Numerical and Experimental Investigations on Cylindrical Critical Flow Venturi Nozzles (CFVN)

FLOMEKO 2019

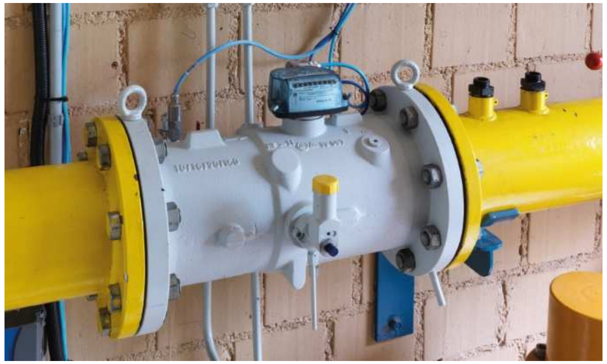
M.A. LAMBERT, R. MAURY, H. FOULON – *CESAME-EXADEBIT s.a.*
J.C. VALIERE, E. FOUCAULT, G. LEHNASCH – *Institut Pprime, UPR 3346 CNRS-Université de Poitiers-ENSMA*

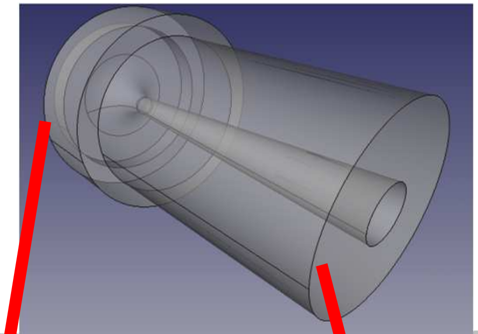
Context

Introduction - Overview:

A way to calibrate flow meters is by using Critical Flow Venturi Nozzles CFVNs as a primary standard.

International standard **ISO 9300** regulates the terms of use of CFVN in flow calibration.





<u>Problematics:</u>

- Improve range of applicability: Reynolds number range under 5×10^5 and over 1×10^7.
- Need less than **0.3%** in terms of uncertainties.
- Understand flow phenomena : laminar turbulent transition ? roughness effect ?
- In terms of CFVN wall surface, roughness is difficult to characterise and to manufacture.

<u>Advantages:</u>

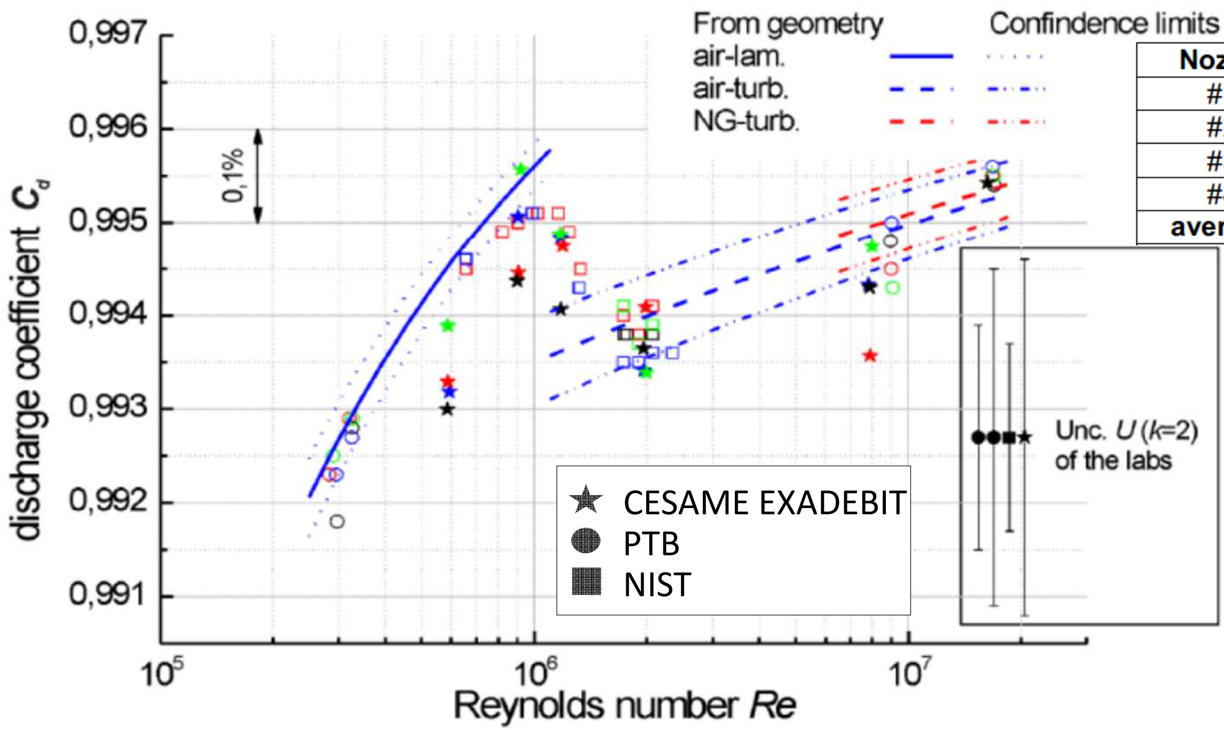
- Stable (reliable in time)
- Easy to transport
- Mono-bloc (no mechanism)
- Stainless steel (solid and replicable)

The evolution of the discharge coefficient of CFVNs

As the discharge coefficient is partially influenced by gas viscosity, it clearly depends on the Reynolds number in the nozzle.

$$Re_D = \frac{4 \cdot Q_{m_{theo}}}{\pi \cdot d \cdot \mu_0}$$

$$C_d = a - b \cdot Re_D^{-n}.$$



Nozzle	Diameter *d* [mm]	R_{throat}
#1	25.3932	2.69
#2	25.3910	2.60
#3	25.3935	2.45
#4	25.3883	2.78
average	**25.3915**	**2.63**

Ref. Mickan, B., Kramer, R., Dopheide, D., Hotze, H.-J., Hinze, H.-M., Johnson, A., Wright, J., Vallet, J.-P., "Comparisons by PTB, NIST, and LNE-LADG in Air and Natural Gas, in Critical VenturiNozzles Agreeing within 0.05 %", Proceedings of the 6th Int. Symposium on Fluid Flow Measurement (ISFFM), Queretaro, Mexico, May 2006.

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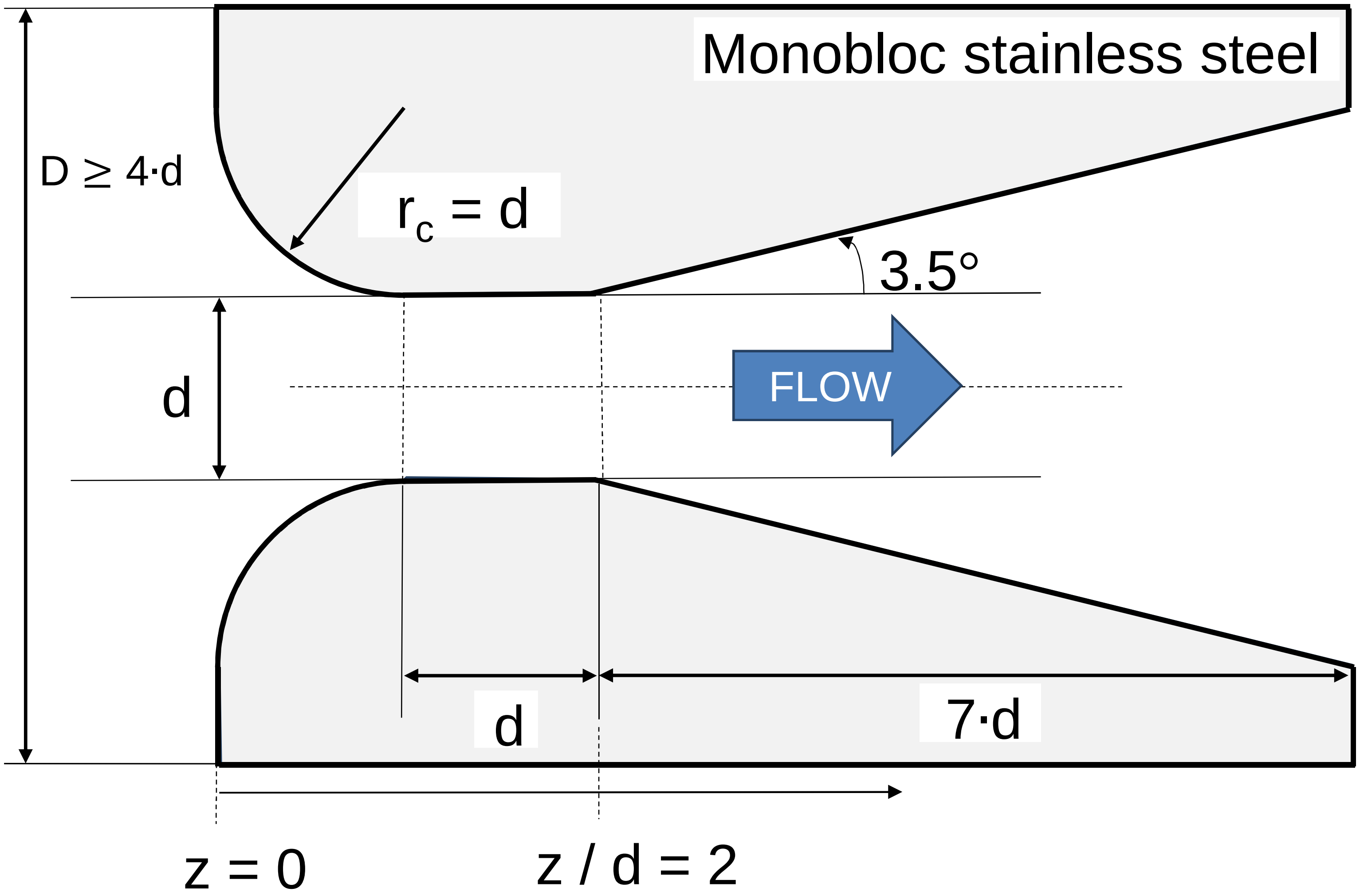
Experimental CFVNs set

Critical nozzles to be investigated (cylindrical shape as recommended by the ISO 9300 standard)

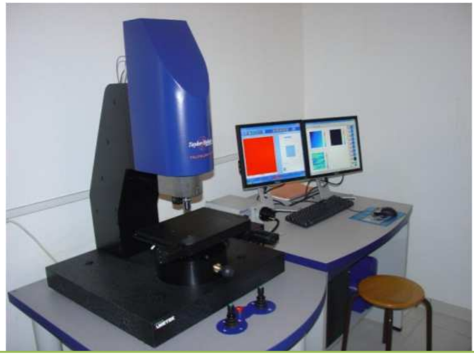
d	Diameter of Venturi nozzle throat (m)
r_c	Radius of curvature of nozzle inlet (m)
D	Diameter of the upstream duct (m)



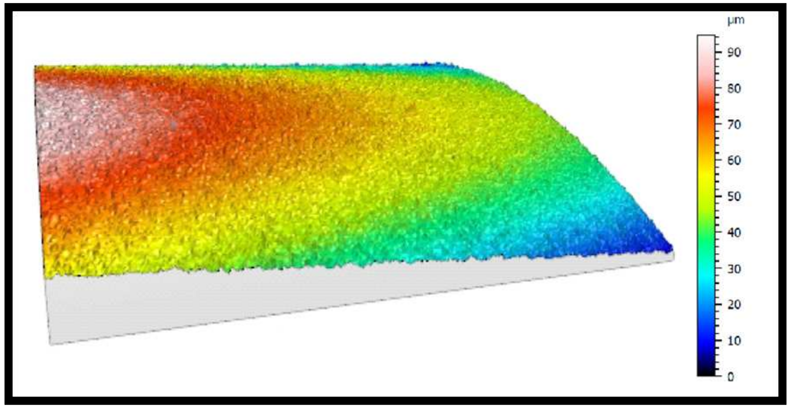
Dimensional characterisation

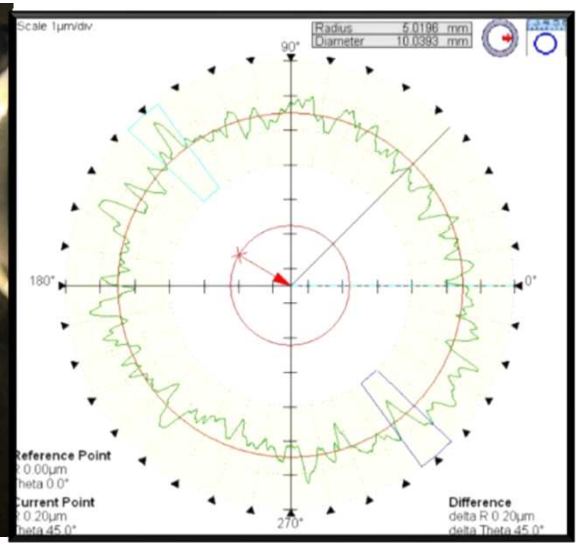
Critical nozzles to be investigated (cylindrical shape as recommended by the ISO 9300 standard)

Characterisation of roughness by different techniques:



Roughness characterisation by silicon moulding (nozzle diameter 5mm *Poitiers university*)





Diameter and cylindricity measurement (nozzle diameter 5mm *IUT Angoulême – Poitiers University*)

Experimental CFVNs set

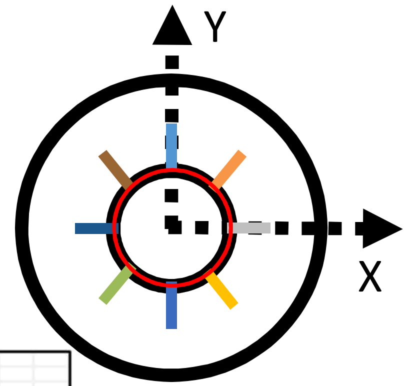
Critical nozzles to be investigated (cylindrical shape as recommended by the ISO 9300 standard)

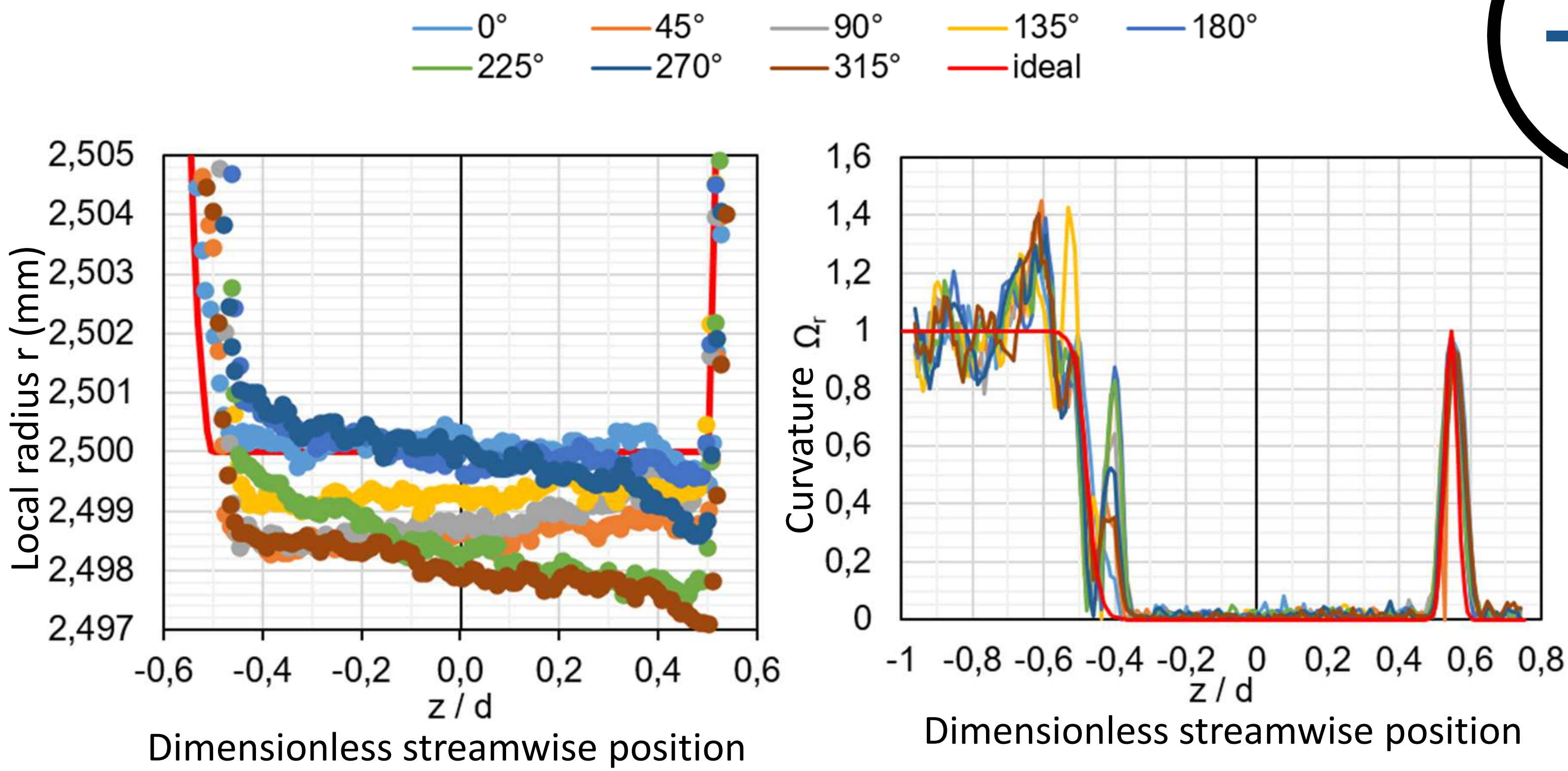
N°	Machined diameter d (mm)	Divergent length	Machined roughness range Ra (µm)		Corresponding non-dimensional roughness Range Ra/d	
1	5	7d	0.4	0.6	8.00010^{-5}	1.20010^{-4}
2	5	7d	0.6	0.8	1.20010^{-4}	1.60010^{-4}
3	5	7d	0.8	1.2	1.60010^{-4}	2.40010^{-4}
4	7.5	7d	0.4	0.6	5.33310^{-5}	8.00010^{-5}
5	7.5	7d	0.6	0.8	8.00010^{-5}	1.06710^{-4}
6	7.5	7d	0.8	1.2	1.06710^{-4}	1.60010^{-4}
7	10	7d	0.4	0.6	4.00010^{-5}	6.00010^{-5}
8	10	7d	0.6	0.8	6.00010^{-5}	8.00010^{-5}
9	10	7d	0.8	1.2	8.00010^{-5}	1.20010^{-4}
10	7.5	16.4d	0.6	0.8	8.00010^{-5}	1.06710^{-4}

Experimental Part

Experimental Part : Study of the dimensional sizes of 10 cylindrical nozzles :

Evaluation of the nozzle shape, examples of local measurements :





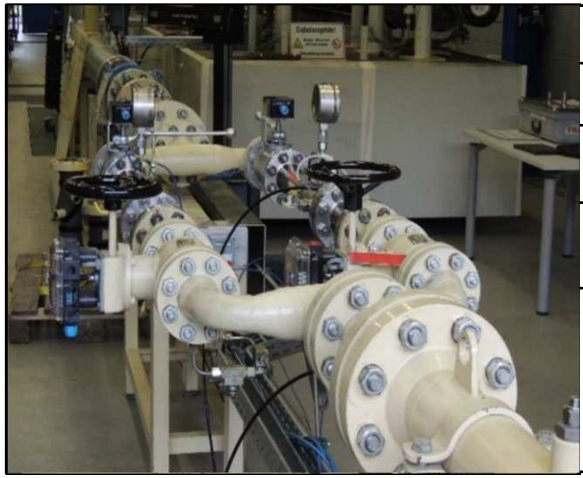
- Variations of the diameter in the cylindrical part due to roughness but also to shape defaults.
- Minimal diameter located mostly at the end of the cylindrical part.
- Dominance of the shape default over the roughness in the Cd evaluation with ω1 and ω2 as mentioned by MICKAN in 2018.
- The need for the equivalent measurements for comparison with the historical nozzle database.

Experimental set-up : NMI Methods

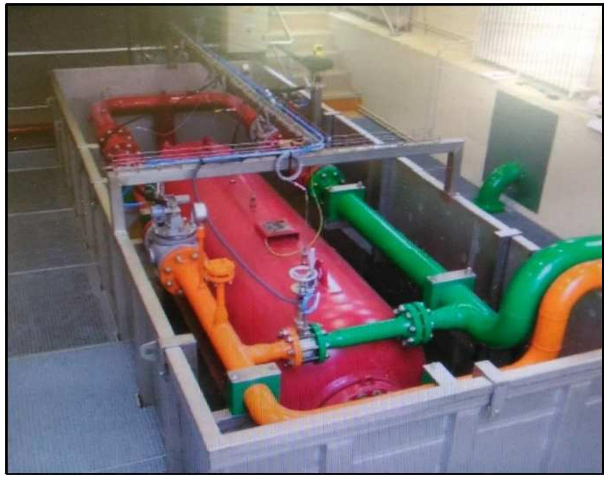
Standard facilities used for the flow rate measurements

NMI	Gas used	Primary standard	Maximum pressure (Bar)
PTB	Air	Bell prover**	8
	Natural gas	piston prover***	56
CESAME-EXADEBIT	Air	pVT,t	65

** Working standards were used for the calibrations in all measurements with air above 100 kPa.
*** Working standards were used for the calibrations in all measurements with natural gas before 2015.



Maximum flow rate	8 m³/h to 7200 m³/h
Pressure range	From 16 bar to 50 bar
Temperature range	From 8 °C to 20 °C (stability <0.1K during test)
Measurement uncertainty	Max. 0.15% (double standard deviation k=2)
Working fluid	Natural gas with uncertainty of C* estimated at 0.065%, (k = 2) and molar mass uncertainty estimated at 0.1% (k = 2)



Maximum flow rate	200 m³/h
Pressure range	From 6 bar to 60 bar
Diameter throat range	From 1.5 mm to 20 mm
Measurement uncertainty	0.11% on AC_D value for pressure up to 60 bar (k=2).
Working fluid	Dry air near ambient temperature with molecular weight of 28.966 g/mole and uncertainty of C* estimated at 0.05% (k=2).

Acknowledgement: This research was partially supported by Bodo Mickan and Ernst von Lavante. Thanks to our colleagues from PTB in Germany who provided insight and expertise.

Ref : Gibson J., Stewart D. “Consideration for ISO 9300-the effects of roughness and form on the discharge coefficient of toroidal-throat sonic nozzles,” Proceedings of ASME FEDSM’03 Honolulu, Hawaii, USA. 2003 July; 6-10.
Ref : Kramer, R., Mickan, B., Hotze, H.-J., Dopheide, D., “The German High-Pressure Piston Prover at PIGSAR™ - the German fundamental standard for natural gas at high pressure conditions, TechTour to the German High-Pressure National Standard PIGSAR™,” Ruhrgas AG, Dorsten, 15.-16. May 2003, CD-ROM, S. 1-21.

Numerical and Experimental Investigations on the Shape and Roughness of cylindrical CFVN

Cesame-Exadebit s.a. & al.

Experimental part

Experimental measurements with roughness of 5mm nozzles

NMI	Gas used	Primary standard	Maximum pressure (Bar)
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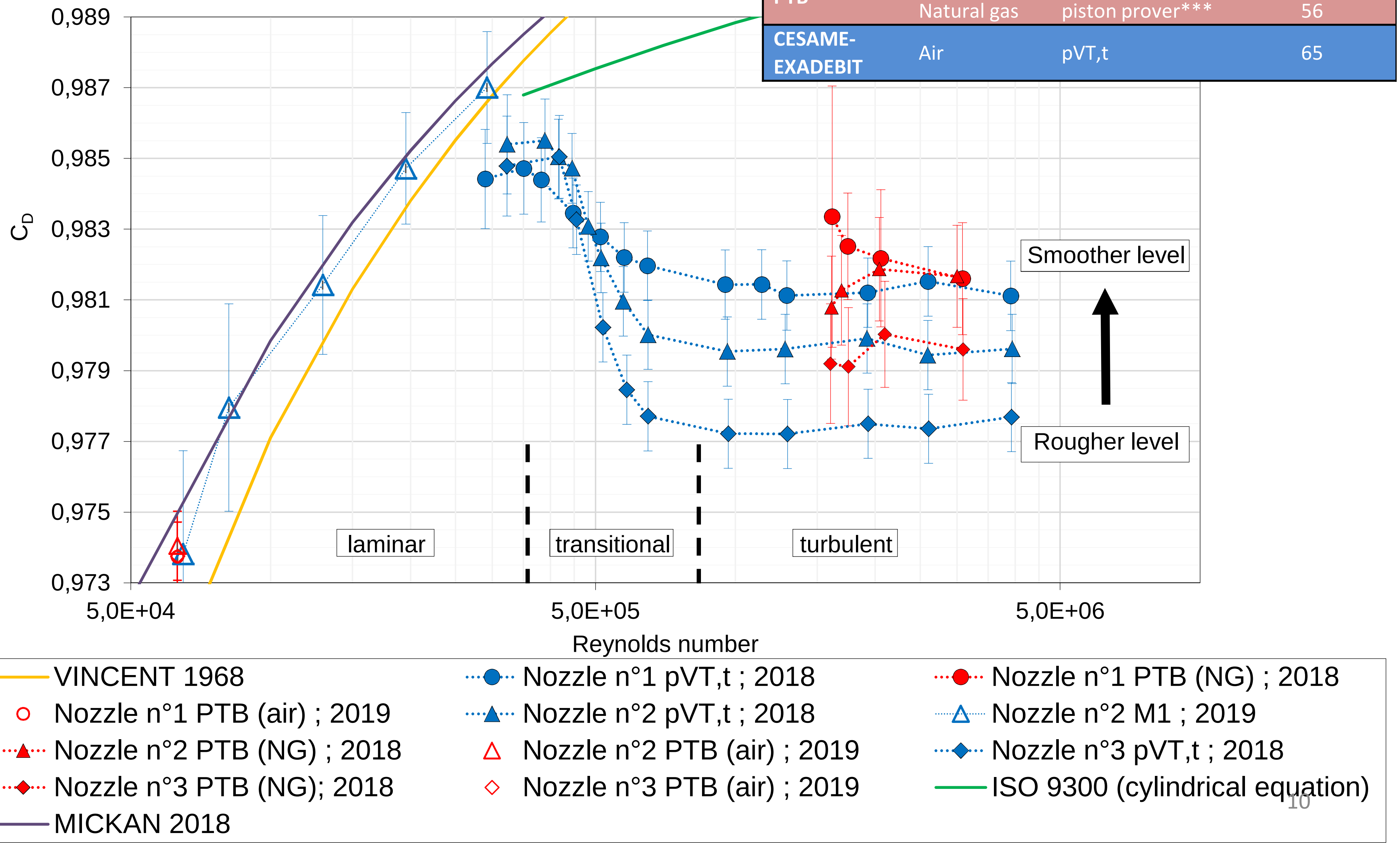
CESAME-EXADEBIT	Air	pVT,t	65



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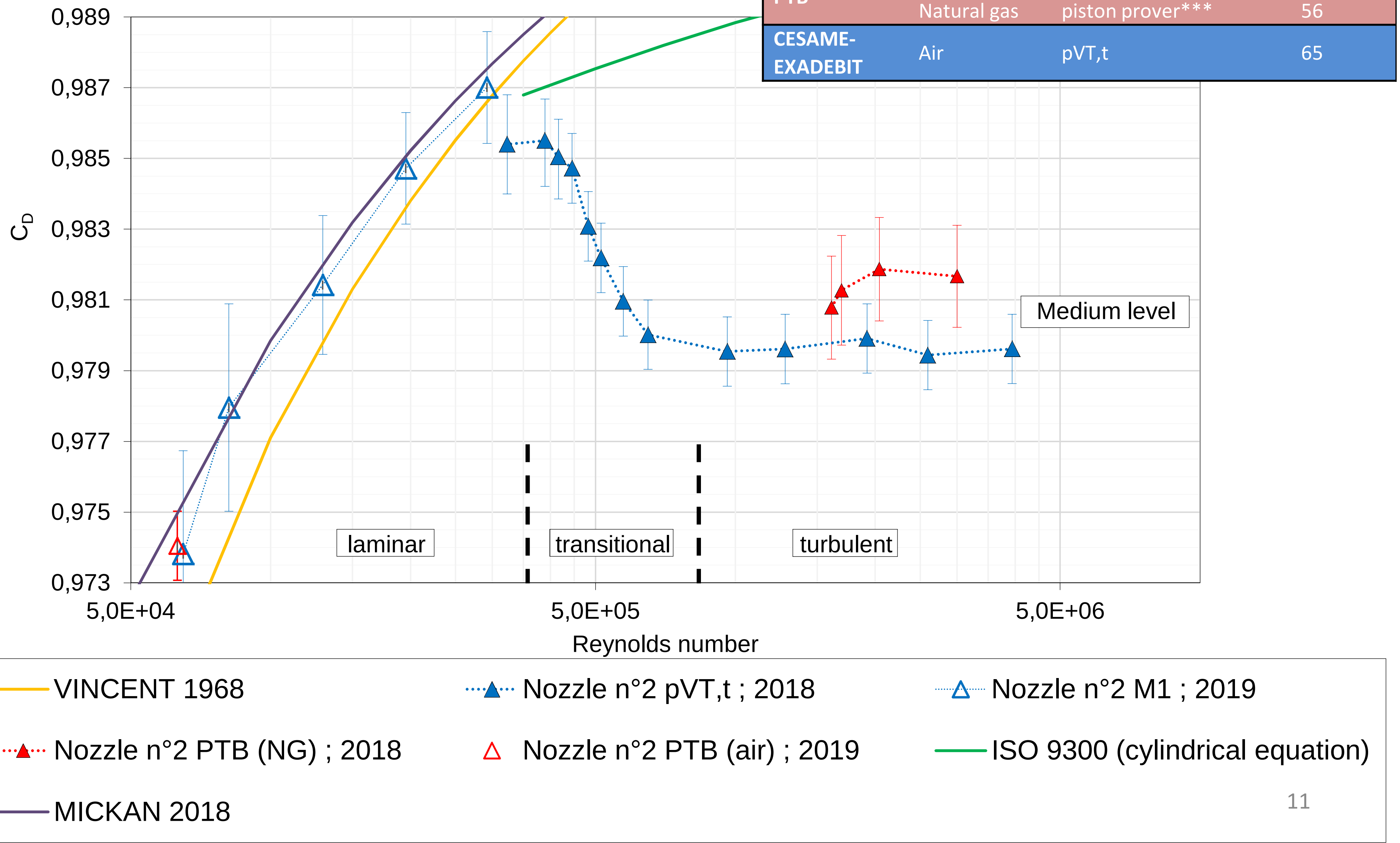


Numerical Part

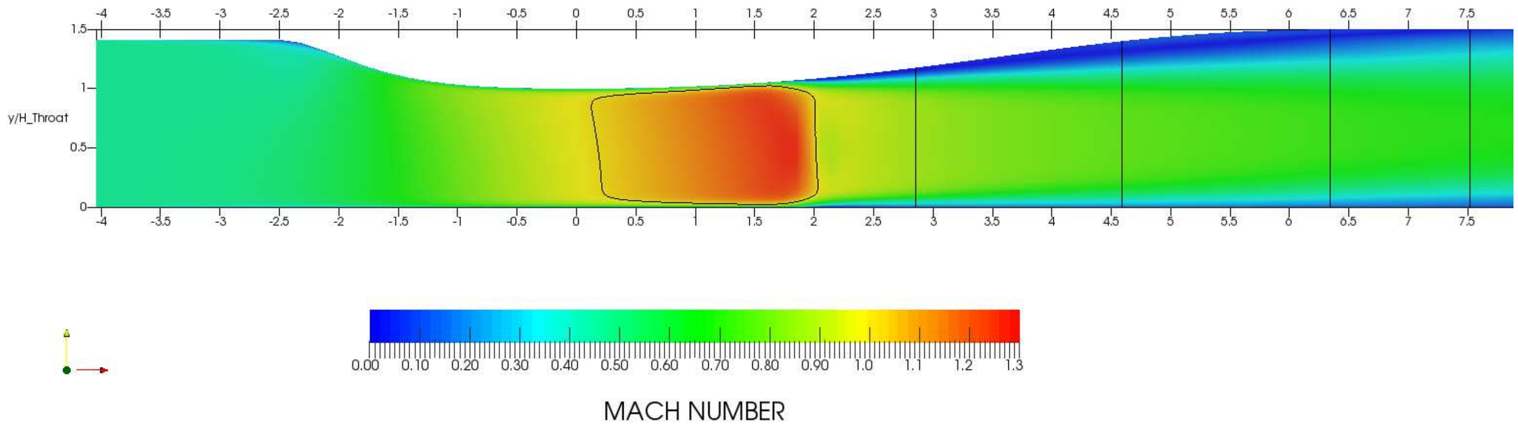
Global Numerical strategy

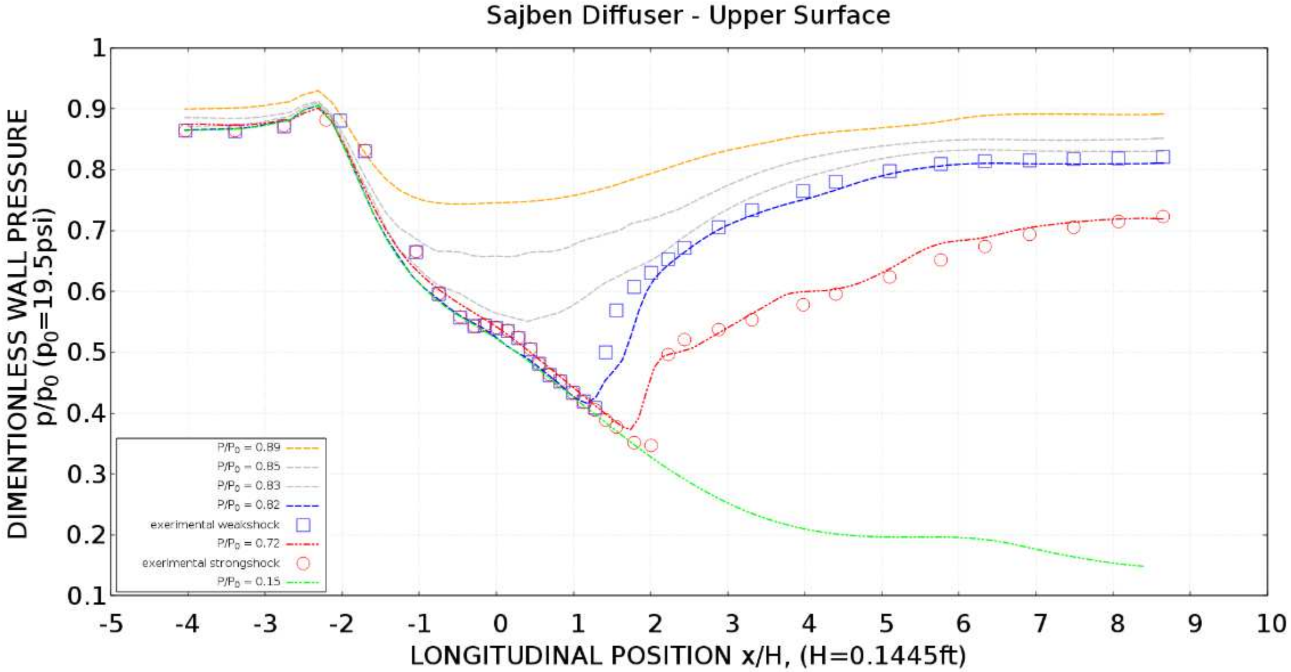
- Compressible Navier-Stokes (RANS).
- Axisymmetric formulation.
- OpenFOAM (rhoCentralFoam)
- Shock capturing (central-upwind schemes) from Kurganov and Tadmor.
- Time discretization : implicit 2nd -order backward.
- TVD 2nd order accuracy (Gauss linear interpolation, Van Leer limiter)
- Laminar/Turbulence model : Spalart Allmaras, k-ω SST and k-ε Realizable.
- Smooth multi block mesh
- Domain Sensibility and Near wall refinement
- Various sensitivity tests : mesh scalability, wall refinement, $\rho \cdot U$ profile extraction and interpolation, boundary layer sensor based on the vorticity,
- Qualitative various classical test cases (shock tube, nozzle 1D, Sajben…)

Ref: Kurganov A. and Tadmor E. New high-resolution central schemes for nonlinear conservation laws and convection – diffusion equations. Journal of Computational Physics, 160(1):241 – 282, 2000

Numerical Part

The famous test case of the transonic diffusor (Sajben) works well here for the strong shock configuration (p/p0=0.72) :

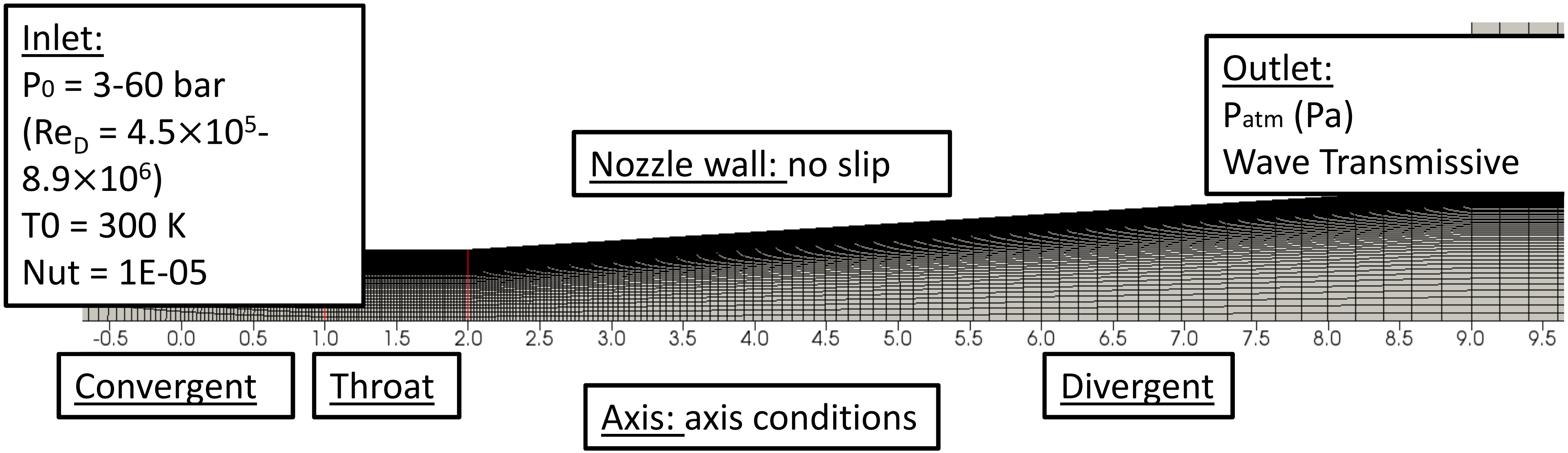




Numerical Part

Total topology and mesh sensitivity analysis

- Simulation 2D axisymmetric
- On a structured mesh
- Multi-block decomposition for parallelisation
- Refinement in the area of interest



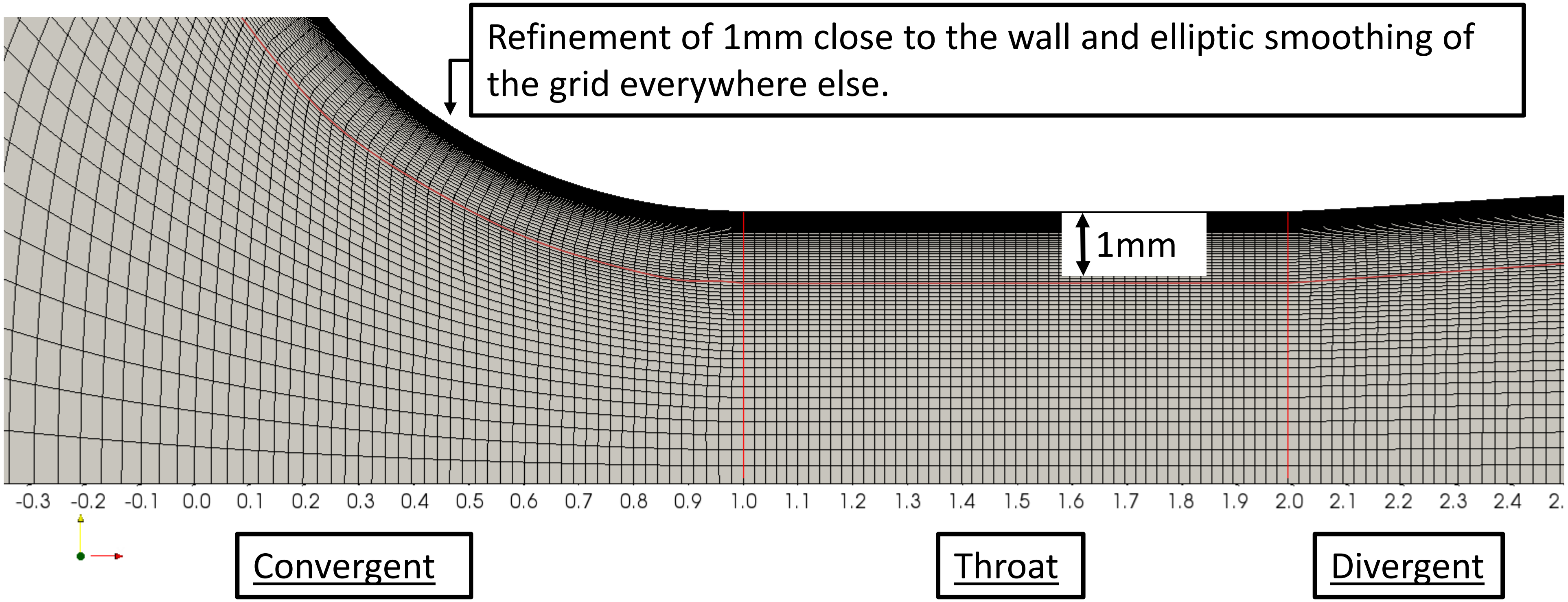
- Working fluid: air (γ=1.4) at T_0 = 300 K
- Pr = 0.72
- Viscosity evaluated with Sutherland law.

Numerical Part

Mesh topology

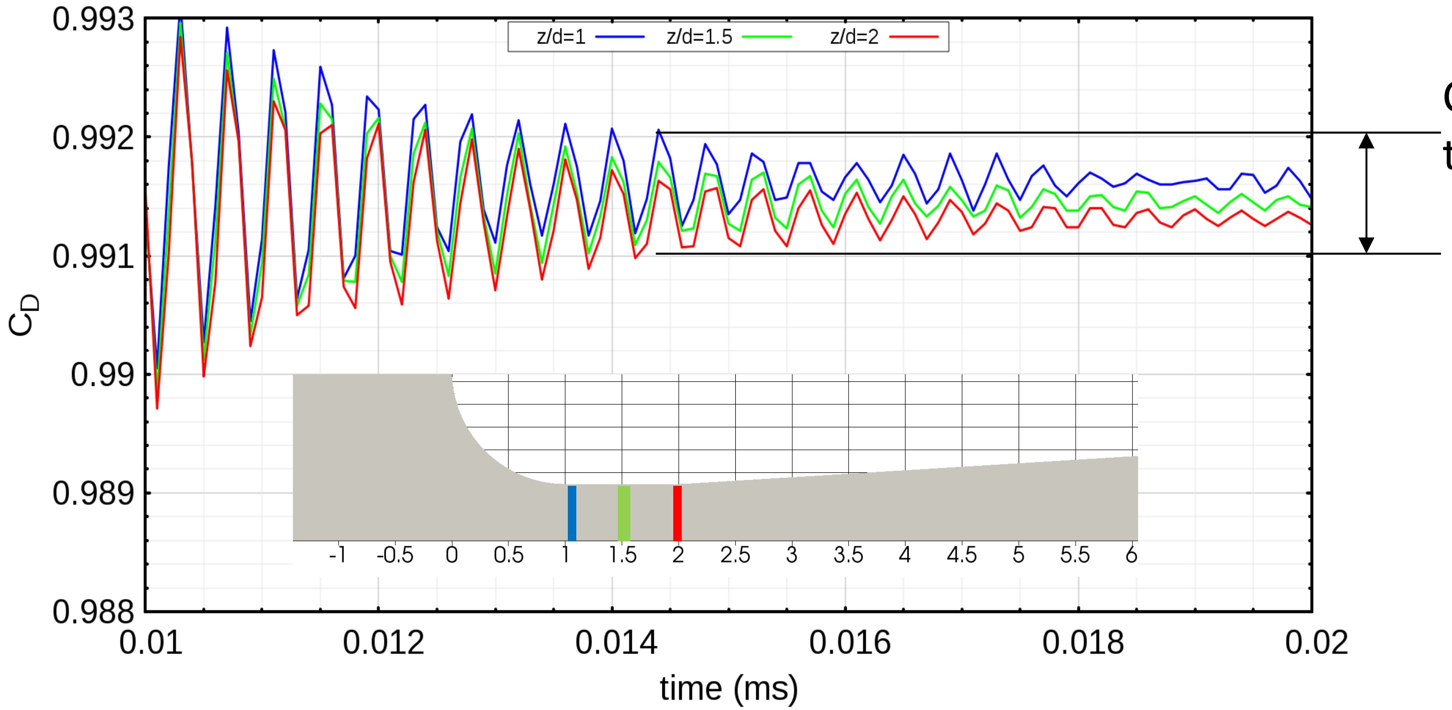
- Structured mesh
- Multi-domain (Refinement in the area of interest)
- Parallelisation

Refinement of 1mm close to the wall and elliptic smoothing of the grid everywhere else.



Numerical Part

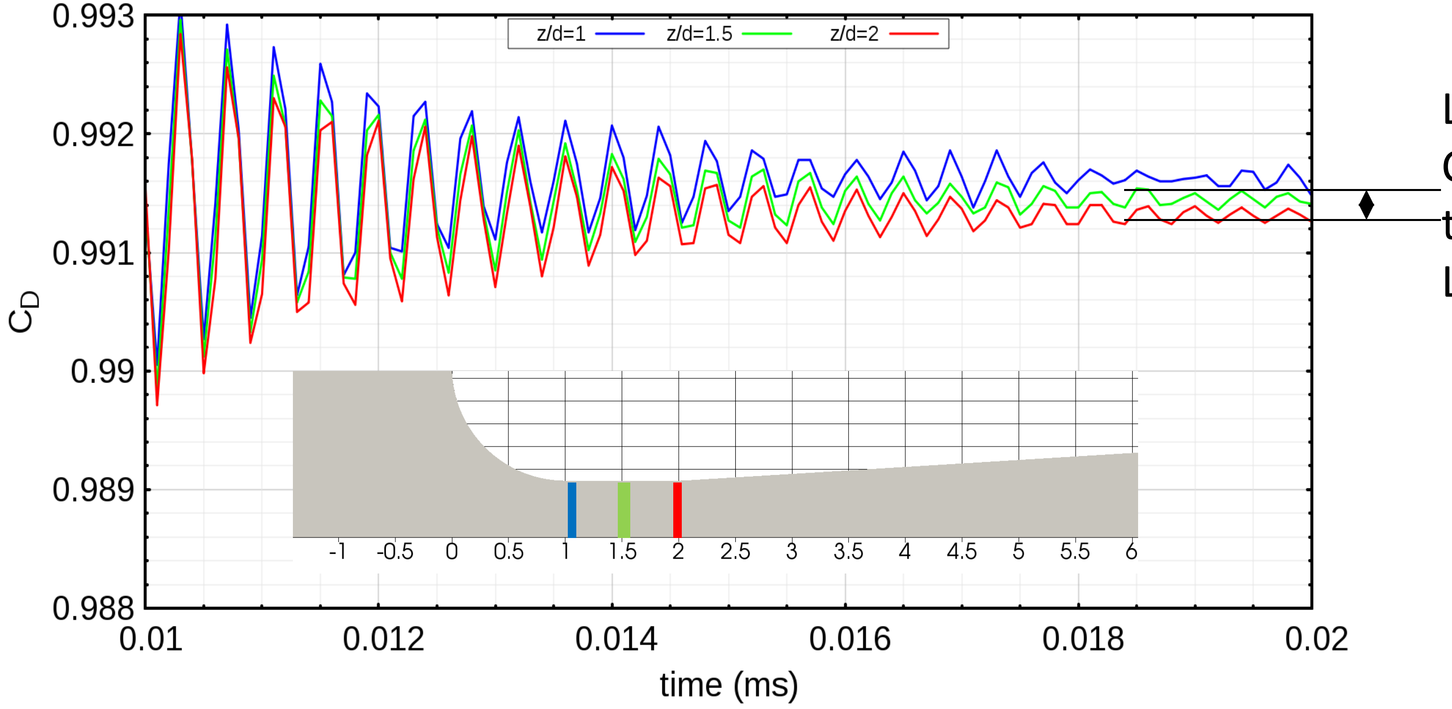
Discharge coefficient evaluation



C_D Evaluation is less than 0.1%.

Numerical Part

Discharge coefficient evaluation

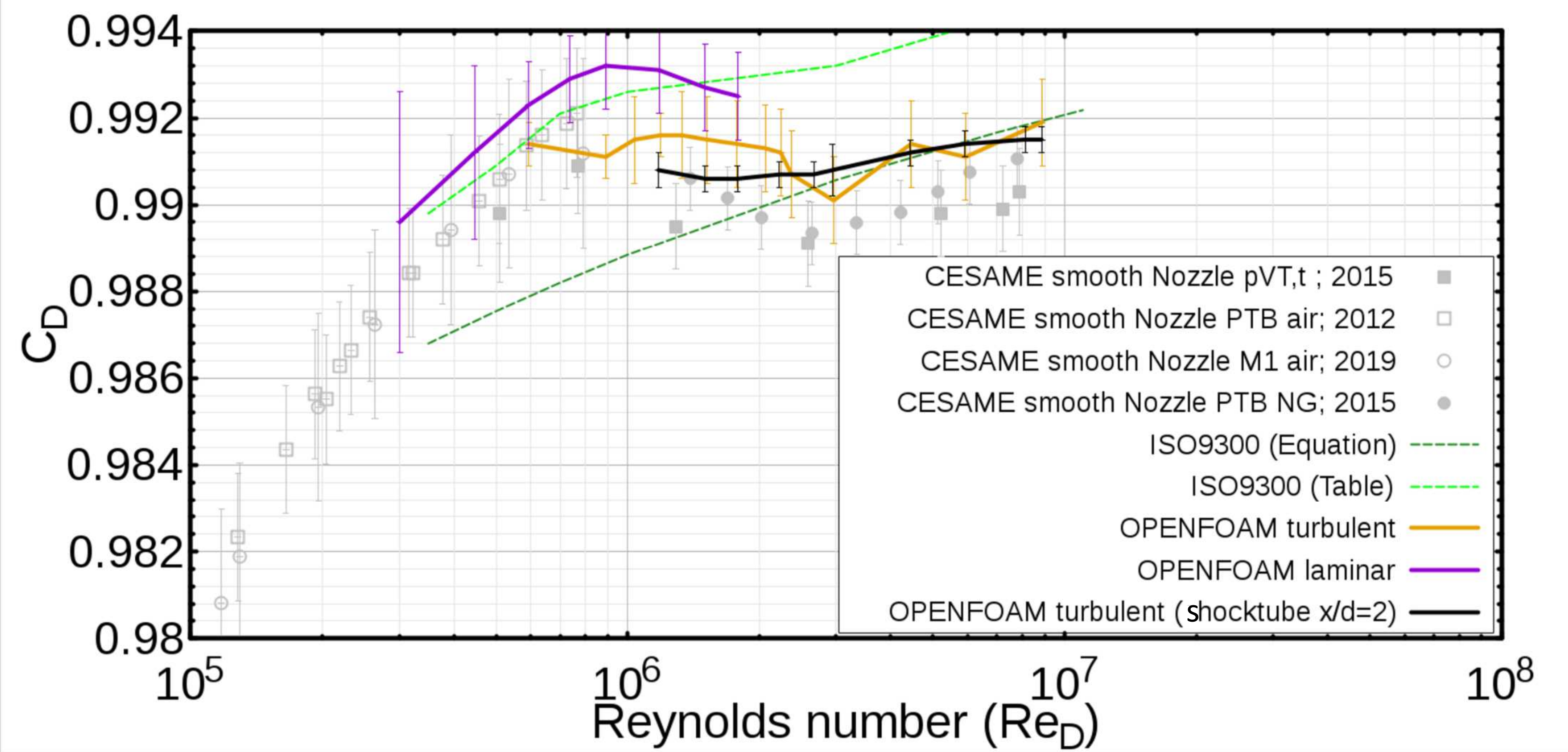


Low variation of the Cd evaluation within the cylindrical part. Less than 0.025%.

Numerical Part

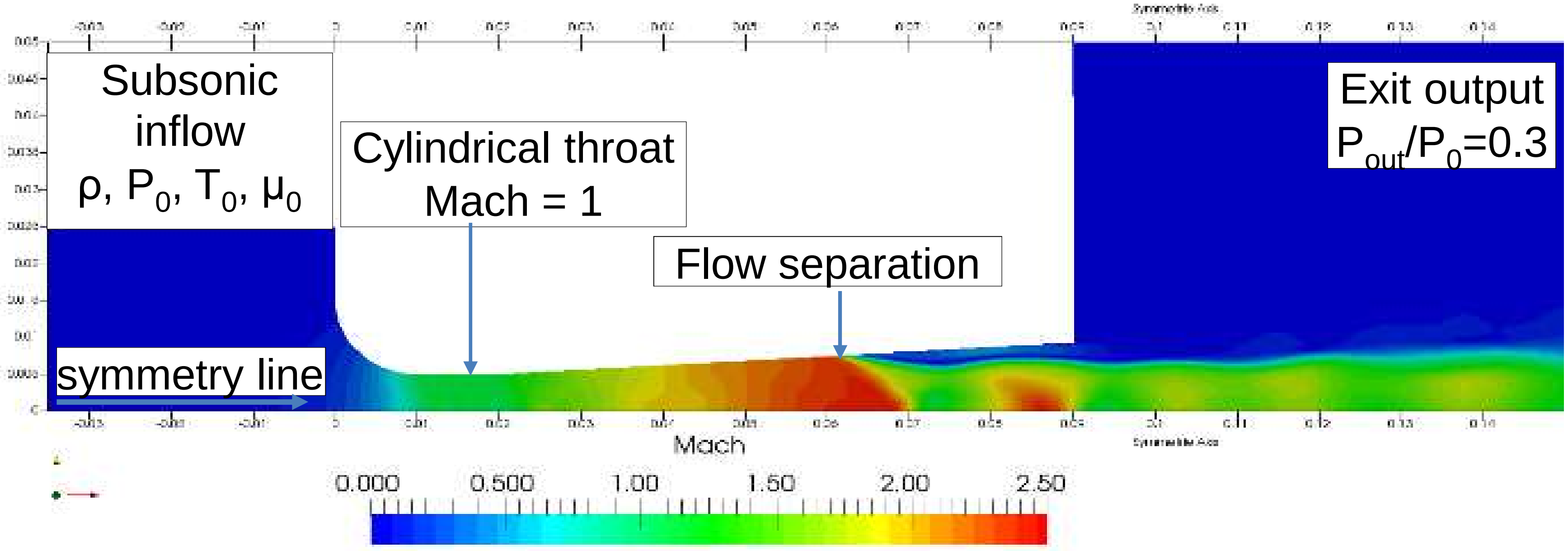
Discharge coefficient evolution (with the input pressure conditions)

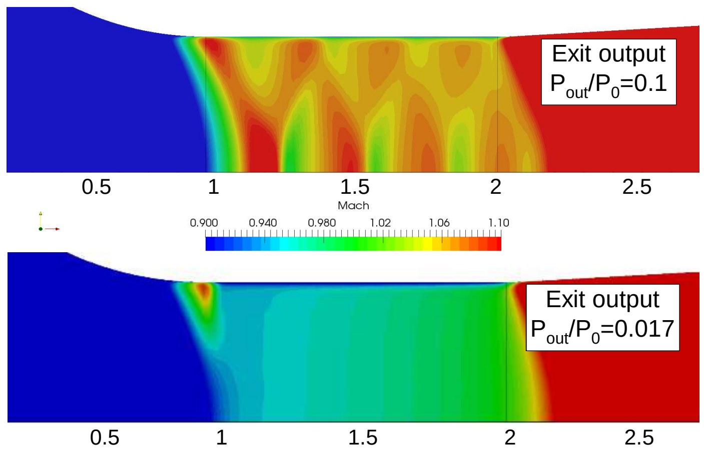
- Initialisation with different method pressure ramps
- Macroscopic performances



Numerical Part

Global flow structure

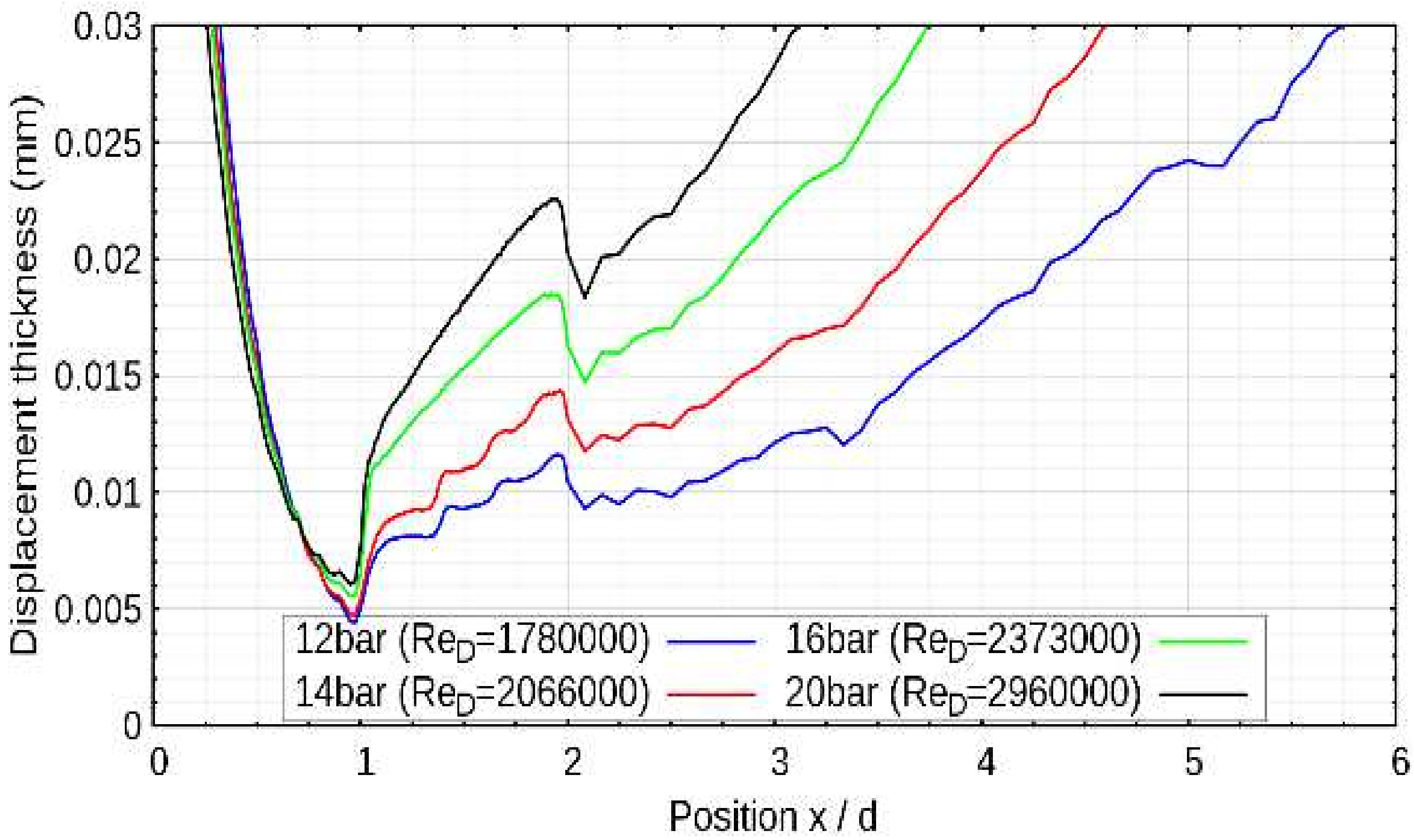




- extensive verification of influence of mesh resolution
- observed with various numerical schemes
- observed with various turbulence models
- observed in purely inviscid simulations
- depends on the initialization

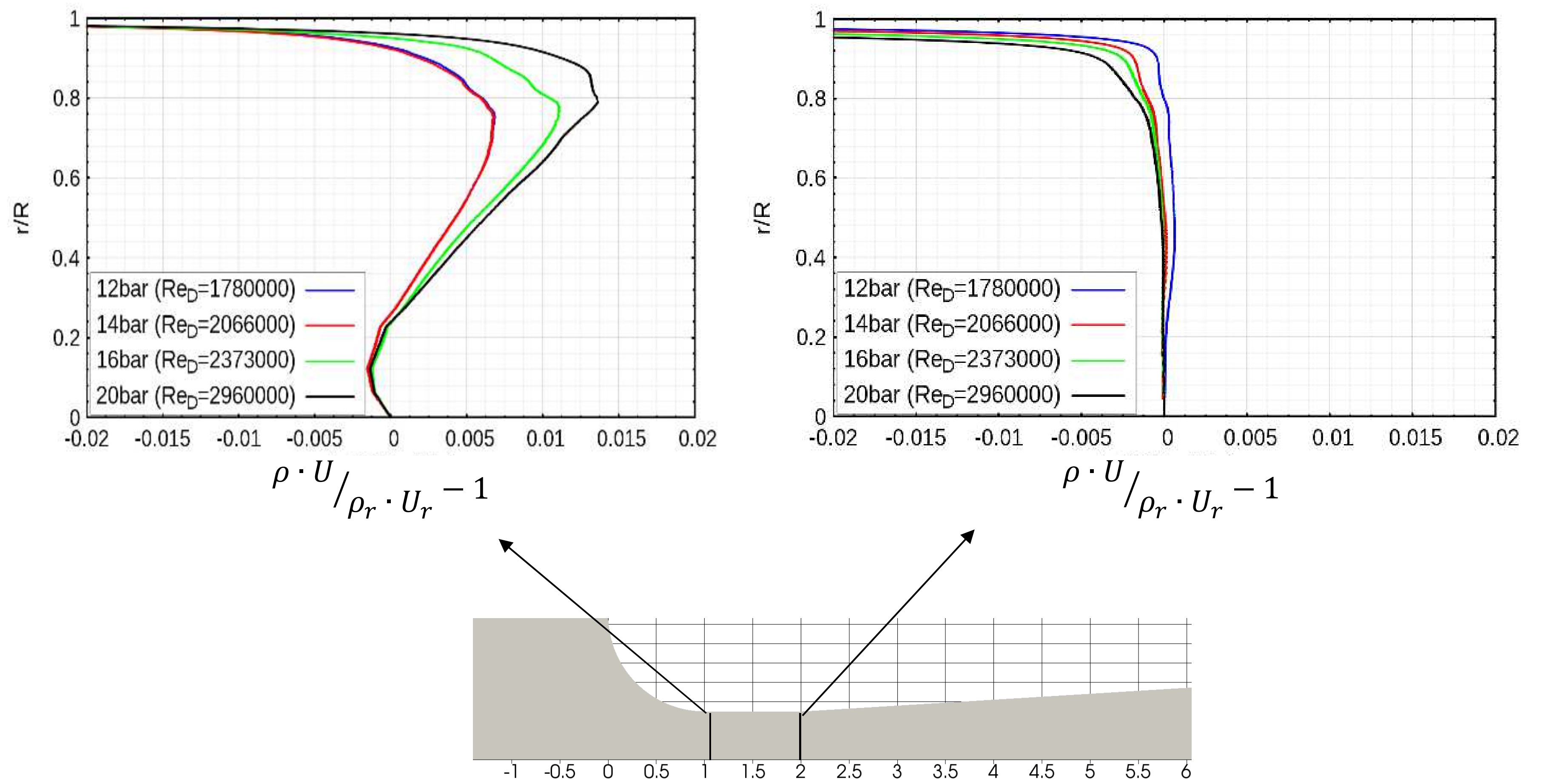
Numerical Part

Displacement thickness evolution with inlet pressure



Numerical Part

Complexed equilibrium within the flow



Conclusion and perspective

- Observed experimentally effects of roughness
- Validation of the numerical strategy
- Observation of original structure especially in the throat (non typical structure) needs to be more extensively characterised
- Possible formation of hystericize depending on the initialisation condition (violent or not)
- The need for a better characterisation of the parameters that drive the flow.

Further investigation is needed:

- Check the existence of hysteresis phenomena
- Detail the link between the change in the whole flow structure
- Identify -> what is due to the BL thickening ?
  -> what is due to the inviscid flow region ?
- Minimal phenomenological model describing the interaction between the boundary layer evolution (displacement thickness) and overall inviscid region.

End

- The end.
- Thank you for your attention.
- Please feel free to ask for any further explanation.