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Prediction of axisymmetric turbulent jet flows using OpenFOAM

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Abstract. *A simulation model is proposed to predict the turbulent jet flow exhausted from axisymmetric nozzles. The compressible Reynolds-Averaged Navier-Stokes (RANS) equations are solved using the open-source code OpenFOAM. An axisymmetric nozzle geometry with diameter of* $0.508m$ *is simulated considering two values of jet acoustic Mach numbers:* 0.5 *and* 0.9*. Numerical errors due to the spatial discretization are assessed. Sensitivity tests to the size of the computational domain and boundary conditions are also addressed. The accuracy of the simulation model is verified through comparisons with experimental data, available in the literature, for mean velocity and turbulent intensity profiles.*

Keywords: *Jet flow, RANS, OpenFOAM*

1. INTRODUCTION

Jet flows are present in different engineering applications. Particularly, the jet formed from the exhaust of turbofan engines has been heavily investigated in the past few decades, as it is one of the most significant source of noise during the take-off. The complex nature of the sound generation mechanism in turbulent flows makes the jet noise one of the most difficult problems in aeroacoustics.

Numerically, turbulent jet flows can be studied via Direct Numerical Simulation (DNS), which consists of the resolution of the full NS equations, without any turbulence modeling. To reach this goal, the grid spacing and time step should account for the dynamics of the finest turbulent scales. In order to minimize computational cost, averaging or filtering procedures are applied to the equations in order to select which range of turbulent scales will be solved and which range will be modeled. Large-Eddy Simulation (LES) resolves only the large scales and models the smaller. This approach significantly reduces the computational cost of simulation compared to DNS, making it more feasible for non-academic cases. The use of LES for sound predictions is also justified by the fact that larger scales are more efficient than small ones as sound sources Labbé *et al.* (2013)

Reynolds Averaged Navier-Stokes (RANS) simulations, applies an statistic average on the equations, yielding and a steady-state simulation. In this way, no turbulent scales are resolved, and their contribution is considered by the use of turbulence closure models. As it does not provide transient results, synthetic turbulence techniques and/or semi-empirical approaches are required for noise source modeling. In this sense, several RANS-based noise prediction methods are present in the literature (Rosa *et al.*, 2016; Lyu *et al.*, 2017).

Numerical simulations involving free and installed jet flows for aeroacoustics have been conducted in the literature involving Navier-stokes LES , LES based on the Lattice Boltzmann Method (LBM) (da Silva *et al.*, 2015; da Silva *et al.*, 2015; Yupa-Villanueva *et al.*, 2019) and RANS simulations (Engblom *et al.*, 2004; Engel *et al.*, 2011). Regarding the use of open-source codes, OpenFOAM (Greenshields, 2020) is an open source CFD library with numerical solvers for a variety of physical problems, which is widely used by academy and industry. The jet-flow problem has been explored using OpenFOAM by some authors (Salehian and Mankbadi, 2020; Kannan, 2015; Kannan *et al.*, 2020).

The objective of this work is to propose and and validate a simulation model in OpenFOAM, to predict the turbulent flow field in axisymmetric subsonic jets. Numerical errors due to the spatial discretization are assessed and sensitivity tests to the size of the computational domain and boundary conditions are also addressed. The idea to obtain an accurate model which can be used to generated a database of jet-flow fields, to be coupled with RANS-based predictions of jet noise.

2. METHODS

2.1 Geometry and Experimental Data

This case is based on the SMC000 nozzle geometry (Brown and Bridges, 2006; Bridges and Wernet, 2010), shown in Fig.1. Bridges and Wernet (2010) present mean axial velocity data (U) and mean axial turbulent intensity (u'/U_j) axial profiles in the jet centerline, lipline and radial profiles in four different axial positions: $x = 4D$, $8D$, $12D$ and $16D$, where $D = 0.508m$ is the nozzle exit diameter. These data were extracted from the reference using the WebPlotDigitizer tool (Rohatgi, 2021) and were used to validate the numerical simulation of jets with acoustic mach numbers of $M_a = U_j/c_0 = 0.5$ and 0.9, where U_j is the maximum axial velocity in the centerline and c_0 is the ambient sound speed.

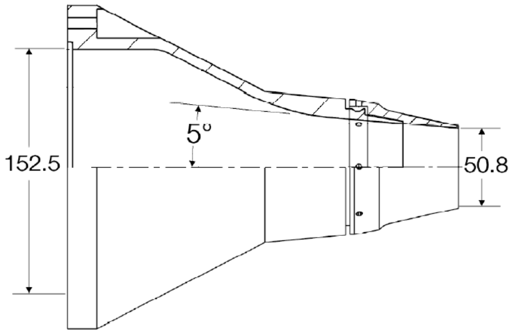


Figure 1: Geometry of the SMC000 nozzle from Brown and Bridges (2006); Bridges and Wernet (2010).

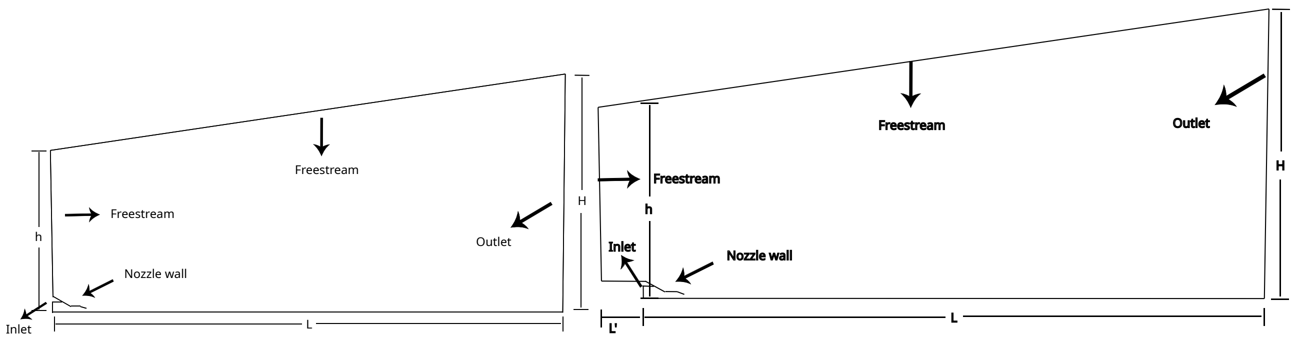
2.2 Computational setup

Compressible RANS simulations were conducted using the k-ϵ turbulence closure model (Launder and Spalding, 1974) implemented in OpenFOAM v8.0.

The two-dimensional computational domain and boundary conditions are depicted in Fig. 2. In order to test the sensitivity of the solution to the domain size, three domains were considered with dimensions described in Tab. 1. The domain "Dom 3" has an upstream extension of length L', in comparison with "Dom 2".

Table 1: Dimensions of the analyzed computational domains.

	Dom 1	Dom 2	Dom3
h	$11.8D$	$23.6D$	$23.6D$
H	$22.7D$	$34.5D$	$34.5D$
L	$75D$	$75D$	$75D$
L'	–	–	$5D$



(a) Dom 1 and 2 (b) Dom 3

Figure 2: Computational domain and boundary conditions.

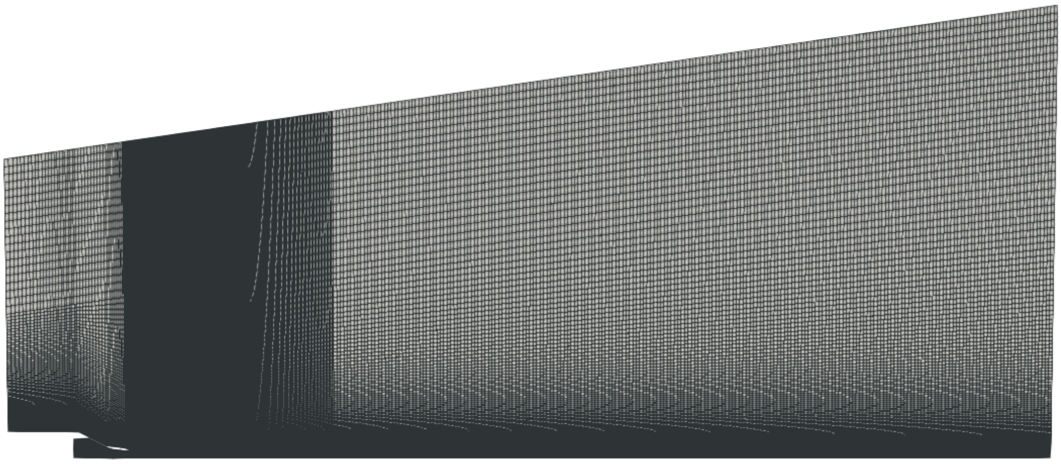
The computational meshes were generated using Gmsh (Geuzaine and Remacle, 2009), an open source mesh generator. Figure 3a show the mesh composed predominately by hexaedra. To simulate an axisymetric problem in OpenFOAM, the domain must be an slice in the circumferential direction. In this sense the mesh was generated in a plane and a rotational extrusion of $5°$ is applied. As the proposal is to use a 2D approach, only one layer of elements are generated in the azimuthal direction. To assess the sensitivity of the results to grid refinement, three meshes were considered as described in Tab. 2 by their number of elements (N).

Regarding boundary conditions, a low free-stream velocity condition of 1 m/s with a free-stream gauge pressure of 0 Pa was imposed at the upper and upstream boundaries. For the outlet, a fixed gauge pressure of 0 Pa was prescribed with a zero-gradient condition for velocity. A no-slip wall condition was used on the nozzle wall. For the nozzle inlet, a total pressure and temperature condition was imposed, calculated according to the jet acoustic Mach numbers of 0.5 and 0.9. The turbulence variables k and ϵ were defined based on a turbulence intensity of $I = 2\%$ and turbulence length scale $L = 0.008D$. In addition, for the front and back faces, the wedge condition was used, as required for axisymmetric simulations in OpenFOAM (Greenshields, 2020).

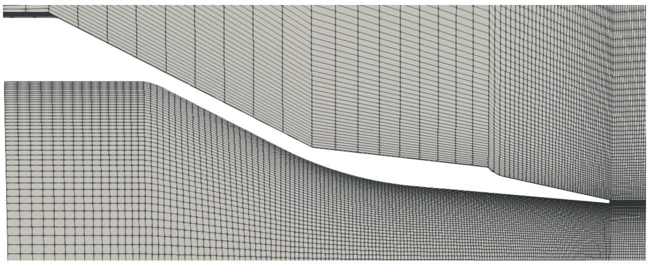
Second order numerical schemes were used. For convective terms, a linear upwind and limited linear schemes were

Table 2: Size of the computational grids.

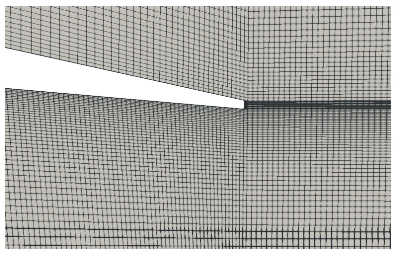
	N
Coarse	0.955×10^5
Medium	1.975×10^5
Fine	4.166×10^5



(a) Full domain



(b) Nozzle region



(c) Nozzle-exit region

Figure 3: Different slices of the computational domain, showing the computational mesh in different regions.

used for velocity and turbulence, respectively; whereas a multi-directional limited linear scheme was used for the gradient terms. For pressure-velocity coupling, the SIMPLE algorithm was chosen.

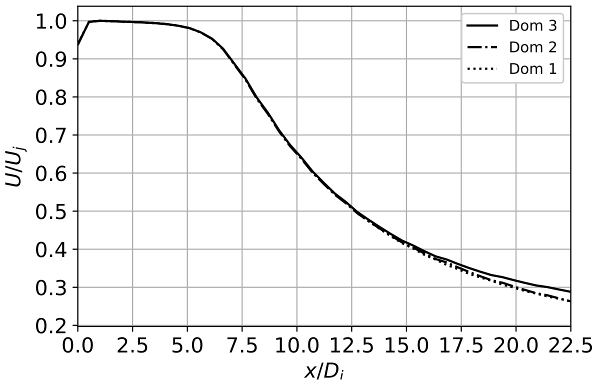
3. RESULTS

3.1 Sensitivity to the size of the domain

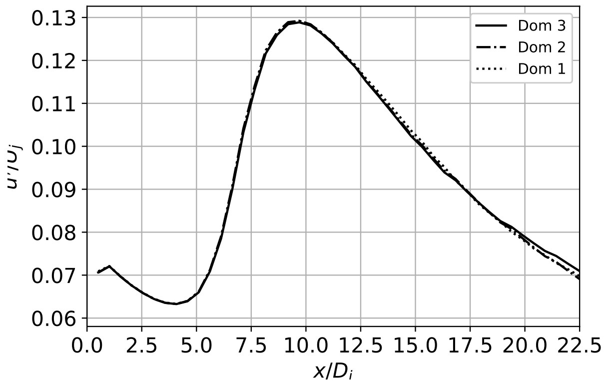
Results obtained from different domains are shown in Fig. 4. Figure 4a show results for the axial velocity and Fig.4b for the axial turbulence intensity (u'/U_j), both at the centerline. On the other hand, Fig. 4c and Fig. 4d depicts radial profiles of axial velocity and turbulence intensity, respectively, at $x = 8D$. No significant differences can be observed between results from different domains. Thus, even the smallest domain can be considered suitable for the simulations.

3.2 Sensitivity to the inlet turbulence intensity

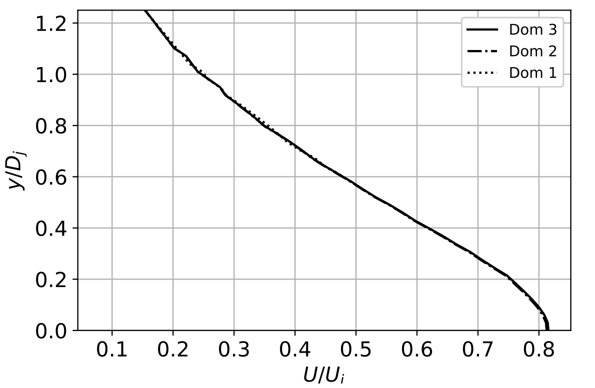
As there is no information regarding the turbulence intensity in the nozzle inlet (I), a sensitivity analysis was conducted to assess the influence of this parameter on the results. Figure 5a depicts results for the axial velocity at the centerline, which show that lowering the turbulence intensity shortens the length of the potential core. Figure 5b shows an in increase in the turbulent intensity inside the potential core when I gets lower. Nevertheless, results for $I = 5\%$ and $I = 10\%$ a very similar, suggesting and independence of the results to the inlet turbulence level for $I > 5\%$.



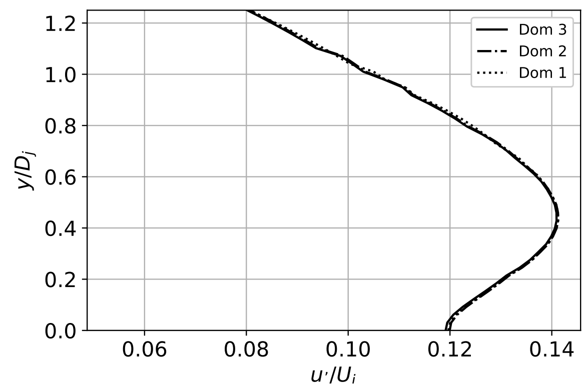
(a) Centerline U/U_j



(b) Centerline u'/U_j

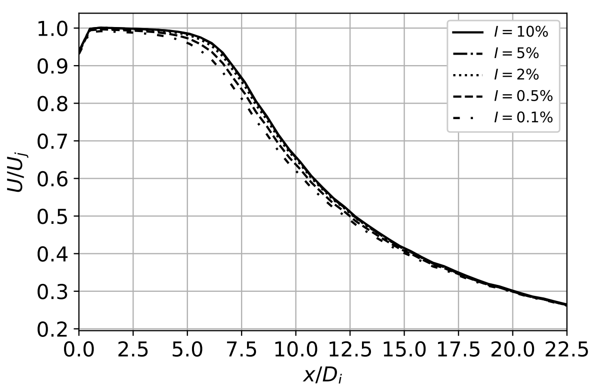


(c) U/U_j - $x = 8D$

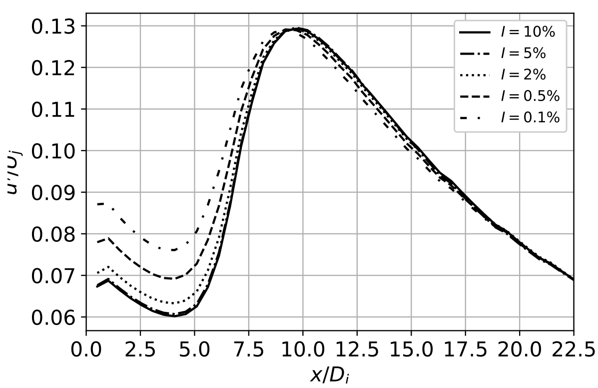


(d) u'/U_j - $x = 8D$

Figure 4: Comparison of the results obtained from different computational domains.



(a) Centerline U/U_j

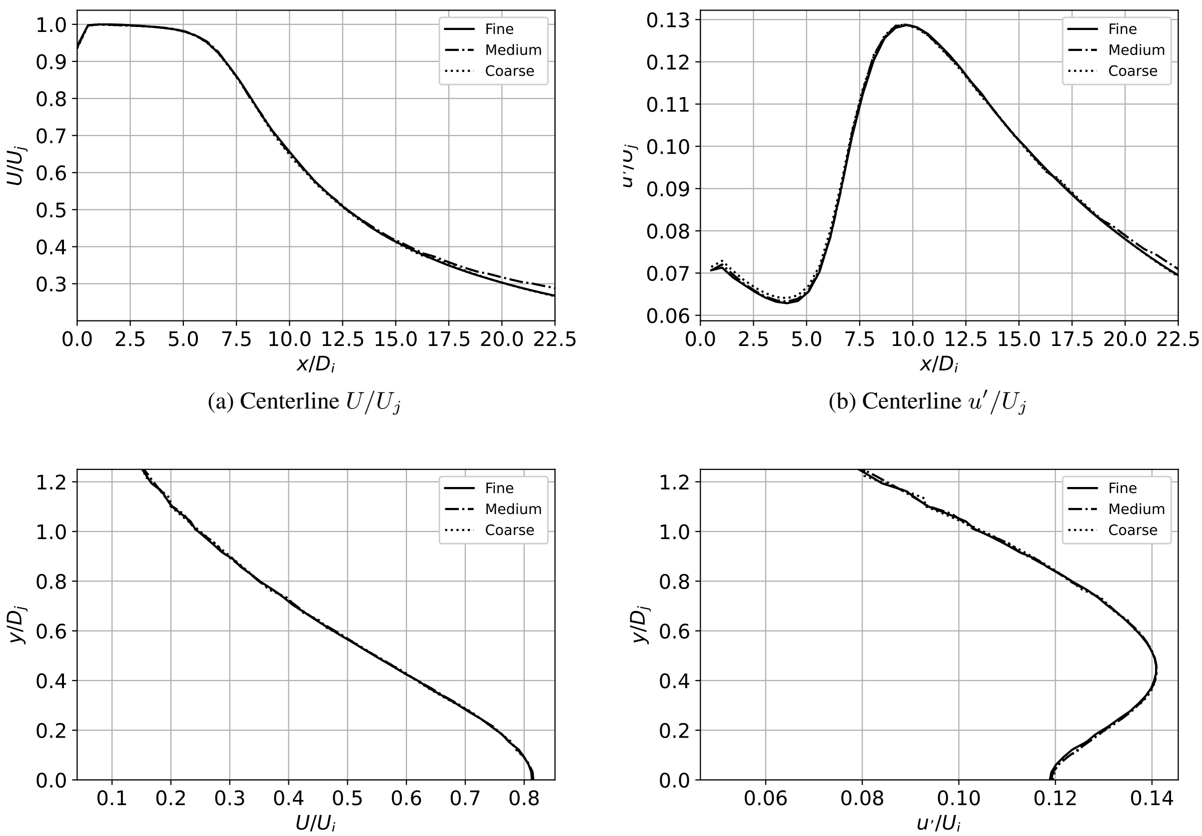


(b) Centerline u'/U_j

Figure 5: Comparison of the results obtained using different inlet turbulence intensity (I).

3.3 Sensitivity to grid refinement

Figure 6 show the comparison of results obtained with different meshes. No significant differences can be observed between meshes on the centerline, lipline and radial profiles, both for velocity and and streamwise turbulence intensity. In this sense, we can conclude that our results are grid-independent.



(a) Centerline U/U_j

(b) Centerline u'/U_j

(c) U/U_j - $x = 8D$

(d) u'/U_j - $x = 8D$

Figure 6: Comparison of the results obtained using different grid refinements.

3.4 Validation with experimental data

Results obtained with Dom 3, medium mesh and $I = 5\%$ are compared with experimental data from Bridges and Wernet (2010). Figure 7 present results for axial profiles at the centerline and lipline. Results show good agreement with experimental data. At the centerline, we can observe that the simulations underpredicted the length of the potential core. Also, results overpredicted the turbulence intensity in the potential core, which is considerably affected by the inlet turbulence intensity as shown in Fig.5. Regarding the lipline, both velocity and turbulence intensity were underestimated. Radial profiles are depicted in Fig.8. Considering the limitations of the modeling, results are in very good agreement with experiments.

Figures 9 and 10 and show the results for $M_a = 0.9$ with inlet turbulence intensity of 2%. In this case, larger deviations from the experiments can be observed, in comparison with the low Mach number case. The potential core length was considerably underestimated, as well as the position of the peak turbulence intensity at the centerline. Consequently, disparities in the radial profiles grow for $x > 8D$. Nevertheless, considering the low computational cost and limitations of the modeling, the numerical results are acceptable.

4. CONCLUSIONS

We have reported numerical predictions of subsonic jet flows using opensource computational tools. The computational domain was proven to be sufficiently large and grid convergence was achieved. On the other hand, the results showed significant sensitivity to the turbulence intensity boundary condition in the nozzle inlet. Nevertheless, results were in good agreement with experimental data for both considered Mach numbers. Future effort will be directed to improve the results for $M_a = 0.9$ and to obtain results with different turbulence closure models.

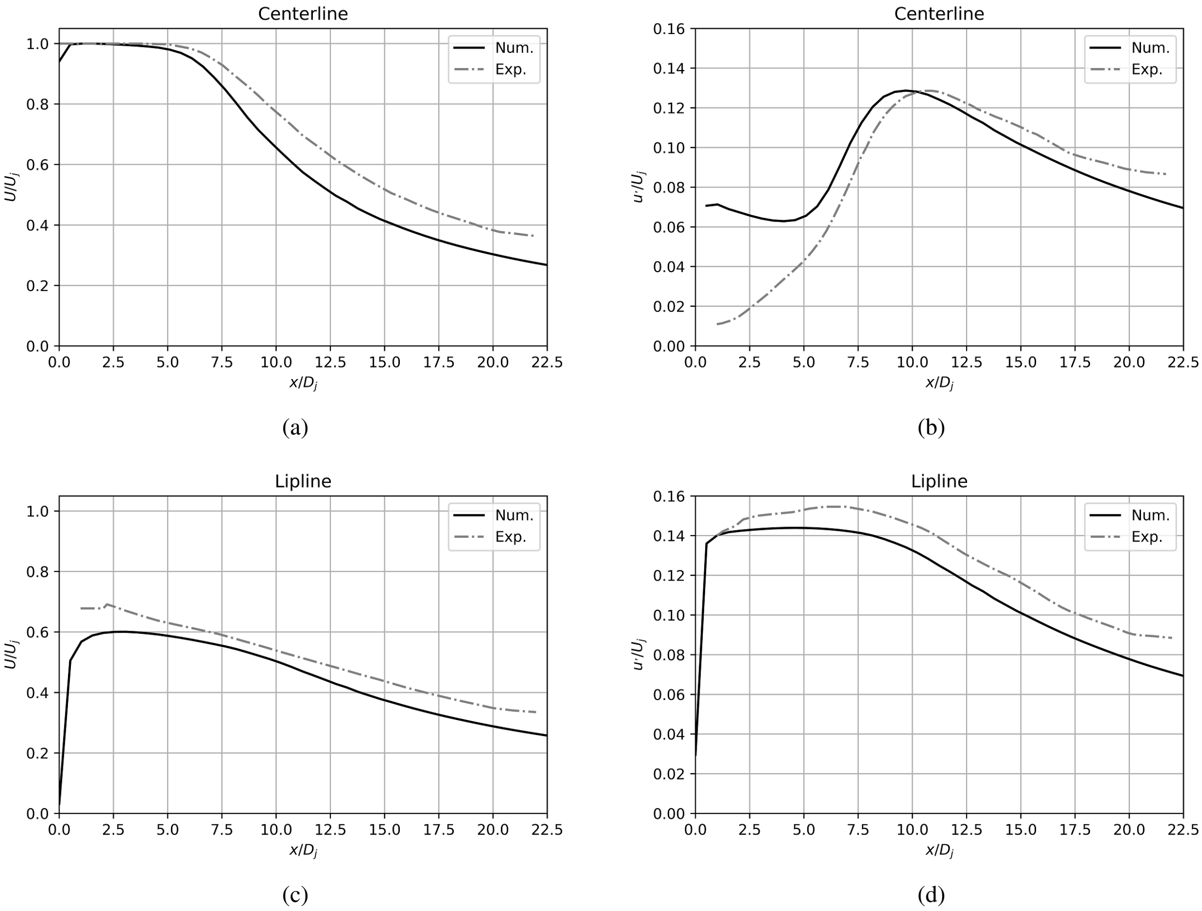
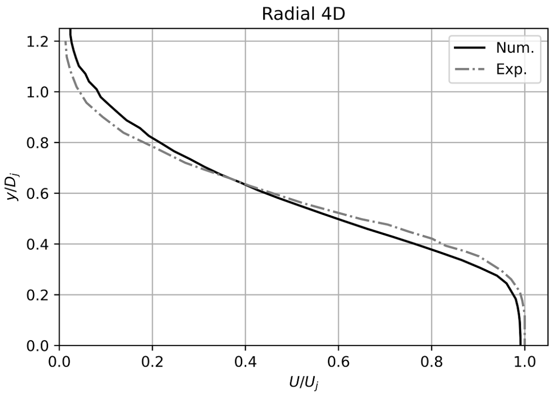
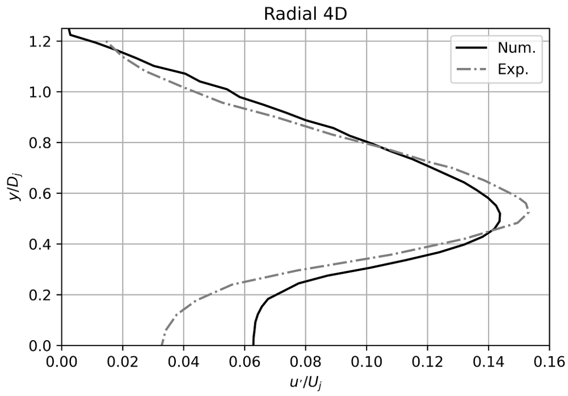


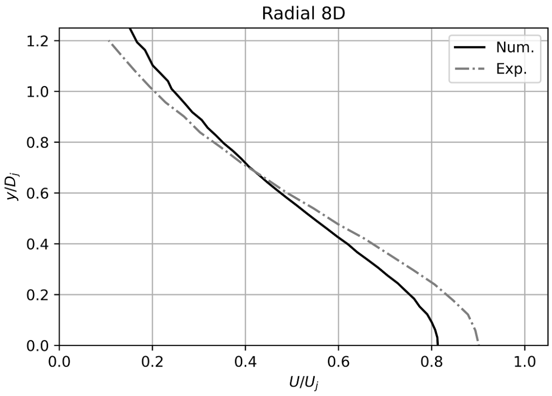
Figure 7: Comparisons of centerline and lipline results with experimental data for the $M_a = 0.5$ jet.



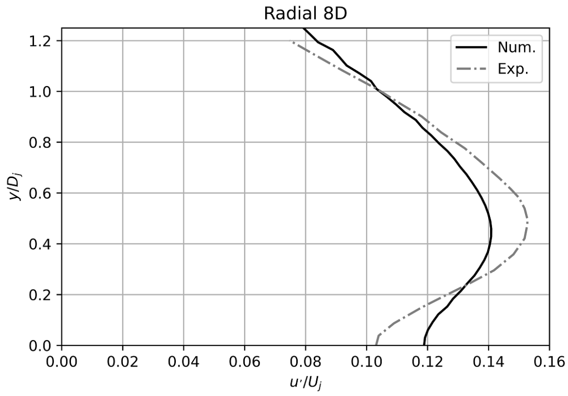
(a) U/U_j - $x = 4D$



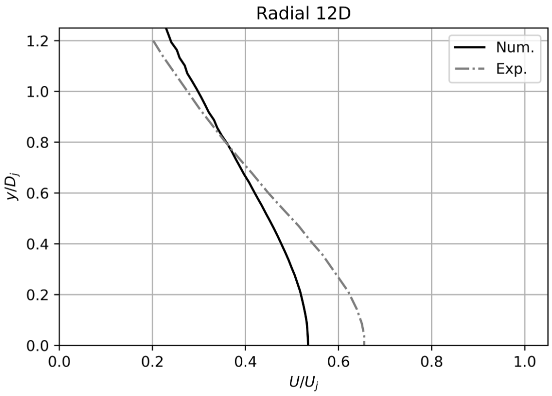
(b) u'/U_j - $x = 4D$



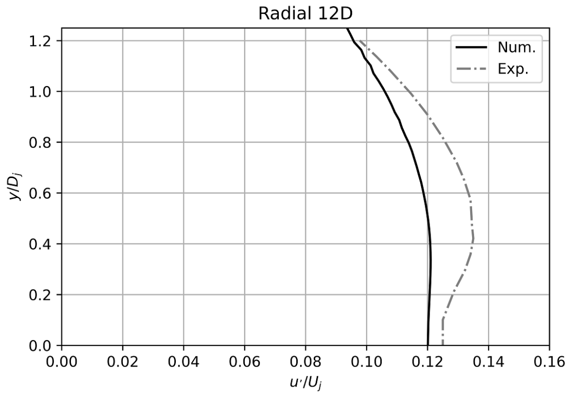
(c) U/U_j - $x = 8D$



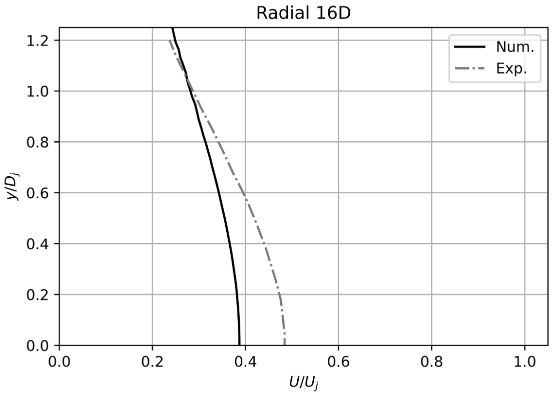
(d) u'/U_j - $x = 8D$



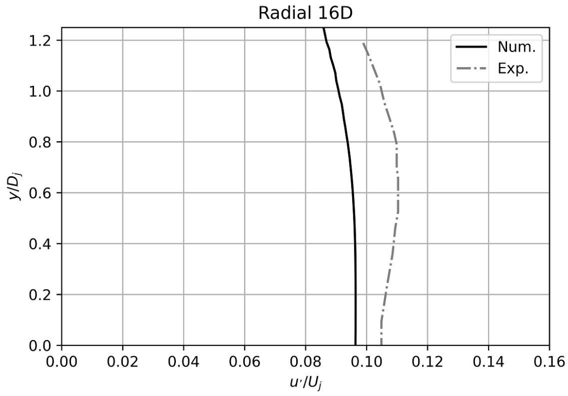
(e) U/U_j - $x = 12D$



(f) u'/U_j - $x = 12D$

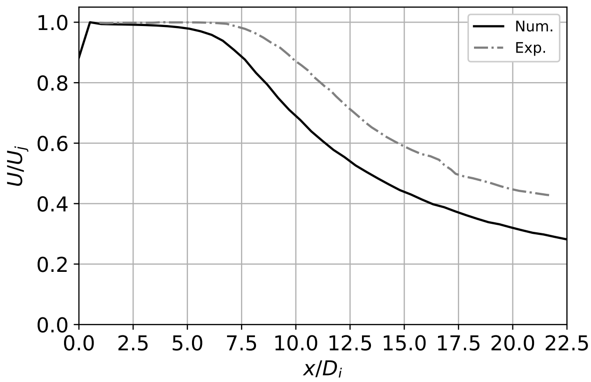


(g) U/U_j - $x = 16D$

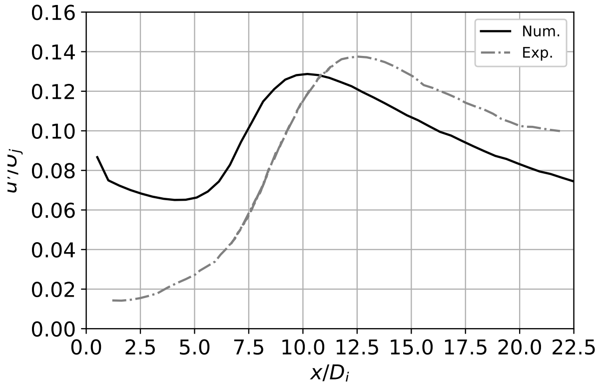


(h) u'/U_j - $x = 16D$

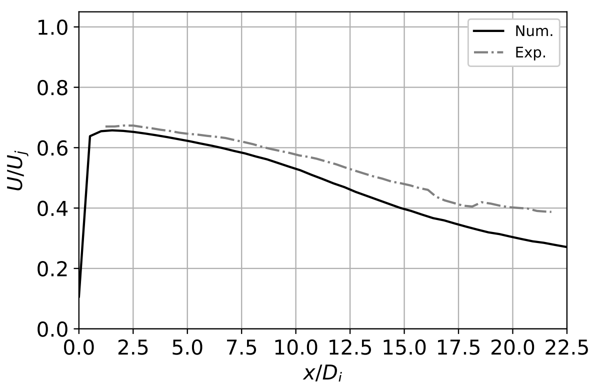
Figure 8: Comparisons of results with experimental data for the $M_a = 0.5$ jet



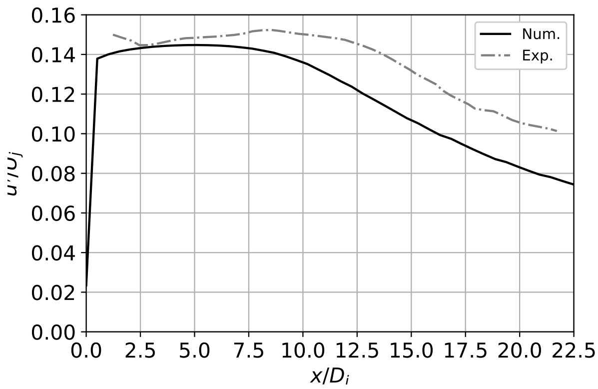
(a)



(b)

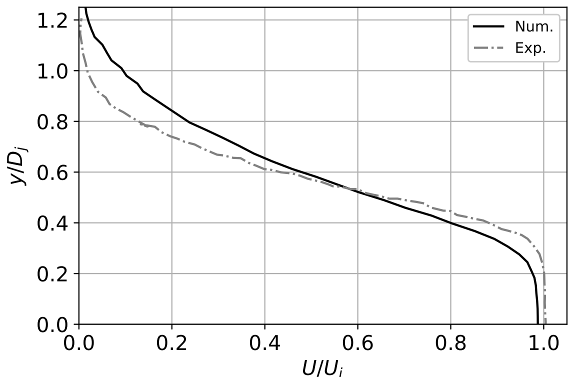


(c)

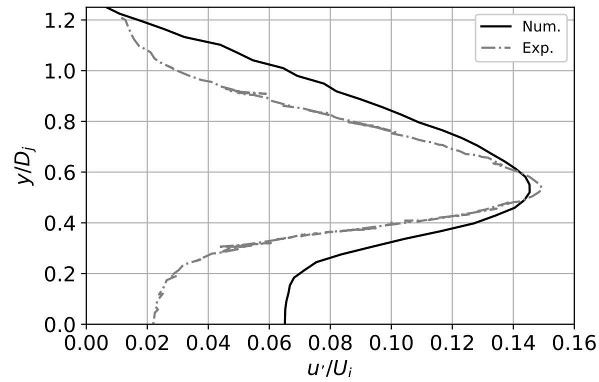


(d)

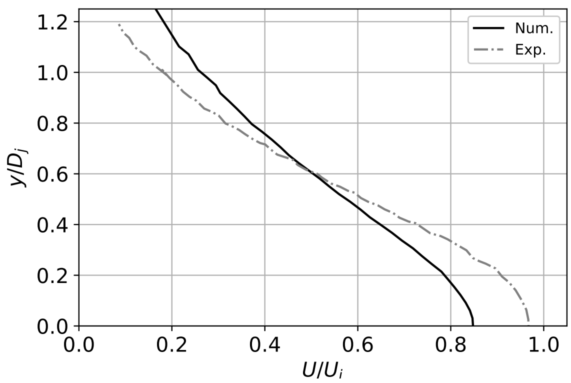
Figure 9: Comparisons of centerline and lipline results with experimental data for the $M_a = 0.9$ jet.



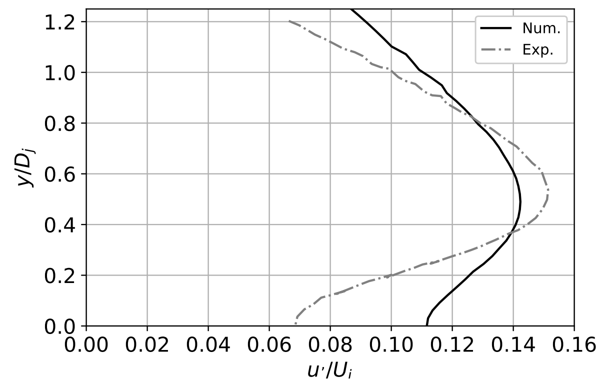
(a) U/U_j - $x = 4D$



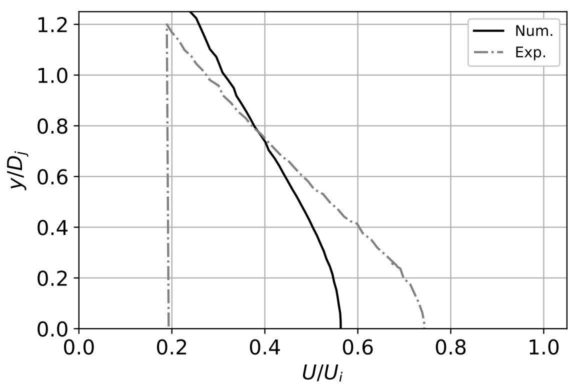
(b) u'/U_j - $x = 4D$



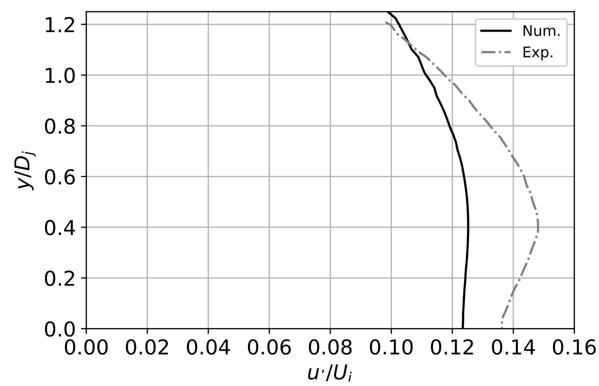
(c) U/U_j - $x = 8D$



(d) u'/U_j - $x = 8D$



(e) U/U_j - $x = 12D$



(f) u'/U_j - $x = 12D$

Figure 10: Comparisons of results with experimental data for the $M_a = 0.9$ jet

5. ACKNOWLEDGEMENTS

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