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

G. Gori\textsuperscript{a,c}, M. Zocca\textsuperscript{a,c}, G. Cammi\textsuperscript{b,c}, A. Spinelli\textsuperscript{b,c}, P. M. Congedo\textsuperscript{d} and A. Guardone\textsuperscript{a,c}

Politecnico di Milano - Italy
\textsuperscript{a} Department of Aerospace Science and Technology
\textsuperscript{b} Energy Department
\textsuperscript{c} CREA Lab

INRIA – France
\textsuperscript{d} CARDAMOM Team
Non-Ideal Compressible-Fluid Dynamics

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

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
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

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Total $T / T_c$</th>
<th>Total $P / P_c$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDM</td>
<td>0.9</td>
<td>0.32</td>
<td>0.81</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Total $T / T_c$</th>
<th>Total $P / P_c$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDM</td>
<td>0.98</td>
<td>0.62</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Ahead of the airfoil, the flow is approximately uniform at Mach 1.5 and $Z$ 0.9.
Test case B: supersonic diamond-shaped airfoil

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

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Total T (reduced)</th>
<th>Total P (reduced)</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDM</td>
<td>0.92</td>
<td>0.32</td>
<td>0.82</td>
</tr>
</tbody>
</table>

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

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.

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.
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
The role of Uncertainty Quantification

Multiple (physical and modelling) sources of uncertainty exist!

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


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.