressible turbulent mixing layers,” *AIAA Journal*, Vol. 29, 1991, pp. 38-946.
4. Clemens, N. T. and Mungal, M. G., “Two- and three-dimensional effects in the supersonic mixing layer,” *AIAA Journal*, Vol. 30, 1992, pp. 973-982.
5. Fourgette, D. C., Mungal, M. G., and Dibble, R. W., “Time evolution of the shear layer of a supersonic axisymmetric jet,” *AIAA Journal*, Vol. 29, 1991, 1123-1130.
6. Morkovin, M. V., “Mach number effects on free and wall turbulent structures in light of instability flow interactions,” *Studies in Turbulence*, edited by T. B. Gatski, S. Sarkar, and C. G. Speziale, Springer-Verlag, New York, 1992, pp. 269-284.
7. Sloan, D. G., Smith, P. J., and Smoot, D. L., “Modeling of Swirl in Turbulent Flow Systems,” *Progress in Energy and Combustion Science*, Vol. 12, 1986, pp. 163-250.
8. Martina, J. E. and Meiburg, E., “On the stability of the swirling jet shear layer,” *Physics of Fluids*, Vol. 8, No. 1, 1994, pp. 242-426.
9. Naughton, J. W., Cattafesta, L. N. III, and Settles, G. S., “An experimental study of compressible turbulent mixing enhancement in swirling jets,” *Journal of Fluid Mechanics*, Vol. 330, 1997, pp. 271-305.
10. Ruith, M. R., Chen, P., Meiburg, E., and Maxworthy, T., “Three-dimensional vortex breakdown in swirling jets and wakes: direct numerical simulation,” *Journal of Fluid Mechanics*, Vol. 486, 2003, pp. 331-378.
11. Hanzhuang, L. and Maxworthy, T., “An experimental investigation of swirling jets,” *Journal of Fluid Mechanics*, Vol. 525, 2005, pp. 115–159.
12. Cheng, G. C., Davis, R. R., Curtis, W. J., Muss, J. A., Greisen, D. A., and Cohn, R. K., ”Development of GOX/Kerosene Swirl-Coaxial Injector Technology,” AIAA Paper 2003-4751.
13. Swithenbank, J. and Chigier, N. A., “Vortex mixing for supersonic combustion,” *Proceedings of the XII International Symposium on Combustion*, The Combustion Institute, 1969, pp. 1152-1162.
14. Povinelli, L. A. and Ehlers, R. C., “Swirling base injection for supersonic combustion ramjets,” *AIAA Journal*, Vol. 10, 1972, pp. 1243-1244.
15. Schetz, J. A. and Swanson, R. C., “Turbulent jet mixing at high supersonic speeds,” *Z. Flugwiss*, Vol. 21, 1973, pp. 166-173.
16. Cutler, A. D., Levey, B. S., and Kraus, D. K., “An experimental investigation of supersonic swirling jets,” AIAA Paper 93-2922.
17. Arakeri, V. H., Krothapalli, A., Siddavaram, V., Alkislar, M. B., and Lourenco, L. M. , “On the use of microjets to suppress turbulence in a Mach 0.9 axisymmetric jet,” *Journal of Fluid Mechanics*, Vol. 490, 2003, pp. 75–98.
18. Krothapalli, A., Venkatakrishnan, L., Lourenco, L., Greska, B., and Elavarasan, R., “Turbulence and noise suppression of a high-speed jet by water injection,” *Journal of Fluid Mechanics*, Vol. 491, 2003, pp. 131–159.
19. Faivre, V. and Poinsot, T., “Experimental and numerical investigations of jet active control for combustion applications,” *Journal of Turbulence*, Vol. 5, No. 1, 2004, pp. 25.
20. Zaman, K. B. M. Q., Reeder, M. F., and Samimy, M., “Control of an Axisymmetic Jet Using Vortex Generators,” *Physics of Fluids*, Vol. 6, No.2, 1994, pp. 778-796.
21. Ahuja, K. K. and Brown, W. H., “Shear Flow Control by Mechanical Tabs,” AIAA Paper 89-0994.
22. B. Callender, E. J. Gutmark, S. Martens, “Far-Field Acoustic Investigation into Chevron Nozzle Mechanisms and Trends,” *AIAA Journal*, Vol. 43, No. 1, 2004, pp. 87-95.
23. Knowles, K. and Saddington, A. J., “A review of jet mixing enhancement for aircraft propulsion applications,” *Journal of Aerospace Engineering*, Vol. 220, No. 2, 2006, pp. 103-127.

Table 1 Flow Conditions

Code	NPR$_j$	M_j	U_j m/s	Re_{Dj} x10^5	Blow pipes	NPR$_t$	M_t	U_t m/s	$\dot{m}_t / \dot{m}_j$ x10^{-3}	C_μ x10^{-4}
M08B	1.52	0.8	262	1.9	-	1.20	0.5	170	-	-
M08T1	1.52	0.8	262	1.9	1	1.20	0.5	170	3.75	24.3
M08T2	1.52	0.8	262	1.9	2	1.20	0.5	170	7.50	48.5
M08T4	1.52	0.8	262	1.9	4	1.20	0.5	170	15.00	97.0
M15B	3.67	1.5	432	1.5	-	1.20	0.5	170	-	-
M15T1	3.67	1.5	432	1.5	1	1.20	0.5	170	1.75	6.9
M15T2	3.67	1.5	432	1.5	2	1.20	0.5	170	3.50	13.8
M15T4	3.67	1.5	432	1.5	4	1.20	0.5	170	7.00	27.6

Figure 1: Closeup of the test nozzle with the tangential blowing injectors.

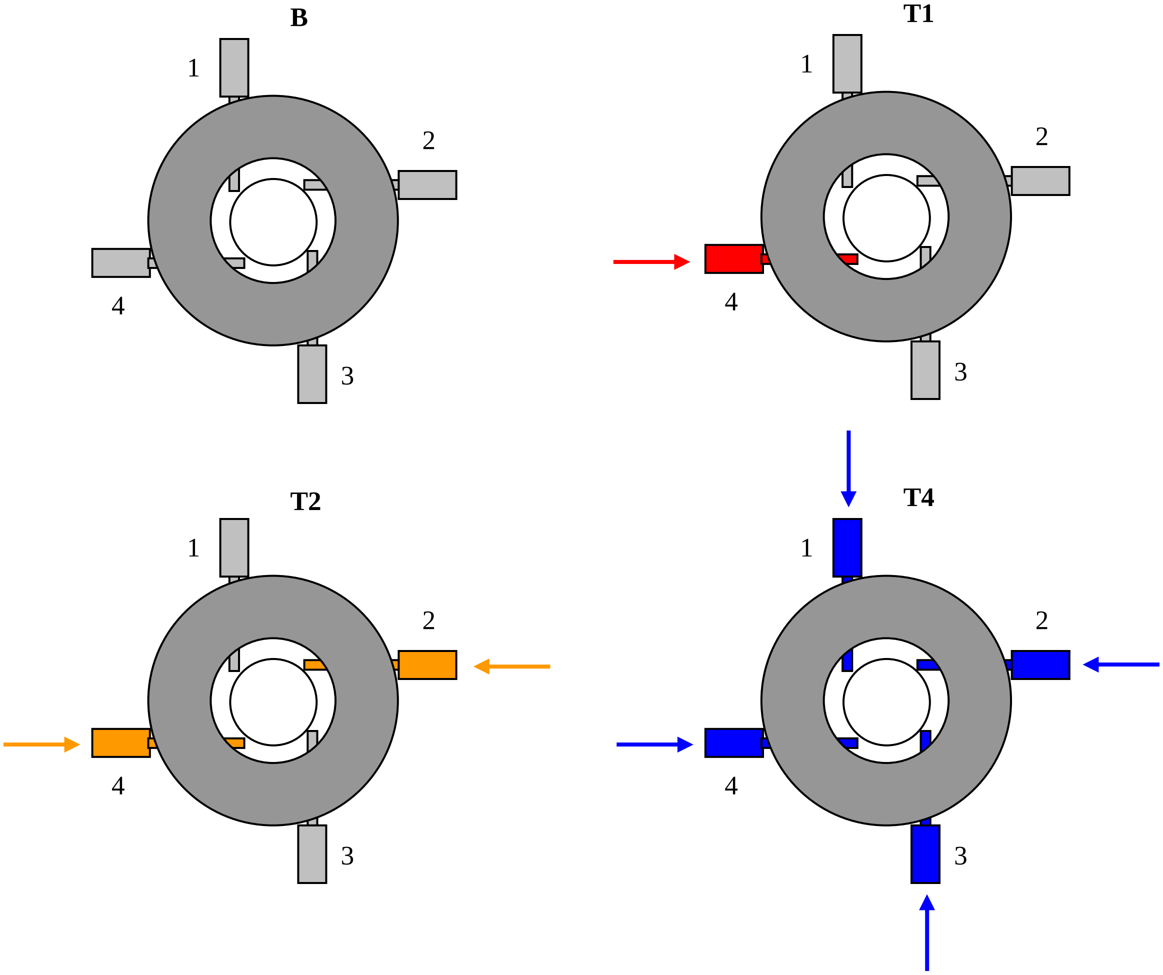

Figure 2: Schematic of the configurations tested.

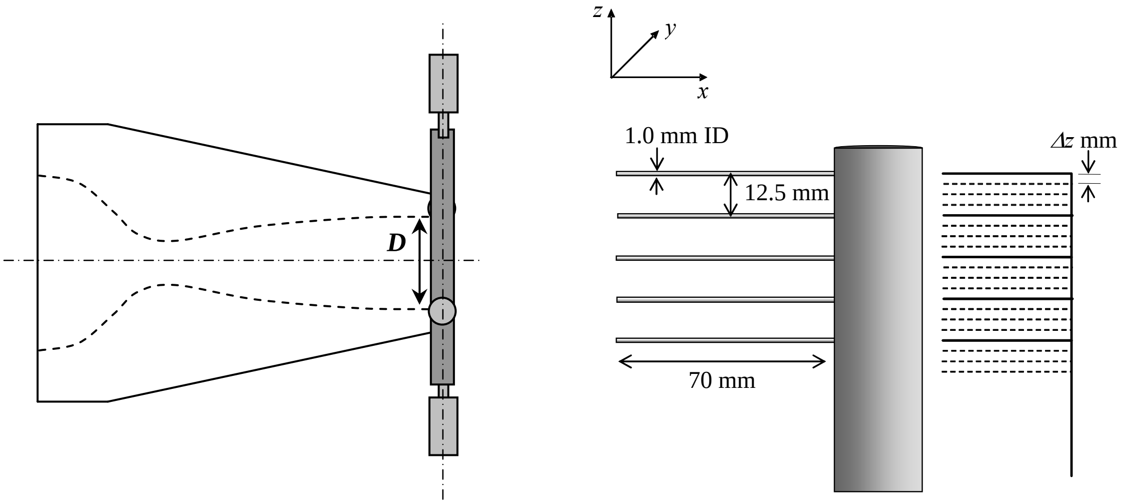

Figure 3: Schematic of the Pitot rake for mean velocity measurements..

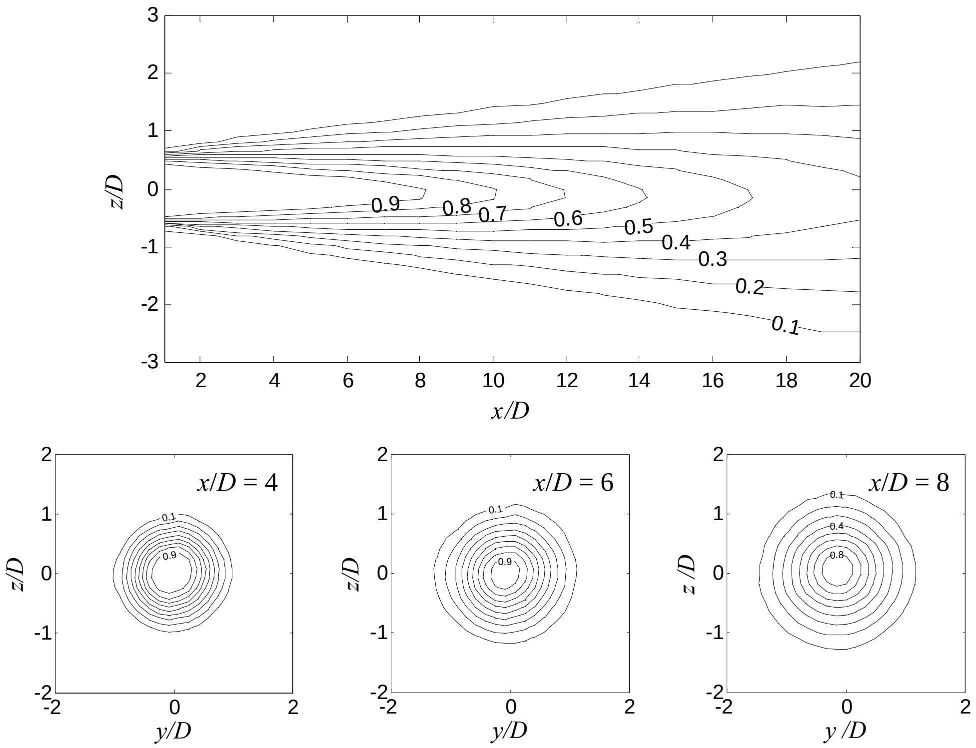

Figure 4: Normalized velocity isocontours of baseline Mach 0.80 jet (M08B).

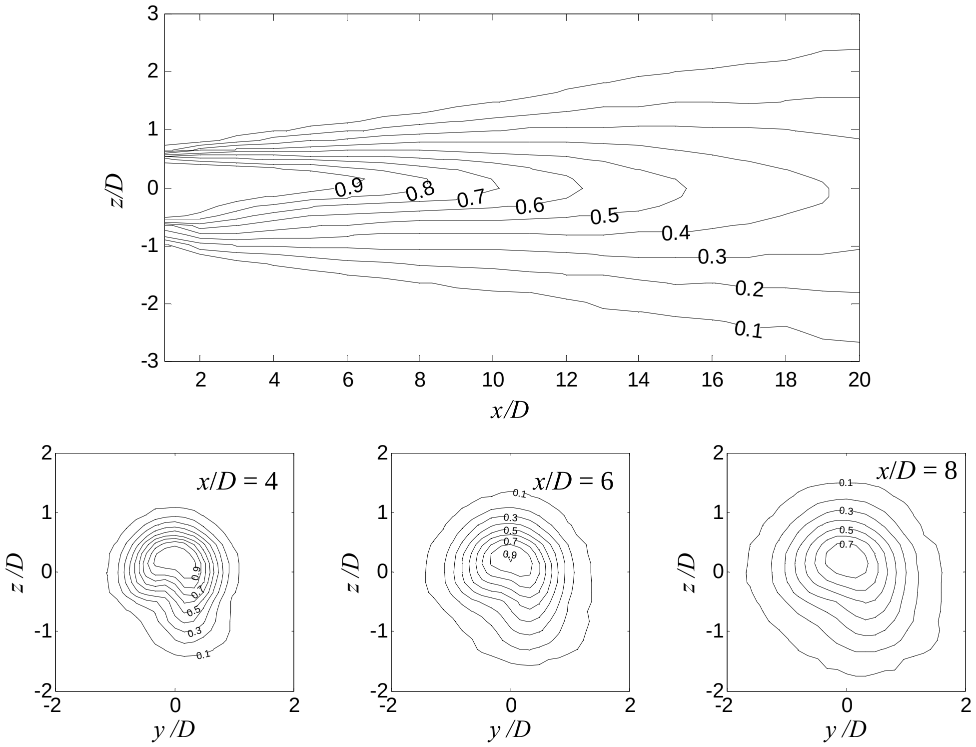

Figure 5: Normalized velocity contours of Mach 0.80 jet with tangential blowing from one port (M08T1).

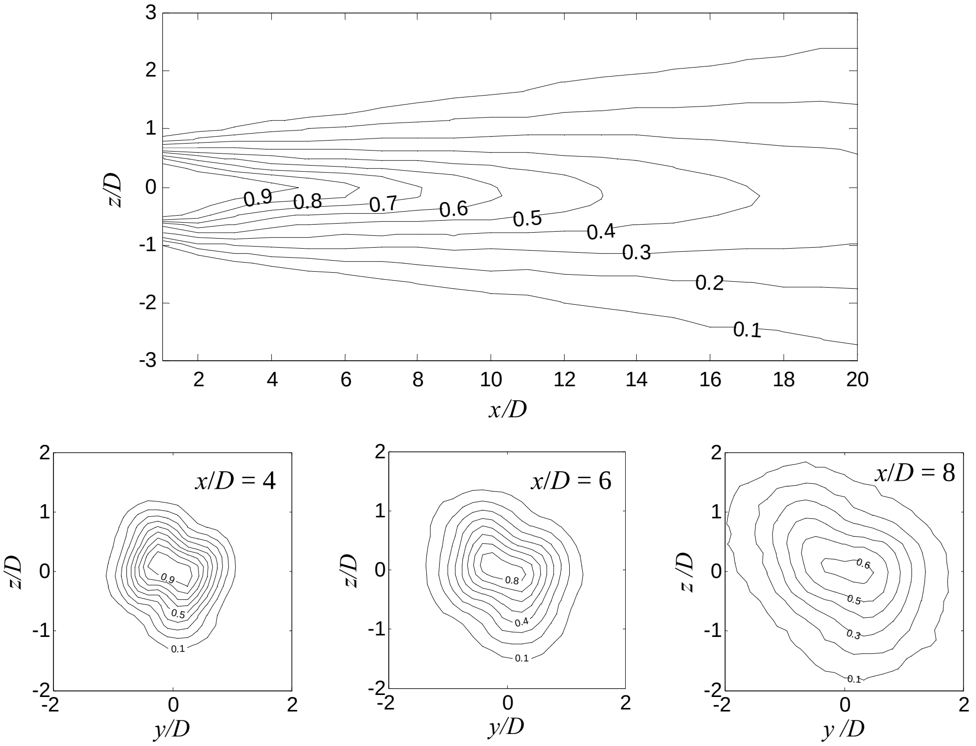

Figure 6: Normalized velocity isocontours of Mach 0.80 jet with tangential blowing from two ports (M08T2).

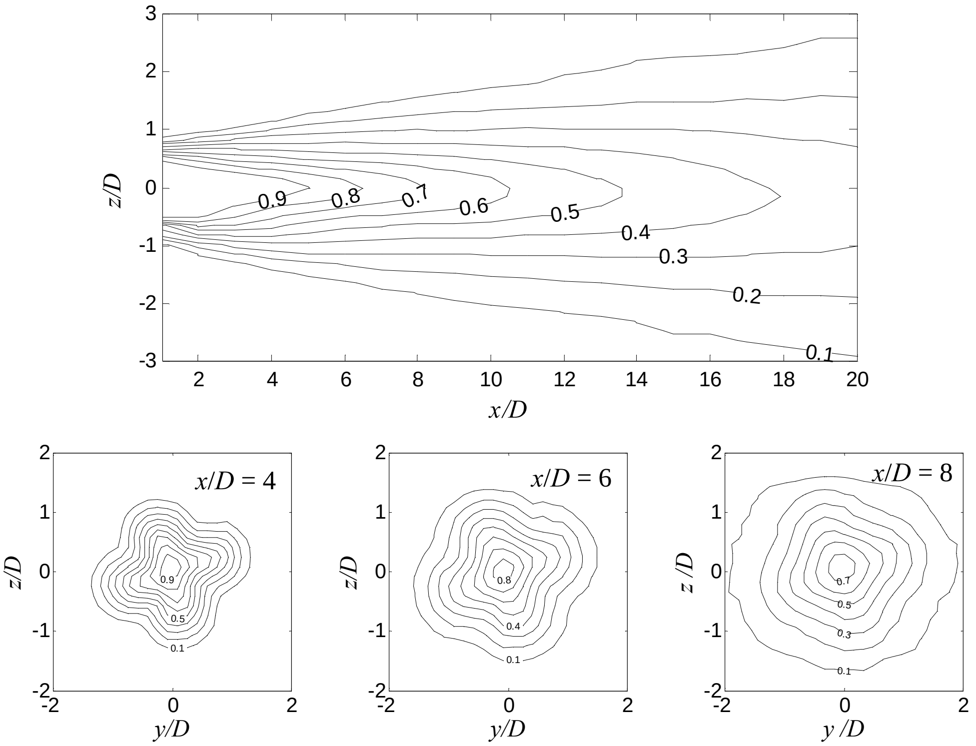

Figure 7: Normalized velocity contours of Mach 0.80 jet with tangential blowing from four ports (M08T4).

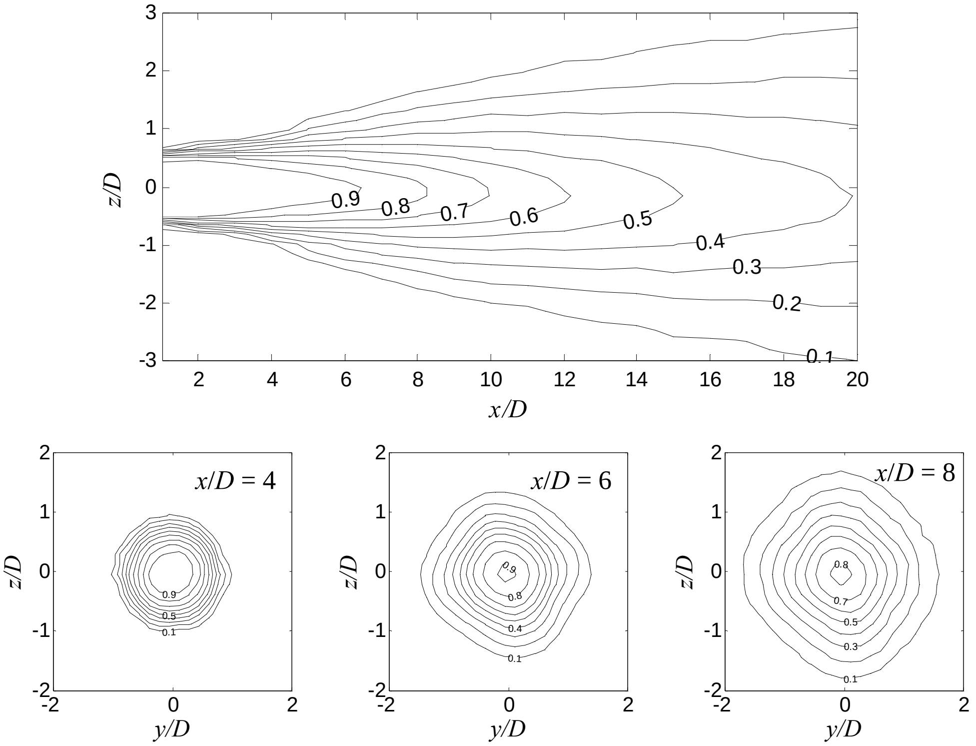

Figure 8: Normalized velocity isocontours of baseline Mach 1.50 jet (M15B).

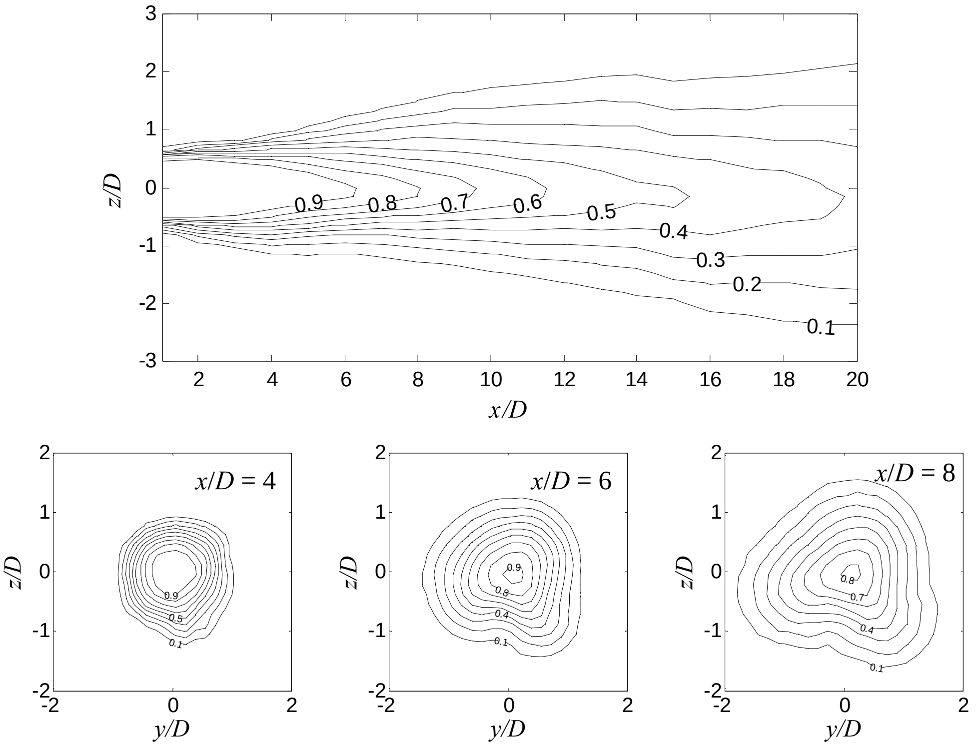

Figure 9: Normalized velocity contours of Mach 1.50 jet with tangential blowing from one port (M15T1).

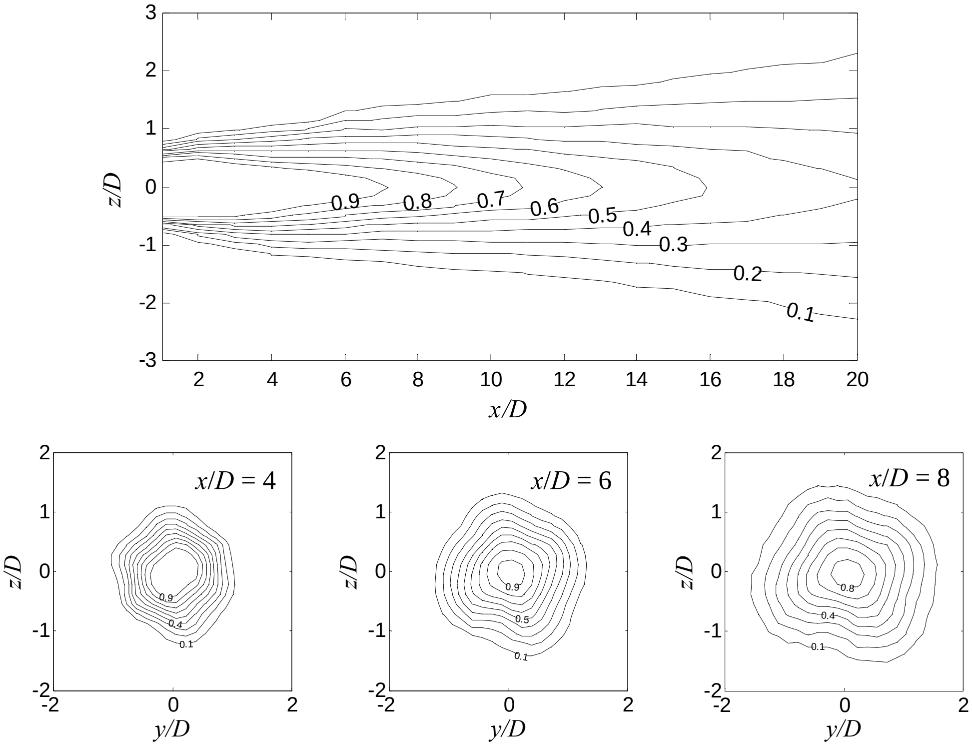

Figure 10: Normalized velocity isocontours of Mach 1.50 jet with tangential blowing from two ports (M15T2).

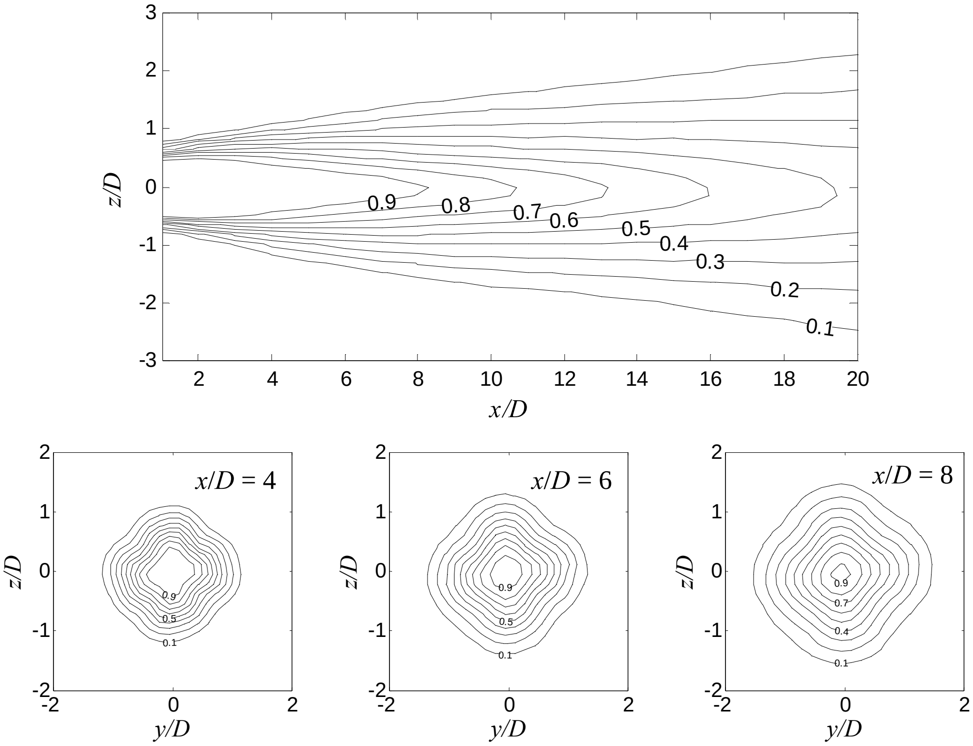

Figure 11: Normalized velocity contours of Mach 1.50 jet with tangential blowing from four ports (M15T4).

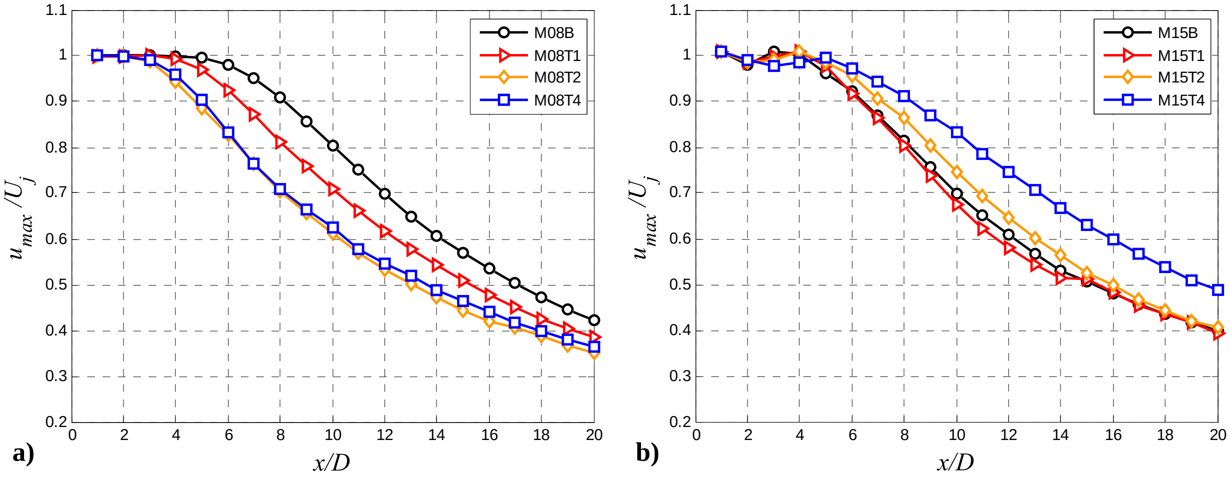

Figure 12: Axial distribution of normalized local maximum velocity for jets at: a) M=0.8; b) M=1.5.