Experimental assessment of the open-source SU2 CFD suite for ORC applications

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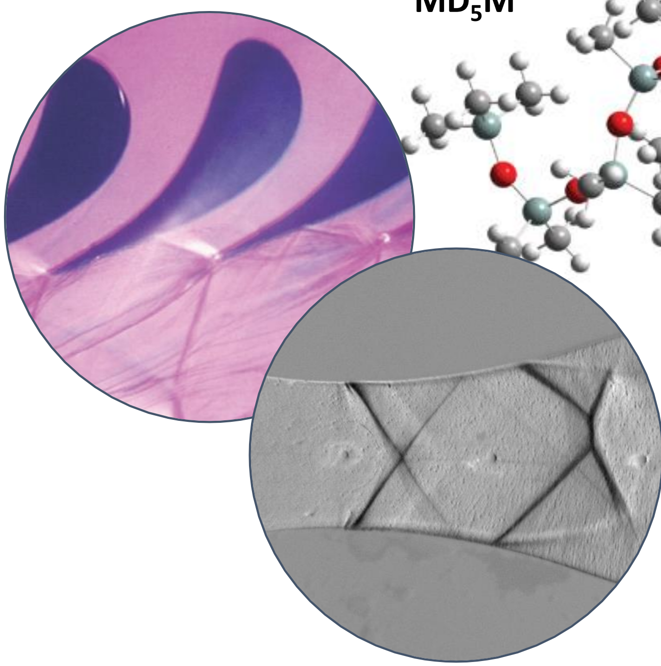
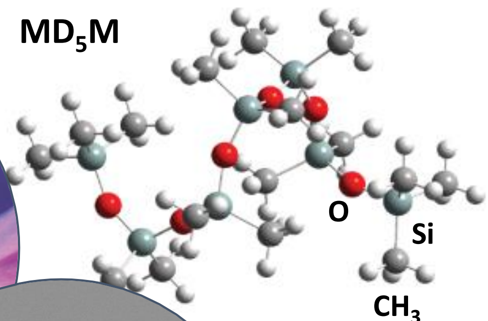
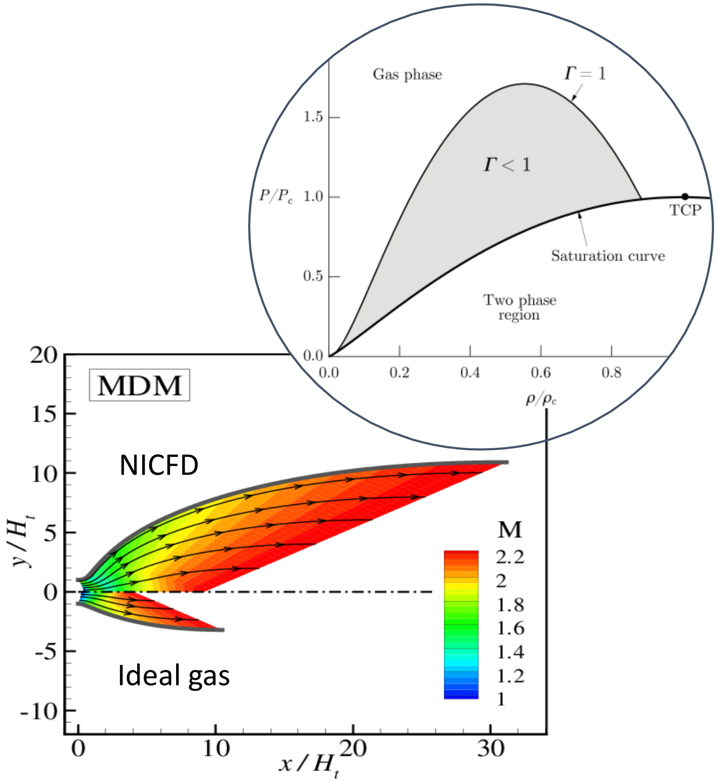
ORC 2017
13 - 15 September
MILANO, Italy

NICFD facts

- High compressibility effects
- Non-monotonic variation of the speed of sound
- Phase transition and TCP effects







Applications

- ORC and SCO2 plants
- Oil & Gas compression/expansion
- Trans-critical heat exchangers
- Refrigeration

…and many others!

Research question

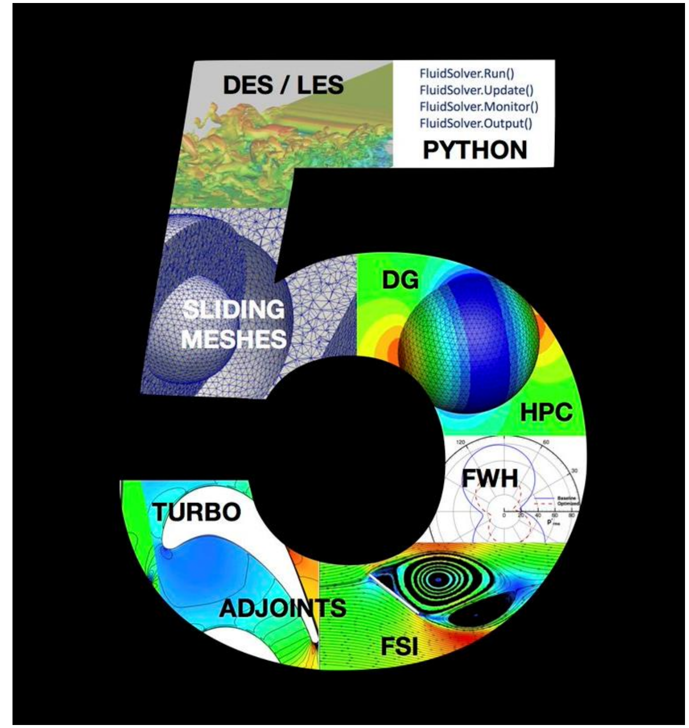
None of currently available NICFD CFD codes was ever validated against experimental measurements in the NICFD regime

OUTLINE

- → The numerical solver: SU2
- → Validation framework
- → Results

The CFD solver

SU2
The Open-Source CFD Code



An open-source collection of software tools written in c++, for performing PDE analysis and solving PDE-constrained optimization problems

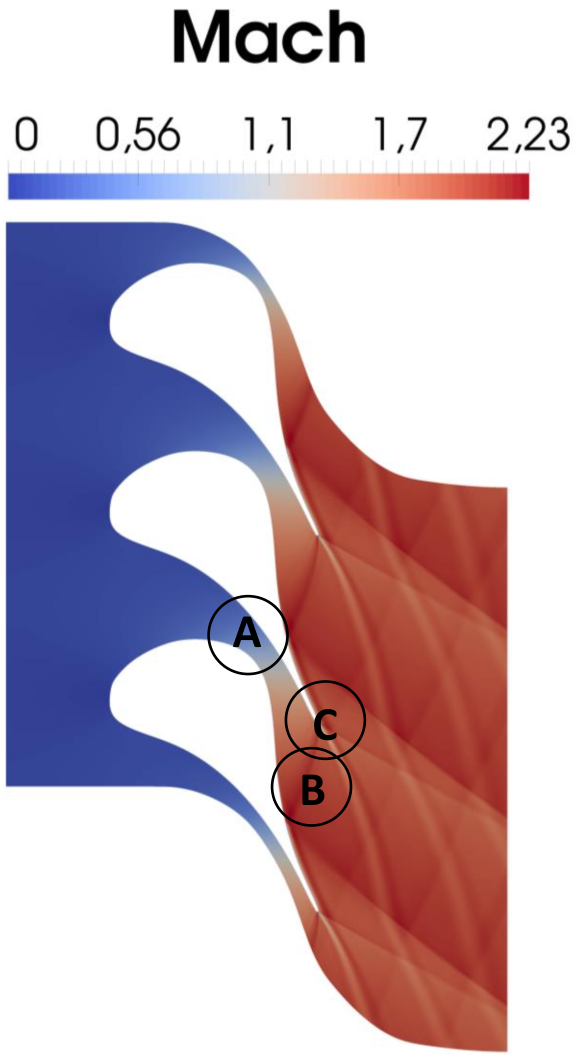
The NICFD CFD solver was added in 2014 thanks to a joint effort of researcher from Politecnico di Milano, from TU Delft and from Stanford University

The validation process: the framework

Steps to validate the numerical NICFD solver against experimental data

- Design simplified experimental benchmark tests
- Running CFD simulations using SU2 with different thermodynamic models
- Make numerical results grid independent using in-house mesh adaptation algorithm
- Carry out Uncertainty Quantification analysis using RobUQ, from INRIA, to assess CFD results against experimental data

The validation process: test cases



We identified 3 characteristic flow configurations that are representative of ORC applications:

A. Converging-diverging nozzle

B. Oblique shockwave and shock-boundary-layer interaction

C. Fishtail shock pattern at the blade trailing edge

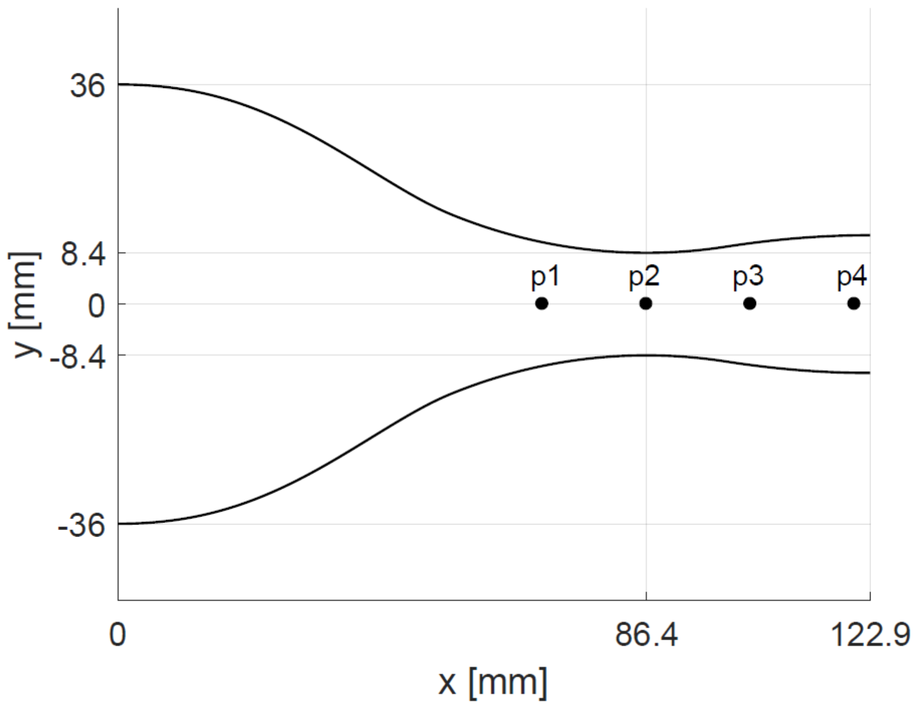
We designed 3 different test cases to validate the NICFD CFD solver

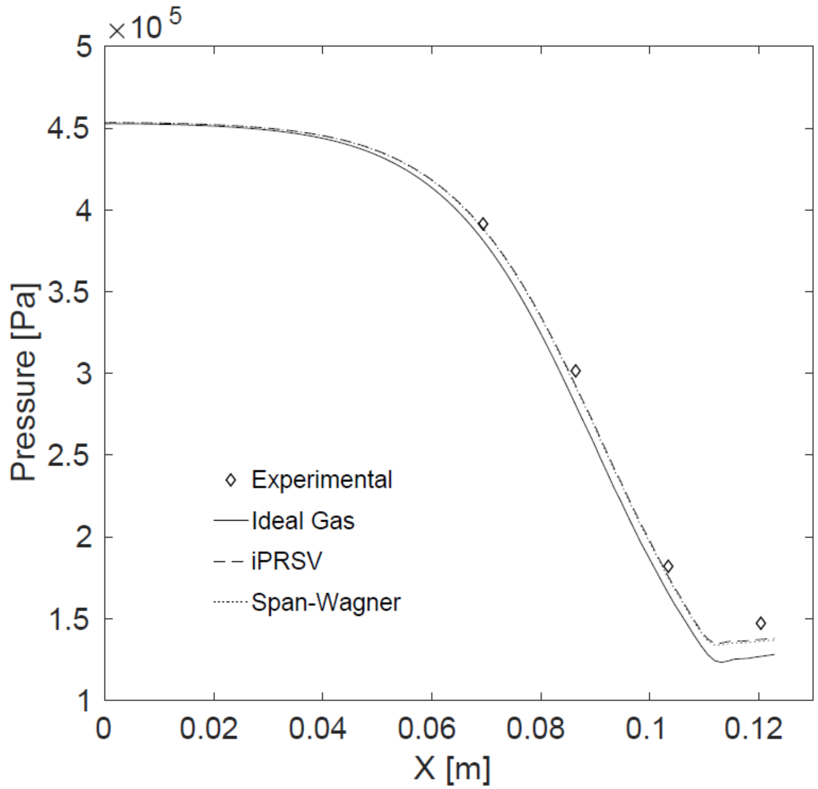
Pressure and temperature measurements, as well as schlieren images, were obtained from the TROVA test rig.

Test case A: Non-Ideal supersonic expanding flow

Fluid	Total T / T_c	Total P / P_c	Z
MDM	0.9	0.32	0.81

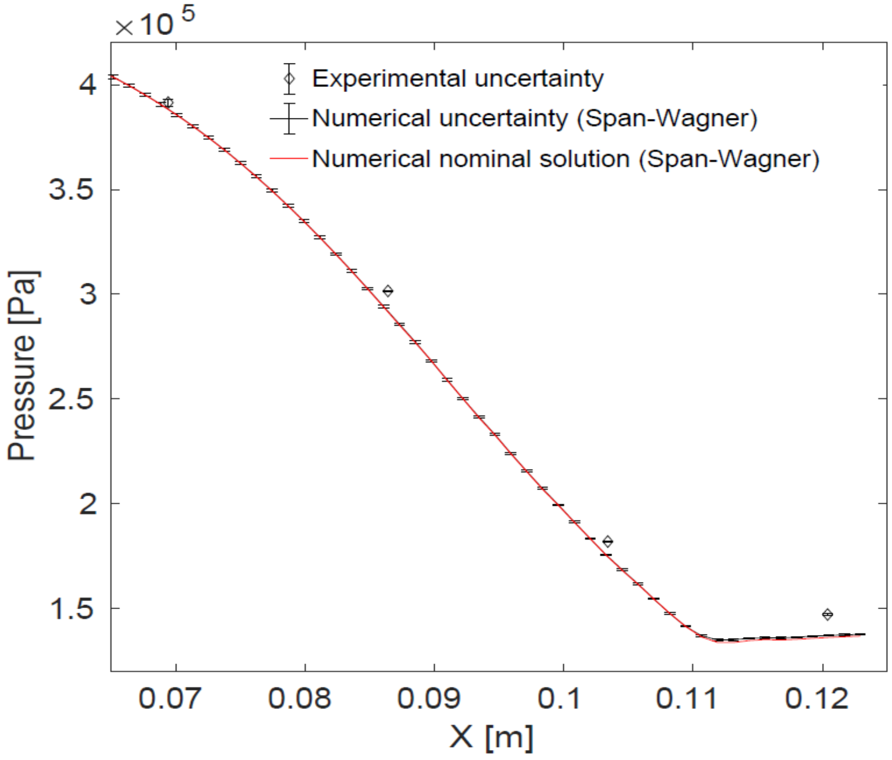
The flow was reproduced using three different equation of state, to evaluate the role of the thermodynamic model on the predicted solution

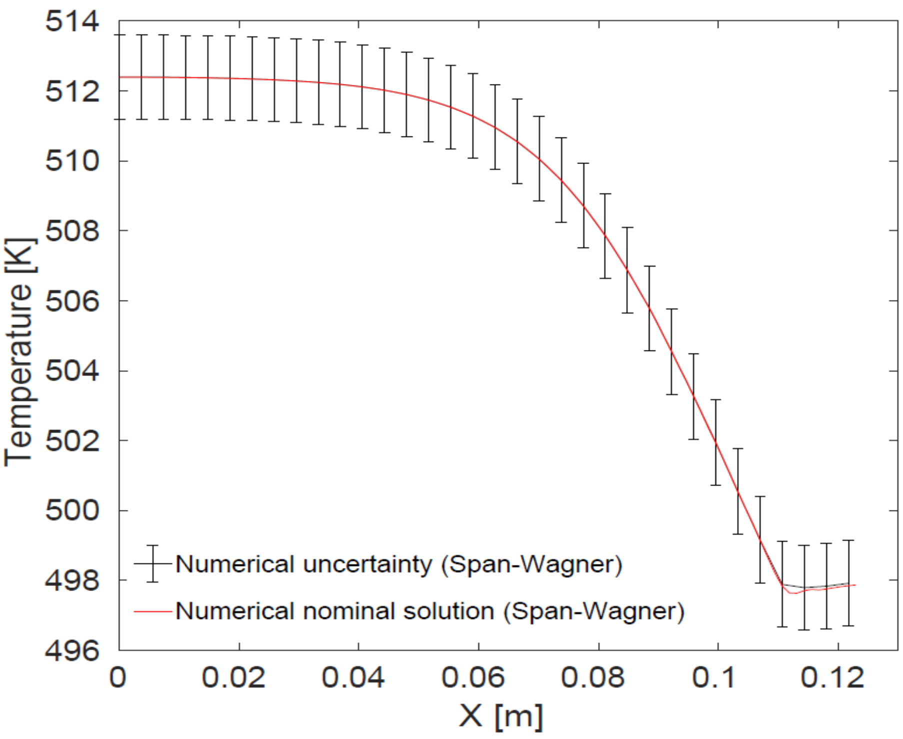




Test case A: Non-Ideal supersonic expanding flow

Results from the uncertainty quantification analysis on the numerical solution



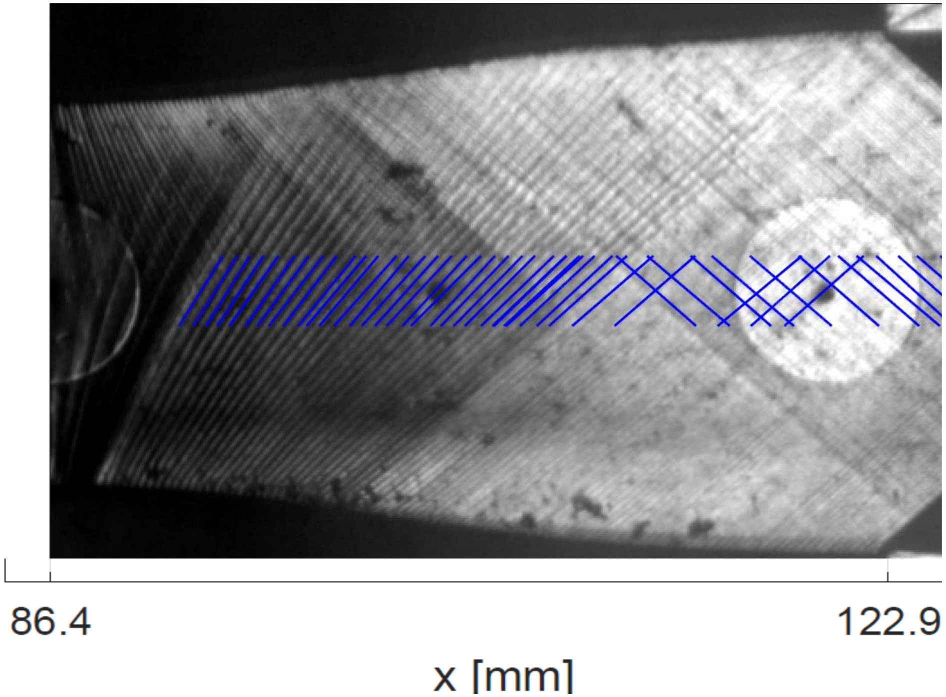


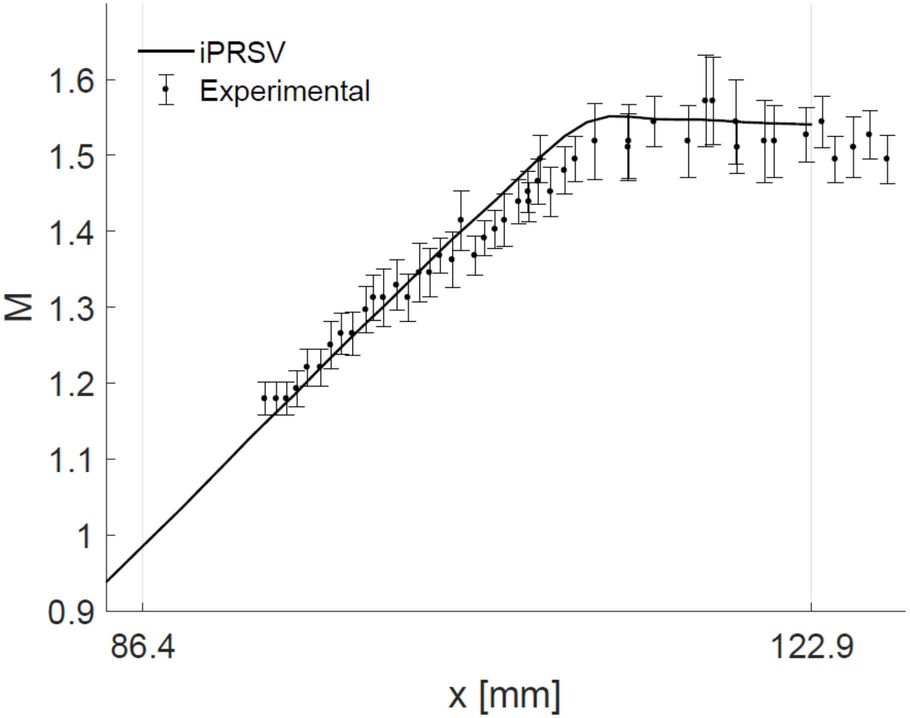
Very good agreement w.r.t. experimental data which proves robust and predictive solution

Robust prediction of the temperature (unc. < 0.2%)

Test case A: Non-Ideal supersonic expanding flow

The Mach number along the nozzle axis was measured from experimental schlieren images.

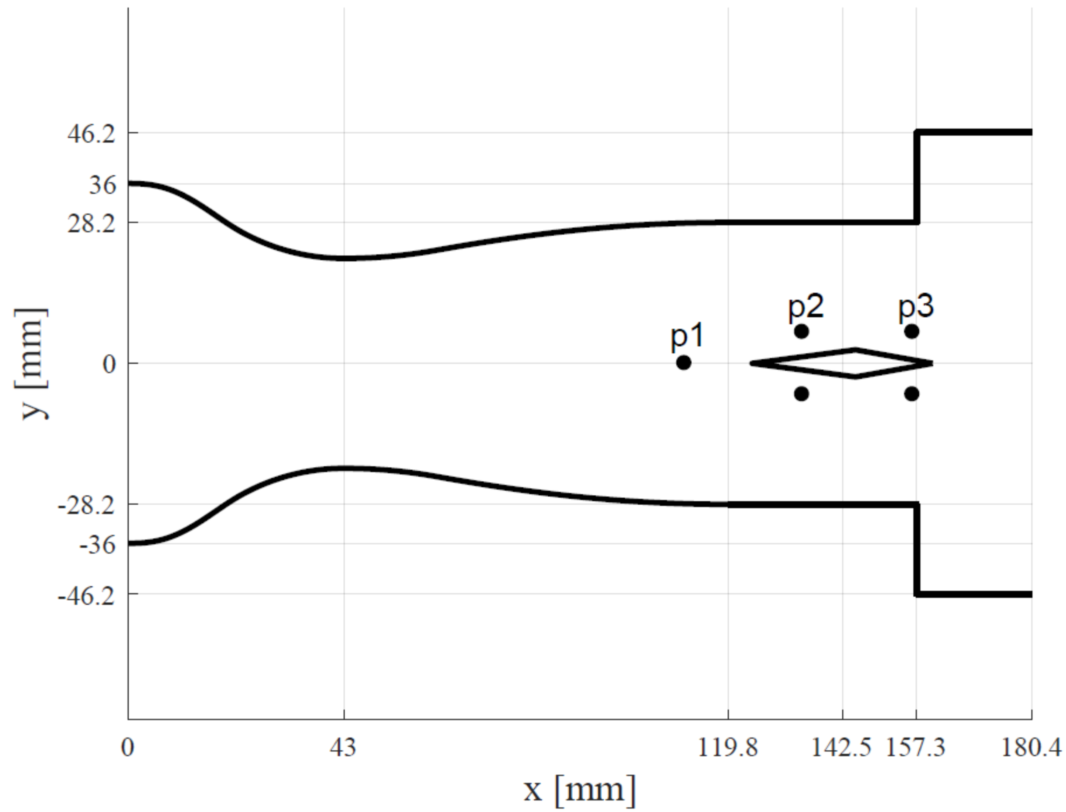




Join the talk: *Experimental observation of non-ideal expanding flows of Siloxane MDM vapor for ORC applications* from G. Cammi on Tuesday 14, afternoon session, Lecture room 03

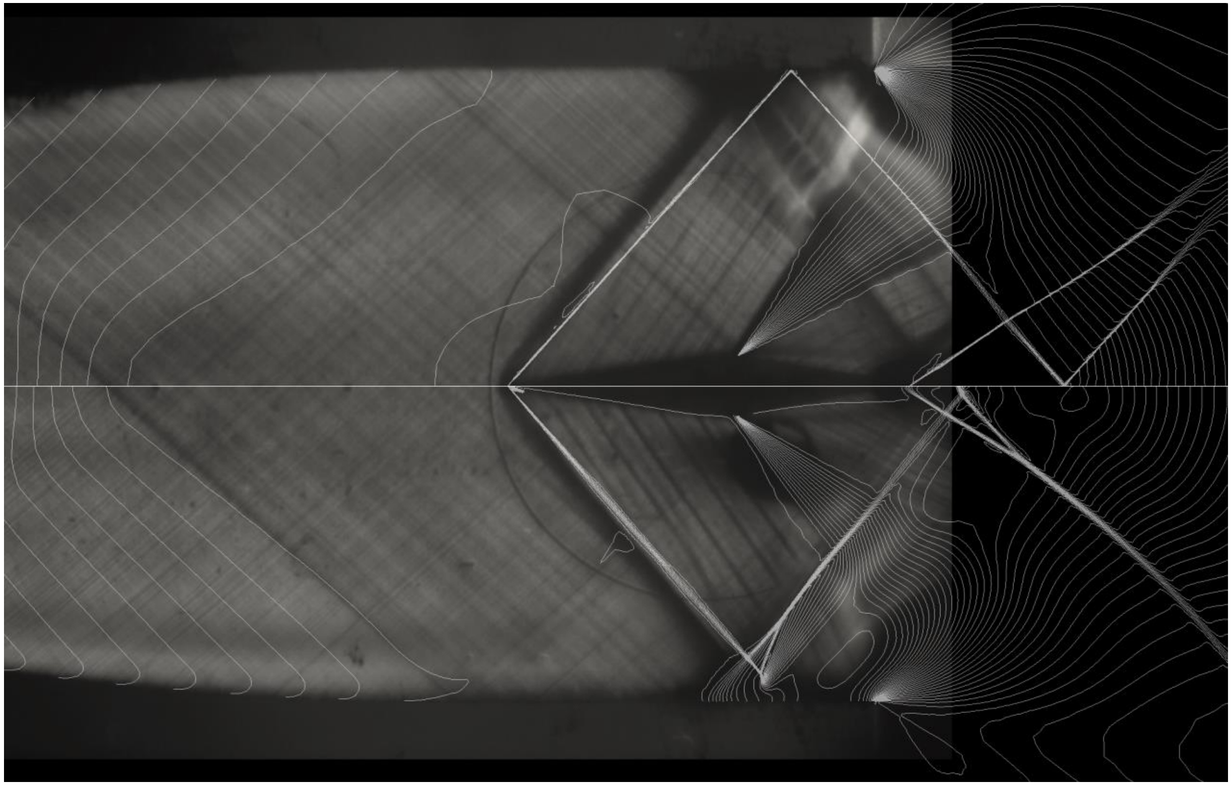
Test case B: supersonic diamond-shaped airfoil

Fluid	Total T / T_c	Total P / P_c	Z
MDM	0.98	0.62	0.7



Ahead of the airfoil, the flow is approximately uniform at Mach 1.5 and Z 0.9.

Test case B: supersonic diamond-shaped airfoil



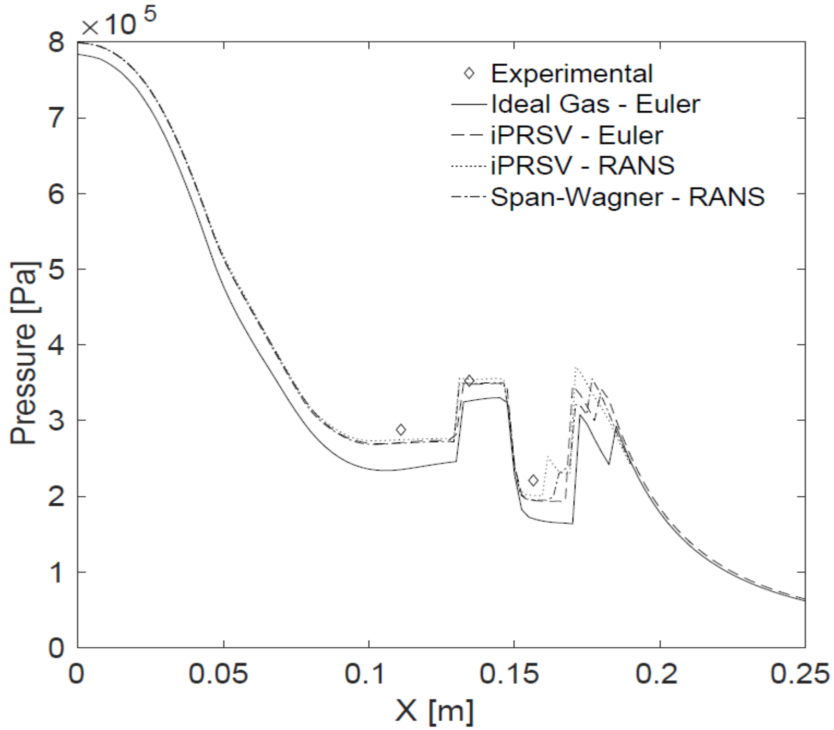
Euler (inviscid)

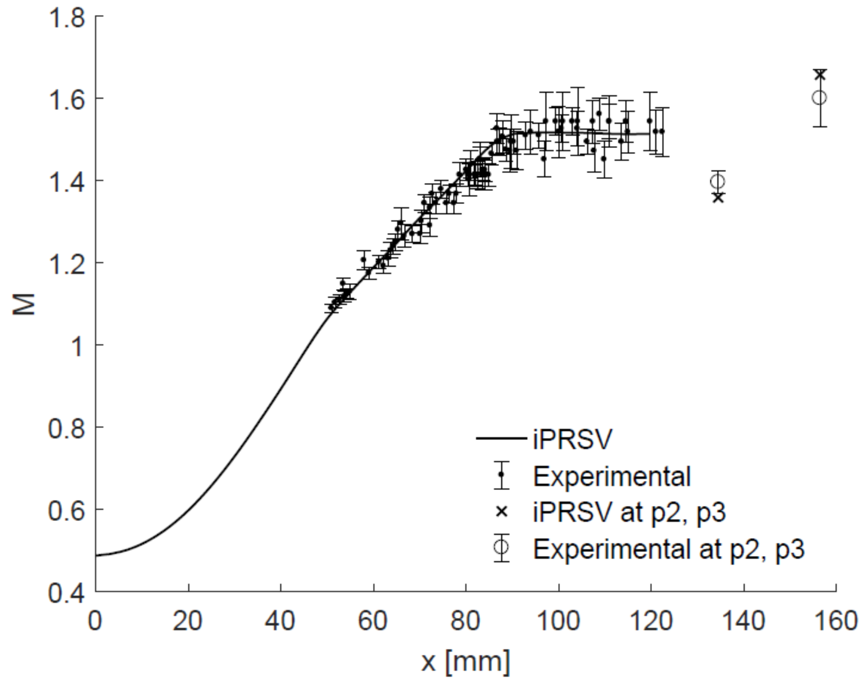
RANS (viscous)
Spalart-Allmaras

The numerical solution includes a shock pattern that matches the one revealed by the experimental schlieren image.

Test case B: supersonic diamond-shaped airfoil

Up to 6 steps of grid adaptation process were enrolled, for both inviscid and viscid simulations. The quality of the solution was improved in the close proximity of shocks.

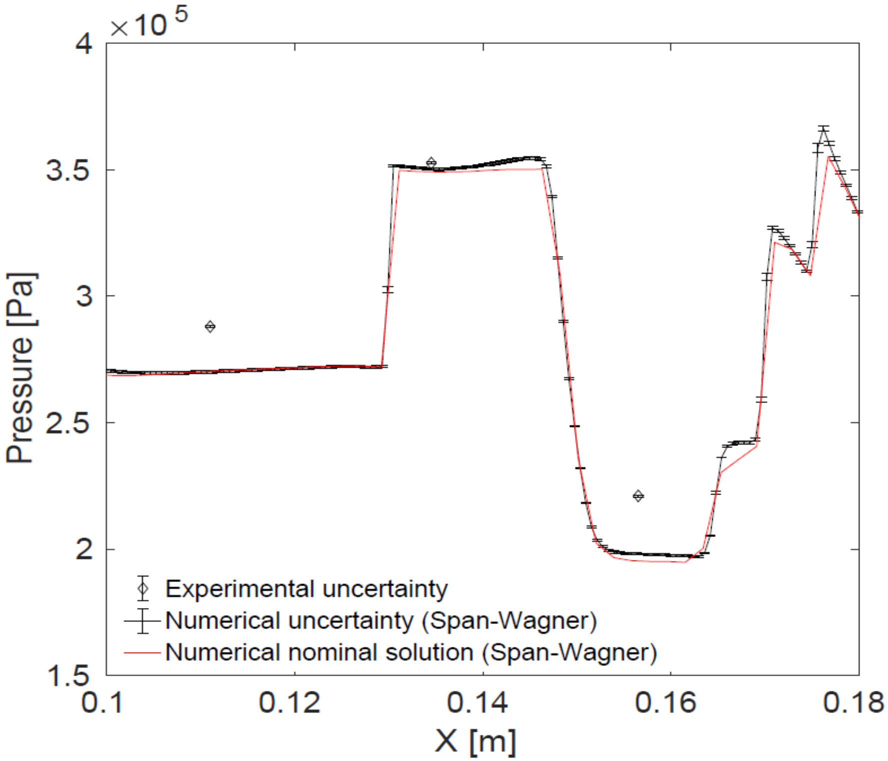


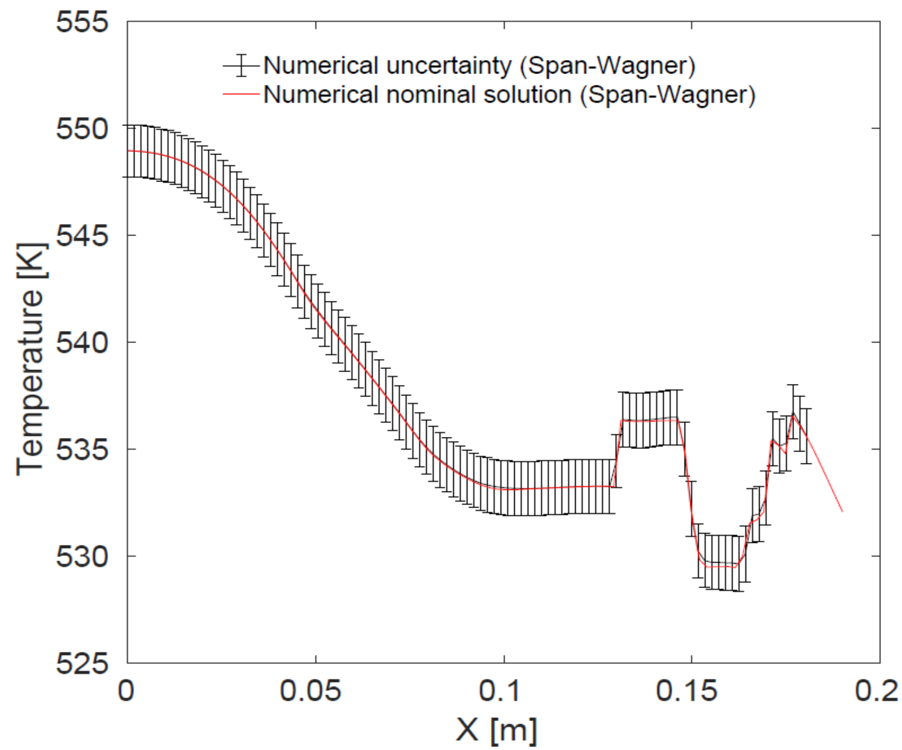


Numerical results are in good agreement with experimental data

Test case B: supersonic diamond-shaped airfoil

Results from the uncertainty quantification analysis of the numerical solution



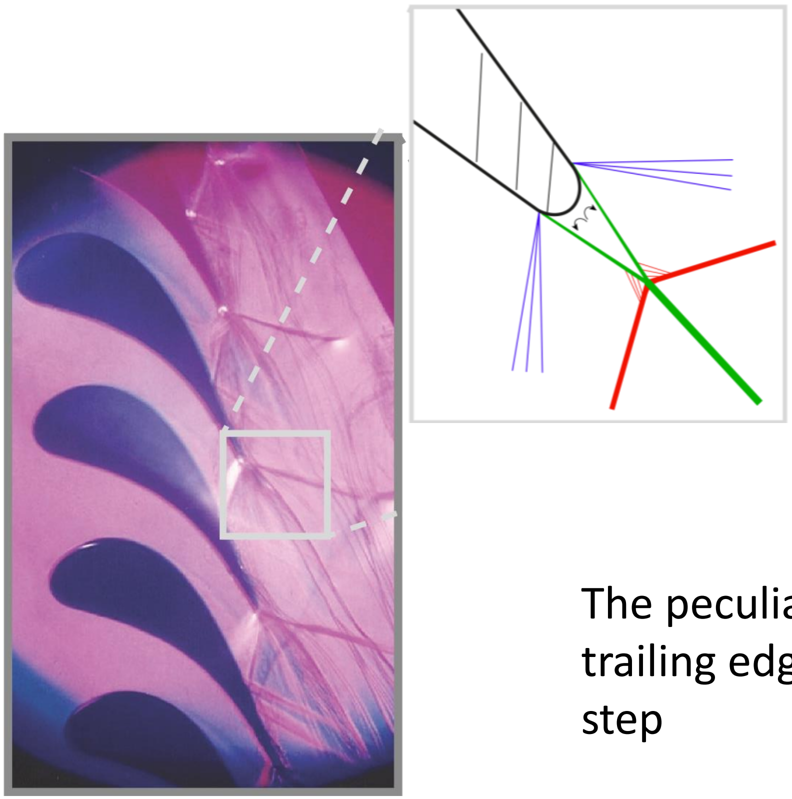


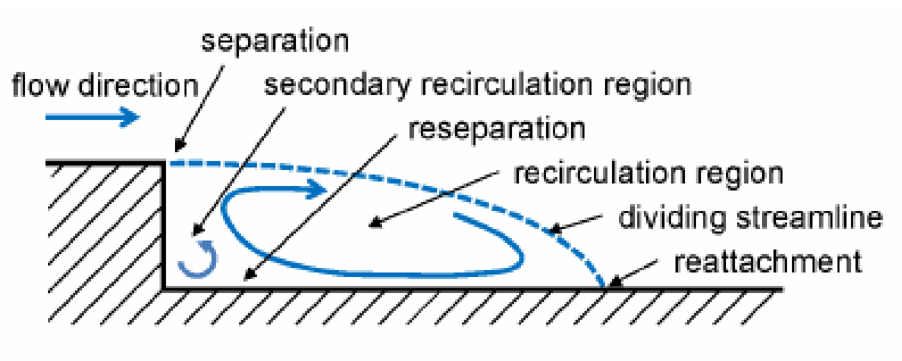
Maximal error of 12% with respect to the experiment

Robust prediction of the temperature (unc < 0.1%)

Test case C: backward facing step

Fluid	Total T (reduced)	Total P (reduced)	Z
MDM	0.92	0.32	0.82



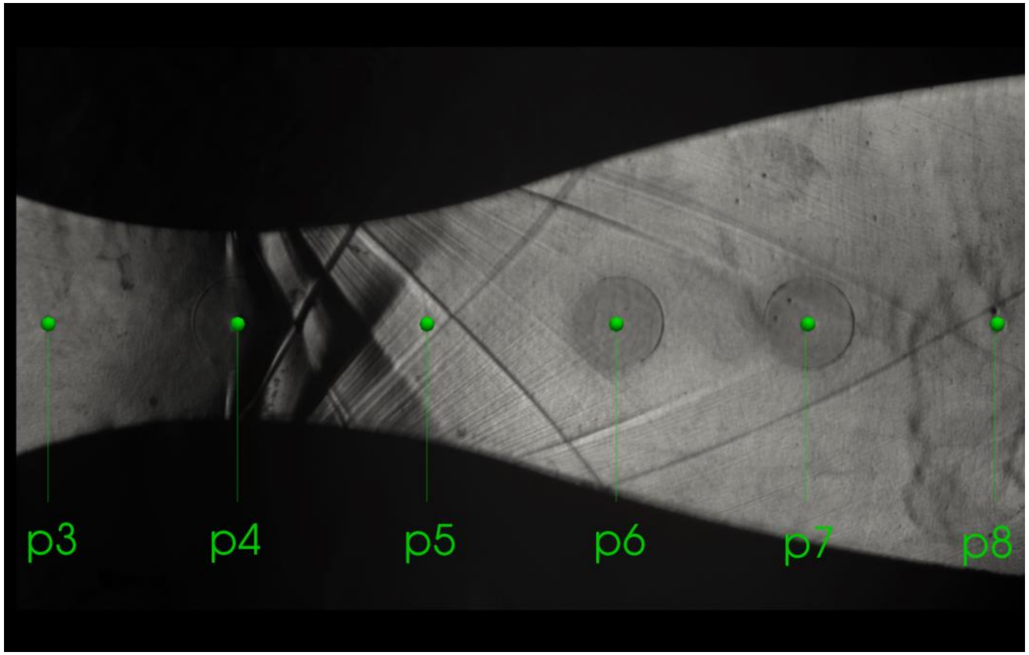


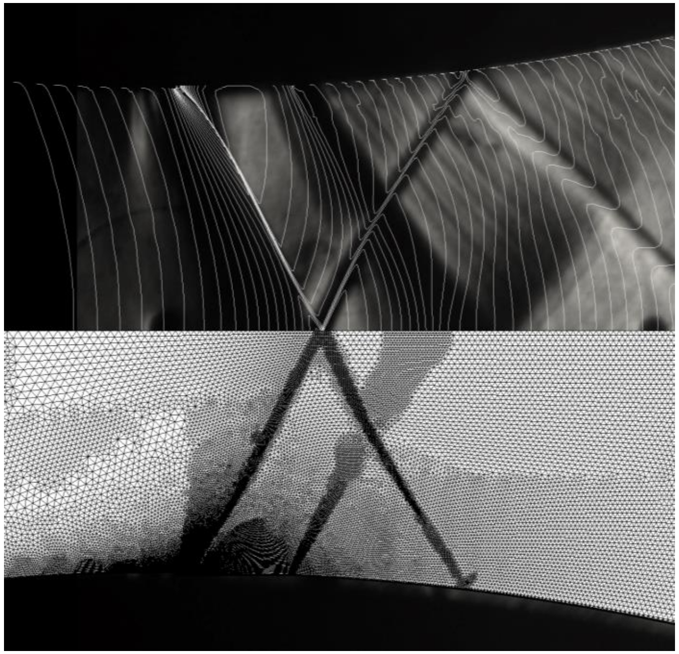
The peculiar flow configuration at the turbine blade trailing edge resembles the flow over a backward facing step

Join the talk: *Non-Ideal fish-tail shocks in ORC turbine cascades* from D. Vimercati on Friday 15, afternoon session, Lecture room 03

Test case C: backward facing step

A small backward facing step is wrought, to set the nozzle throat.





Up to 3 steps of grid adaptation procedure were enrolled, for both inviscid and viscid simulations. The quality of the solution was improved in the close proximity of shocks.

Test case C: backward facing step

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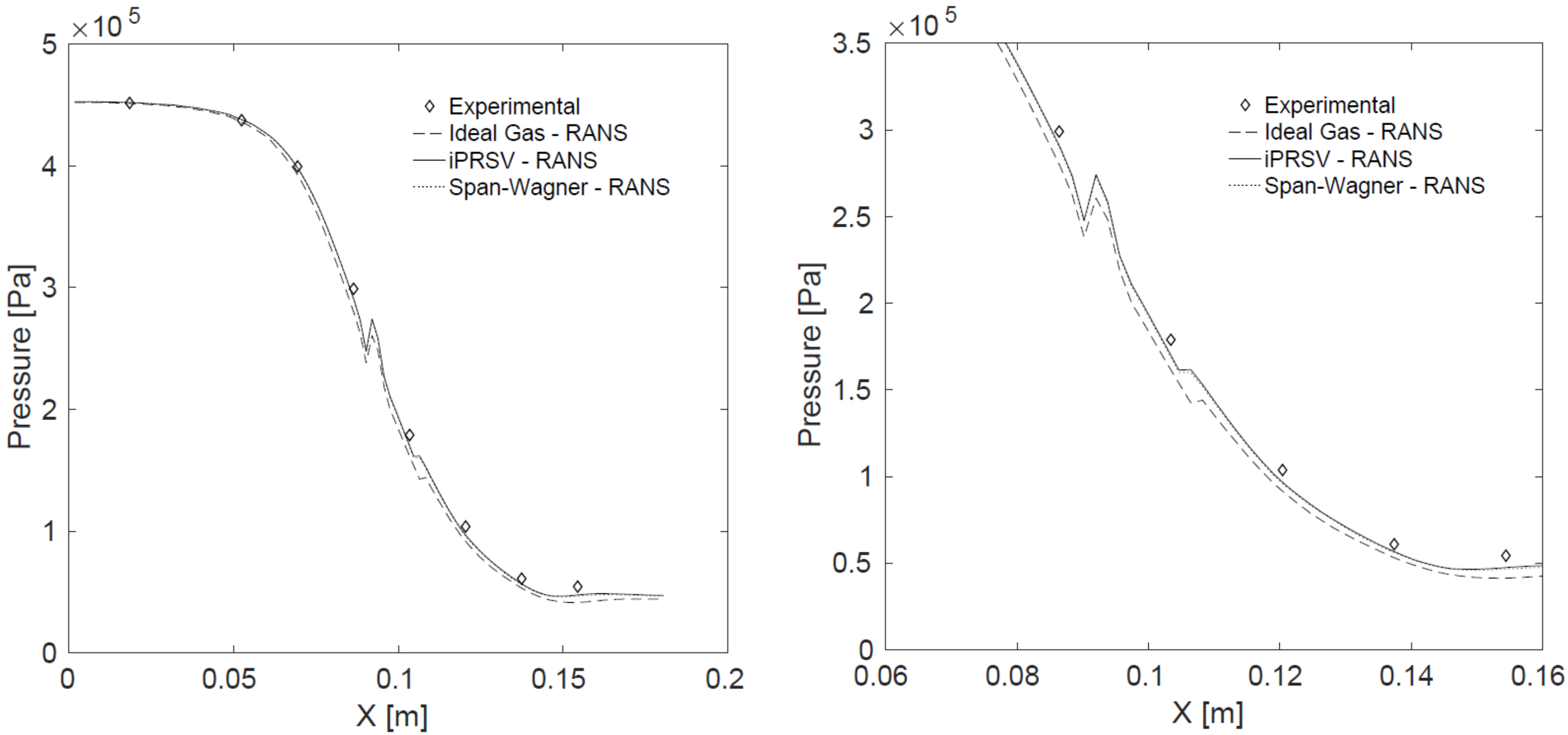


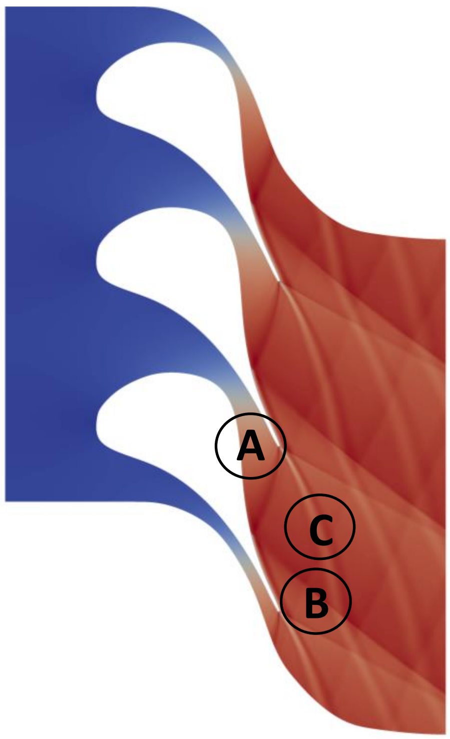
Numerical results are in good agreement with experimental data

Conclusions

- For the first time, the capabilities of a Non-Ideal Computational Fluid Dynamics (NICFD) solver were assessed against experimental results regarding flows of fluid in a non-ideal regime.

- The NICFD CFD solver from the SU2 open-source suite proved to predict fairly accurate results, for a set of exemplary test cases of interest for ORC applications

- Uncertainty Quantification was carried out proving small error bars for the numerical solution, pressure (<0.01%) and temperature (0.2%).



Very robust and predictive numerical solution with respect to the experiments!

Ongoing work…

- Experimental activity: Laser Doppler Velocimetry (LDV) using the TROVA test rig, carry out direct measurement of pointwise flow velocity.
- Design new experiments to explore more thoroughly the NICFD region
- Foster the Uncertainty Quantification analysis to improve the validation process of NICFD solvers.

…questions?

Thanks for your attention!

Join the lab tours to discover the CREALab!

The research is funded by the European Research Council under Grant ERC Consolidator 2013, project NSHOCK 617603

European Research Council
Established by the European Commission

The role of Uncertainty Quantification

Multiple (physical and modelling) sources of uncertainty exists!

The main goal of the Uncertainty Quantification is to take into account system uncertainties (parameters, measurements, motel etc) in order to quantify the statistical variability of a quantity of interest.

We will focus on the propagation of experimental uncertainties through the CFD code to compare numerical and experimental error bars.

Need for an efficient stochastic method to propagate uncertainty

The validation process: setting up the UQ framework

Coupling SU2 with a non-intrusive library, RobUQ from INRIA

RobUQ includes innovative methods for solving forward and inverse UQ problems and optimization under uncertainties problems.

- A Polynomial-Chaos based method is used
- Based on the state-of-the-art papers[1], we will only consider uncertainties on the initial conditions
- Uncertainties on the thermodynamic model are neglected with respect of other sources of uncertainty[2]
- Considered uncertainties are on the initial value of pressure and temperature

[1] P.M. Congedo, C. Corre, P. Colonna, J. Witteveen, G. Iaccarino, *Backward uncertainty propagation method in flow problems: application to the prediction of rarefaction shock-waves,* **Comput. Methods Appl. Mech. Engrg** 2012, Volume 213-216, Issue:1, pp.314-326.

[2] P. Cinnella, P.M. Congedo, V. Pediroda, L. Parussini, *Quantification of Thermodynamic Uncertainties in Real Gas Flows*, **International Journal of Engineering Systems Modelling and Simulation**, Vol. 2, Nos ½, 2010, pp 12-24

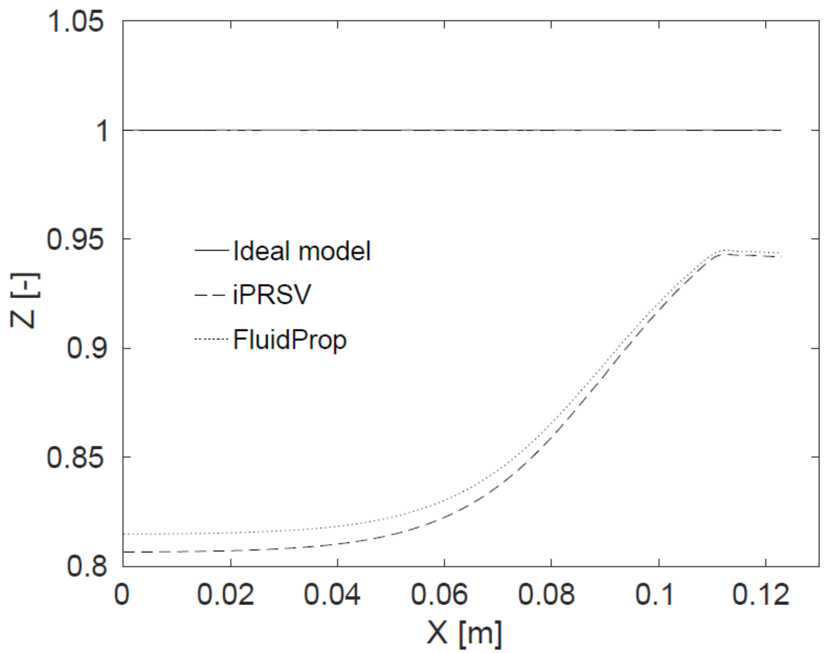
Computational framework: why SU2?

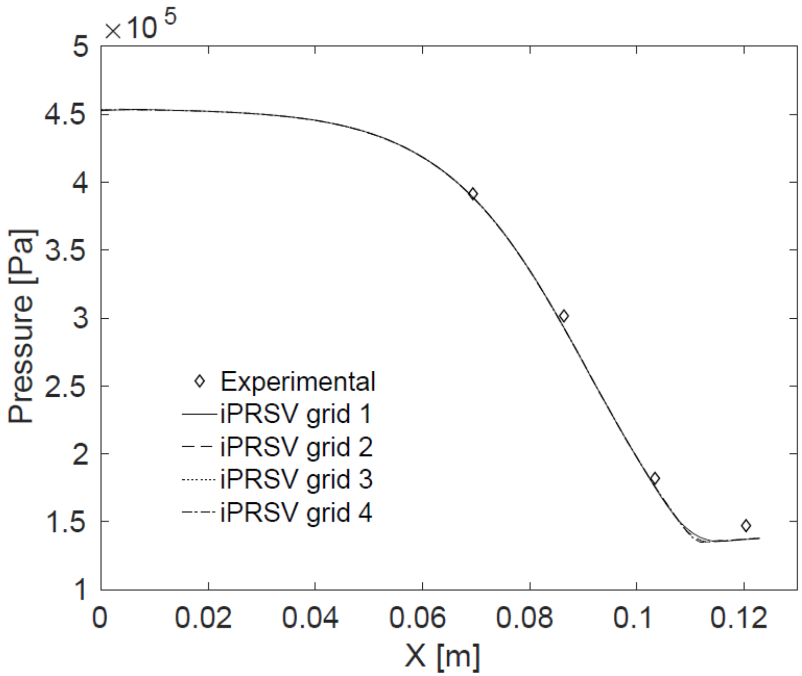
- **An open-source model**: basic formulation with a reasonable set of initial capabilities
- **Portability**: SU2 has been developed using ANSI c++ and only relies on widely available, well supported, open-source software
- **Flexibility**: required to re-purpose existing software for new and different uses. Reusability and encapsulation enabling a common interface for all the necessary components.
- **Gradient availability**: for many applications it is important to obtain grad of the responses computed by SU2 to variations of design parameters

New capabilities are continuously added by an international team of developers spread all over the world: fluid models, turbomachinery design, grid adaptation, sliding meshes and many others…

Test case A: Non-Ideal supersonic flow

Grids with a different level of resolution to assess the dependency of the solution from the spatial discretization (300 to 15000 grid points), for inviscid simulations

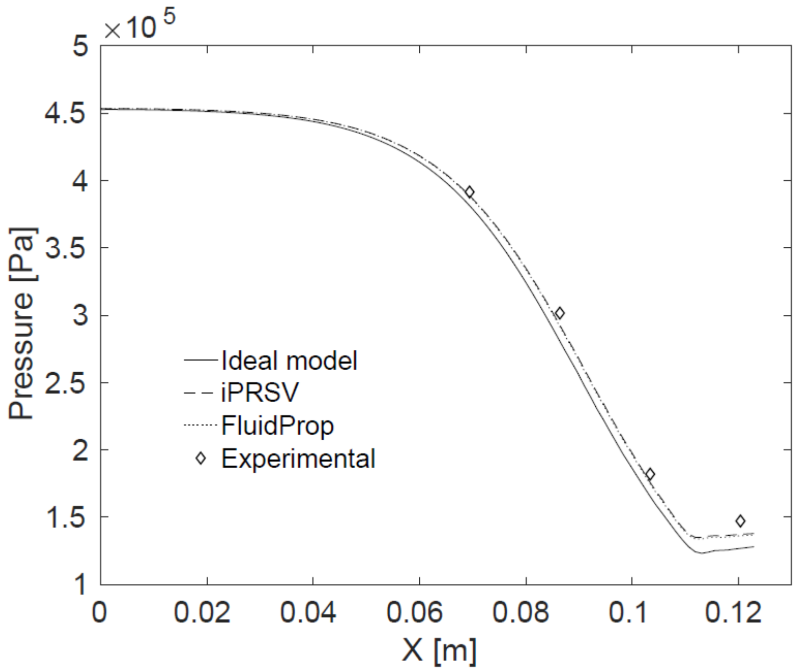


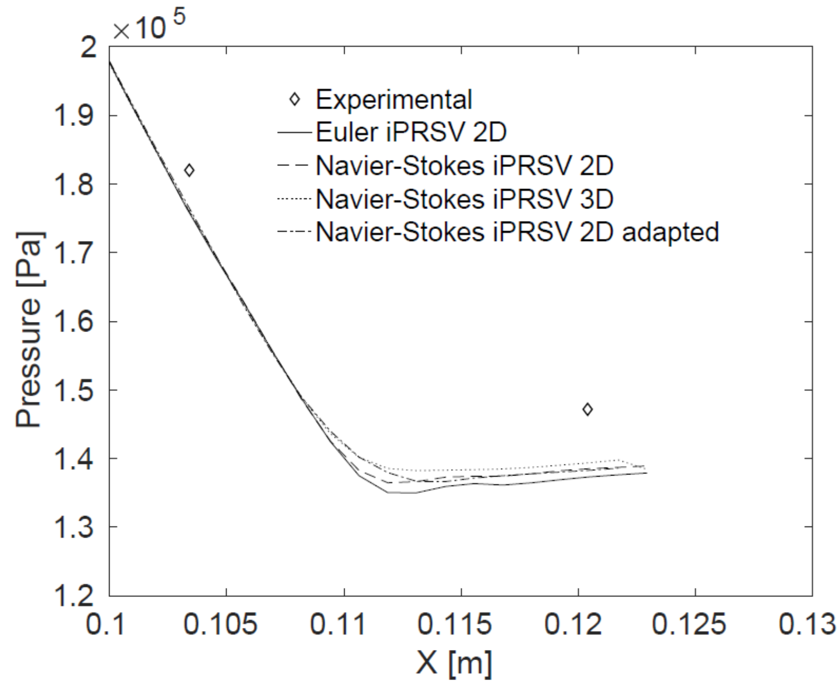


The pressure trend reconstructed numerically fairly matches experimental measurements!

Test case A: Non-Ideal supersonic flow

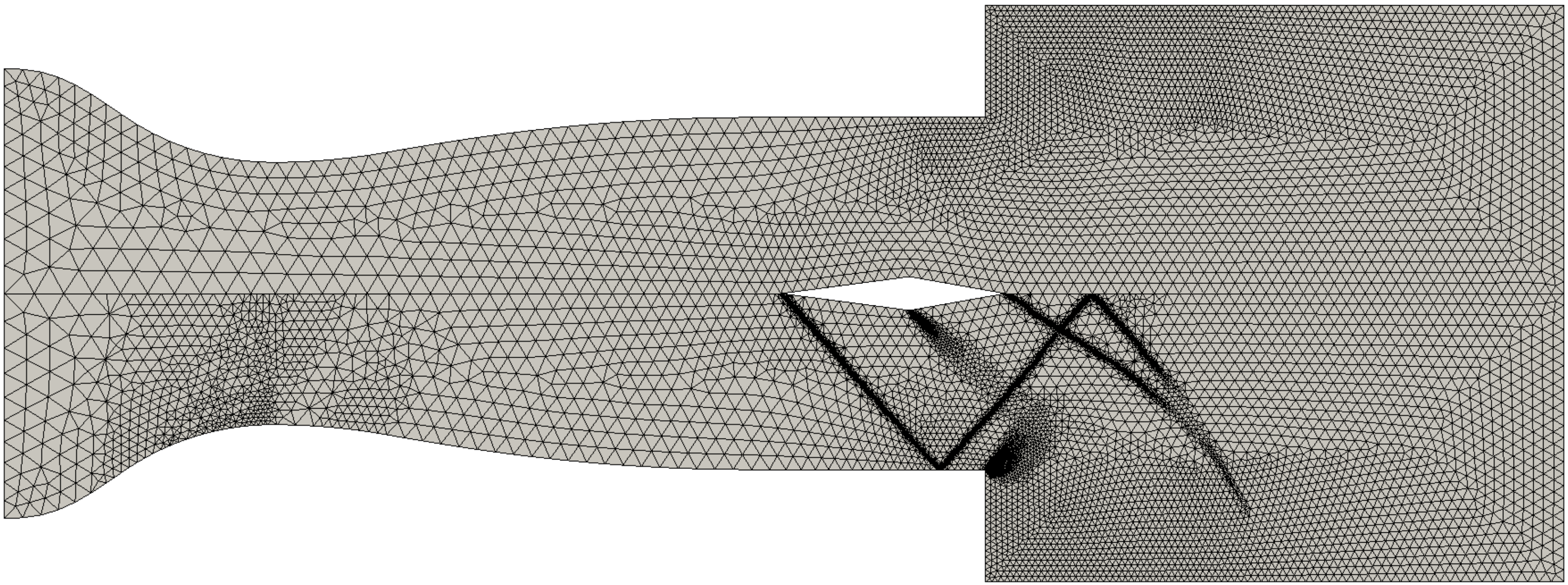
The very same test case was reproduced exploiting state-of-the-art EoS (the Helmholtz EoS embedded in the FluidProp library) and relaxing the inviscid assumption.





Discrepancies, with respect of experimental measurements, are found in the close proximity of the discharge section.

Test case B: supersonic diamond-shaped airfoil



A mesh adaptation tool, developed at Politecnico di Milano, was coupled to SU2 to improve the quality of the grid in high gradient-regions and preserve a reasonable computational cost.