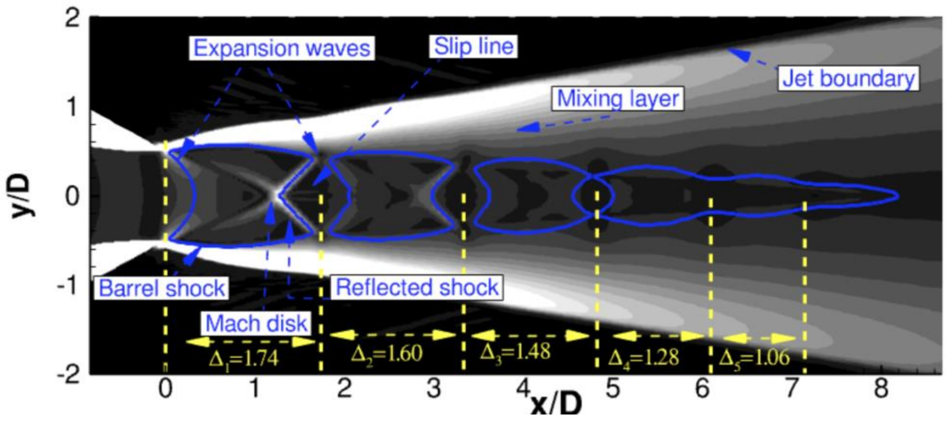
Dynamics of Jet Expansion and Impingement Across a Spectrum of Nozzle Pressure Ratios



Ozgur Tumuklu

Rensselaer Polytechnic Institute

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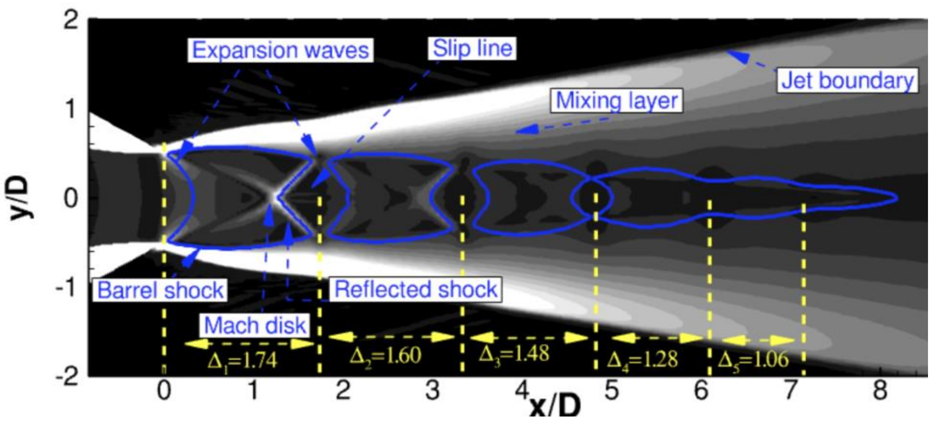
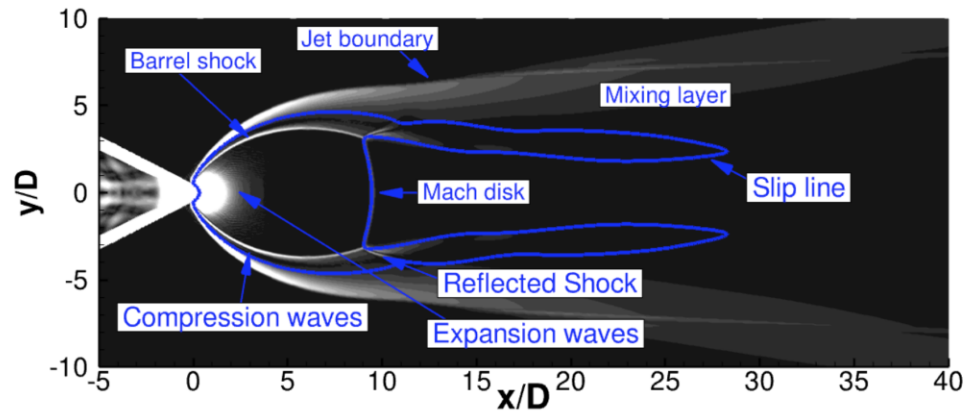
Background

NTR= 8; NPR=4.03
(P_0 = 408.2 , P_∞=101.3 kPa)



NTR= 8; NPR=258
(P_0 = 408.2 , P_∞=1.6 kPa)



This works briefly aims to:

- investigate the expansion characteristics of the jet under varying Nozzle Pressure Ratios (**NPRs**) and Nozzle Temperature Ratios (**NTRs**).
- carry out high-fidelity simulations of turbulent flows until the **continuum assumption** no longer holds.
- determine flow field and turbulence parameters of jets at **relatively low ambient pressures**.

Solver

- An open-source framework* is used to model to model.
- The solver utilizes a first-order explicit Euler scheme for time integration and employs a **second-order semi-discrete central scheme** by Kurganov*, complemented by the van Leer limiter for convective fluxes.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \mathbf{u}] = 0$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot [\mathbf{u}(\rho \mathbf{u})] + \nabla p + \nabla \cdot \mathbf{T} = 0$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla [\mathbf{u}(\rho E)] + \nabla \cdot [\mathbf{u} p] + \nabla \cdot (\mathbf{T} \cdot \mathbf{u}) + \nabla \cdot \mathbf{j} = 0$$

$$\frac{D(\rho\omega)}{Dt} = \nabla \cdot (\rho D_\omega \nabla \omega) + \frac{\rho \gamma G}{\nu} - \frac{2}{3}\rho\gamma\omega(\nabla \cdot \mathbf{u}) - \rho\beta\omega^2 - \rho(F_1 - 1)CD_{k\omega} + S_\omega,$$

$$\frac{D(\rho k)}{Dt} = \nabla (\rho D_k \nabla k) + \rho G - \frac{2}{3}\rho k(\nabla \cdot \mathbf{u}) - \rho\beta^* \omega k + S_k$$

$$\nu_t = a_1 \frac{k}{\max(a_1\omega, b_1 F_{23}\mathbf{S})} \qquad k = \frac{3}{2}\left(I\,|u_{\text{ref}}|\right)^2 \qquad \omega = \frac{k^{0.5}}{C_\mu^{0.25} L}$$

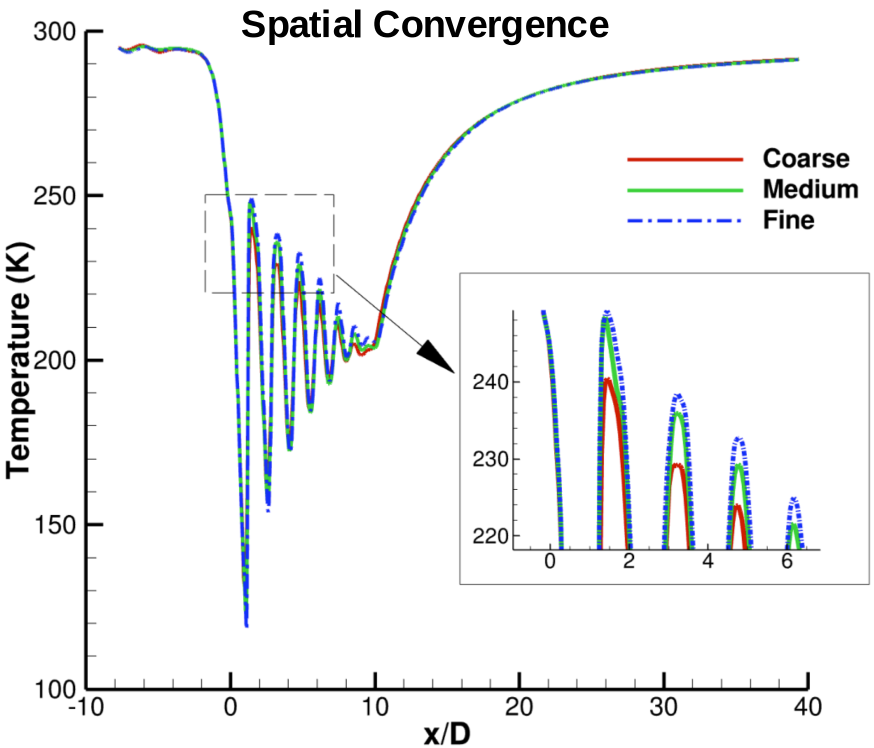
OpenFOAM® Gmsh

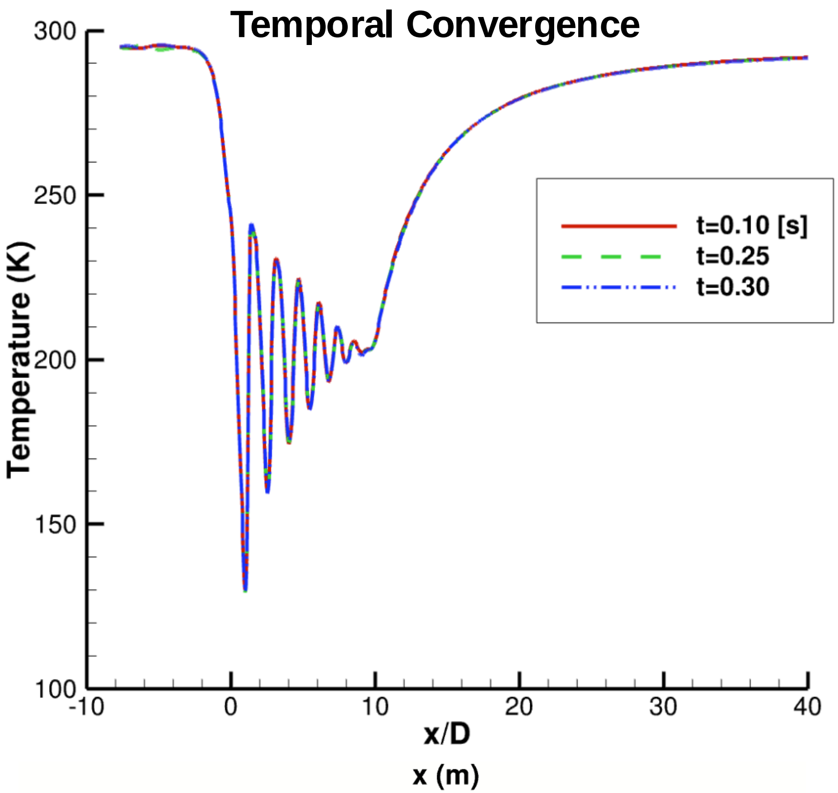
*Kurganov, A., and Tadmor, E., "New high-resolution central schemes for nonlinear conservation laws and convection–diffusion equations," Journal of computational physics, Vol. 160, No. 1, 2000, pp. 241–282

OpenCFD Ltd., **OpenFOAM**: The Open Source CFD Toolbox, 2023. URL https://www.openfoam.com, retrieved from https://www.openfoam.com.

Geuzaine, C., and Remacle, J.-F., "**Gmsh**: A 3-D finite element mesh generator with built-in pre- and post-processing facilities," , 2023. URL http://gmsh.info, version 4.9.4

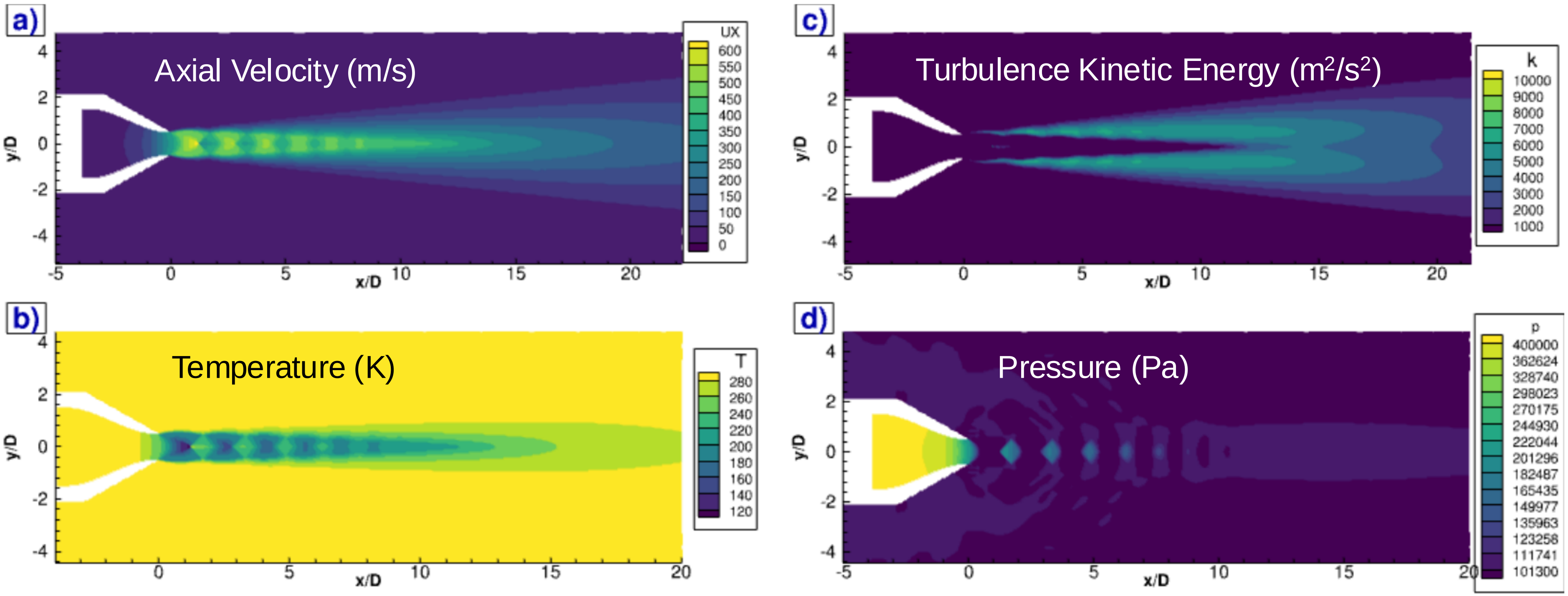
Grid and Time Convergence





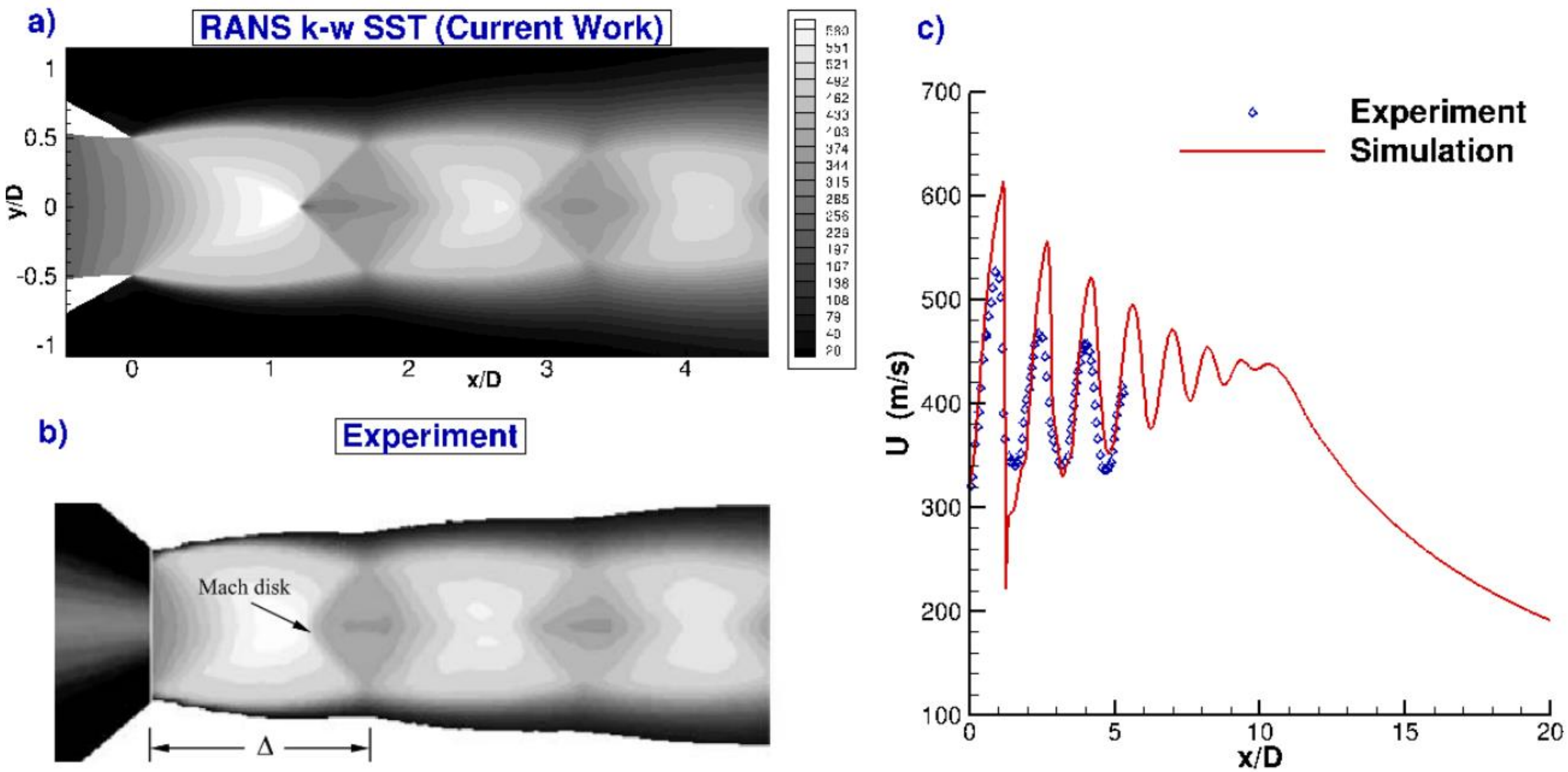
- Three different grid resolutions were used: coarse with 244,728 grid points, medium with 353,073 grid points, and fine with 418,218 grid points to ensure the spatial convergence.
- 0.1 seconds is sufficient to achieve a **time-convergent** solution for this case.

Expansion Characteristics for NPR=4.03 and NTR=1



- The mean axial velocity peaks at approximately twice the nozzle exit velocity (317 m/s) at the jet center.
- The turbulence kinetic energy is maximum in the **mixing layer**.
- The propagation of the **acoustic waves** is seen in the pressure field.

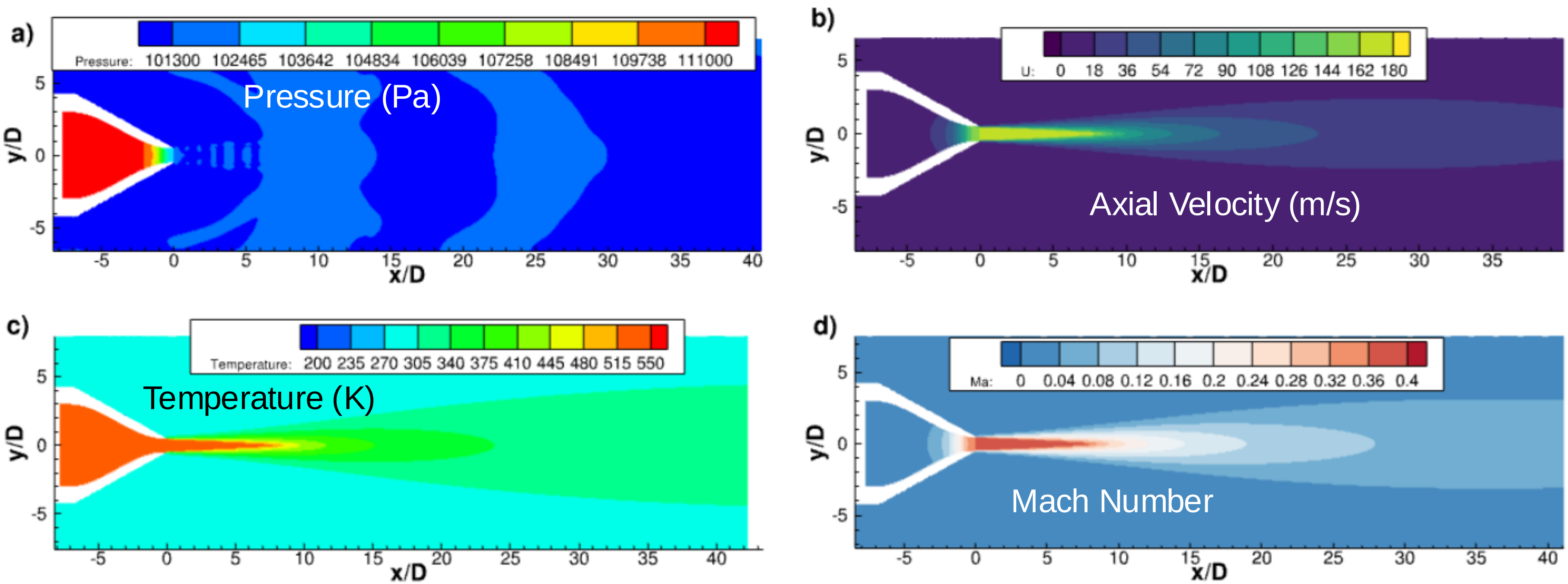
Comparisons with the Experiments*



- The mean velocity magnitude is in good agreement with the measurements.
- The differences can be attributed to the resolution limitations that cannot be captured by the cameras and the possible **smearing of data during post-processing** of the experiment.

*Henderson, B., Bridges, J., and Wernet, M., "An experimental study of the oscillatory flow structure of tone-producing supersonic impinging jets," Journal of Fluid Mechanics, Vol. 542, 2005, pp. 115–137.

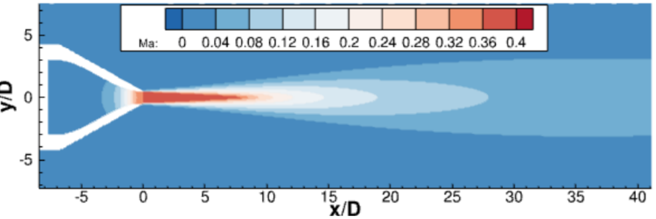
Expansion Characteristics for NPR=1.1 and NTR=1.813*



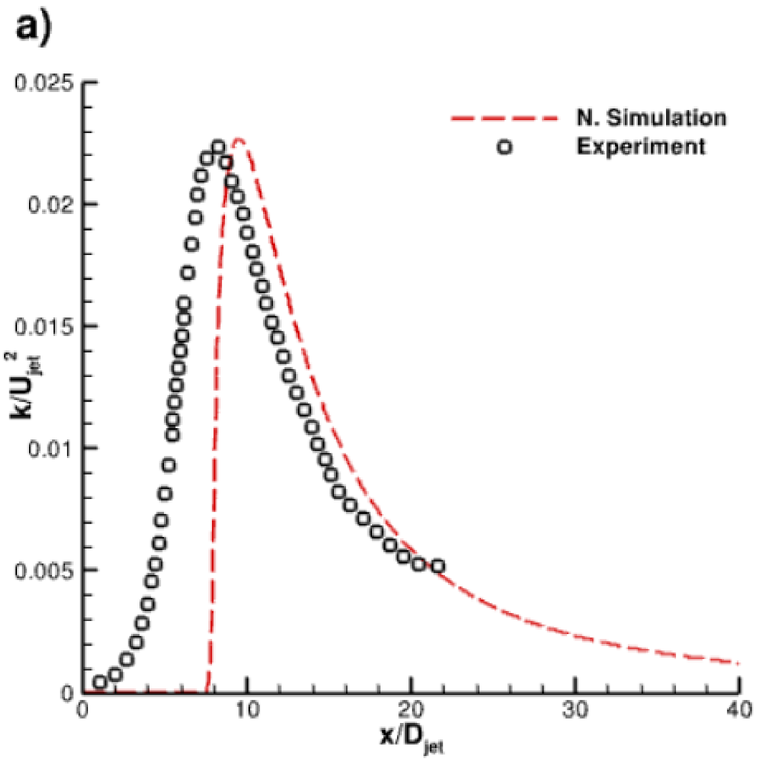
- Further comparisons with experiments* were carried out to compare mean and **turbulent flow properties at a low NPR.**

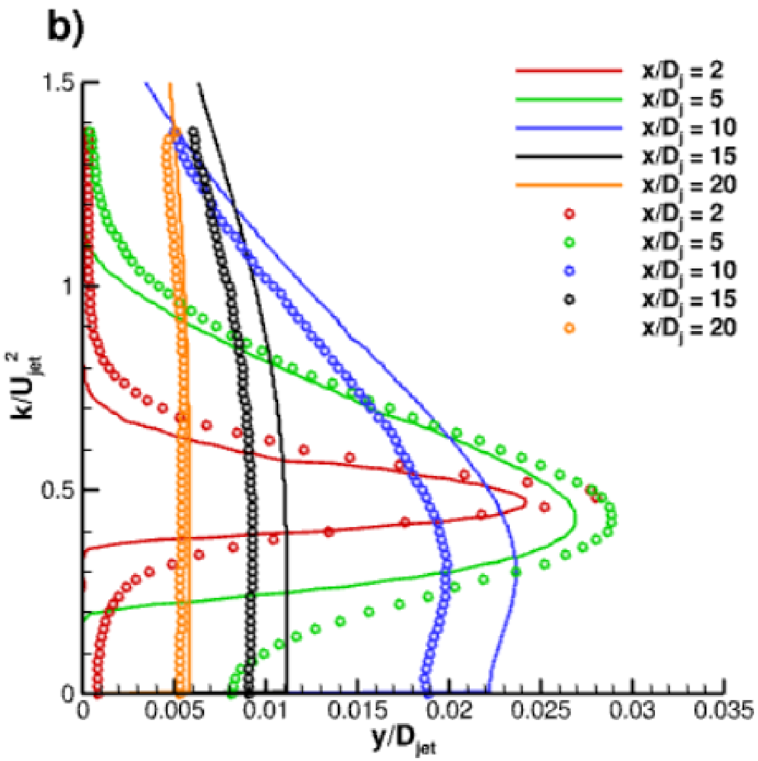
*Seiner, J. M., Ponton, M. K., Jansen, B. J., and Lagen, N. T., "The effects of temperature on supersonic jet noise emission," Tech. Rep. DGLR/AIAA 92-02-046, 14th DGLR/AIAA aeroacoustics conference, 1992.

Comparisons With Experiments*



Turbulence Properties

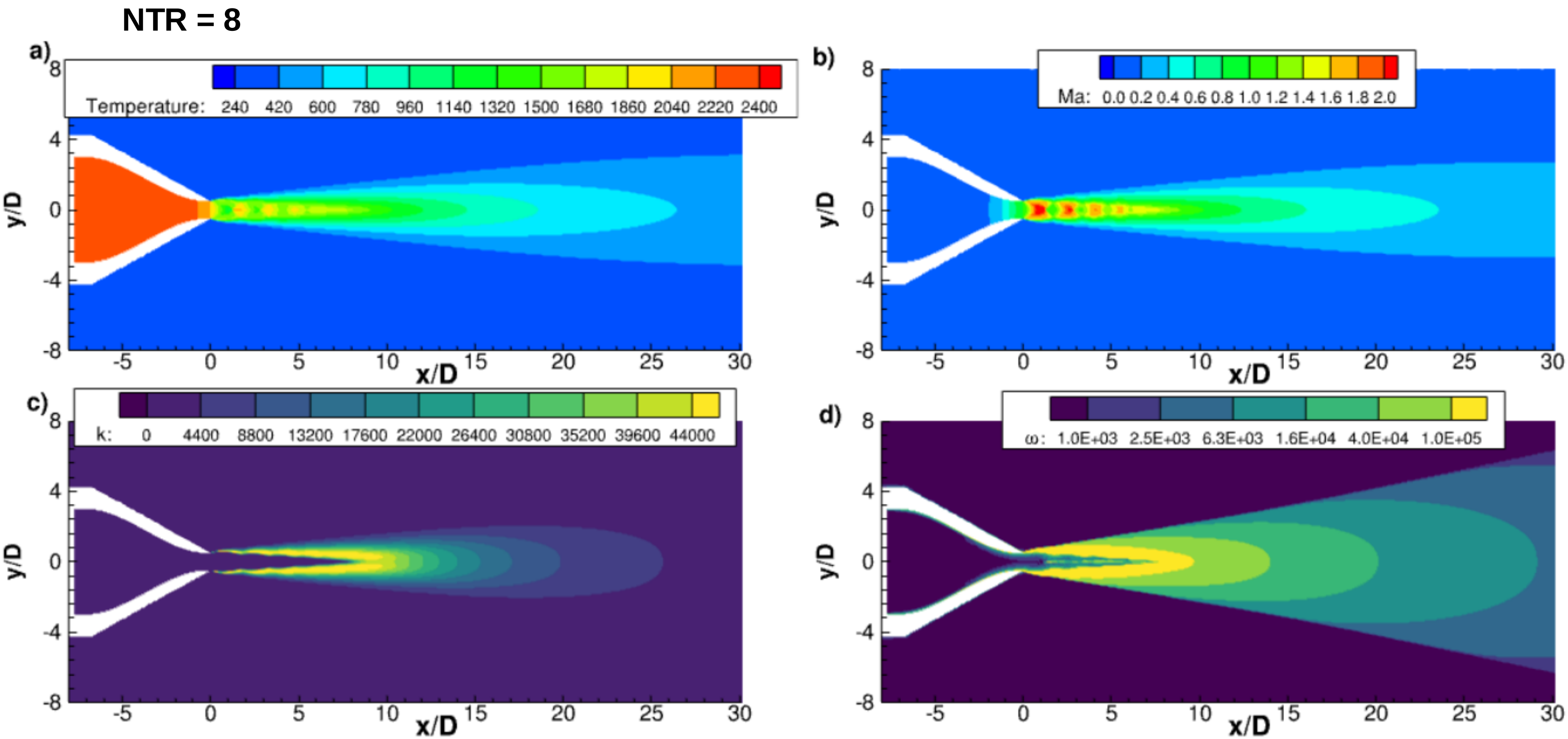




- The intensity of the TKE is **maximum** downstream of the core region.

*Seiner, J. M., Ponton, M. K., Jansen, B. J., and Lagen, N. T., “The effects of temperature on supersonic jet noise emission,” Tech. Rep. DGLR/AIAA 92-02-046, 14th DGLR/AIAA aeroacoustics conference, 1992.

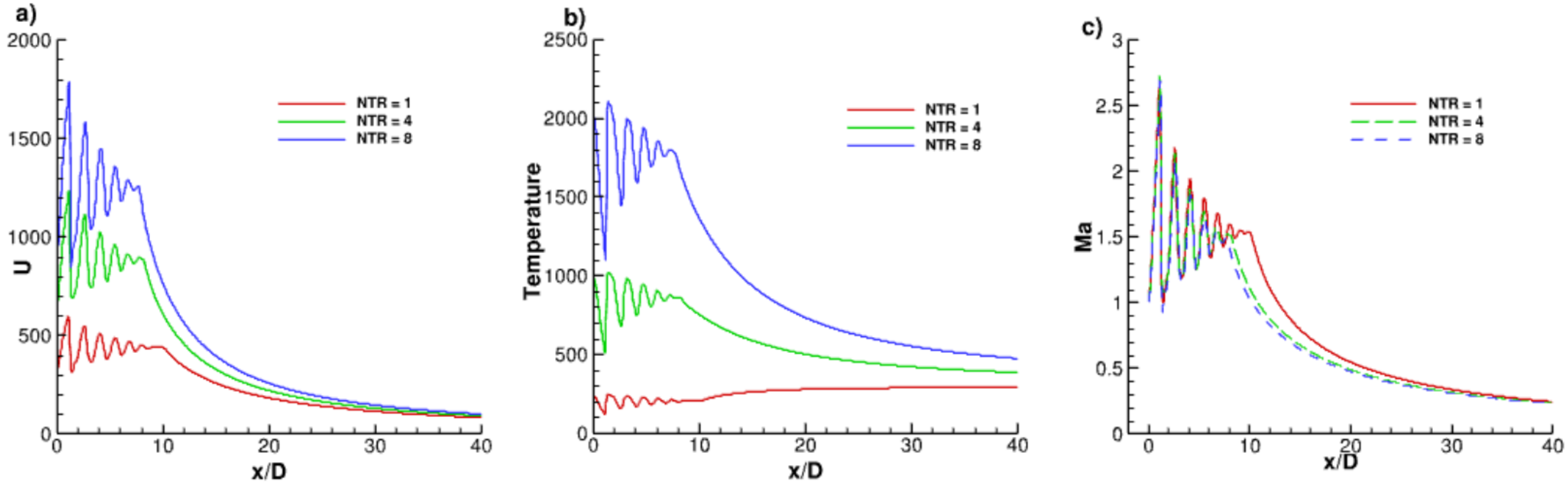
Effects of NTRs on the Jets for NPR=4.03



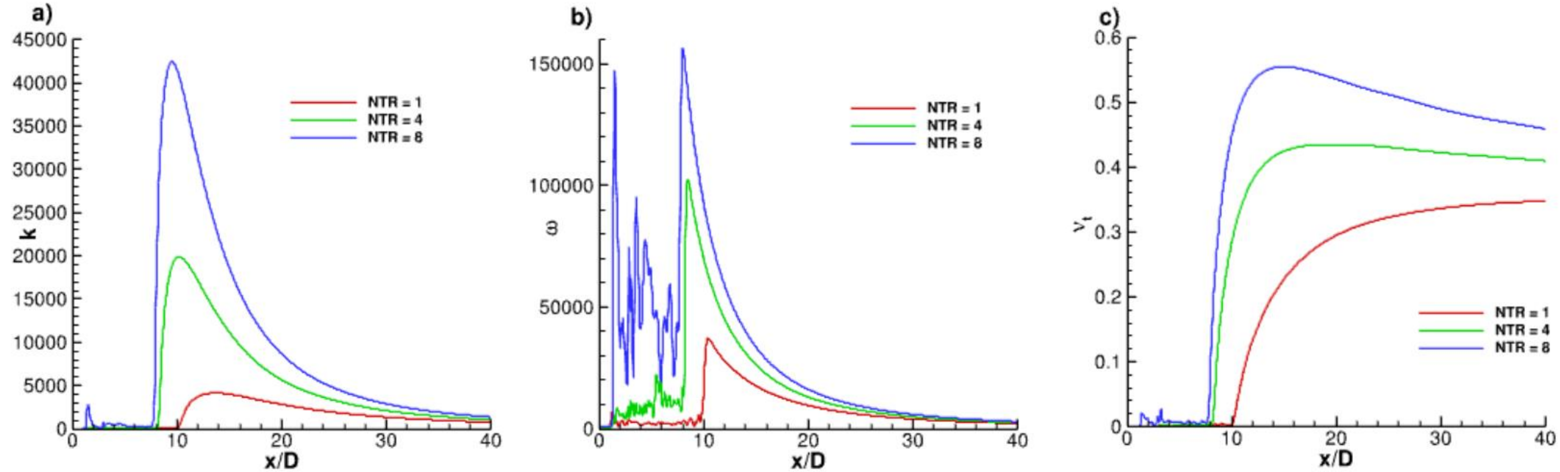
- NTR has small effect on the structure of shock diamonds.
- It significantly affects **the turbulence properties**.
- The number of shock diamonds decreases with higher **NTRs.**

Effects of NTRs on the Flows

Mean Flow



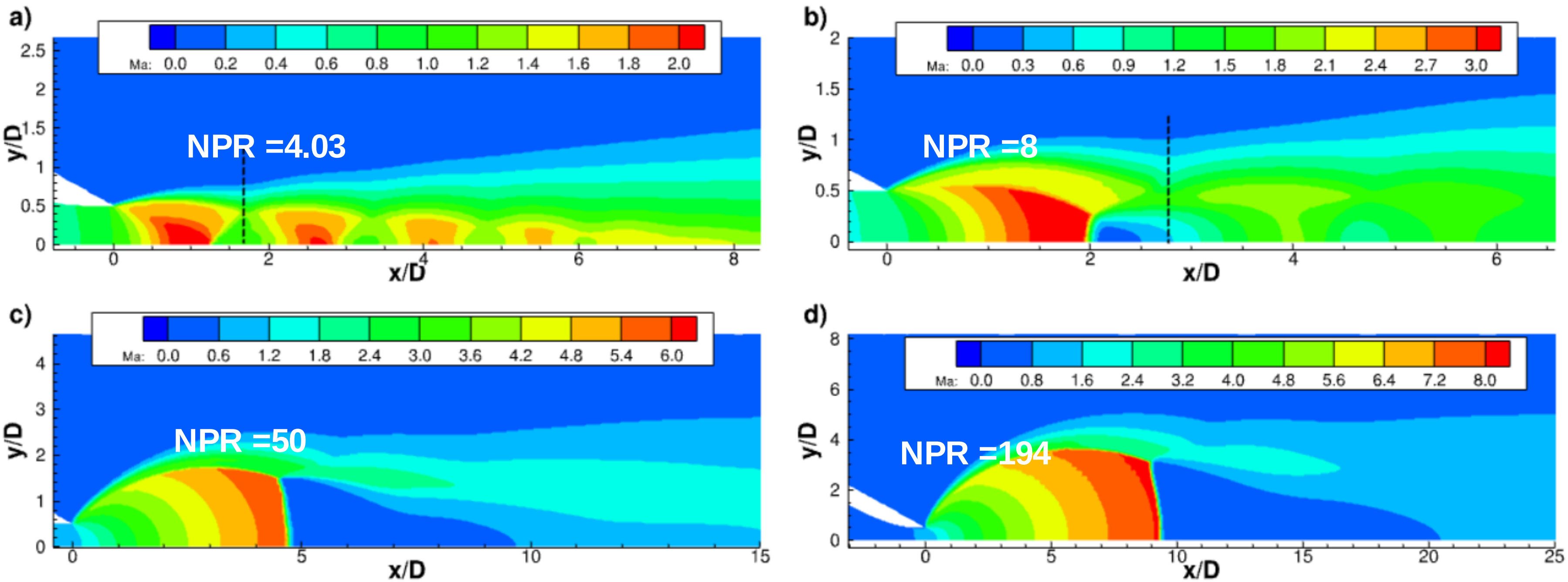
Turbulence Properties



- The turbulence kinetic energy increases almost linearly with NTR in the mixing layer.

*McGuirk, J., and Feng, T., “The near-field aerodynamic characteristics of hot high-speed jets,” Journal of Fluid Mechanics, Vol. 915, 2021, p. A120.

Expansion Characteristics for NPRs

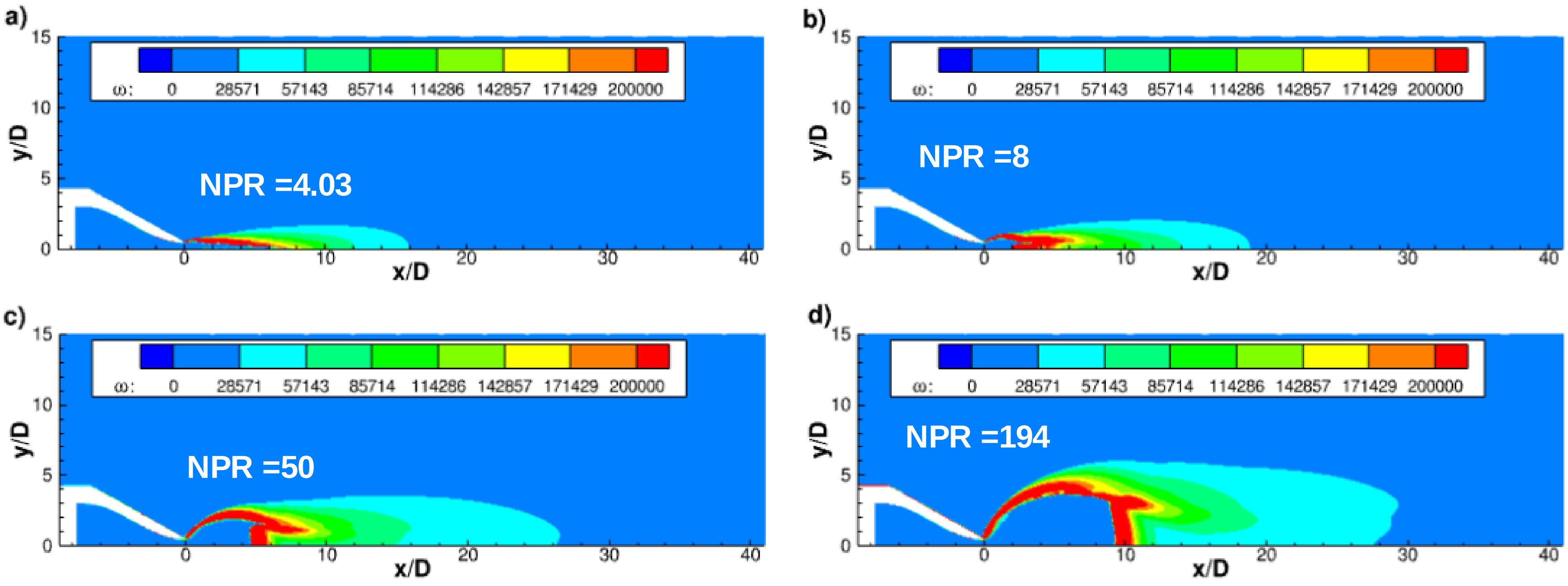


- The repetitive shock diamonds disappear with higher NPRs.
- The length of the first shock cell increases with NPR.
- The size of the Mach disk increases with NPR, and the normal shock becomes more curved.

$$\frac{L_{\mathrm{MD}}}{D} = 0.645497\sqrt{\mathrm{NPR}}.$$

Franquet, E., Perrier, V., Gibout, S., and Bruel, P., "Free underexpanded jets in a quiescent medium: A review," Progress in Aerospace Sciences, Vol. 77, 2015, pp. 25–53.

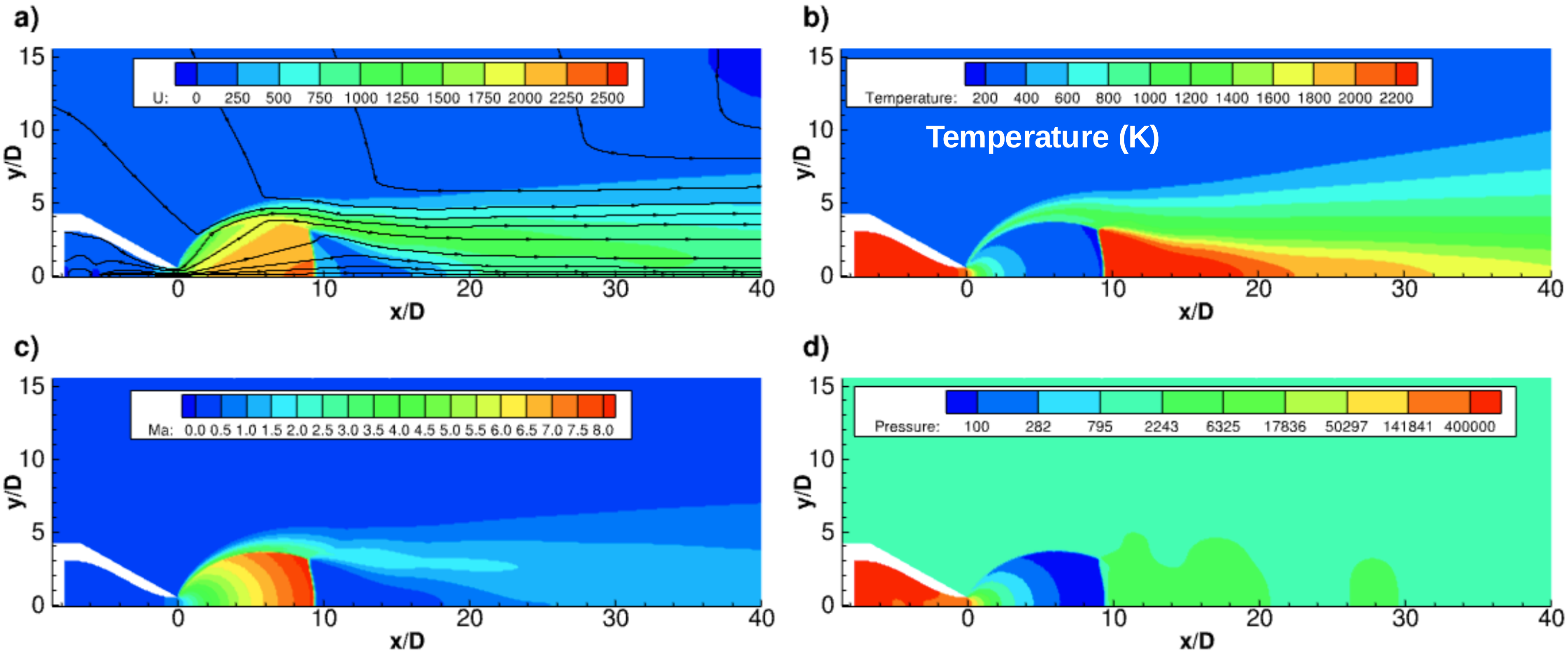
Variation of Turbulence Parameters with NPRs



- The turbulence kinetic energy significantly **increases** with NPR, especially in the mixing layer and downstream of the Mach disk.

- The size of the **eddies becomes** smaller downstream of the Mach disk and in the mixing layer, as indicated by the increase in specific dissipation rates at these locations.

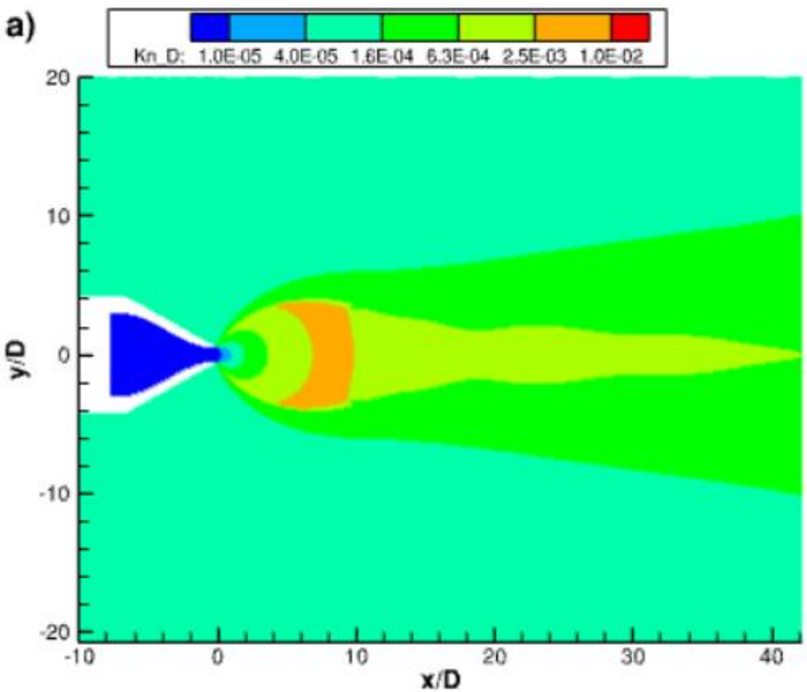
Flow Field with NPR= 256



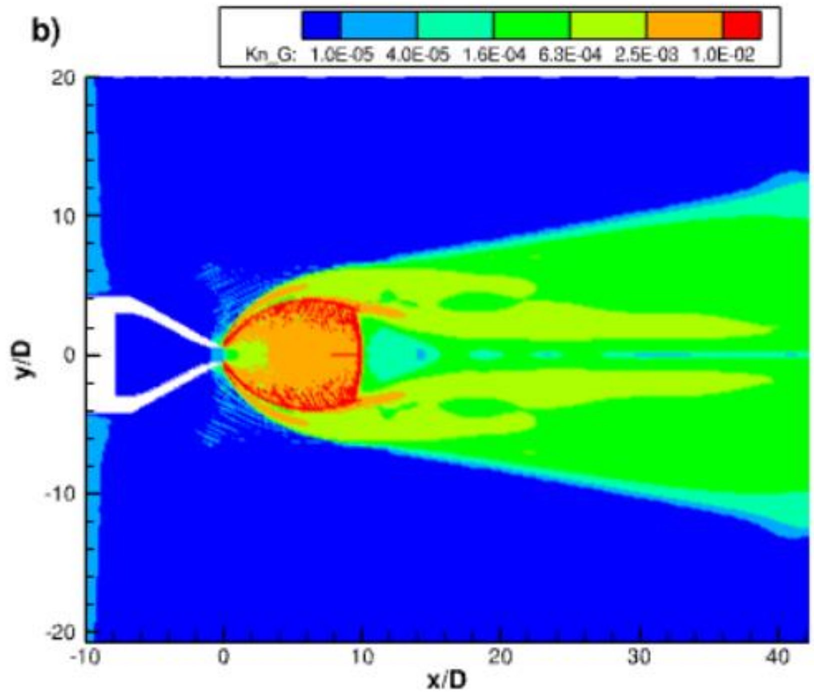
- The streamwise velocity increases dramatically inside the potential core, while the temperature decreases to about 200 K from the stagnation temperature of 2360 K.
- The flow becomes hypersonic and **nonequilibrium effects** have to be taken into account for accurate results.

Rarefied Effects for NPR= 256

Knudsen Number (Kn)



The gradient-length-local Kn

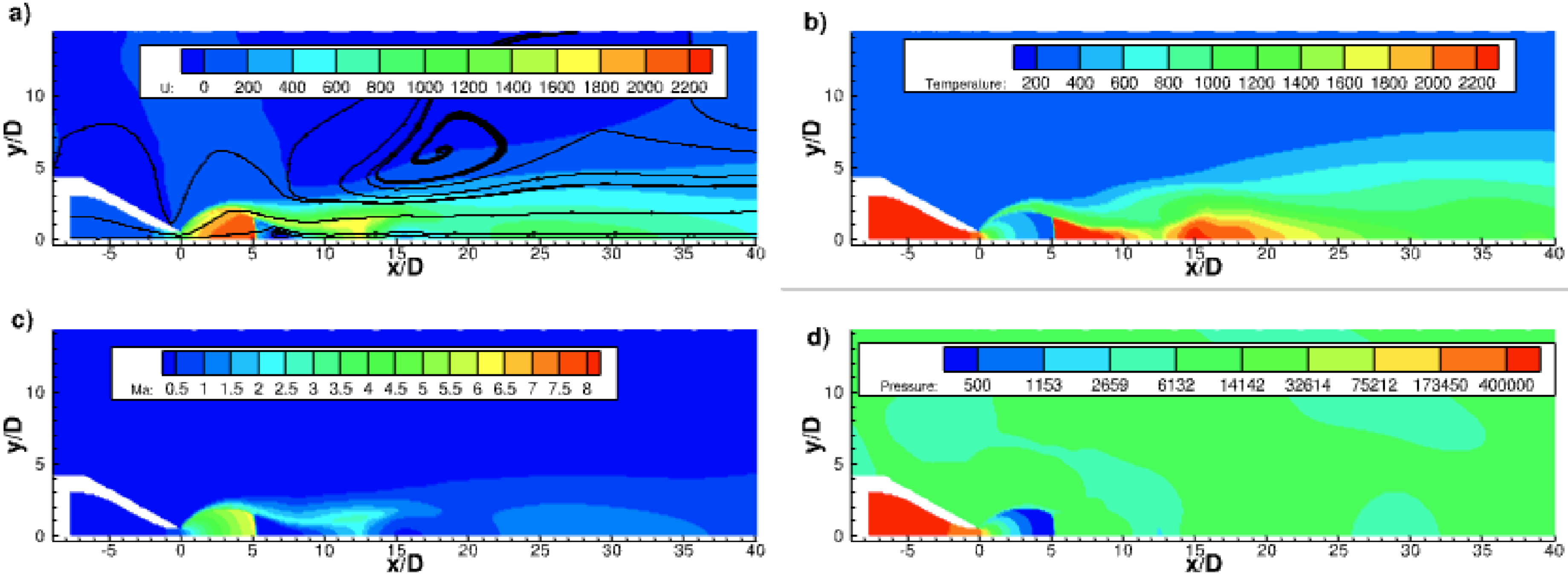


- The nozzle-diameter-based Knudsen number, λ/D, is less than 0.01; therefore, the flow can be assumed to be in the continuum regime.

- On the other hand, the gradient-local-length Knudsen number becomes relatively larger, especially near the barrel shock and Mach disk.

$$\lambda = \frac{1}{\sqrt{2}\pi d^2 n} \qquad \mathrm{Kn}_{LG-\rho} = \frac{\lambda}{\rho}|\nabla\rho|$$

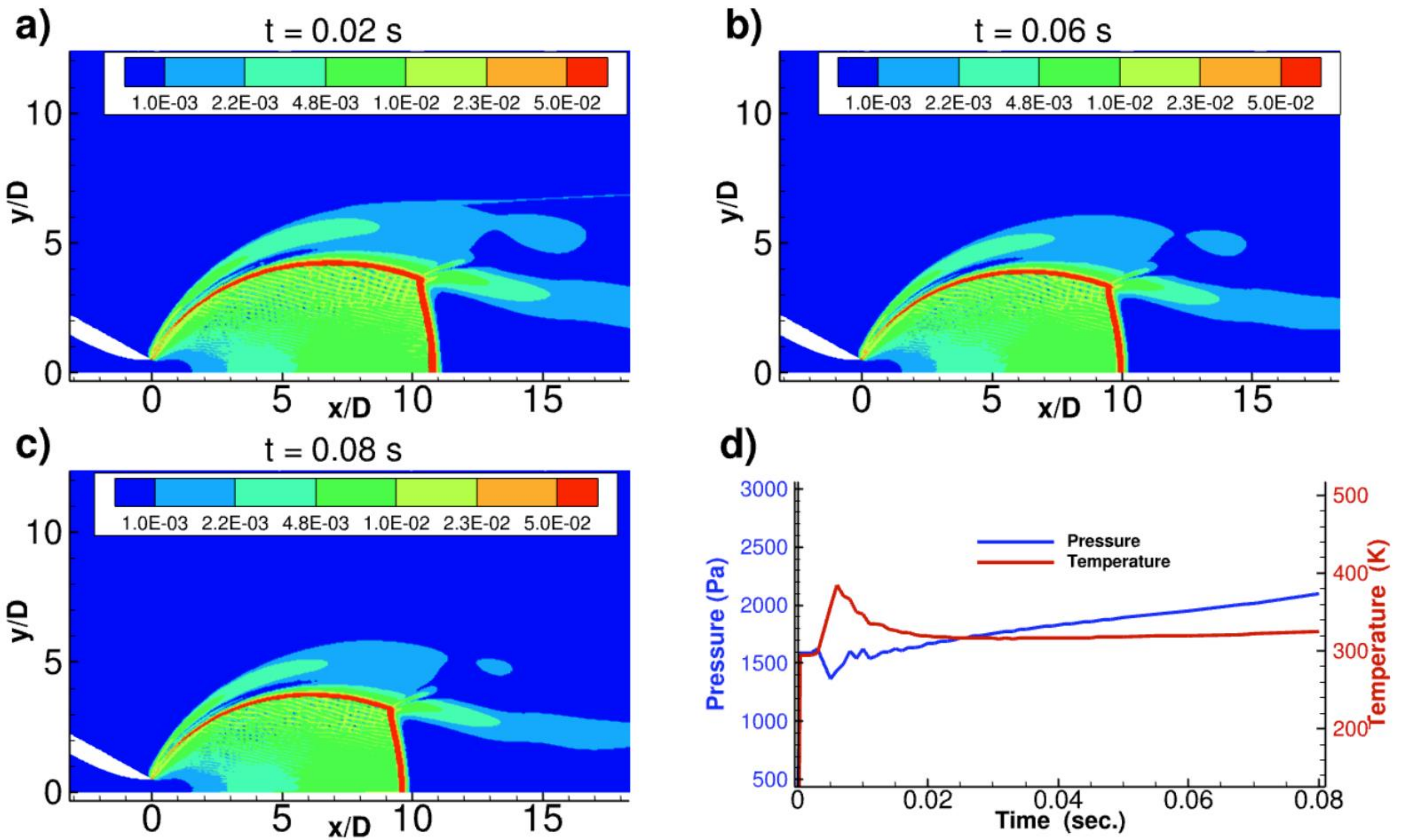
Expansion Characteristics for NPR=68



- The constant pressure boundary condition stipulates that the ambient pressure remains the same over time, whereas the **zero-pressure gradient boundary condition** allows for an increase in the pressure field since the nozzle exit pressure is higher than the ambient pressure.

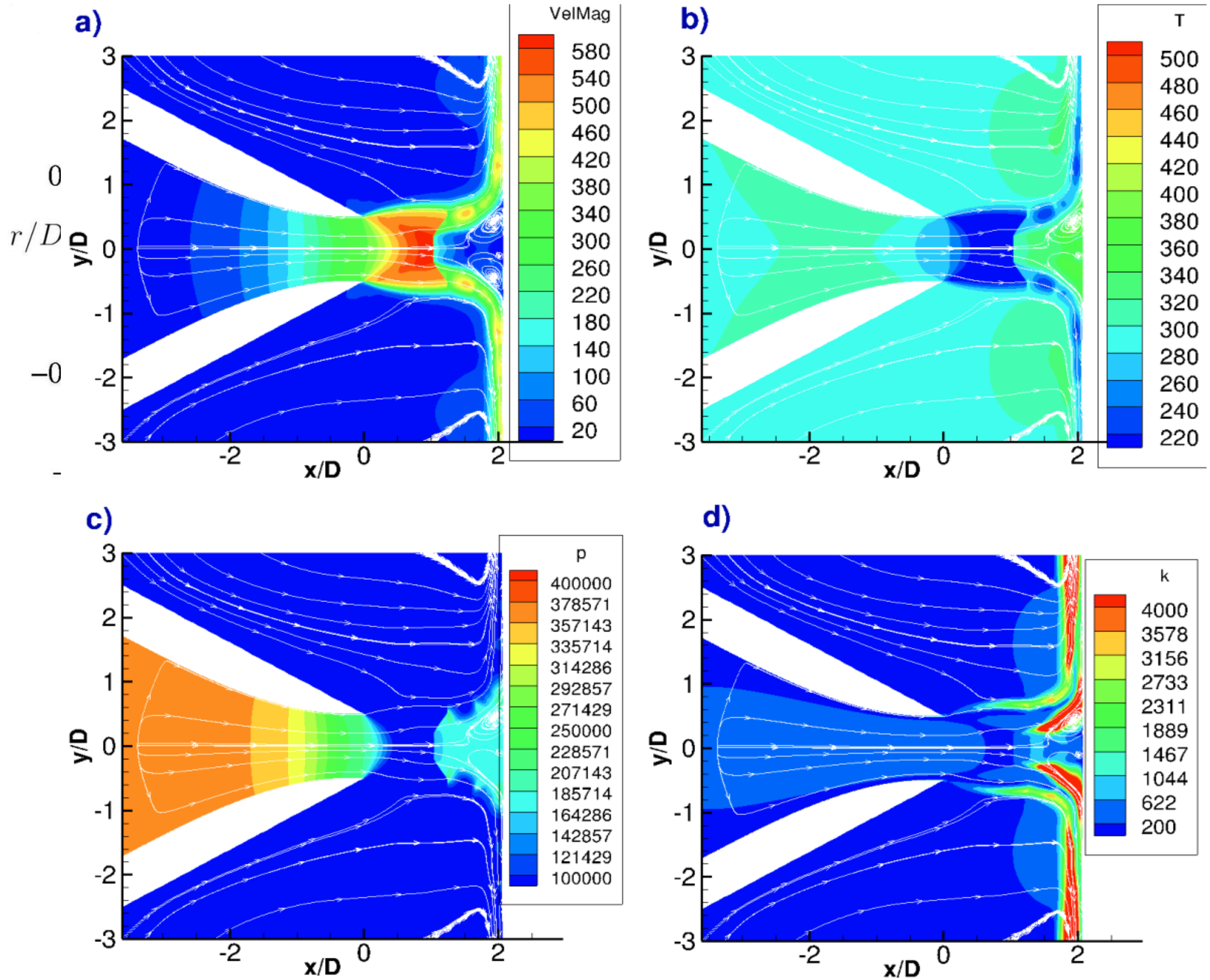
- **Oscillatory behavior** is observed for the constant pressure BC when the NPR is large.

Temporal Evolution of the Jet with NPR= 256



- The zero gradient boundary condition allows for the **build-up of pressure**.

Jet Impinging at NPR=4.08 (Ongoing)



Conclusions

- Numerical simulations were conducted to characterize the expansion behavior of compressible turbulent jets at various NPRs and NTRs.
- The length of the potential core tends to decrease with higher NTRs.
- The continuum breakdown parameter for the lowest ambient pressure case of 1.58 kPa was calculated.
- The spatial distribution of turbulence parameters at various ambient pressures was also documented.

Acknowledgement

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