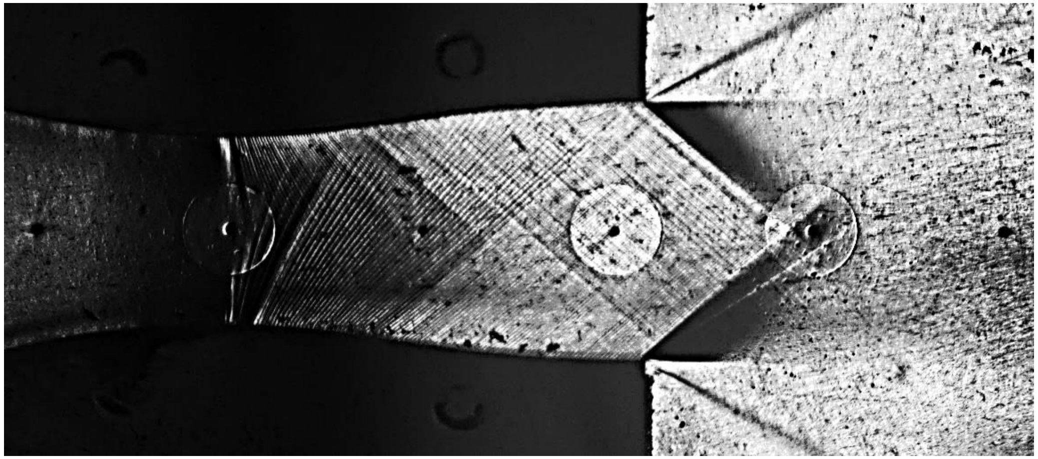
4th International Seminar on ORC 2017 POWER SYSTEMS

13 - 15 September
MILANO, Italy

Advancements in experiments on non-ideal compressible flows for ORC applications

Andrea Spinelli



CREALab

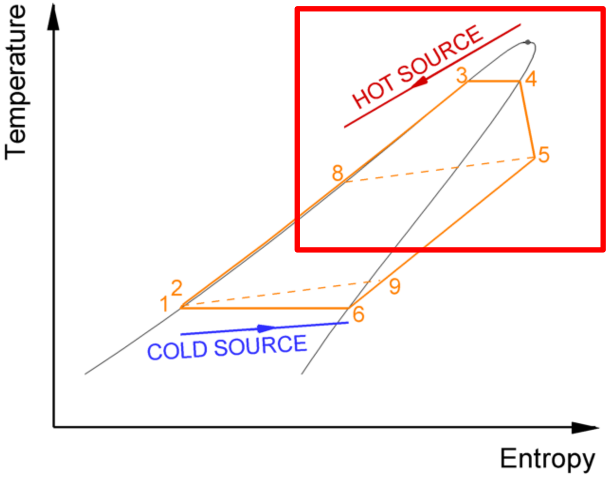
POLITECNICO MILANO 1863

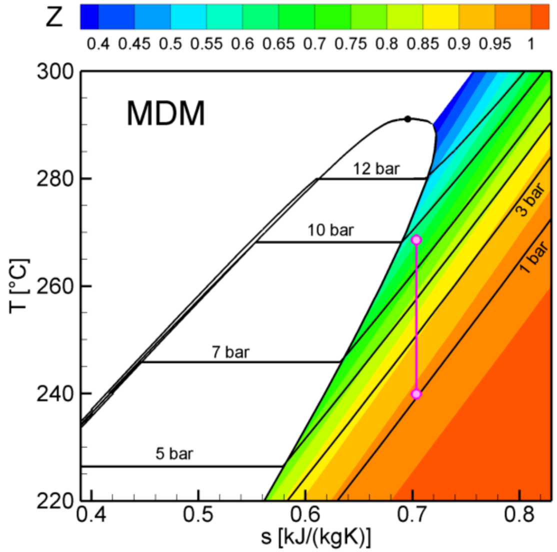
Experiments in NICFD for ORCs

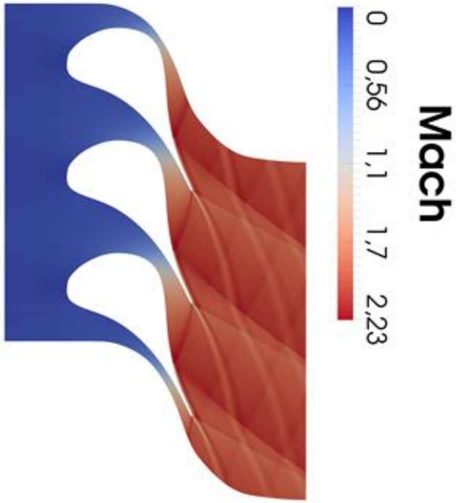
Non-ideal compressible flows of organic vapors

- Compressible $M > 0.3$ but typically higer $\rightarrow M \approx 2$
- $Pv \neq RT$ proximity to saturation curve and critical point
- TMD state relatively high T & moderate P

→ Typical blade passages flows of ORC **turboexpanders**





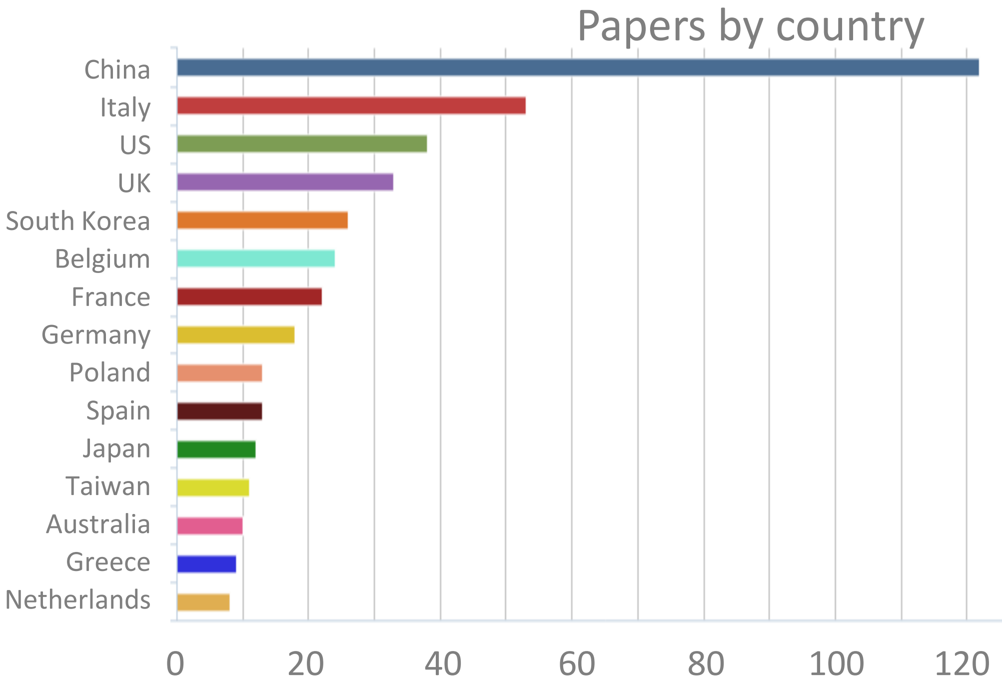


Interest

Experiments for ORCs

Title-Abs-Key

Experimental & Organic & Rankine & Cycle



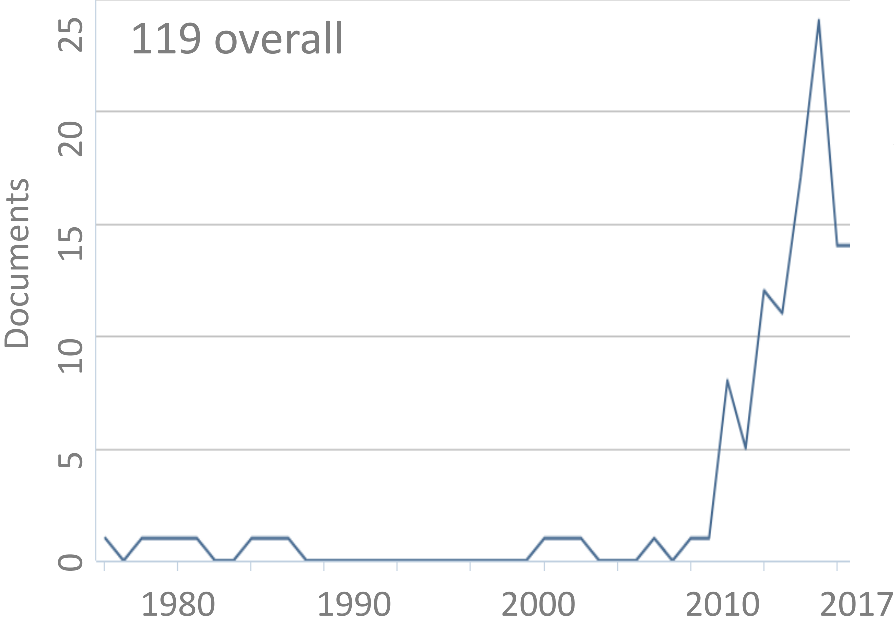
Interest

Experiments for ORC Turbine

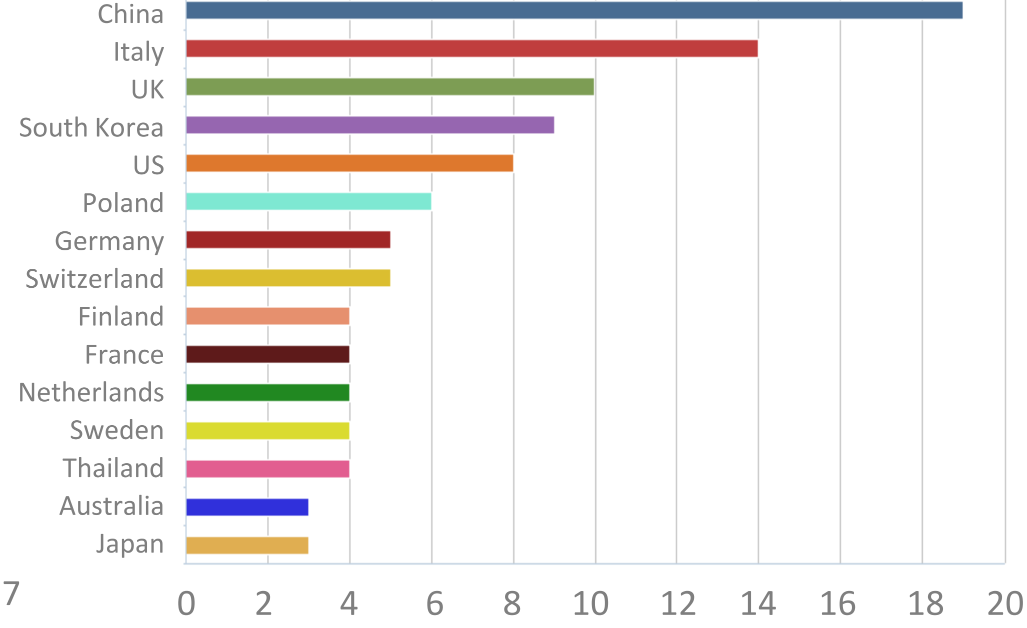
Title-Abs-Key

Experimental & Organic & Rankine & Cycle & Turbine

Papers by year



Papers by country



Interest

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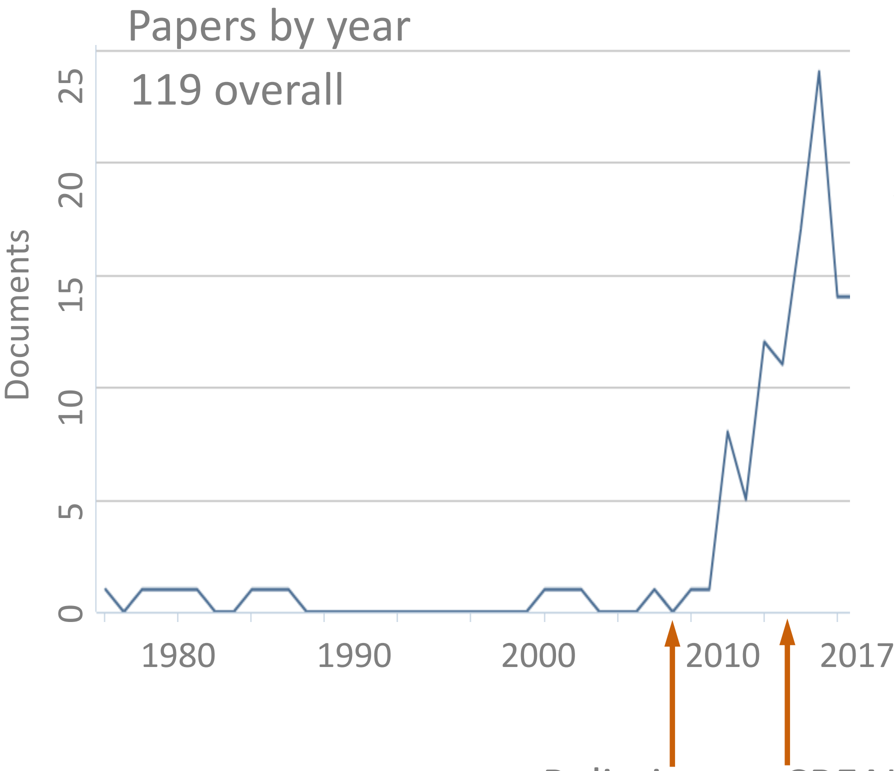

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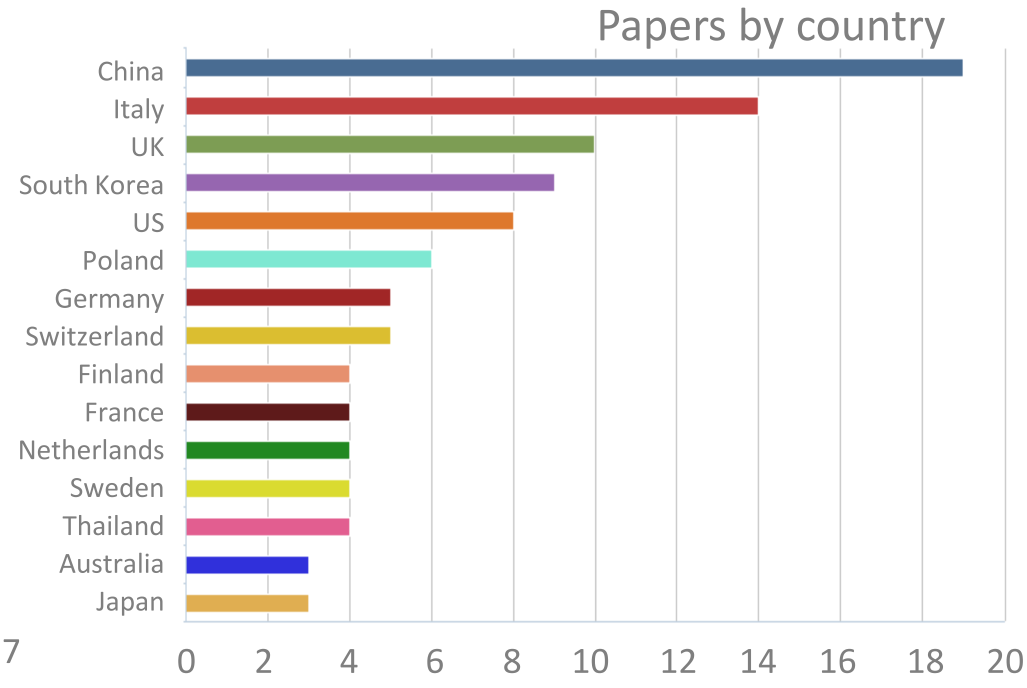
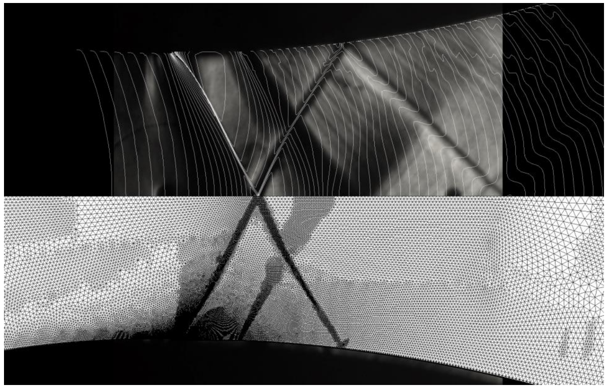


Discussion



Challenges in experiments for ORCs

→ Design experiments

→ Manage facilities/measuring techniques

→ Perform test/understand results

CREA Lab experience

- Issues/solutions – trials/errors – failures /successes – open problems
  - some peculiar of expander flow experiments
  - some shared with test of other ORC components

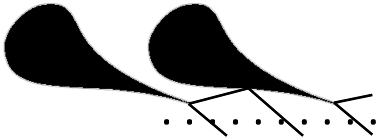
  → worth to share aspects of experimentation

→ Best solutions? Comprehensive options? Exhaustive findings?

NO! → Applied methodology for experiments in ORCs

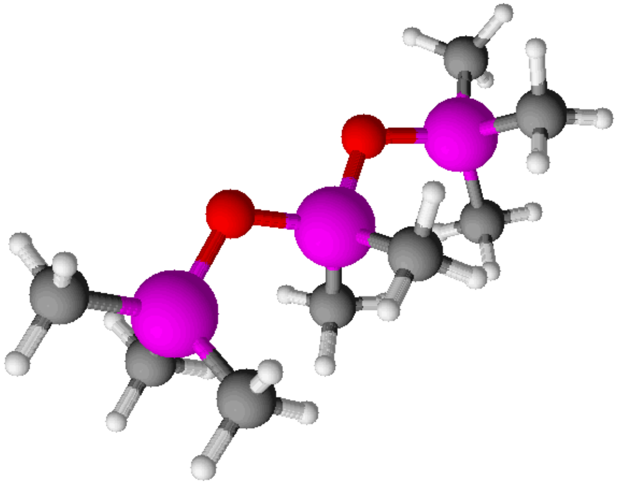
Summary

- Need of experiments
- Provide experimental data
- Challenges in ORCs
- Experimental apparatuses: options & management
- Measuring techniques: peculiarities in ORC flows
- Some achievements
- Conclusions and outlook



Need of experiments

Flow features



Complex flows in ORC turbine passages

- High compressibility $\downarrow c \quad \uparrow M$
- High non-ideal effects

Proper flow modeling

- Not straightforward
- Crucial $\rightarrow \quad \eta_{turbine} \quad \rightarrow \quad \eta_{cycle}$

being *‘the expander the key component of ORCs’* (1)

and *‘improvement of the expander fluid-dynamic performance directly affects the power output […] often without affecting the unit cost’* (

1 Macchi E., Astolfi M. *Organic Rankine Cycle (ORC) power systems.* New York Woodhead , Elsevier, 2017

2 Colonna P. et al. *ORC power systems: Concept, current technology, applications, outlook.* ASME JGTP, 2015

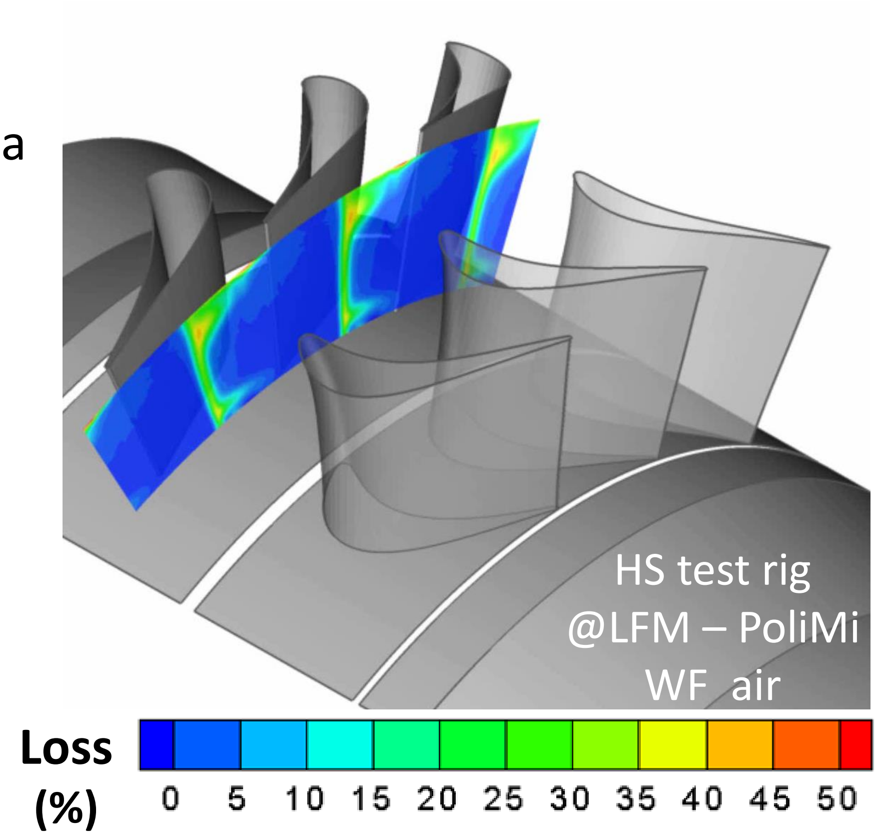
Detailed flow modeling

Demand for detailed experiments

- Design tools demand for accurate data
- CFD codes + TMD models verification
- Tool refinement → reliability

Provide experimental data

- What to measure
- At which points
- In which test section/device
- Reaching mesuring points
- With proper instrumentation



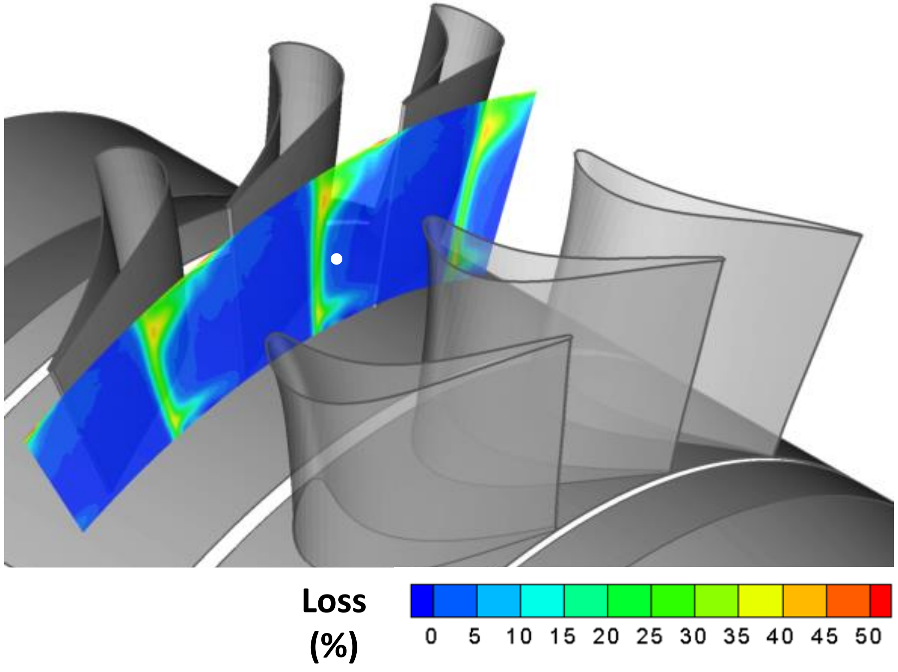
Provide experimental data

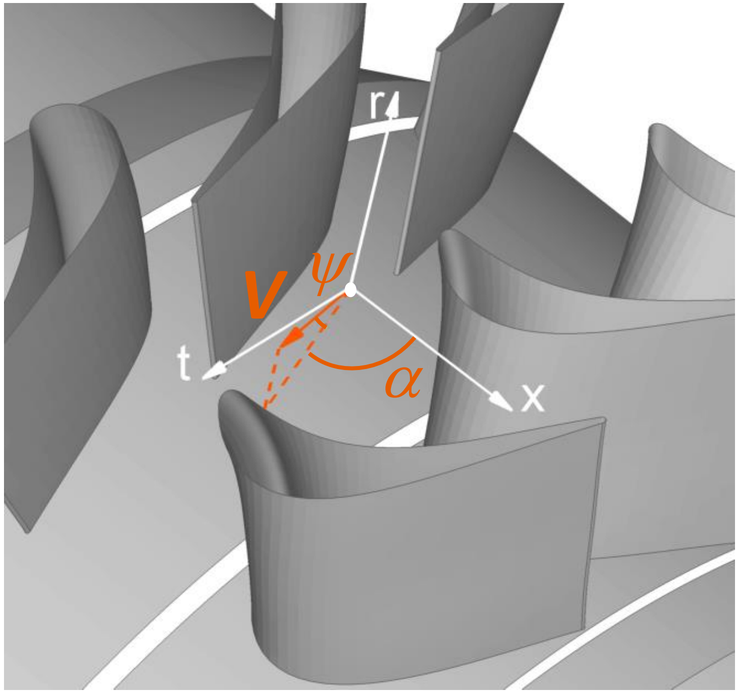
Properties of significance

Turbine passage flow characterized by

- P_T, T_T $\Delta P_T\,, \Delta T_T$ → losses, work
- $\boldsymbol{V}$ 3D (V, α, ψ) → work, KE losses, incidence/deviation
- $P\,, M$ boundary condition & compressibility

→ Related by fluid EoS

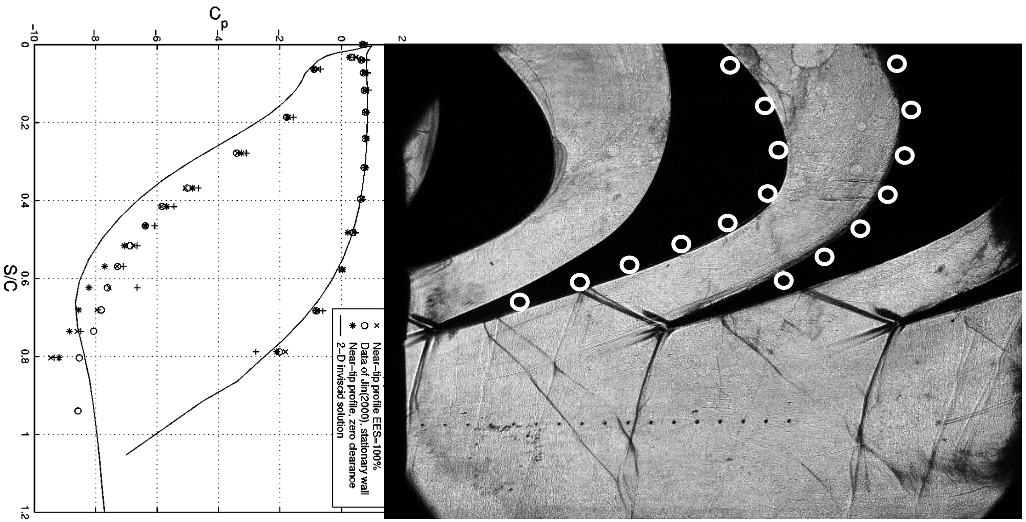




Measuring domain

Within blade channels

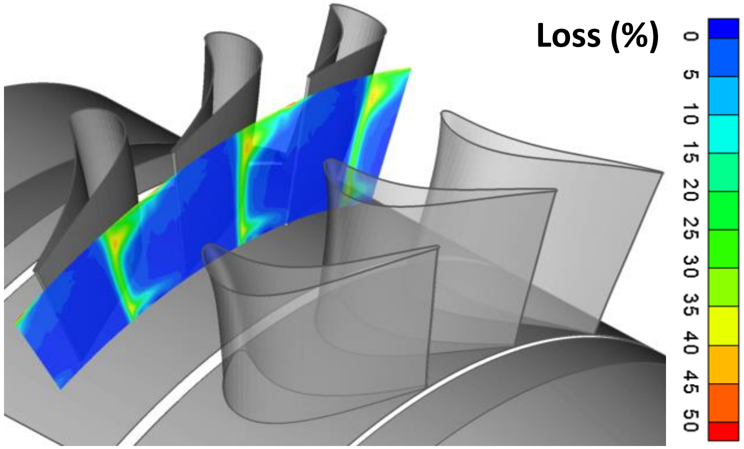
- ✓ Wall taps/Schlieren/LDV (PIV)
  - → blade $P, \nabla\rho, \boldsymbol{V}$
  - → NO aerodynamic calibration
- ✗ Intrusive probes $P_T, T_T, P, \boldsymbol{V}$



→ Best possible space resolution

Upstream/downstream rows

- ✓ Add Intrusive probes $P_T, T_T, P, \boldsymbol{V}$
- ✗ **Aerodyn. calibration required**



Device & Test section

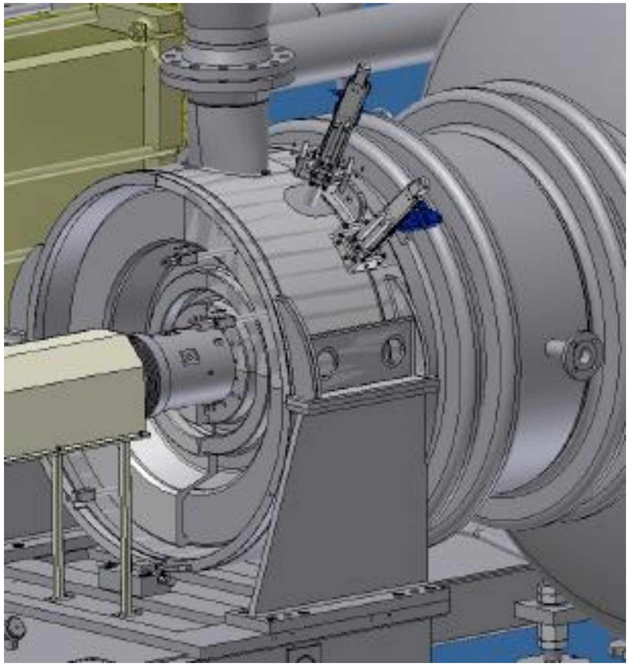
Industrial ORC modules – field operating

- Medium/large size
- Customized accesses → probes upstream/downstream **stages**
  → traversing: blade span
  → NO optical windows
- Limited availability → plant operator
- Operating conditions → dictated by $\dot{W}$, $\dot{Q}$

Limited investigation

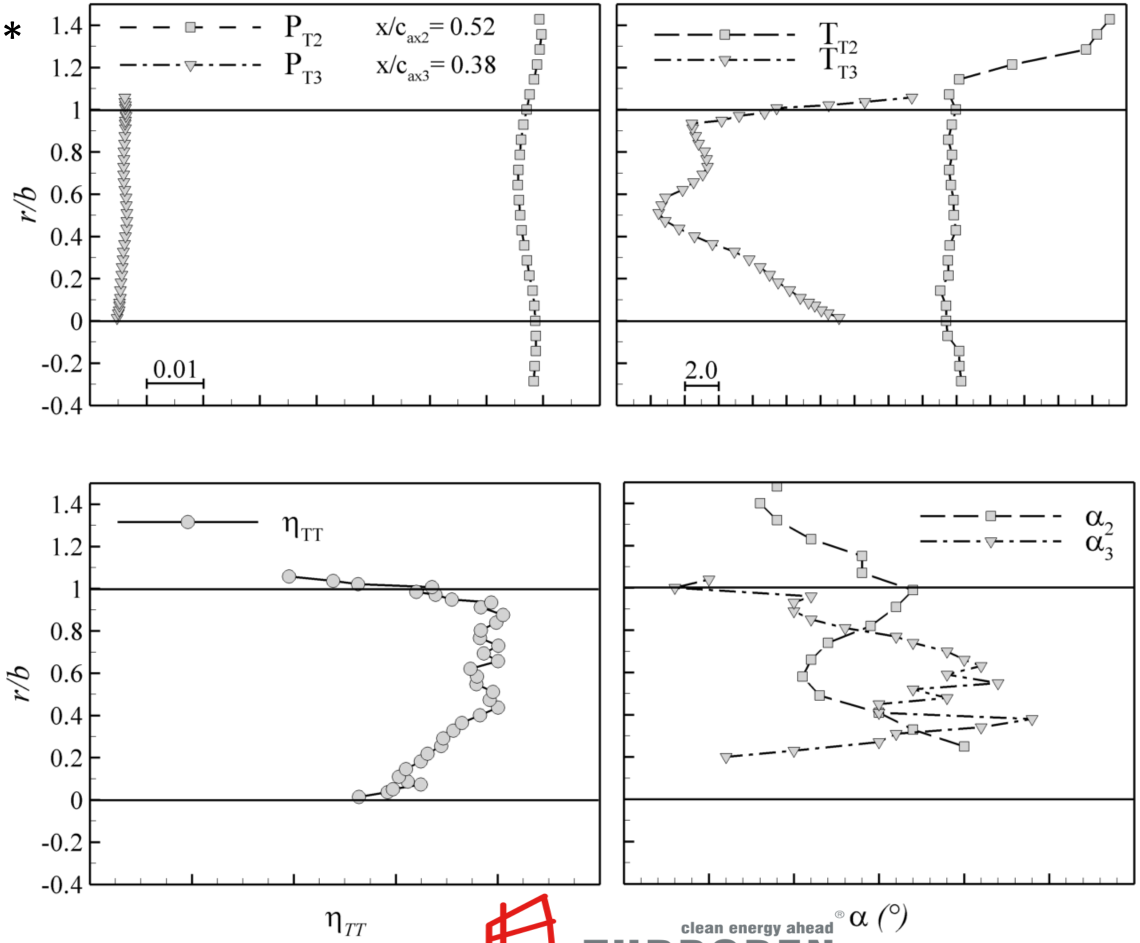
- Relatively low M
- NO tangential span traversing
- Aero-calibrated probes NOT AVAILABLE

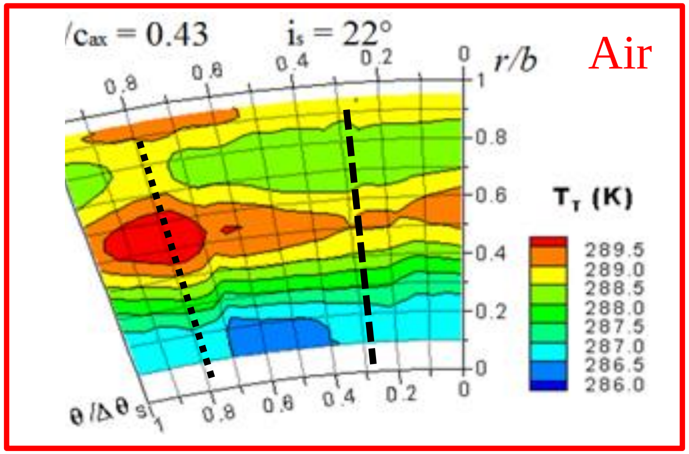
  nulling mode → P_T, T_T, α for ~ 2D flows



Industrial ORC modules

n radial time-averaged distribution of P_T, T_T, α where ~ 2D flow





* Year: 2008 Courtesy of TURBODEN clean energy ahead

a group company of MITSUBISHI HEAVY INDUSTRIES, LTD.

Research facilities – Cascade tunnels

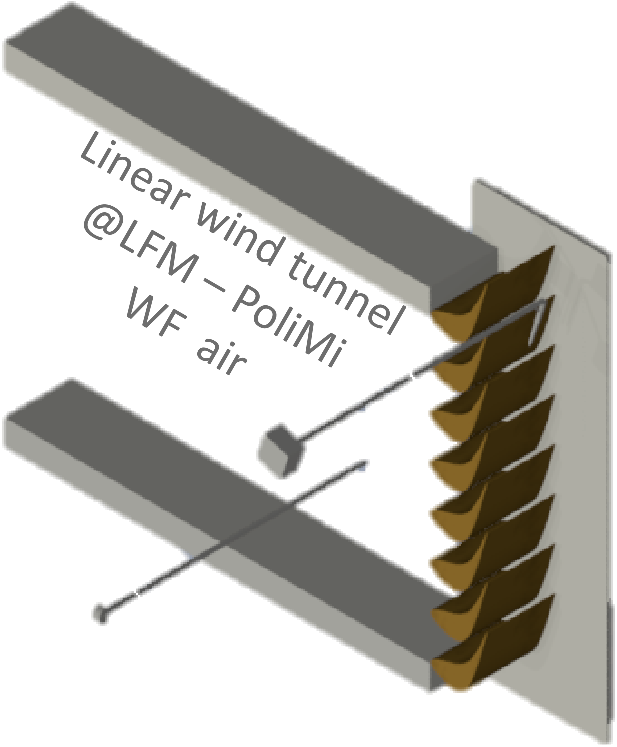
Linear cascade test section

- Easy access → probes upstream/downstream blades
  - → traversing: blade span & tangential
  - → blade/endwall taps
  - → optical windows

Limitations

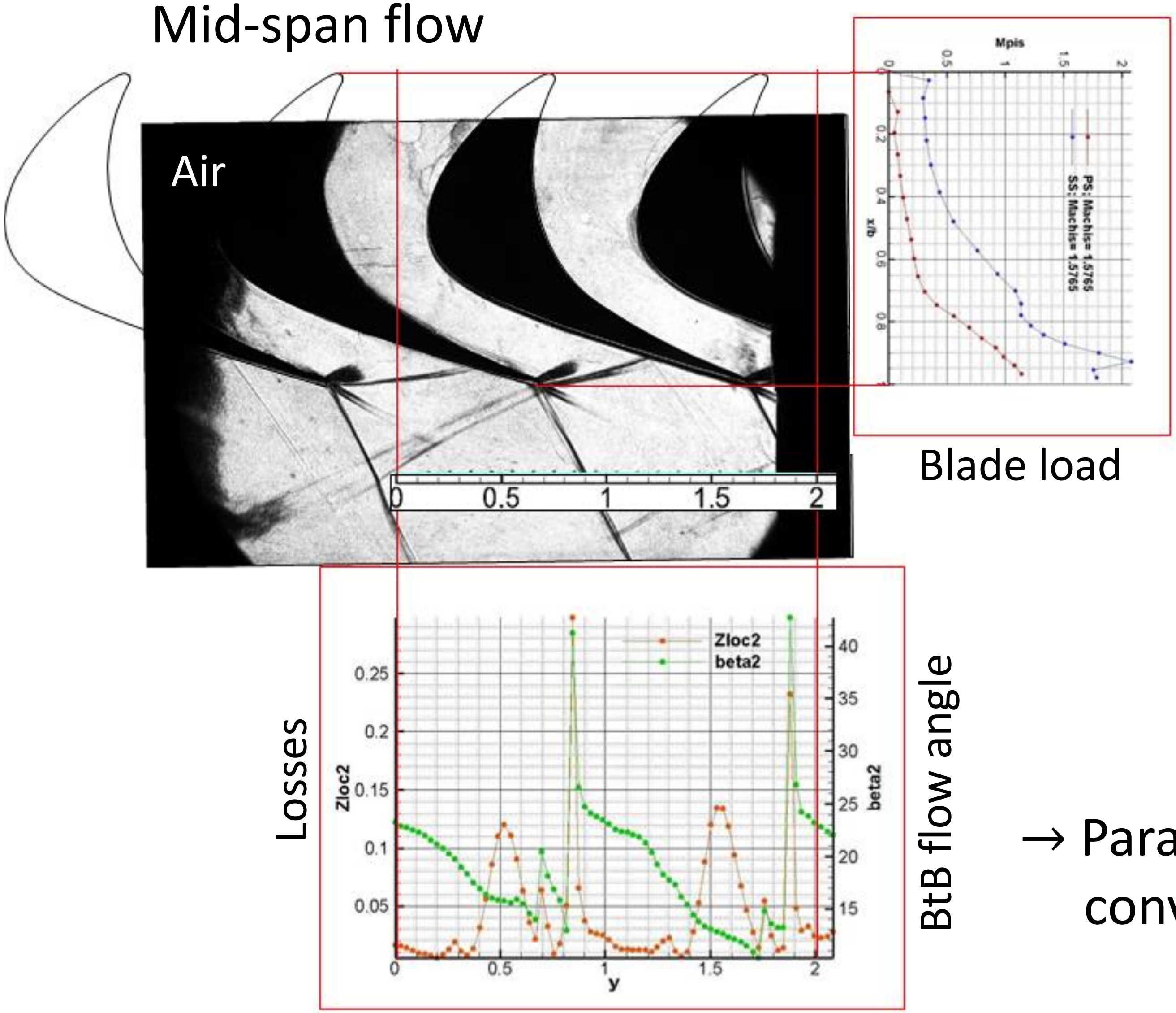
- High cost to attain detailed mapping
- Aero-calibrated probes NOT AVAILABLE
- Suitable for axial machine

→ Good results achievable for ~ 2D flows



Achievable for ~ 2D flows

Mid-span flow



Blade load

Losses

BtB flow angle

→ Paradigm since 1970s conventional WFs

Nozzle based tunnels

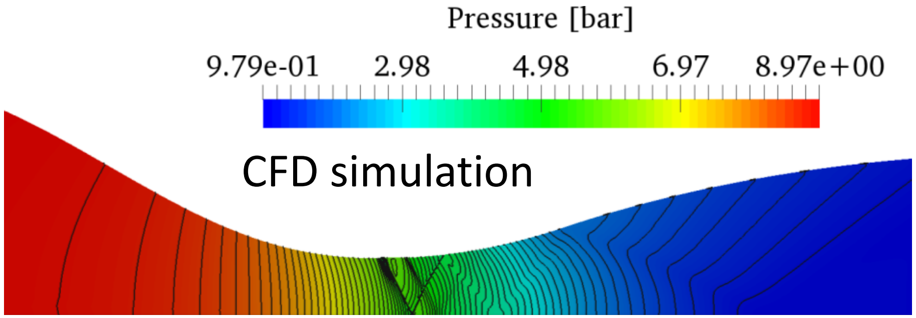
Nozzles

- Simplest geometry expanding the flow
- Small dimensions allow detailed investigation → limited $\dot{m}$

Enable the study of turbine-like phenomena

- Isentropic expansion processes
- Shock waves & expansion fans (wind tunnel mode)

Simple experiments → Test cases for validation



Nozzle test sections

Easy access – Planar nozzle

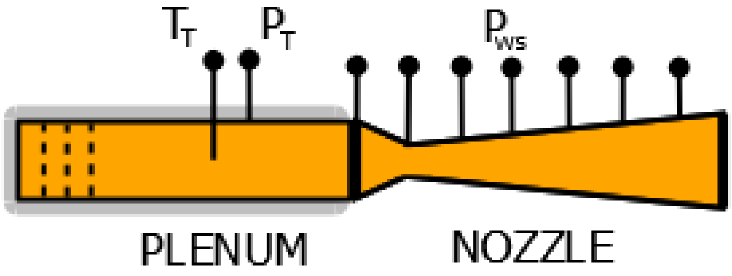
- Probes upstream P_T, T_T
- Wall taps P
- Optical windows $\boldsymbol{V}, M, \nabla\rho$
- Object/probe insertion

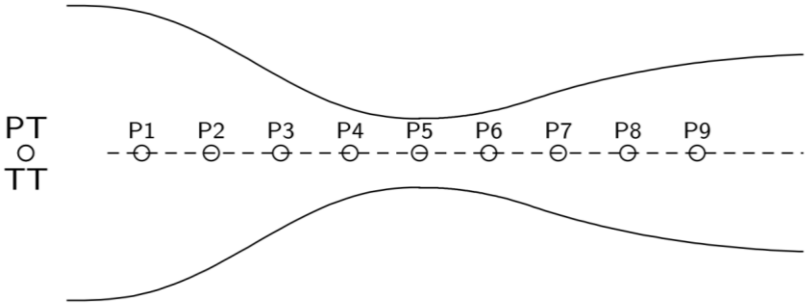
Advantages

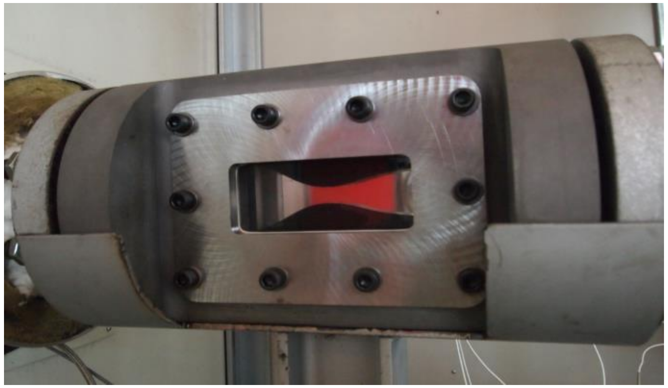
- **Large isentropic core flow**
- Aero-calibrated probes NOT required
- Possible reference flow for calibration

Limitations

- Absence of blade row flow features
  → semi-bladed channel
  → secondary flows, deviation





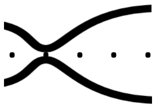


Existing facilities for detailed flow studies

Reserch facilities for detailed study of ORC expanding flows					
Facility	**Institution**	**Cycle**	**Operation**	**Test section**	**Year of publ.**
TROVA	PoliMi	Rankine	Batch	Nozzle	2010
CLOWT	Muenster U	Gas	Continuous	Nozzle/Cascade	2015
Whittle LT	Cambridge U	-	Batch	Nozzle	2016
ORCHID	TU Delft	Rankine	Continuous	Nozzle	2016

All facilities can operate with diverse organic fluids

Nozzle flow experiments is the preferred choice



→ Paradigm of early 1900s exp. on gasdynamic foundations

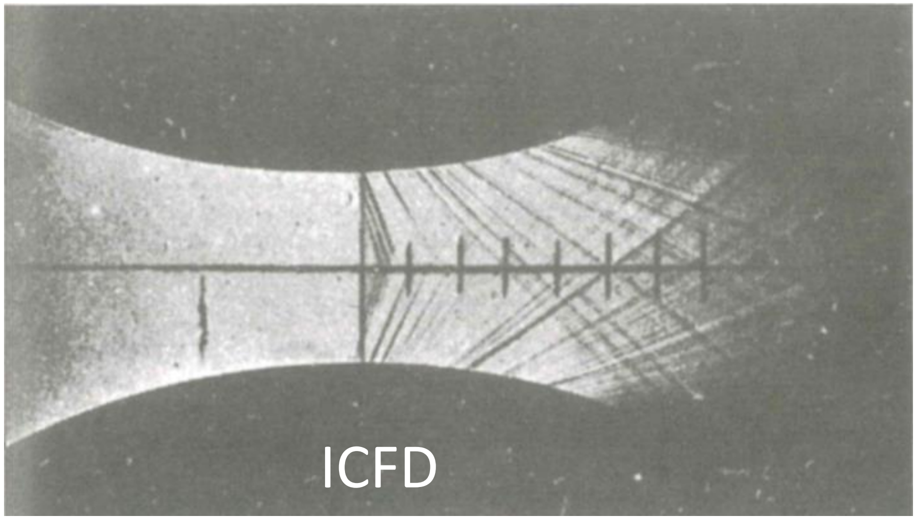
Nozzle based experiments

Meyer nozzle experiment

WF Air

Year 1908

Z_{inlet} = 1



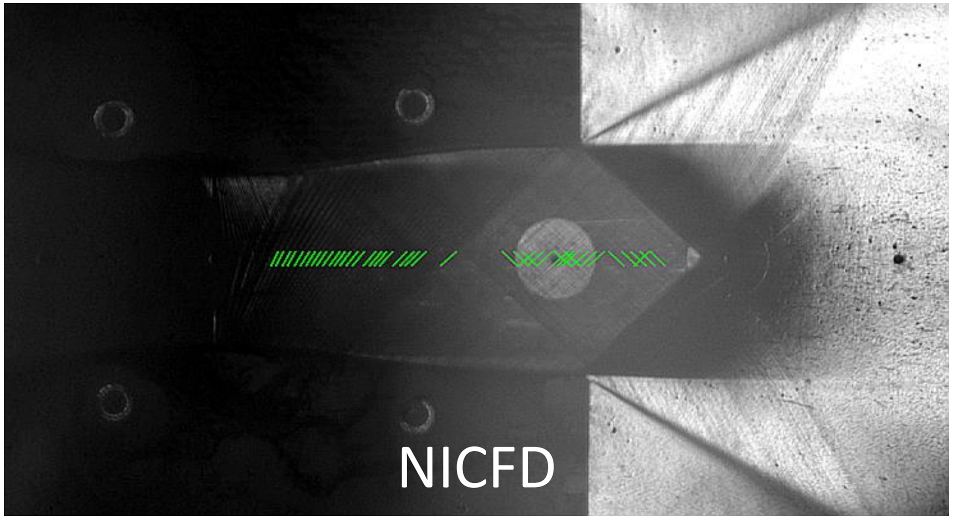
Conventional fluid machines

Nozzle experiment @ CREA Lab

WF Octamethyltrisiloxane – MDM

Year 2016

Z_{inlet} = 0.65



ORC turboexpanders

Nozzle based experiments

Meyer nozzle experiment

WF Air

Year 1908

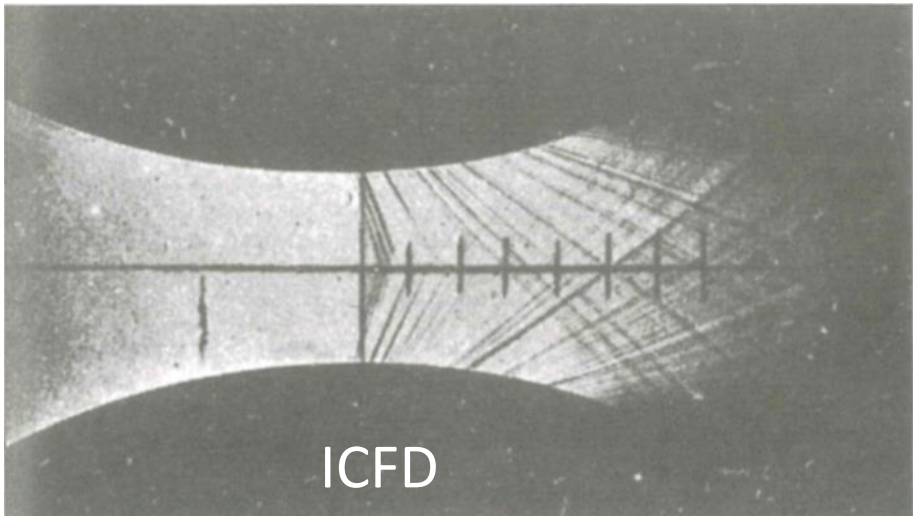
Z_{inlet} = 1

Nozzle experiment @ CREA Lab

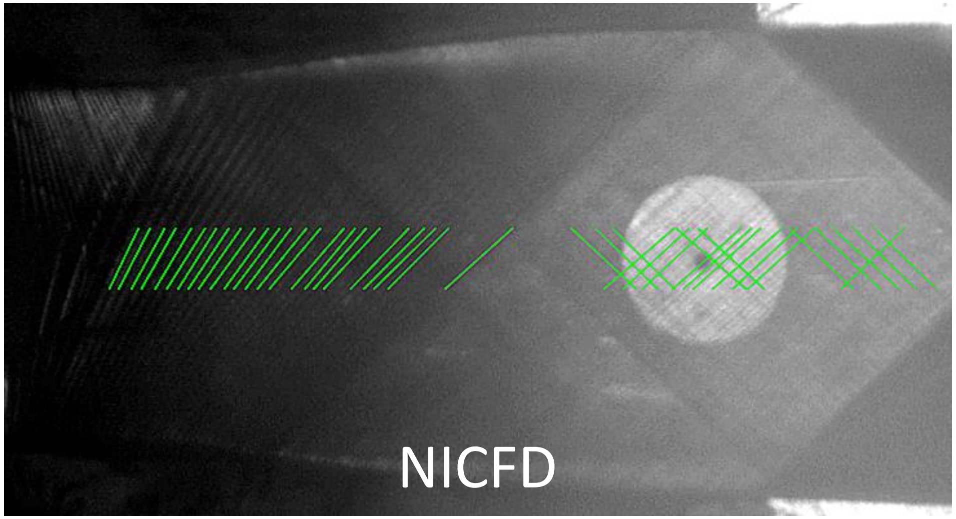
WF Octamethyltrisiloxane – MDM

Year 2016

Z_{inlet} = 0.65



conventional fluid machines



ORC turboexpanders

Challenges in ORCs

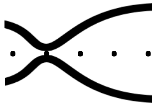
Challenges in experiments for ORCs

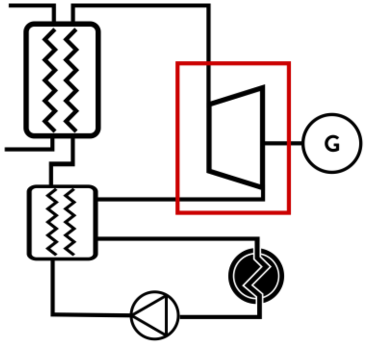
Design of experiments/interpretation of results

- Modeling thermo-physical properties of WFs
- Theoretical understanding non-ideal flow behavior
- Simulating non-ideal flows + UQ

Perform the experiments in ORC environment

- Conceive/design/implement experimental apparatuses
- Manage test rigs
- Select/adapt/renew measuring techniques

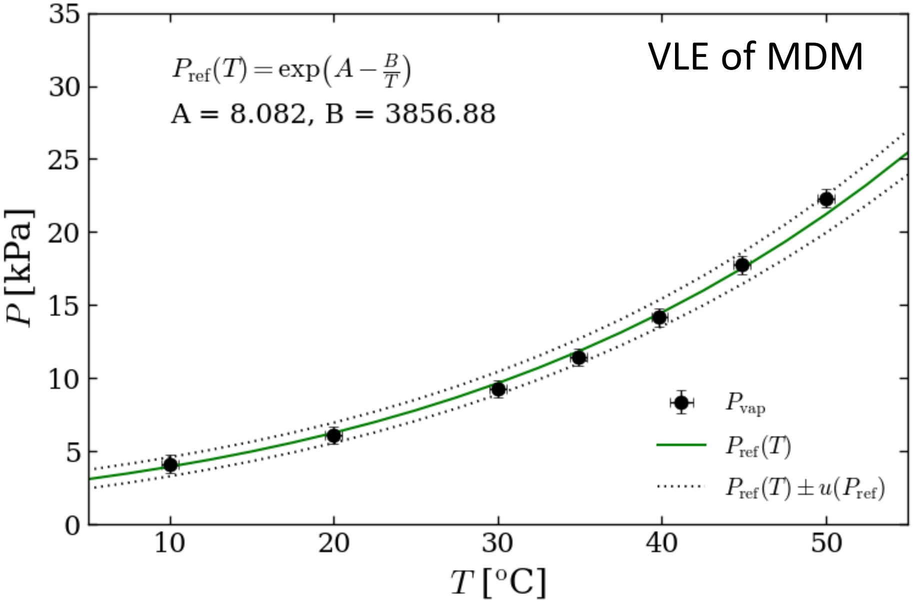


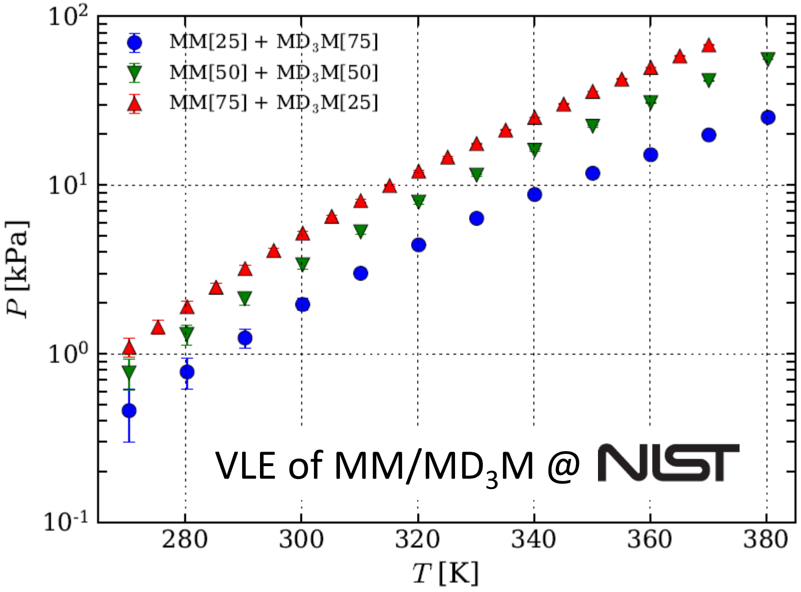


Thermo-physical properties of WFs

Experiments & modeling

- Thermodynamic properties – LVE/PVT/Critical Point
- Pure fluids and mixtures
- Thermal stability limit
- Transport properties

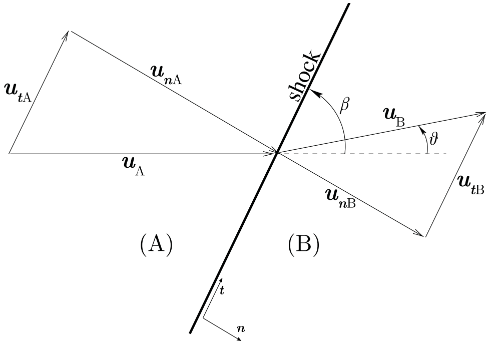


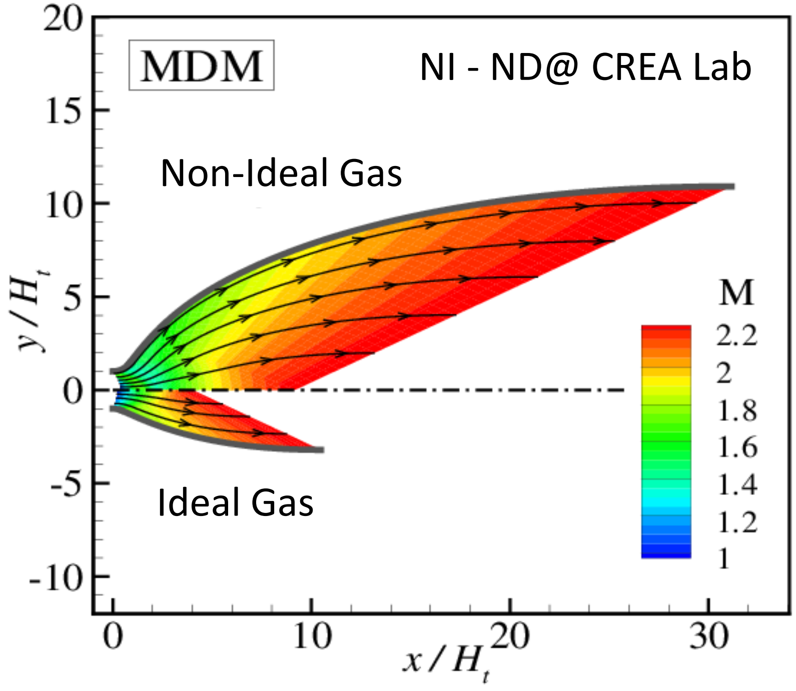


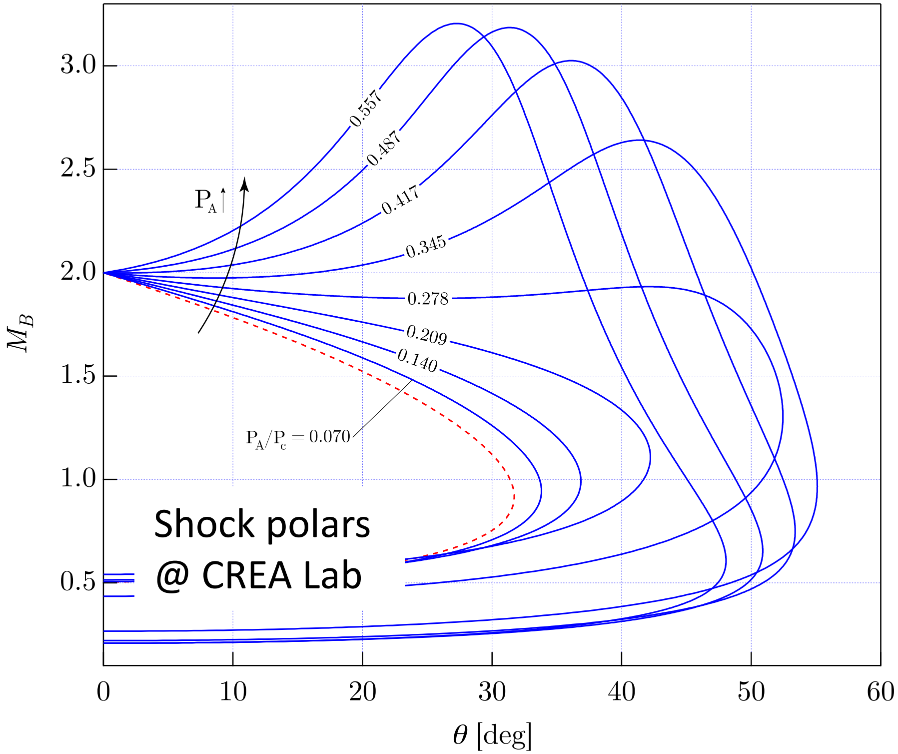
Non-ideal flow behavior

Theoretical effort

- Quasi-1D theory + simple TMD model (e.g. vdW)
- Analytical solution & identification of flow regimes
- Non-ideal/Non-conventional/Non-classical







Non-ideal flow simulations

NICFD solvers

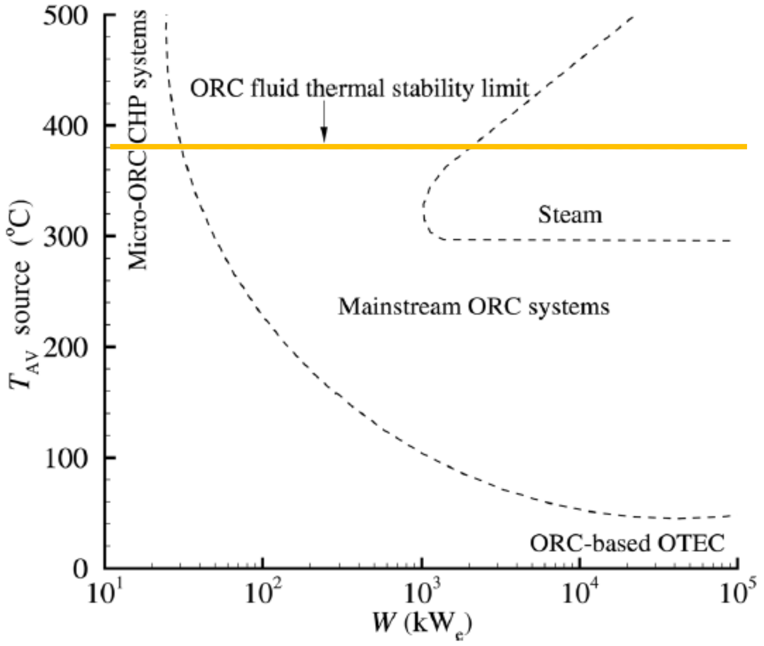
- Coupling with accurate thermodynamic models
- Grid adaptation
- Implementing uncertainty quantification (UQ)
- Code validation

Virtual Schlieren @ CREA Lab

SU2 validation @ CREA Lab

Experimental challenges in ORC environment

- High T, up to 400 °C → materials & sealing
- Vapor desirous to condense → complementary heating, purging
- Fluid not releasable to atm → closed loops & sealing
- Possible low P_{cond} → sealing
- Toxic/flammable fluids → ventilation, atex devices
- Fluid can decompose → T_{limit} information, avoid contamination



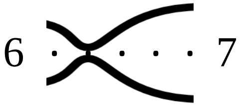
→ Thermal stability experiments

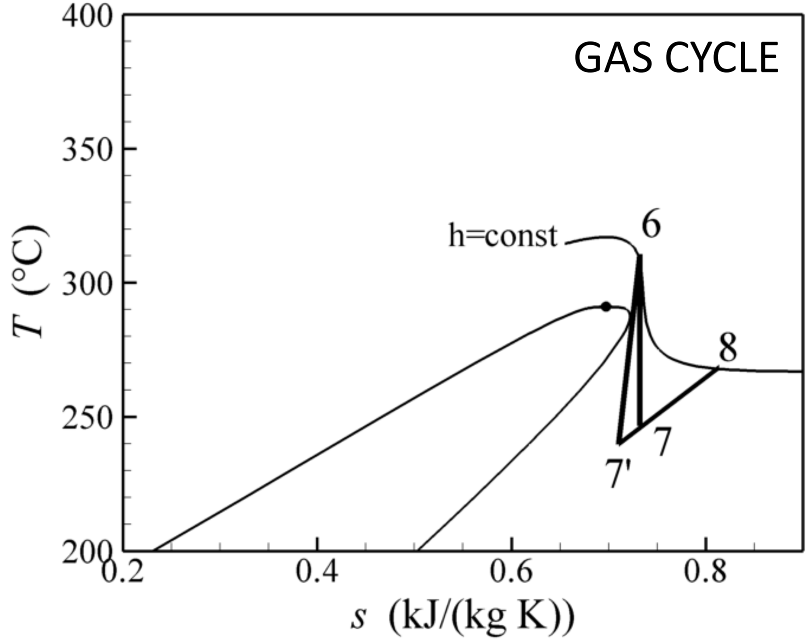

TheSta @ CREA Lab

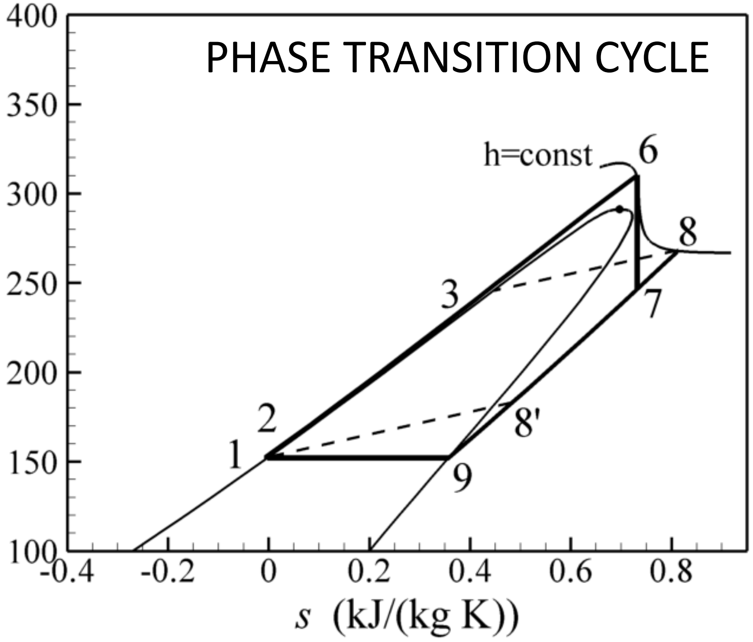
Experimental apparatuses

Thermodynamic cycles – Continuous

Given OP_{des} & A_{th}





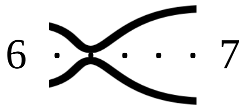


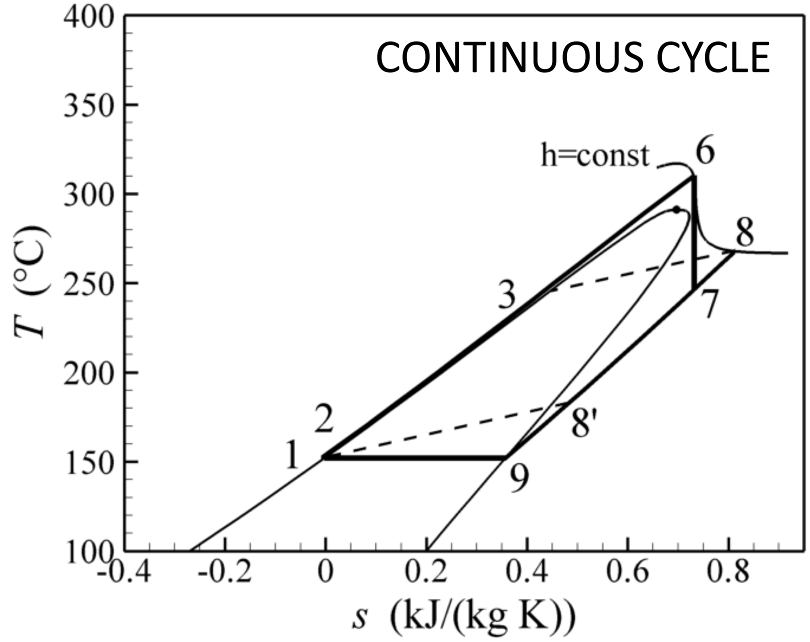
- ✓ Low $\dot{Q}$
- ✗ High $\dot{W}_{compression}$ (↓ diffuser)
- ✗ Compressor complexity
- ✗ Low operation flexibility
- ✗ Heating system required
- ✗ Liquid phase not available

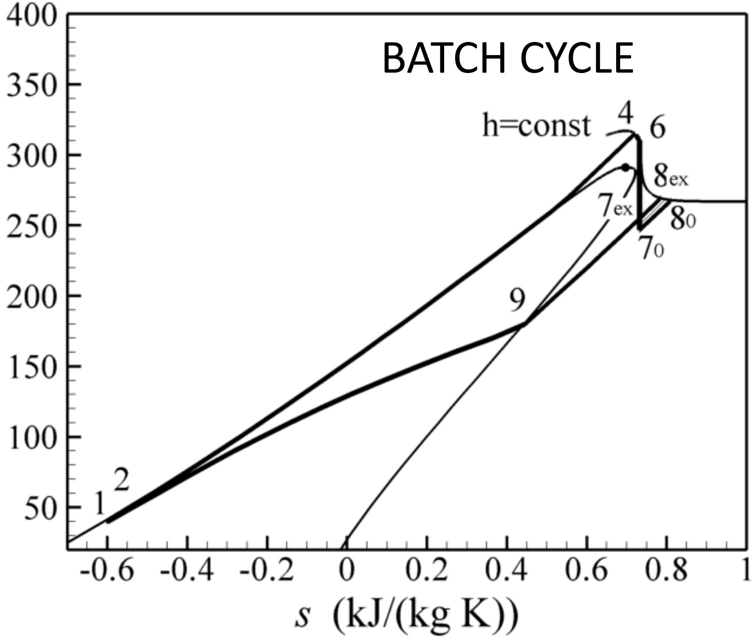
- ✓ Low $\dot{W}_{compression}$
- ✓ Low pump complexity
- ✓ High operation flexibility
- ✓ Rankine cycle states available
- ✗ High $\dot{Q}$

Operational mode

Given OP_{des} & A_{th}







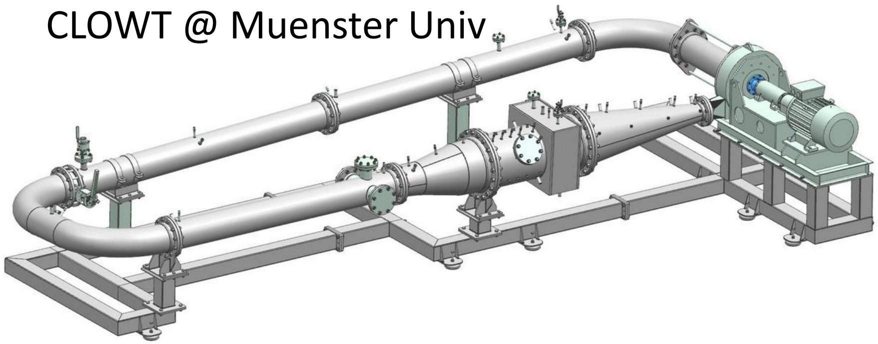
- ✓ Long test runs
- ✓ Steady nozzle flow
- ✓ Wide OP range
- ✗ High $\dot{Q}$
- ✗ Higher investment cost

- ✓ Very low $\dot{Q}$
- ✓ Lower investment cost
- ✓ Easy test set up
- ✓ Sequence of steady nozzle flows
- ✗ Short test run
- ✗ Reduced OP range

Plant construction

Few considerations

Size	Dictated by WF, TMD region, measurement resolution
Materials	Carbon steel vs stainless steel
Control system	PC based
WF flexibility	Relatively easy to reach (phase transition cycles)
Safety	ATEX may be required
	Safety valves + bursting disks



CLOWT @ Muenster Univ

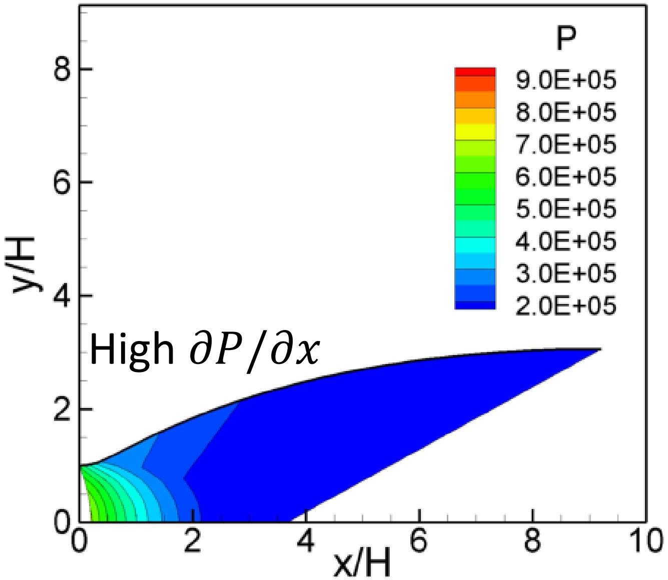
ORCHID @ P&P TUDelft

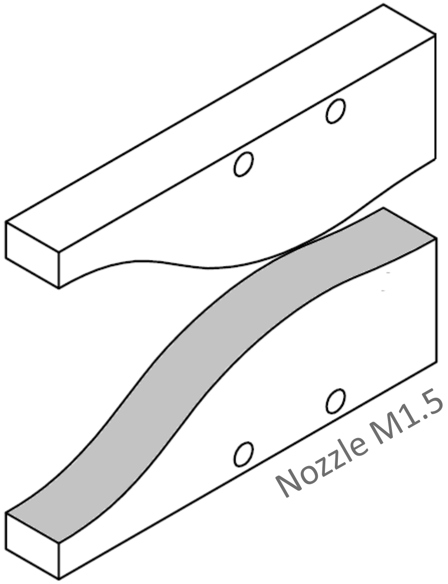
TROVA @ CREA Lab-PoliMi

Nozzle design

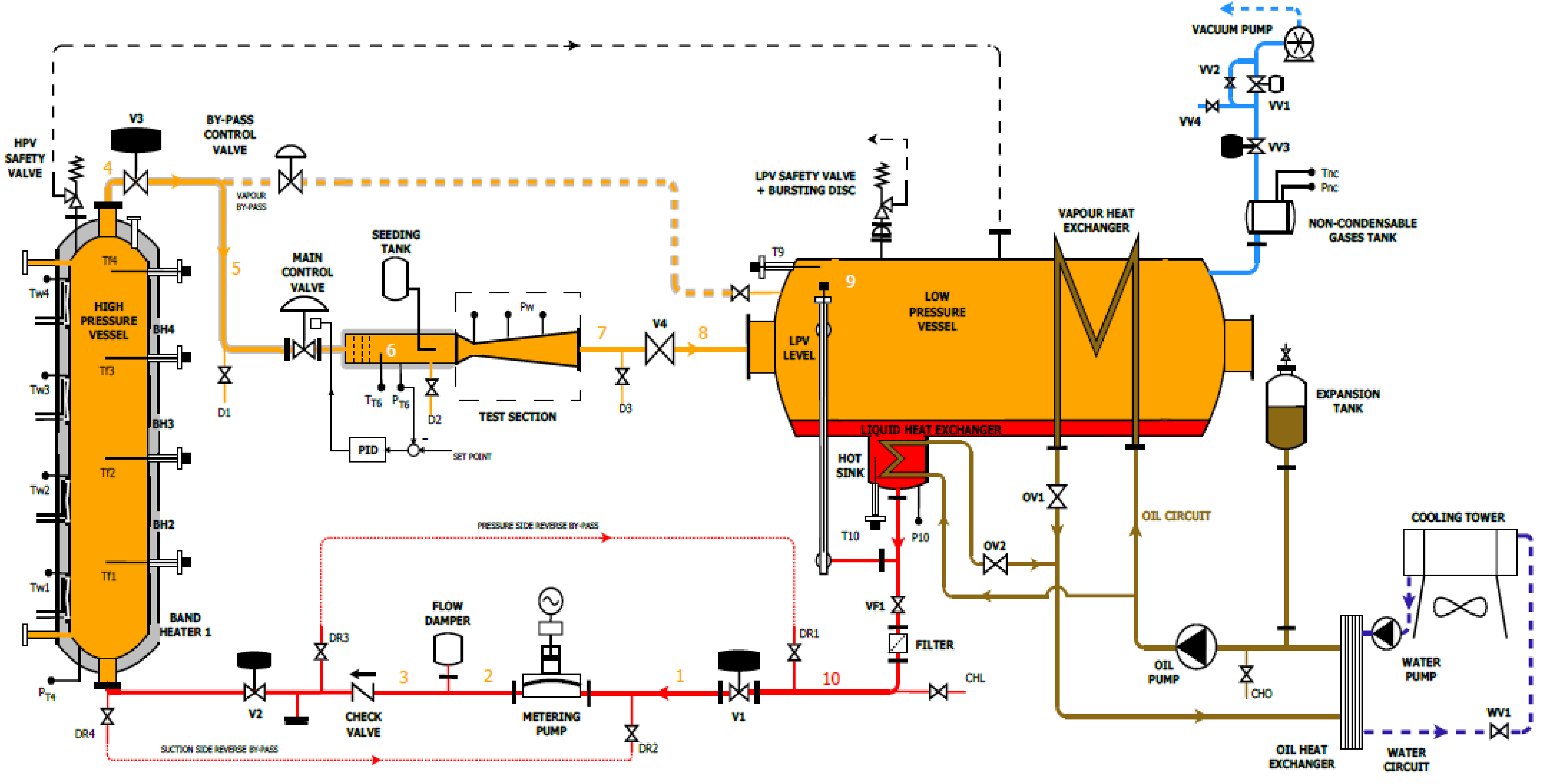
Profile design

○ Divergent	MOC – good approach, proven by experiments
○ Convergent	smooth transition to throat of y'' (CFD verification)
○ Throat	no singularities for low curvature (recommended)
○ Roughness	enhanced for direct M measurements





The TROVA @ CREA Lab



Plant management

Issues – Sealing

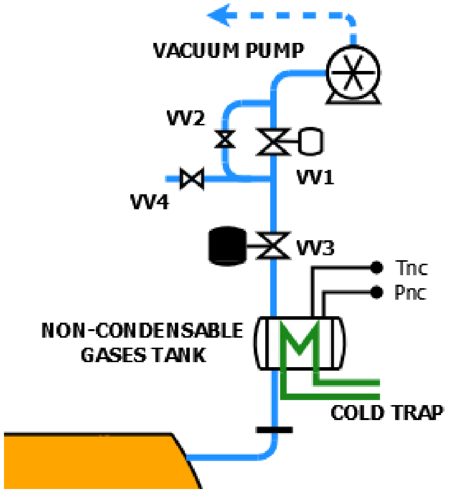
Pressure & vacuum/low & high T

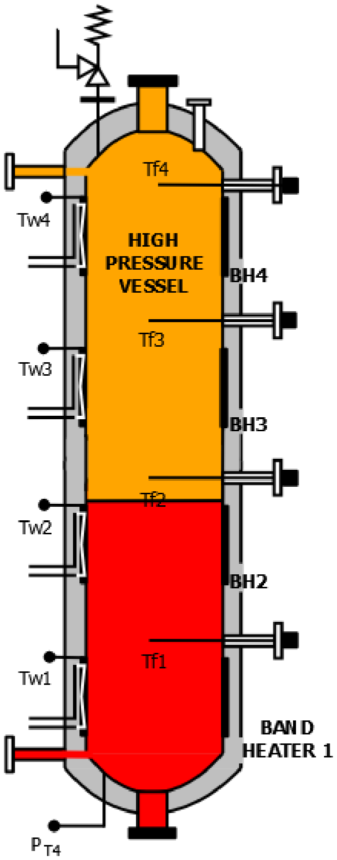
○ Joints	threads … are threat	
	valve stem packing	
○ Gasket type	planar	→ regular surfaces & strong tightening
	o-rings	→ weak tightening, vacuum grooves
○ High T materials & compatibility	steel, copper	→ not for optical windows
	graphyte	→ not for o-rings
	for o-rings	→ **FKM**, silicone (210 °C) PTFE (300 °C) NO spring back FFKM (310 °C) high cost

Issues – Vacuum

Vacuum system

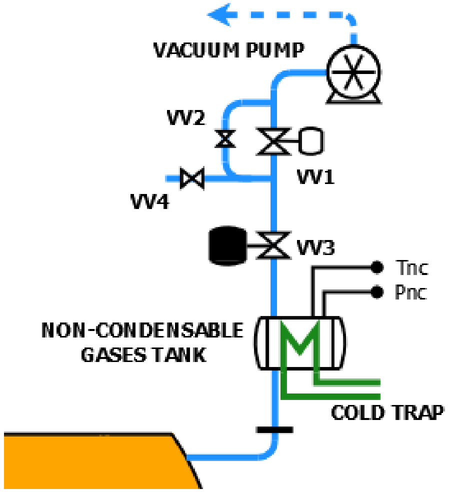
○	Vacuum keeping	size dependent
○	Evacuation	at each start & during operation
○	Minimum P	P_{sat} @ T_{amb} – plant stop
○	Avoid air intake	WF contamination O_2, H_2O inert gases at plant stop
○	Vacuum pump	cold traps recommended frequent oil inspection

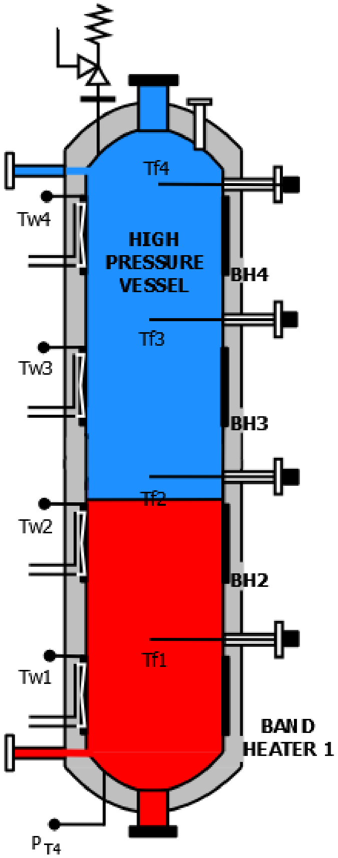




Vacuum system

○ Vacuum keeping	size dependent
○ Evacuation	at each start & during operation
○ Minimum P	P_{sat} @ T_{amb} – plant stop
○ Avoid air intake	WF contamination O_2, H_2O inert gases at plant stop
○ Vacuum pump	cold traps recommended frequent oil inspection

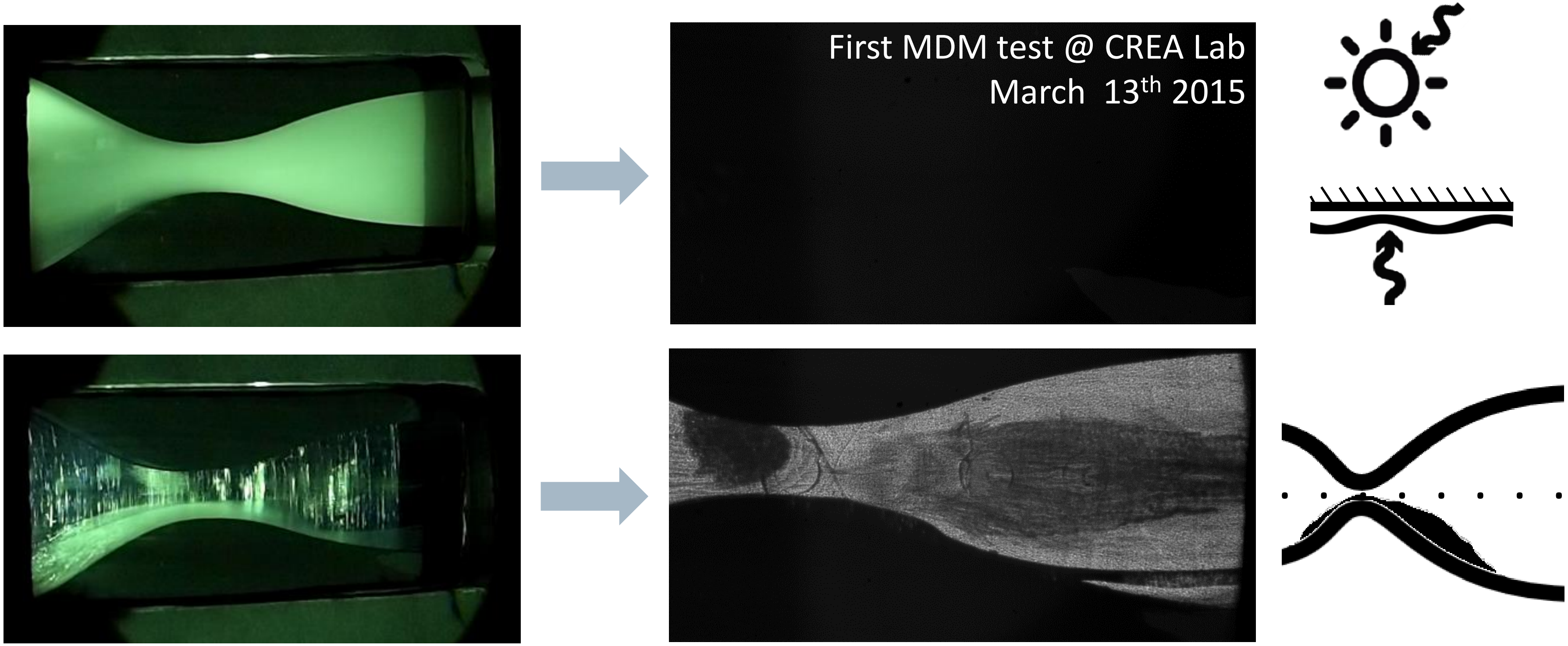




Issues - Condensation

Undesired condensation

- Additional heating mandatory up to the test section
  → optical measurements
  → avoid liquid blockage & nozzle reshape



First MDM test @ CREA Lab
March 13th 2015

CAMERA

SCHLIEREN

Issues - Cleanliness

Solid particles/liquids/greases

○ Residuals	construction/assembling/commissioning
○ Purposely inserted	seeding particles (LDV/PIV)
○ Generated	fluid decomposition (even limited)

Consequences

○ Damaging	coarse particles & high T/high sealing valves
○ Test section soiling	optical access hindered (also nm particles)

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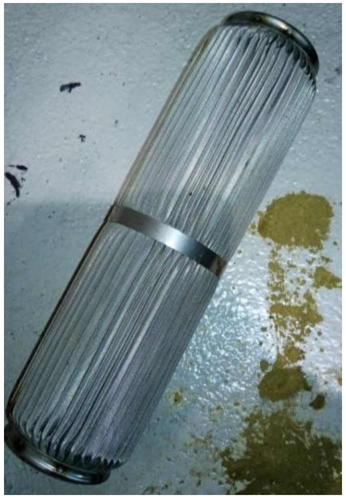


→ Enhance vacuum sealing

→ Fluid degassing

→ Cleaning + filtration

→ Post-exp WF analysis

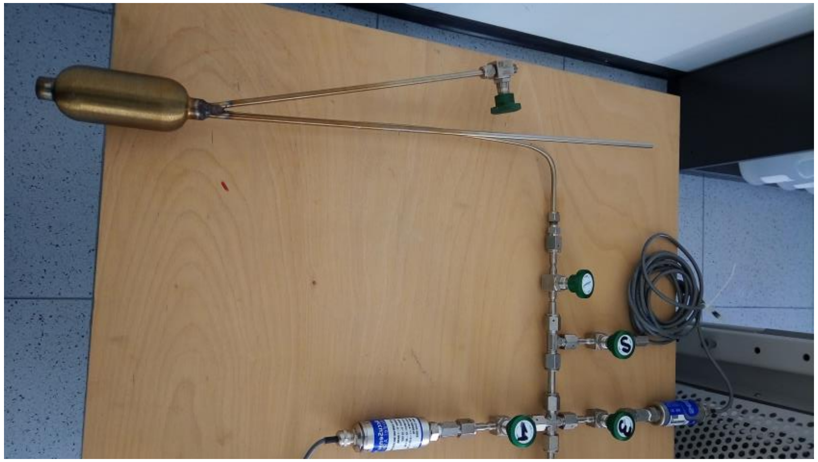
Measuring techniques

Pressure – P, P_T

Sensor requirements

- High accuracy to catch non-ideal effects
- Fluid compatibility
- Possibly high $f_{n,sensor}$ appreciated also for steady flow

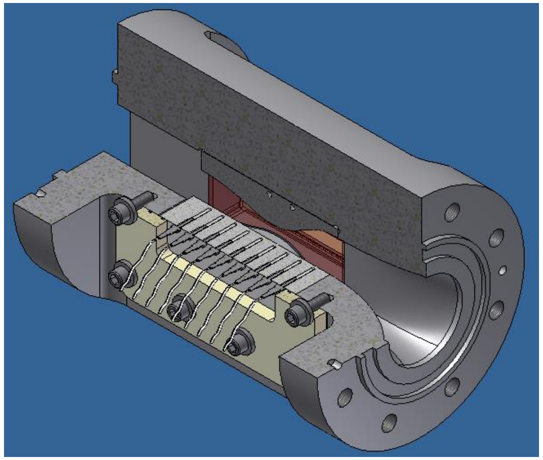
Mounting	T OP	T variation	Miniaturization	Condensation	f response
Local/Flush	$\sim T$ vapor	Variable	Required	No	High
Remote	$\sim T$ room	$\sim$ Constant	Not required	Yes	Low



Pressure sensors

Candidate sensor type

- Piezoresistive local/remote mounting
- Capacitive remote mounting



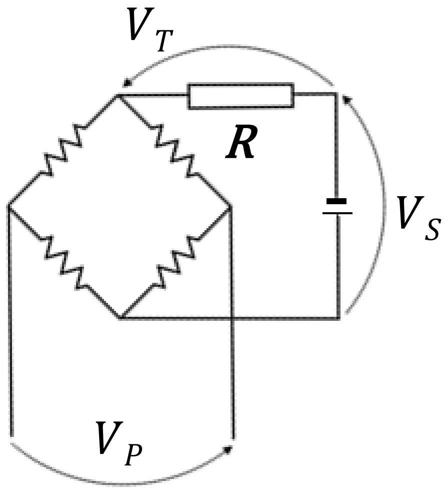
Piezoresistive transducers

U (% FS)	Maximum T (°C)	$f_{n,sensor}$ (kHz)	T sensitivity	Fluid compatibility
$\sim$ 0.1	500	250 ÷ 1000	Yes	High

Calibration

Static calibration

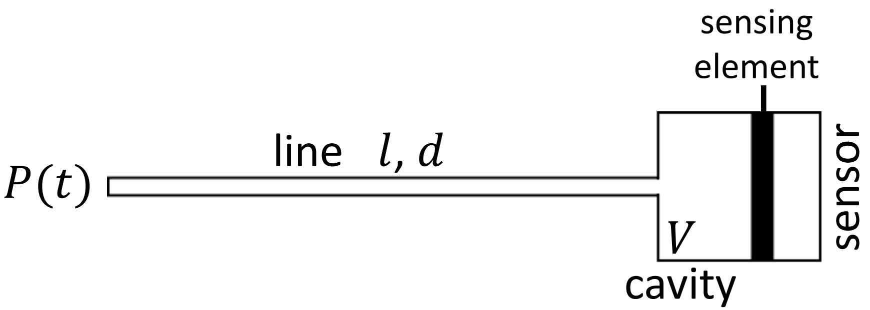
- ○ T compensation for local mounting → P & T calibration

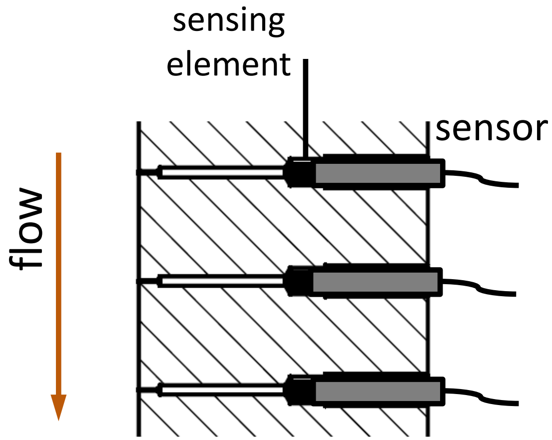


Dynamic response estimation

- ○ Line cavity system
- ○ $f_n \propto c d (V l)^{-1/2}\,,\;\; f_r = f_n\sqrt{1-\zeta^2}$

f_r, d = 2 mm	l = 10 mm	l = 100 mm	l = 1000 mm
MDM vapor	300 Hz	120 Hz	20 Hz
N_2	1000 Hz	400 Hz	70 Hz



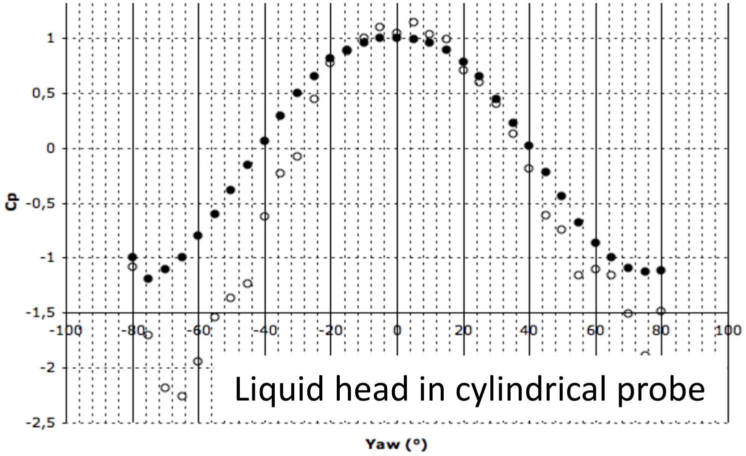


Issues

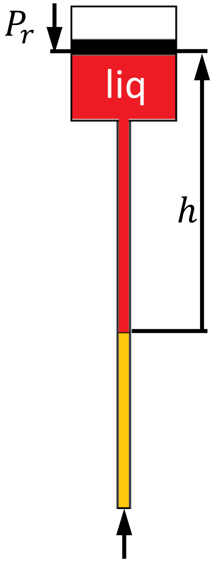
Condensation in lines

- Liquid heads MUST be avoided

10 mm MDM ≈ 0.8 mbar
→ horizontal lines/purging
→ local mounting

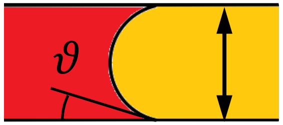


Liquid head in cylindrical probe



$$P \approx P_r + \rho_{liq} g h$$

- Laplace-Young ΔP ~ negligible for low σ fluids



$$\Delta P = \frac{4\ \sigma\ cos\vartheta}{d}$$

Fluid	ϑ (°)	σ (N/m)	d (mm)	ΔP (mbar)
MDM	0÷10	0.015	2	0.3

- Liquid ejection (P ↓/line purging) → possible optical disturbance

Temperature – T_T

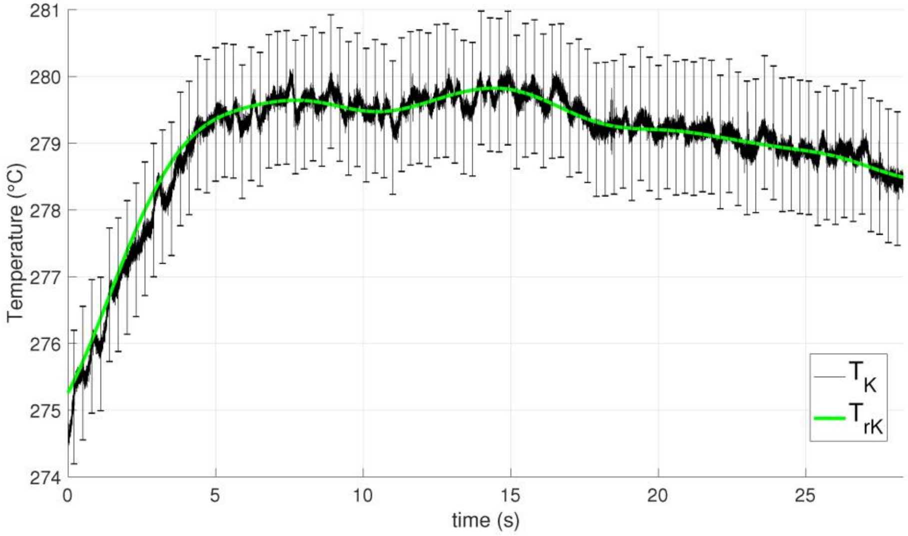
Sensors

RTDs	high accuracy & low f response	→ steady flows
Thermocouples	good accuracy & higher f response	→ transient
Dynamic response	well below P sensors	
Fluid compatibility	good	

Thermocouples

- Time constant
  - → miniaturization recommended
  - → exposed junction preferred

TC	U (°C)	d (mm)	Junction	τ_{est} (s)
J	1.2	0.70	exposed	1.30
K	1.0	0.25	sheathed	0.25
K	0.6	0.10	exposed	0.12

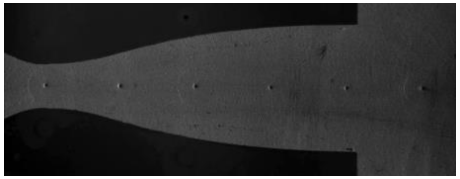


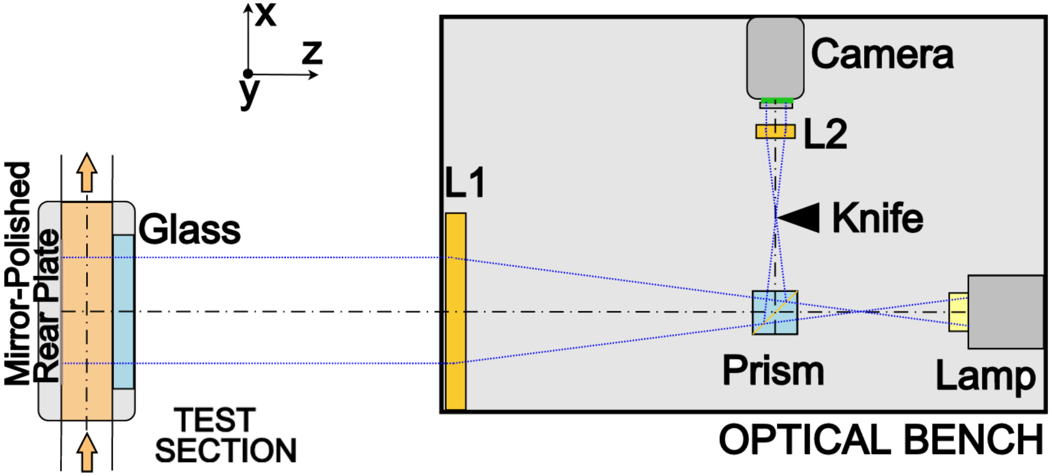
Schlieren – $\nabla \rho$

Configurations

Single passage
- ✗ 2 optical access – NO plate
- ✗ lower sensitivity
- ✓ no mirror polished surface
- ✓ reduced meas. range issue

Double passage
- ✓ 1 optical access+plate easy align.
- ✓ higher sensitivity
- ✗ mirror polished surface
- ✗ increased meas. range issue





Issues – Measuring range

$\nabla\rho$ visualization

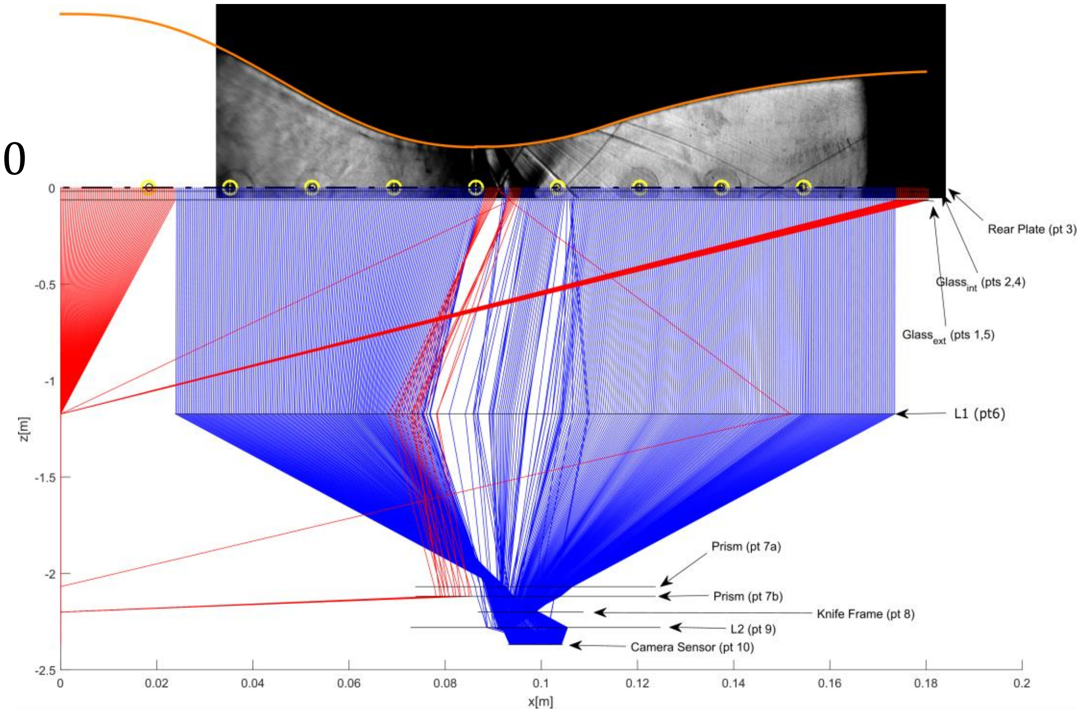
- Light ray deviation $\varepsilon_x \propto \frac{\partial n}{\partial x}$ and $\frac{\partial n}{\partial x} = K\frac{\partial \rho}{\partial x}$ Gladstone-Dale
- Isentropic process

$$\frac{\partial n}{\partial x} = K\frac{1}{c^2}P_T\frac{\partial (P/P_T)}{\partial x}$$

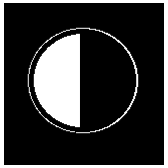
$$\frac{K_{MDM}}{K_{air}} \approx 2 \text{ and } \frac{{c_{air}}^2}{{c_{MDM}}^2} \approx 10$$

$$\rightarrow \quad \varepsilon_{x,MDM} \gg \varepsilon_{x,air}$$

Ray path



Knife frame



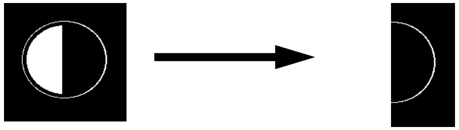
Issues – Measuring range

Influence of P_T and c for organic vapor

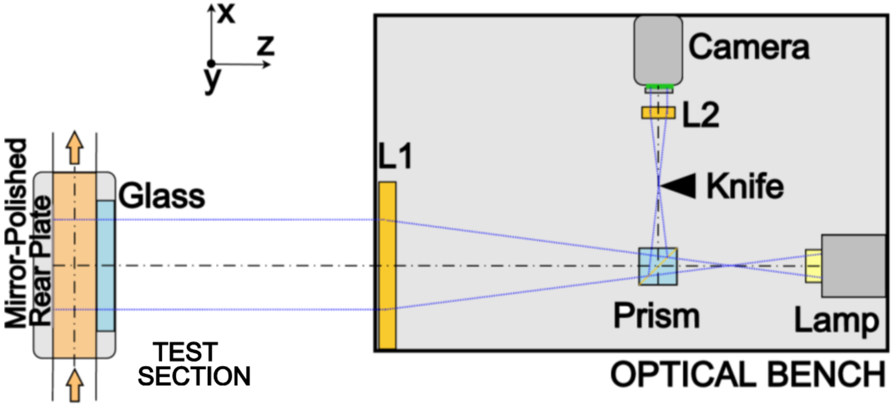
$$\frac{\partial n}{\partial x} = K \frac{1}{c^2} P_T \frac{\partial (P/P_T)}{\partial x}$$

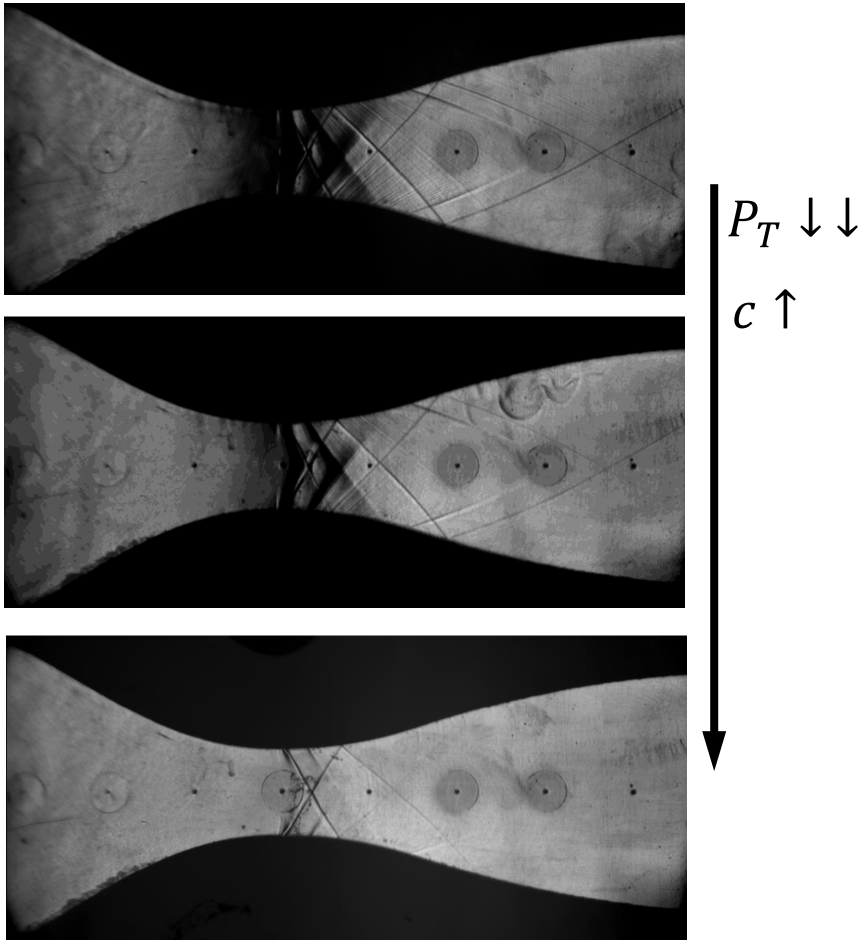
Solutions

- Remove all unnecessary obstacles



- Proper selection/arrangement





$P_T \downarrow\downarrow$

$c \uparrow$

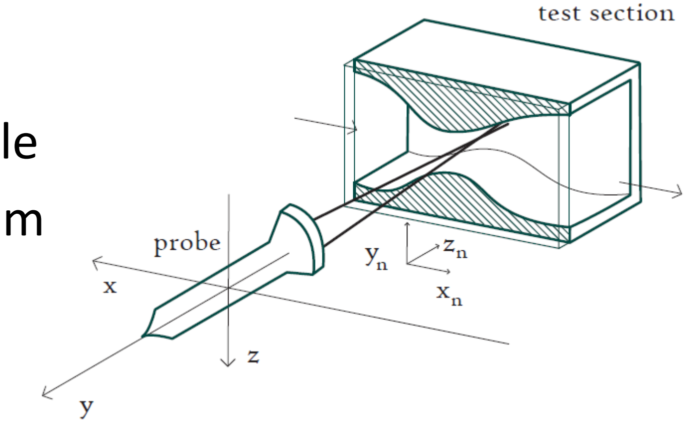
Direct V measurement

Key for TMD model verification

✓ No calibration required

✗ Challenging flow seeding → proper particle

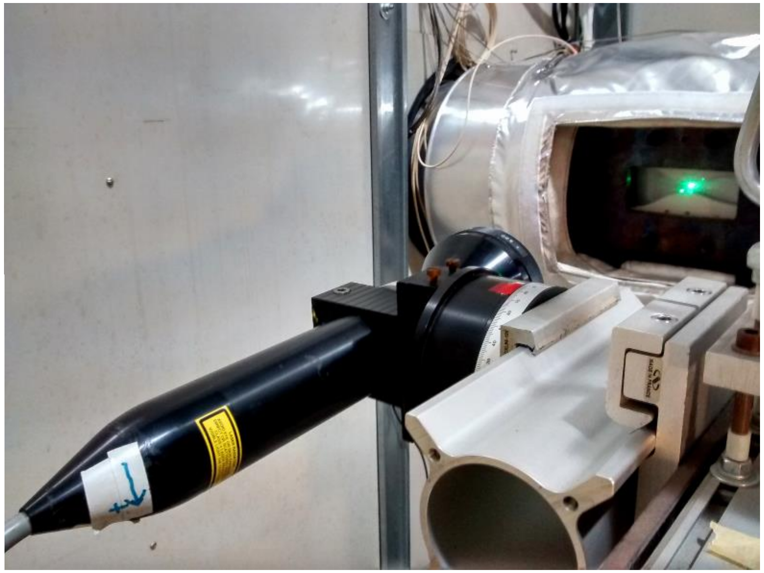
→ seeding system



Seeding strategy & particles

- Solid particles
- Spray of liquid WF/particle suspension upstream of the test section

→ still open problem



Test	TiO_2		SiO_2	
	$d_p = 1\,\mu m$	$d_p = 0.5\,\mu m$	$d_p = 1\,\mu m$	$d_p = 0.5\,\mu m$
MDM_2	5.57%	2.35%	4.06	1.61%
MDM_{1st}	3.86%	1.36%	2.70	0.90%

Maximum slip factor

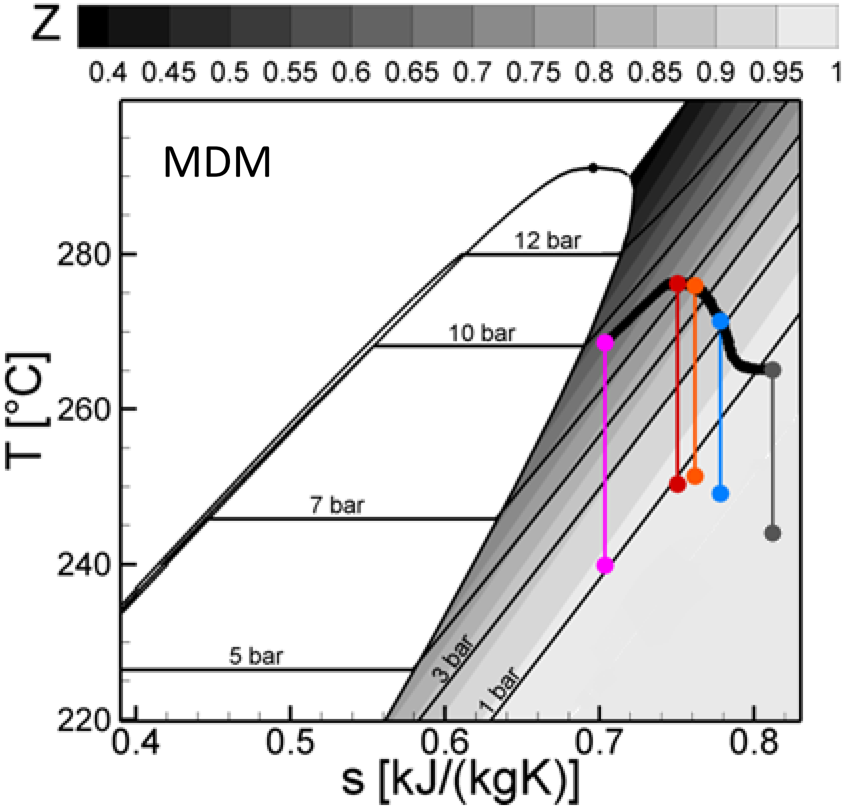
✓ Some achievements

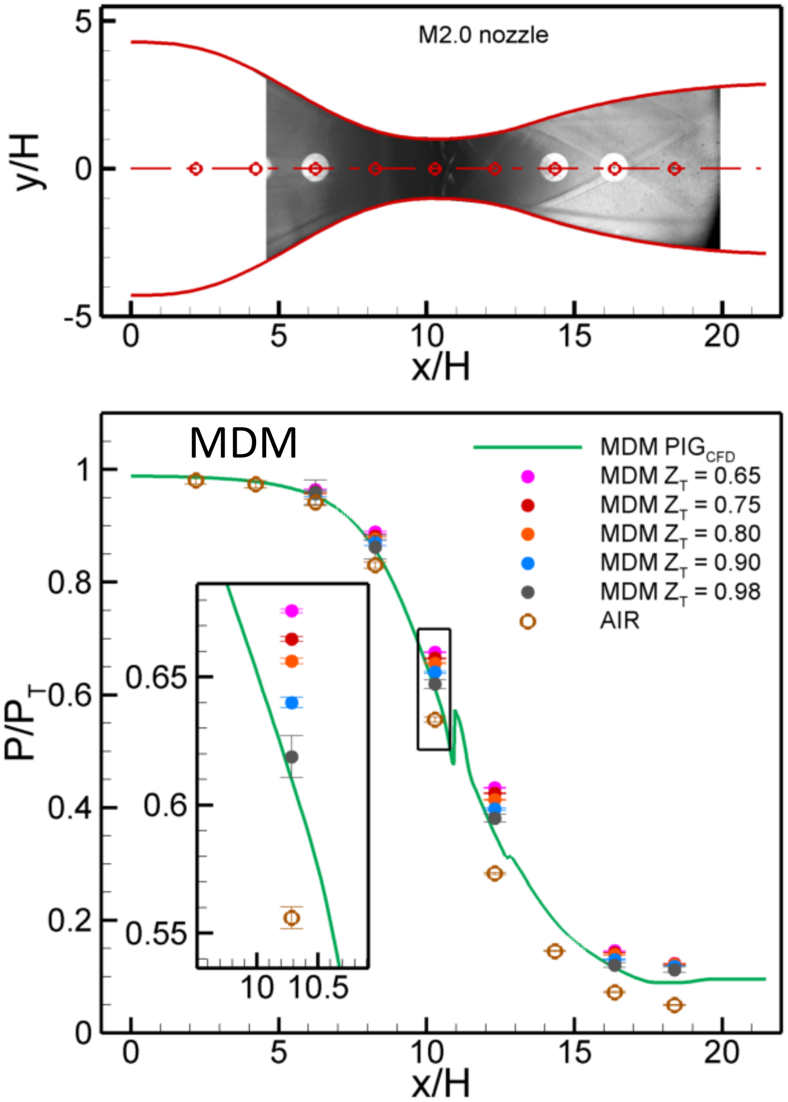
Non-ideal nozzle expansion – P/PT

Significant non ideal effects

$Z_T \approx 0.80$ difference to PG @ throat

-6% on P/PT, -20% on ρ, +16% on V

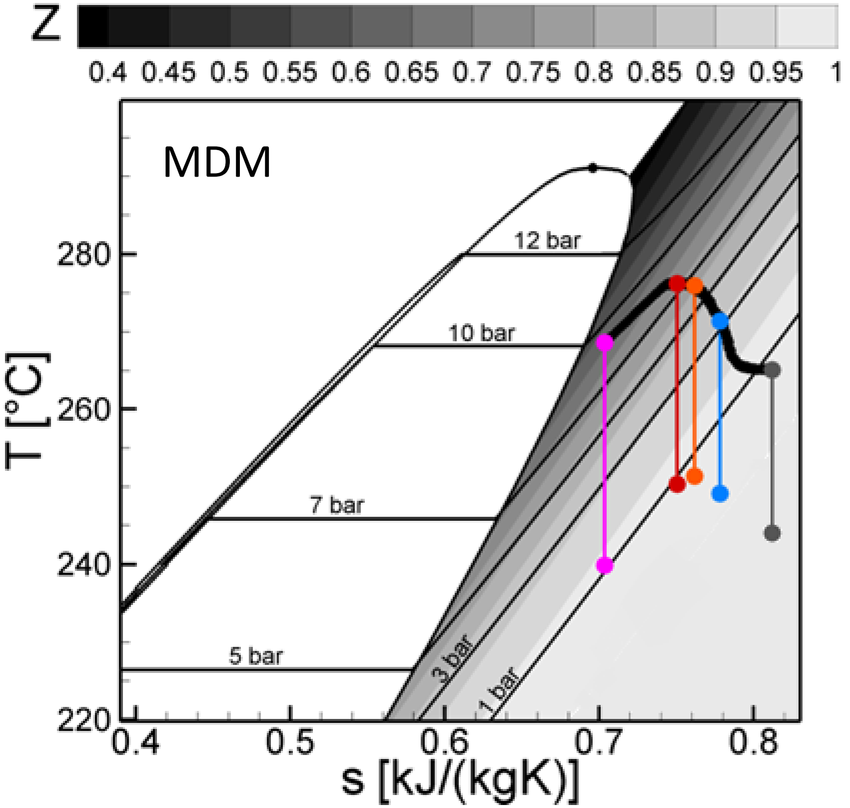


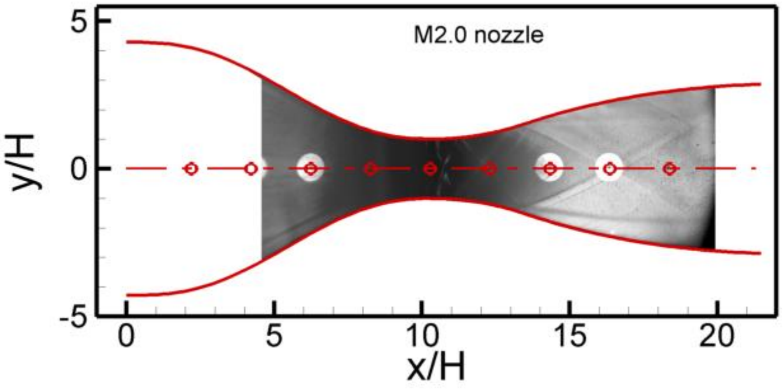


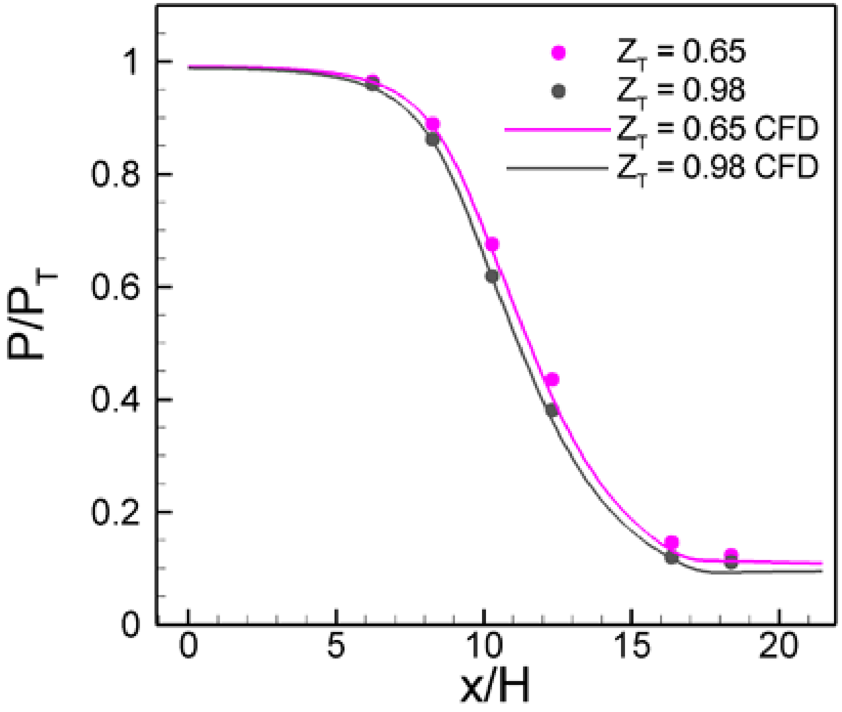
CFD Comparison

Good agreement

- SU2 solver: 2D inviscid + iPRSV model
- Difference below 5%

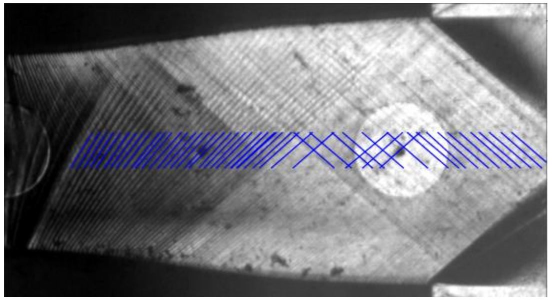




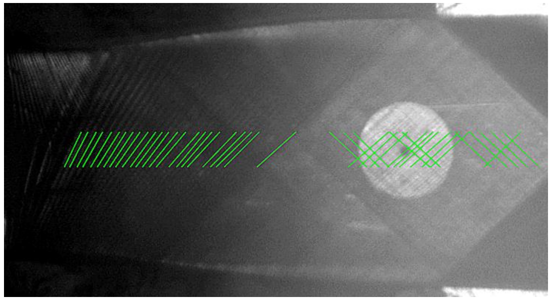


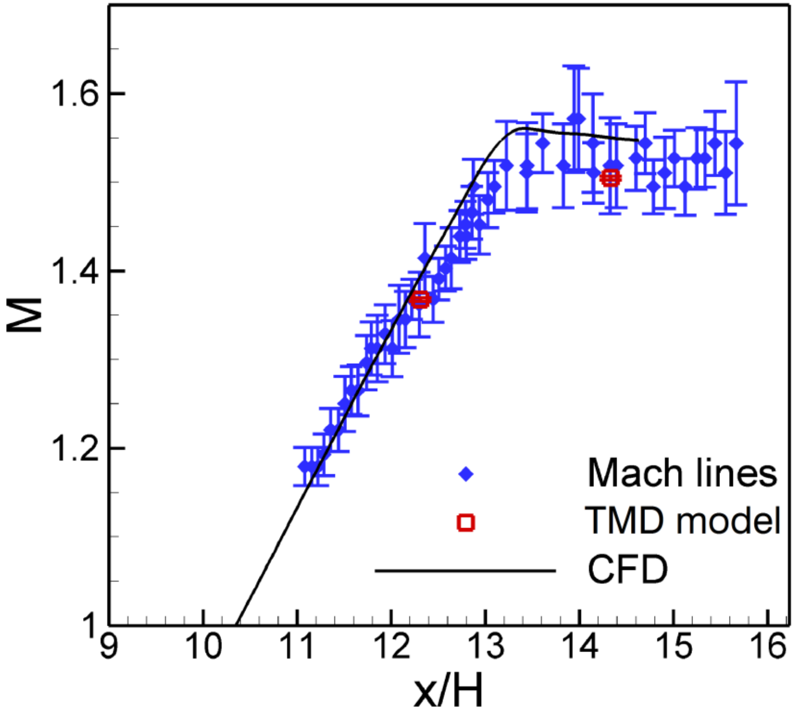
Mach number measurement

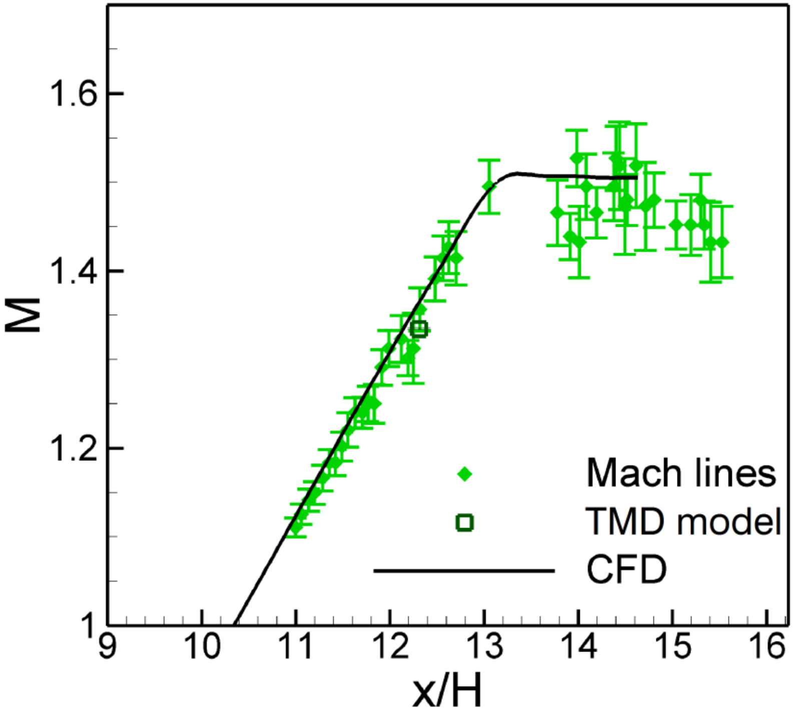
Through Mach waves detection



$$M = \frac{1}{\sin(\mu)}$$



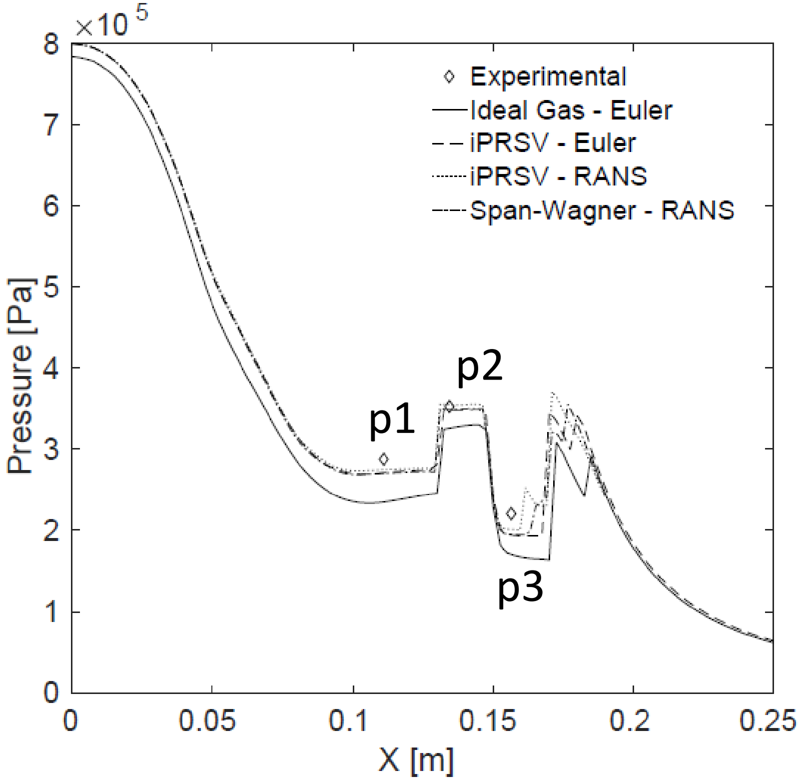


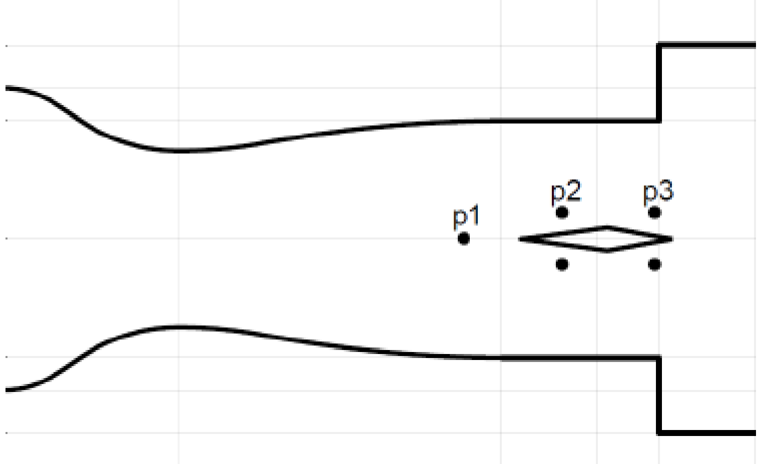


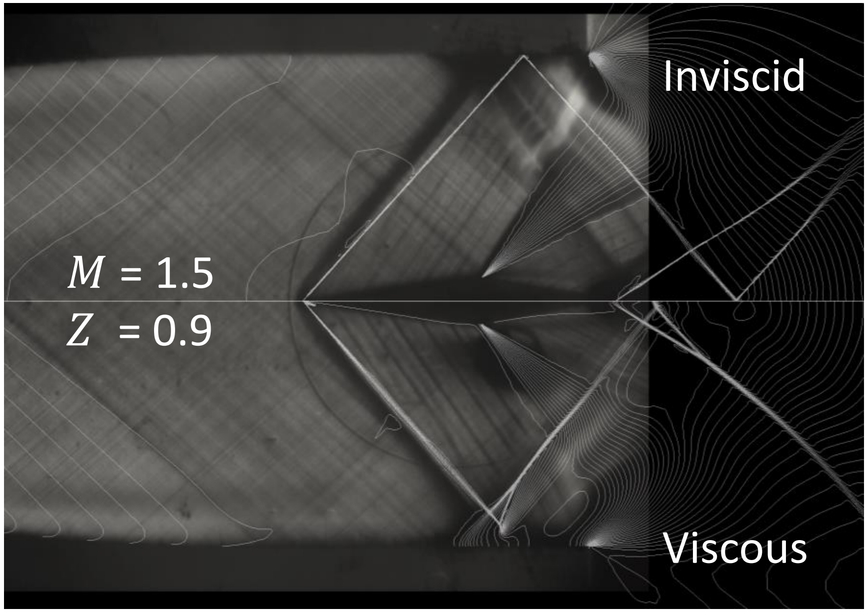
Supersonic airfoil

Appreciable non-ideal effects

- In shock/expansion patterns
- Good Exp./CFD agreement for accurate TMD models



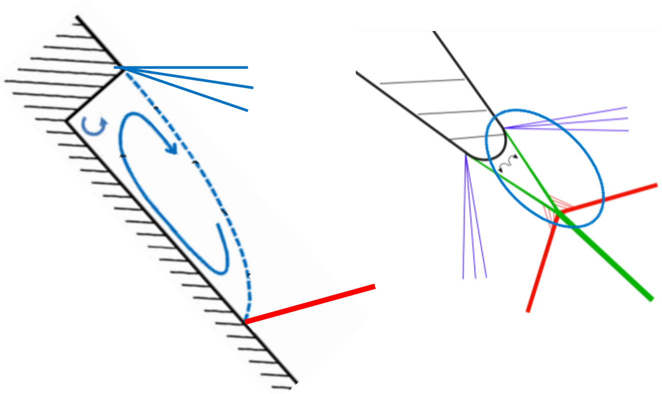


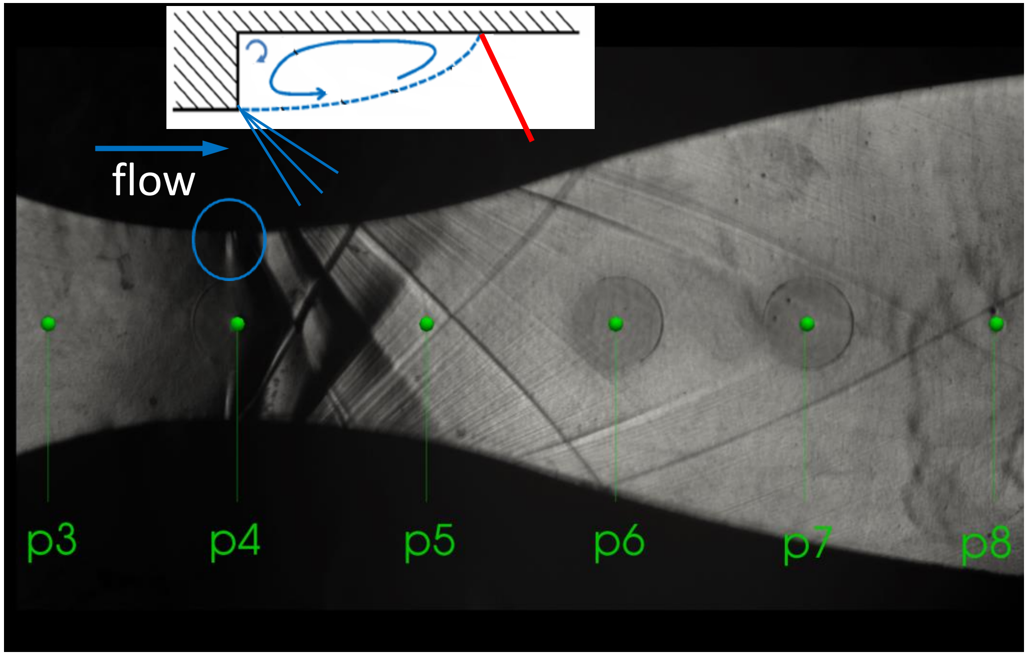


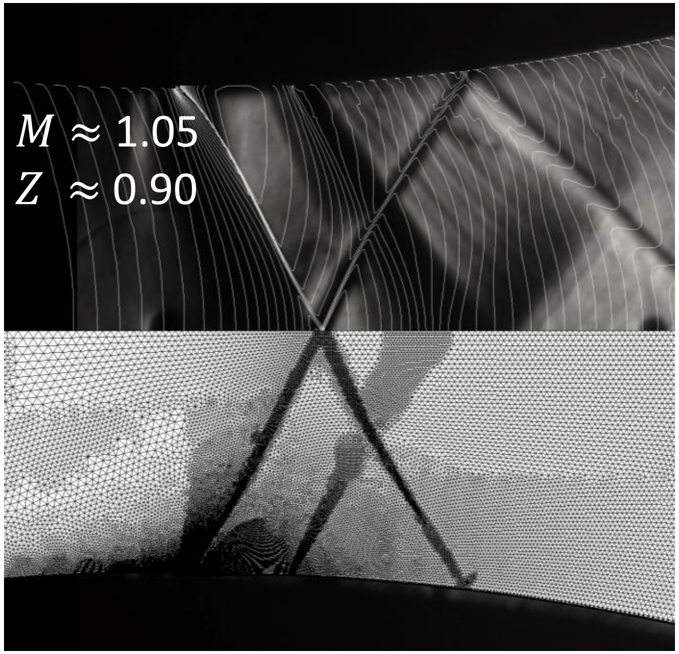
Backward facing step

Typical flow pattern at blade TE

- Large $\nabla\rho$ due to high compressibility
- Fan/separation/shock structures
- Well captured by SU2 through grid adaptation





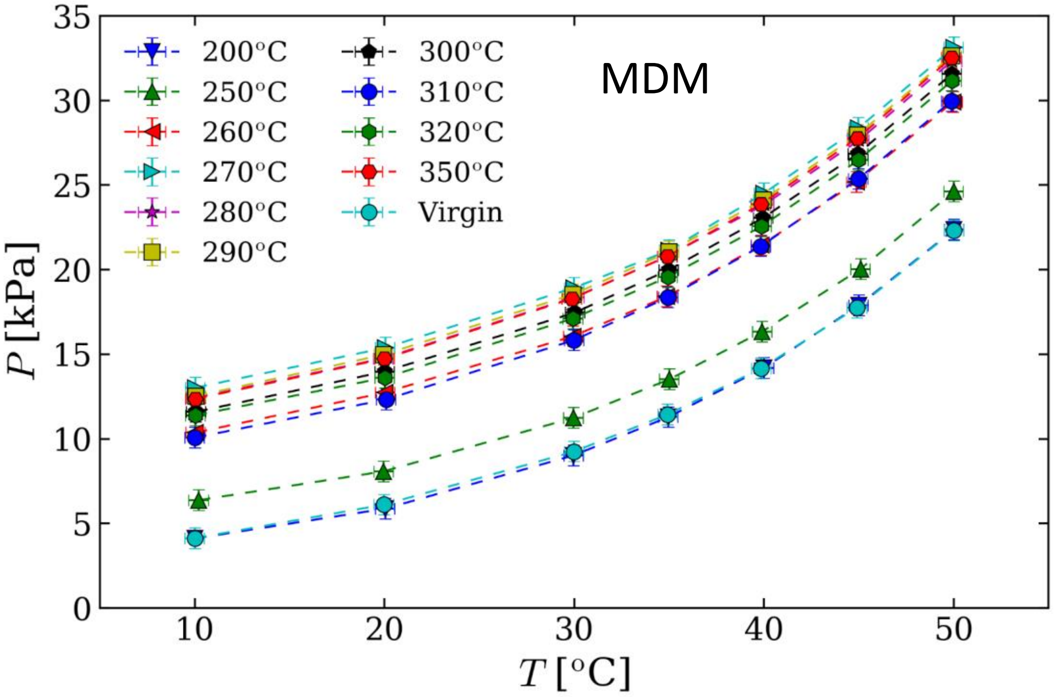


Thermal stability

Tests on pure & binary mixtures

- Linear siloxanes: MM, MDM, MD_2M, MD_3M
- $\forall \; T_{stress}$: cycles of P_{sat}/80h thermal stress/ P_{sat}
- Chemical analysis of liquid & vapor fractions

Component	Vapor [μmol]
Methane	0.948
Ethylene	0.025
Ethane	0.05
CO_2	0.524



Component	Reference [%]	Liquid [%]
MOH	0.0028	0.0061
MM	0.0028	0.0182
MDM	99.972	99.917
D_4	0.0117	0.0145
MD_2M	0.0039	0.0113
Undefined	0.0065	0.0287

☰ Conclusions & Outlook

Experiments in non-ideal flows for ORCs

Conclusions

- Key to refine design tools → turbine & cycle performances
- Entail diverse challenges → exp. activity & fluid/flow modeling
- Overcome some of them → highly rewarding results
- Encouraging experimental work → feel free to fail & share

Outlook

- Perform direct velocity measurements
- Design & aerodynamically calibrate probes (sensor embedded FRAPP)
- Test actual turbine blade shapes

- Assess the potentiali of thermal stability of mixtures (already ongoing)

🙏 Acknowledgements

Support

2008 – 2010

clean energy ahead®
TURBODEN
a group company of MITSUBISHI HEAVY INDUSTRIES, LTD.

Since 2013

erc
European Research Council
Established by the European Commission

Consolidator Grant 2013, Prof. A. Guardone Project NSHOCK

People

People

Prof. Mario Gaia

Prof. Carlo Osnaghi

Thank you for your attention

Information

References

- Available soon with the presentation at: crealab.polimi.it

Laboratory tour available also this morning. Ask the help desk.

Research ORC modules

Actual ORCs for research needs

- Medium/large plant size
- Access design → probes upstream/downstream **blade rows**
  → traversing: blade span, possible tangential
  → possible optical windows
- Full availability & flexible operating conditions

Limitations

- VERY HIGH COST!!!
- Aero-calibrated probes NOT AVAILABLE

→ Size reduction

- Limits for detailed flow mapping
- Good for global measurements

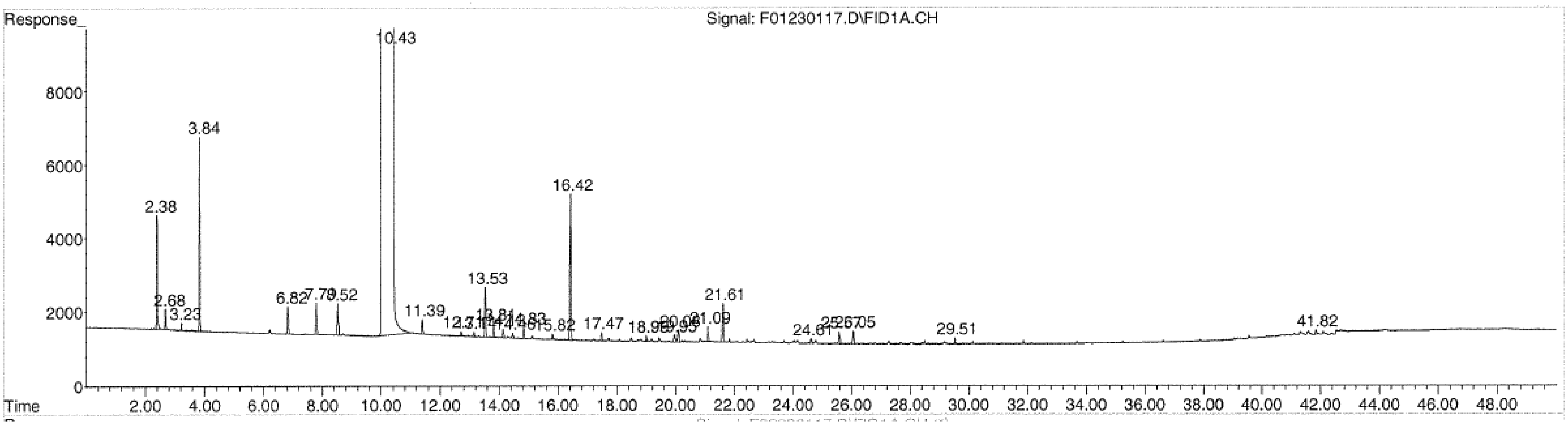
KIER ORC Loop

Small research ORCs

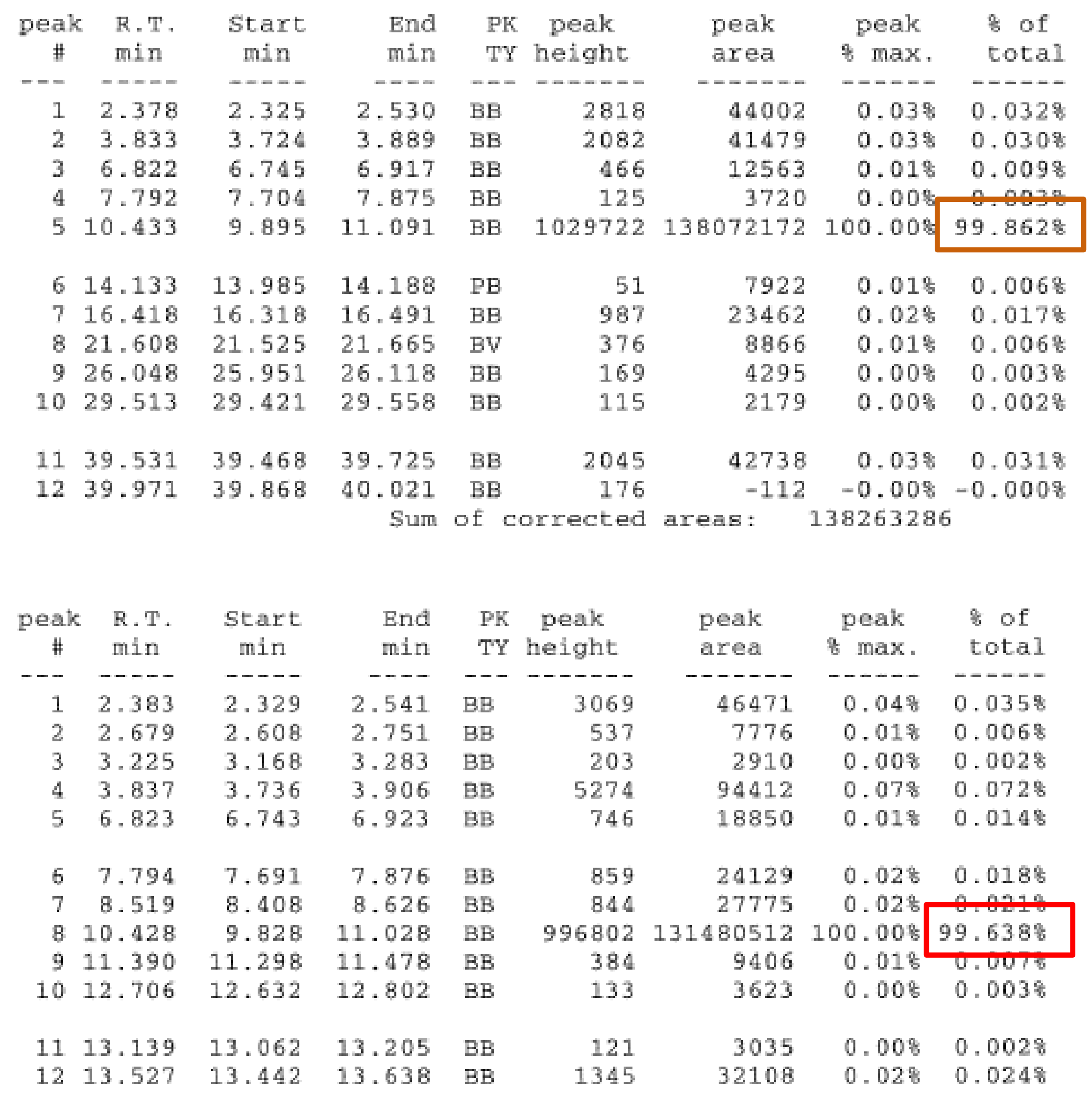
Recent ORC modules for turbine research(3)

Module	Institution	Expander	$\dot{W}_{\mathrm{out}}$ (kW)	Working fluids	Year of publ.
KIER ORC Loop	KIER	Rad-IN-T	~ 35	R245fa	2011
Jiaotong ORC Loop	Xi'an Jiaotong U	Ax-T	~ 10	R123	2012
ORC Test Bench	LU Hannover	Ax-T	~ 20	Ethanol	2015
High Pressure Loop	U Queensland	Rad-IN-T	~ 20	HFC-HC-CO_2 (R245fa)	2016
ICE WHR Loop	Lappeenranta UT	Rad-IN-T	~ 15	MDM	2016
ORCHID	TU Delft	Diverse (R-IN-T)	up to 100	Diverse (MM)	2016
Liège ORC Loop	U Liège	Rad-IN-T	~ 3.5	R245fa, R1233zd	2017

3) Research modules in the mini/small power range, suitable for research on turboexpanders

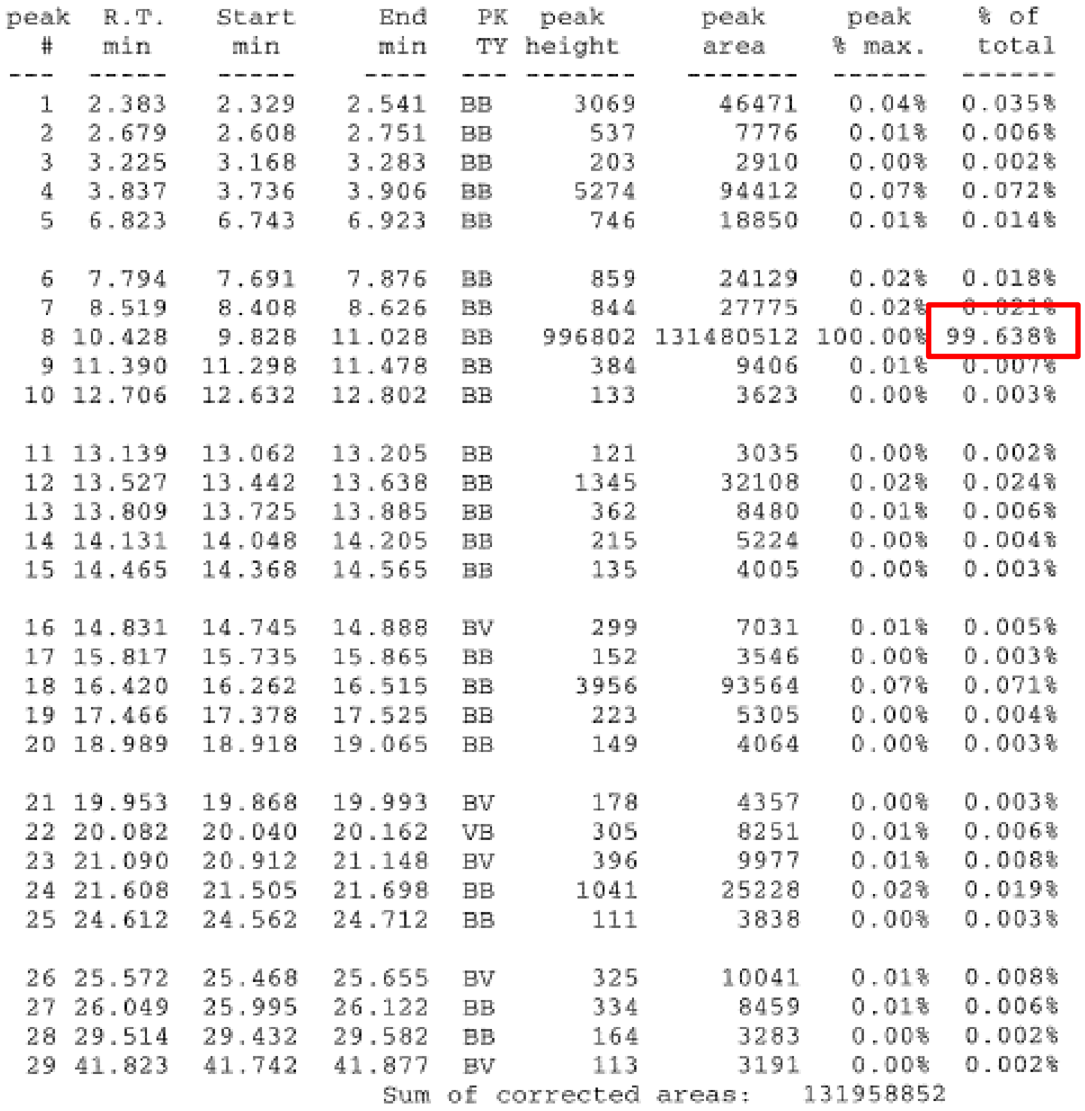


Response_
Signal: F01230117.D\FID1A.CH
8000
6000
4000
2000
0
Time
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
32.00
34.00
36.00
38.00
40.00
42.00
44.00
46.00
48.00
10.43
3.84
2.38
16.42
13.53
2.68
3.23
6.82
7.79
9.52
11.39
21.61
17.47
21.09
24.61
29.51
41.82



```
peak   R.T.    Start      End    PK   peak      peak     peak    % of
  #    min      min       min    TY  height     area    % max.   total
 ---  -----    -----     ----   ---  -------  --------  ------  ------
   1   2.378    2.325    2.530  BB      2818     44002   0.03%  0.032%
   2   3.833    3.724    3.889  BB      2082     41479   0.03%  0.030%
   3   6.822    6.745    6.917  BB       466     12563   0.01%  0.009%
   4   7.792    7.704    7.875  BB       125      3720   0.00%  0.003%
   5  10.433    9.895   11.091  BB   1029722 138072172 100.00% 99.862%

   6  14.133   13.985   14.188  PB        51      7922   0.01%  0.006%
   7  16.418   16.318   16.491  BB       987     23462   0.02%  0.017%
   8  21.608   21.525   21.665  BV       376      8866   0.01%  0.006%
   9  26.048   25.951   26.118  BB       169      4295   0.00%  0.003%
  10  29.513   29.421   29.558  BB       115      2179   0.00%  0.002%

  11  39.531   39.468   39.725  BB      2045     42738   0.03%  0.031%
  12  39.971   39.868   40.021  BB       176      -112  -0.00% -0.000%
                              Sum of corrected areas:    138263286
```

```
peak   R.T.    Start      End    PK   peak      peak     peak    % of
  #    min      min       min    TY  height     area    % max.   total
 ---  -----    -----     ----   ---  -------  --------  ------  ------
   1   2.383    2.329    2.541  BB      3069     46471   0.04%  0.035%
   2   2.679    2.608    2.751  BB       537      7776   0.01%  0.006%
   3   3.225    3.168    3.283  BB       203      2910   0.00%  0.002%
   4   3.837    3.736    3.906  BB      5274     94412   0.07%  0.072%
   5   6.823    6.743    6.923  BB       746     18850   0.01%  0.014%

   6   7.794    7.691    7.876  BB       859     24129   0.02%  0.018%
   7   8.519    8.408    8.626  BB       844     27775   0.02%  0.021%
   8  10.428    9.828   11.028  BB    996802 131480512 100.00% 99.638%
   9  11.390   11.298   11.478  BB       384      9406   0.01%  0.007%
  10  12.706   12.632   12.802  BB       133      3623   0.00%  0.003%

  11  13.139   13.062   13.205  BB       121      3035   0.00%  0.002%
  12  13.527   13.442   13.638  BB      1345     32108   0.02%  0.024%
```



```
peak   R.T.    Start     End    PK  peak      peak     peak    % of
  #    min      min      min    TY height     area    % max.   total
---  -----    -----     ----   --- -------  --------  ------  ------
  1   2.383   2.329    2.541   BB     3069     46471   0.04%  0.035%
  2   2.679   2.608    2.751   BB      537      7776   0.01%  0.006%
  3   3.225   3.168    3.283   BB      203      2910   0.00%  0.002%
  4   3.837   3.736    3.906   BB     5274     94412   0.07%  0.072%
  5   6.823   6.743    6.923   BB      746     18850   0.01%  0.014%

  6   7.794   7.691    7.876   BB      859     24129   0.02%  0.018%
  7   8.519   8.408    8.626   BB      844     27775   0.02%  0.021%
  8  10.428   9.828   11.028   BB   996802 131480512 100.00% 99.638%
  9  11.390  11.298   11.478   BB      384      9406   0.01%  0.007%
 10  12.706  12.632   12.802   BB      133      3623   0.00%  0.003%

 11  13.139  13.062   13.205   BB      121      3035   0.00%  0.002%
 12  13.527  13.442   13.638   BB     1345     32108   0.02%  0.024%
 13  13.809  13.725   13.885   BB      362      8480   0.01%  0.006%
 14  14.131  14.048   14.205   BB      215      5224   0.00%  0.004%
 15  14.465  14.368   14.565   BB      135      4005   0.00%  0.003%

 16  14.831  14.745   14.888   BV      299      7031   0.01%  0.005%
 17  15.817  15.735   15.865   BB      152      3546   0.00%  0.003%
 18  16.420  16.262   16.515   BB     3956     93564   0.07%  0.071%
 19  17.466  17.378   17.525   BB      223      5305   0.00%  0.004%
 20  18.989  18.918   19.065   BB      149      4064   0.00%  0.003%

 21  19.953  19.868   19.993   BV      178      4357   0.00%  0.003%
 22  20.082  20.040   20.162   VB      305      8251   0.01%  0.006%
 23  21.090  20.912   21.148   BV      396      9977   0.01%  0.008%
 24  21.608  21.505   21.698   BB     1041     25228   0.02%  0.019%
 25  24.612  24.562   24.712   BB      111      3838   0.00%  0.003%

 26  25.572  25.468   25.655   BV      325     10041   0.01%  0.008%
 27  26.049  25.995   26.122   BB      334      8459   0.01%  0.006%
 28  29.514  29.432   29.582   BB      164      3283   0.00%  0.002%
 29  41.823  41.742   41.877   BV      113      3191   0.00%  0.002%
                   Sum of corrected areas:     131958852
```

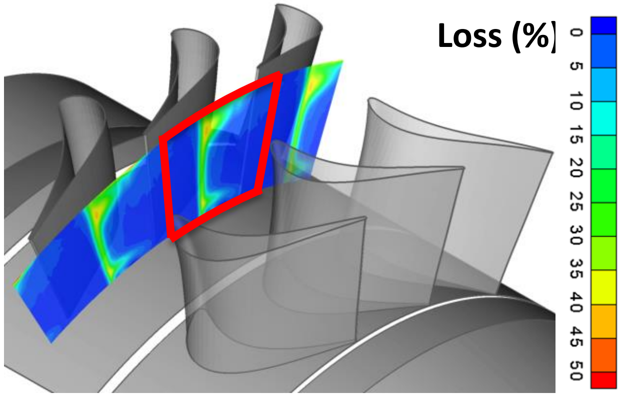
Resolution

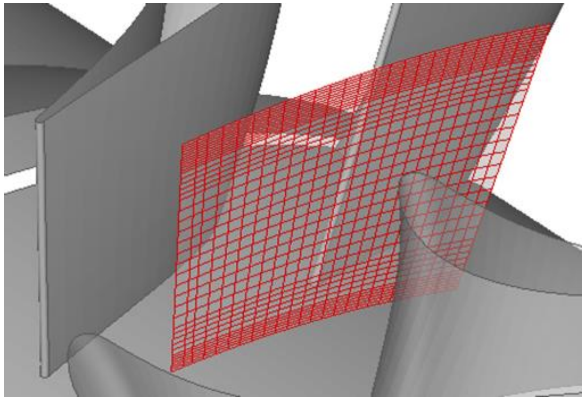
Space

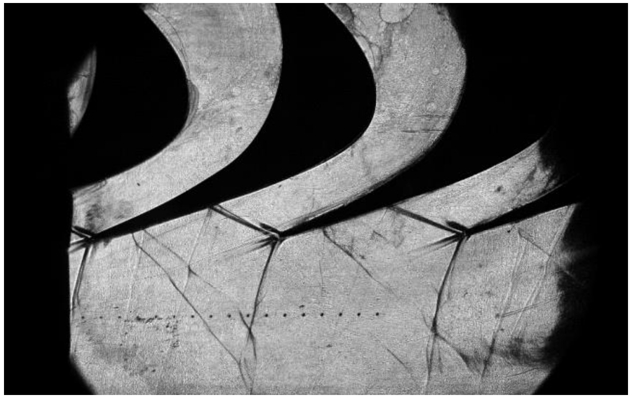
- ○ As high as possible → detailed measurements
  → capture flow gradients

Time

- ○ Fixed blade → steady/slow transient
- ○ Rotating blades → average
  → time resolved $f_{blade\ pass} \sim 10^0 \div 10^2$ kHz
  → dynamic calibration & vane field REQUIRED



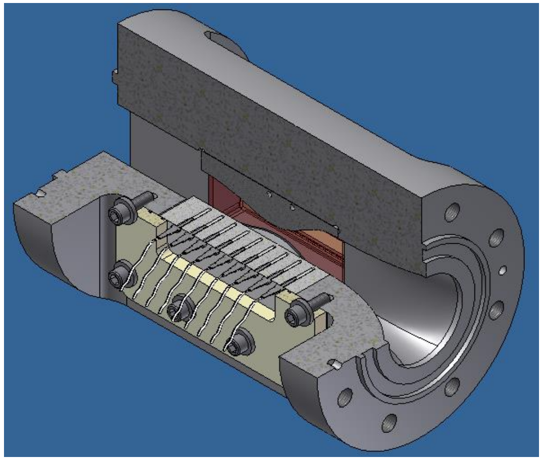


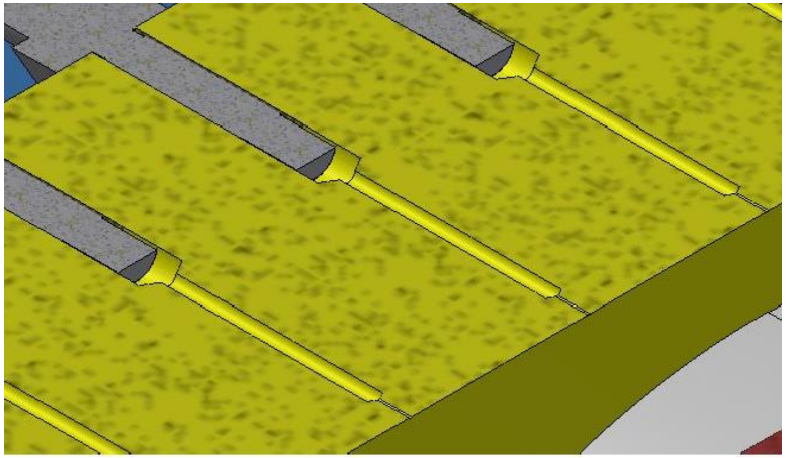


Pressure sensors

Our choice

- Piezoresistive + local mounting
  → nozzle based experiments





- Capacitive + remote mounting
  → thermal stability tests

Issues – Miscellaneous

Cavitation

○ $\dot{V}$ reduction	→ pump intake cooling → reduce installation height → pressurize condenser (batch cycles only)
○ Side level meters	→ useless

Calibration

Static calibration in P & T

- Compensation resistor $\boldsymbol{R}$

Dynamic response estimation