UNIVERSITY OF FERRARA
- EX LABORE FRUCTUS -

DE: Department of Engineering Ferrara

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Experimental and numerical characterization of an oil-free scroll expander

Milan, September 15, 2017

4th International seminar on ORC Power Systems

ORC 2017 13 - 15 September MILANO, Italy

Introduction – 1

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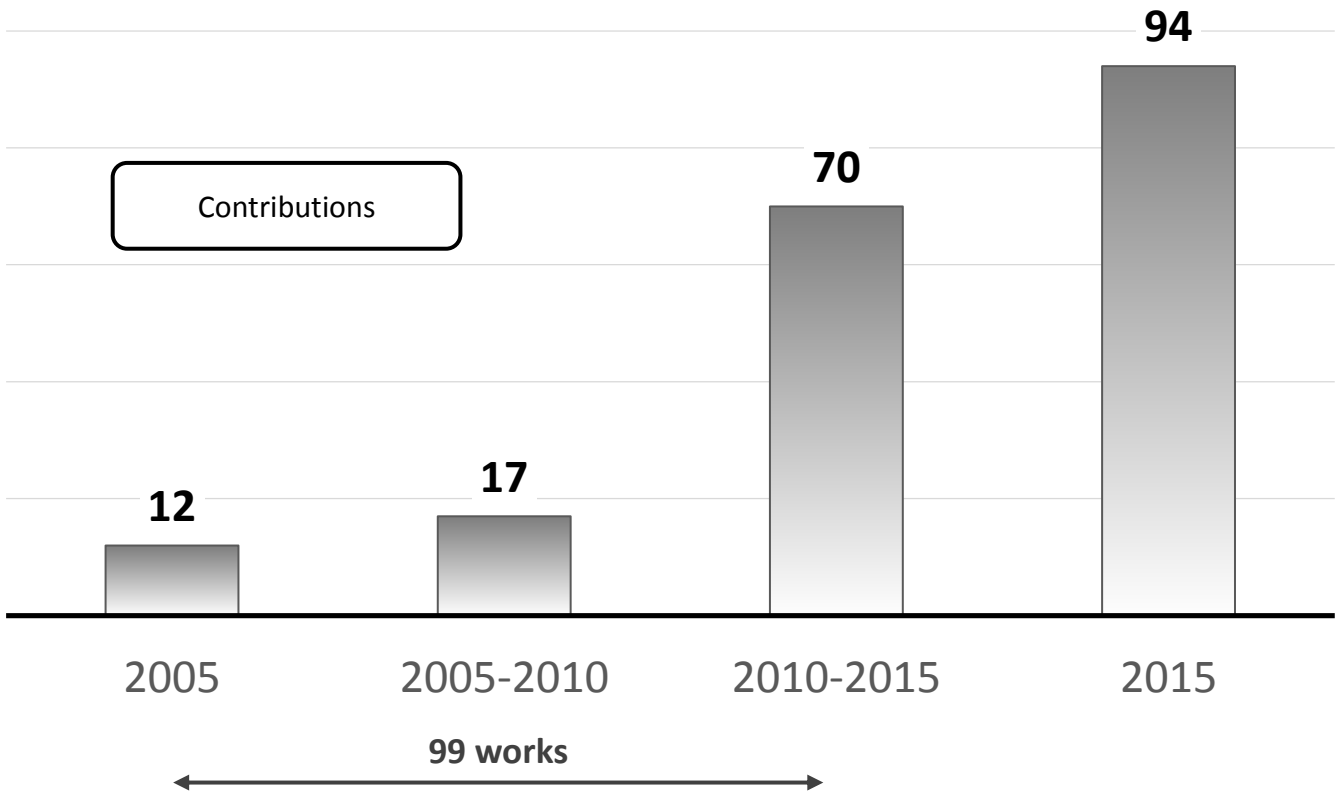
Organic
Rankine
Cycle



Landelle, Arnaud, et al. "Organic Rankine cycle design and performance comparison based on experimental database." *Applied Energy* (2017).

Introduction – 2

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Organic
Rankine
Cycle

Expander

- Scroll Hermetic
- Gerotor
- Scroll
- Pneumatic Drill
- Rotary Vane
- Turbine Radial
- Turbine Axial
- Swash-plate Piston
- Screw Single
- Screw Twin
- Scroll Open-Drive
- Rolling-piston
- Scroll Semi-Hermetic
- Piston

Landelle, Arnaud, et al. "Organic Rankine cycle design and performance comparison based on experimental database." *Applied Energy* (2017).

Introduction – 3

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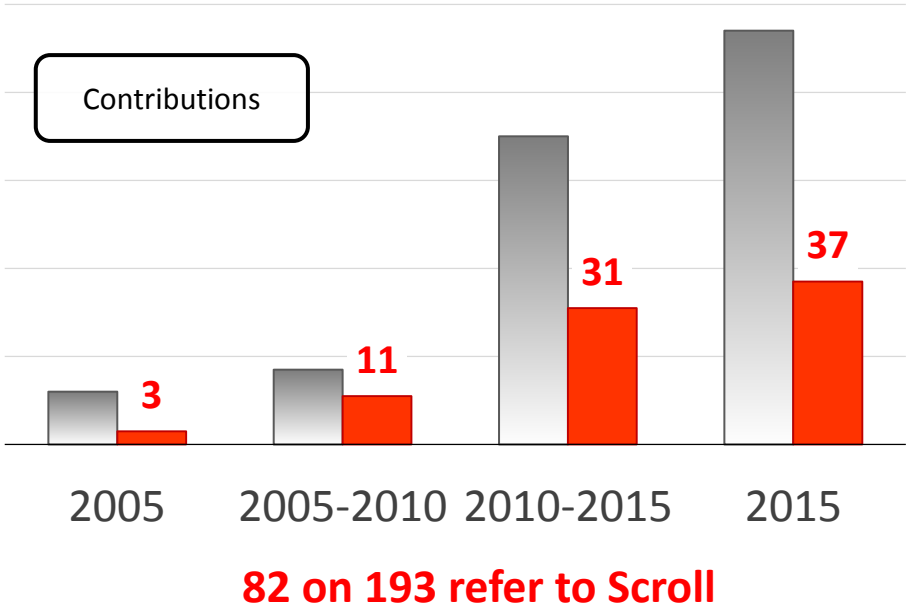
Organic
Rankine
Cycle



82 on 193 refer to Scroll

Expander

- Scroll Hermetic
- Gerotor
- → **Scroll**
- Pneumatic Drill
- Rotary Vane
- Turbine Radial
- Turbine Axial
- Swash-plate Piston
- Screw Single
- Screw Twin
- → **Scroll Open-Drive**
- Rolling-piston
- → **Scroll Semi-Hermetic**
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Landelle, Arnaud, et al. "Organic Rankine cycle design and performance comparison based on experimental database." *Applied Energy* (2017).

Introduction – 4

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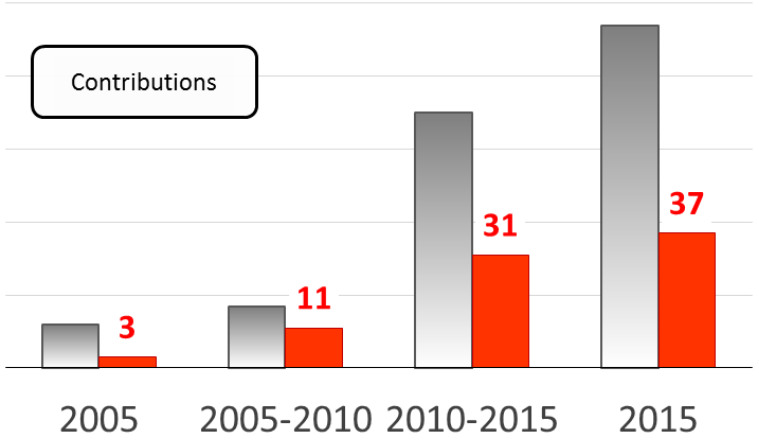

Scroll Expander

Usually P_{el}< 2 kW

Researchers	Expander type	Working fluids	Isentropic efficiency (%)	Power [kW]	Rotate speed [rpm]	Pressure ratio
Yamamoto et al. [150]	Radial-inflow turbine	R123	48	0.15	17,000	–
Nguyen et al. [151]	Radial-inflow turbine	*n*-pentane	49.8	1.44	65,000	3.45
Yagoub et al. [152]	Radial-inflow turbine	HFE-301	85	1.50	60,000	1.1
		n-pentane	40	1.50	60,000	1.3
Inoue et al. [153]	Radial-inflow turbine	TFE	70–85	5–10	15,000–30,000	4.8
Kang [154]	Radial-inflow turbine	R245fa	78.7	32.7	63,000	4.11
Pei et al. [155]	Radial-inflow turbine	R123	65	1.36	24,000	5.2
Li et al. [156]	Radial-inflow turbine	R123	68	2.40	40,000	6.3
Zanelli and Favrat [157]	Scroll expander	R134a	63–65	1–3.5	2400–3600	2.4–4.0
Mathias et al. [158]	Scroll expander	R123	67, 81, 83	1.2,1.38, 1.75	3670	8.8,5.5,3.1
Peterson et al. [159]	Scroll expander	R123	45–50	0.14–0.24	600–1400	3.28–3.87
Wang et al. [88]	Scroll expander	R134a	70–77	0.5–0.8	1015–3670	2.65–4.84
Saitoh et al. [160]	Scroll expander	R113	65	0–0.46	1800–4800	–
Kim et al. [161]	Scroll expander	Water	33.8	11–12	1000–1400	10.54–11.5
Manolakos et al. [162]	Scroll expander	R134a	10–65	0.35–2	300–390	–
Lemort et al. [86,87]	Scroll expander	R123	42.5–67	0.4–1.8	1771–2660	2.75–5.4
	Scroll expander	R245fa	45–71	0.2–2	–	2–5.7
Guangbin et al. [163]	Scroll expander	Air	–	0.4–1.1	1740–2340	3.66
Wang et al. [164]	Screw expander	Air	26–40	0.5–3	400–2900	–
Smith et al. [165]	Screw expander	R113	48–76	6–15.5	1300–3600	2.11
Baek et al. [166]	Reciprocating piston expander	CO_2	10.5	24.35	114	2.1
Zhang et al. [167]	Reciprocating piston expander	CO_2	62	–	306	2.4
Mohd et al. [101]	Rotary vane expander	R245fa	43–48	0.025–0.032	2200–3000	21.54–24.17
Yang et al. [102]	Rotary vane expander	CO_2	17.8–23	–	300–1500	–
Qiu et al. [168]	Rotary vane expander	HFE7000	52.88–55.45	1.66–1.72	841–860	2.063–2.095

Bao, J., Zhao, L., "A review of working fluid and expander selections for organic Rankine cycle", *Renewable and Sustainable Energy Reviews* (2013).

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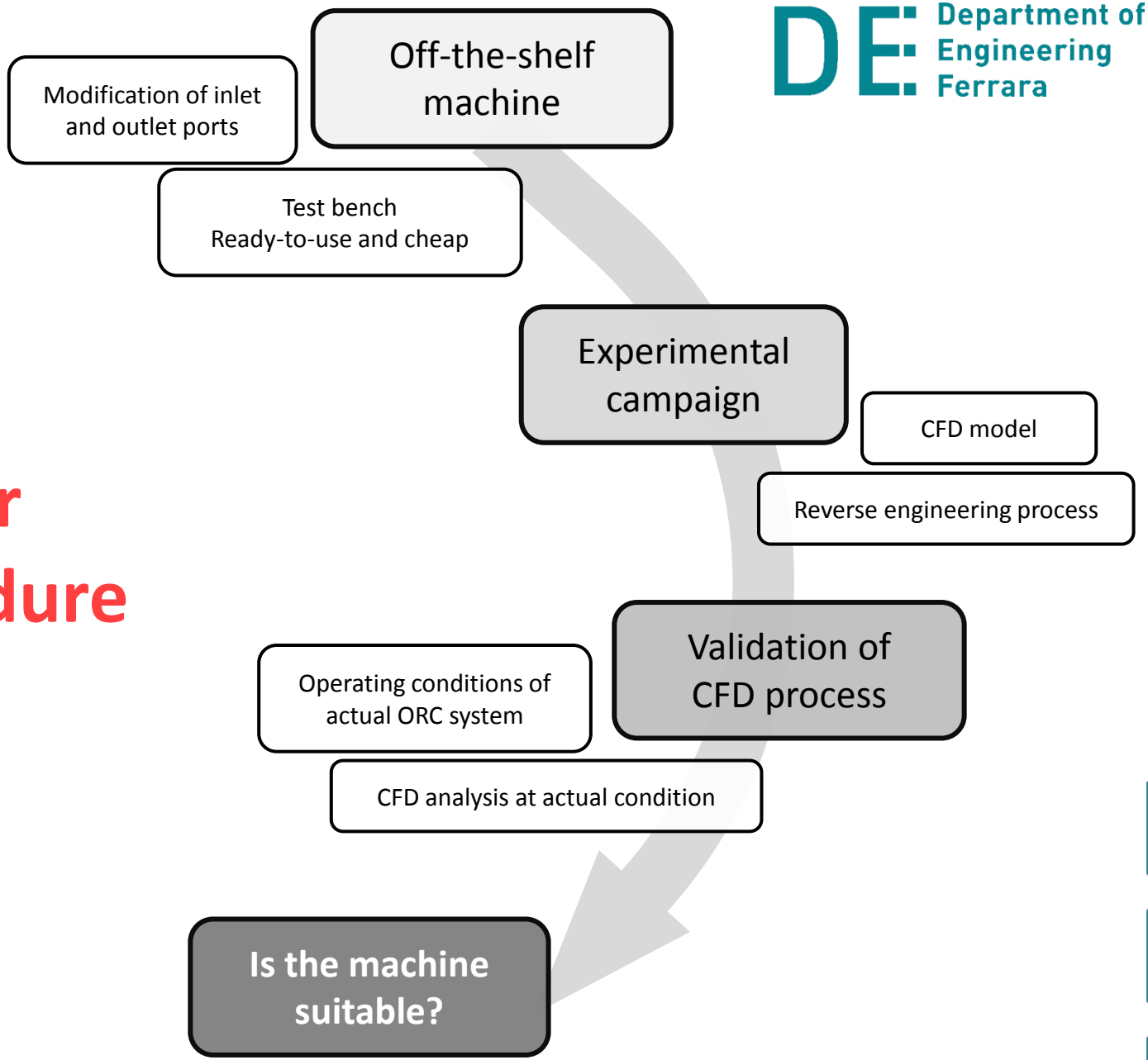
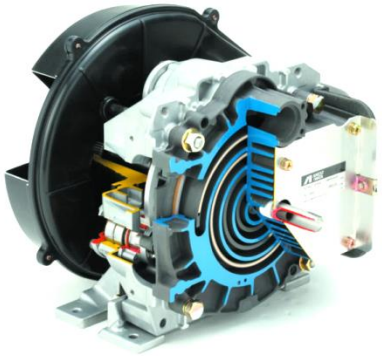
Our Procedure

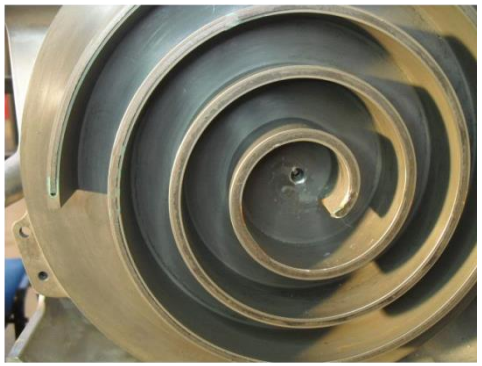


Scroll Compressor



Stator

Nominal power	5.5 kW
Volume ratio	3.5
Displacement	73,000 mm^3/rev
Rotational velocity	2600 rpm (MAX)
Flank gaps	20 – 100 µm



Rotor

Off-the-shelf machine

Experimental campaign

Validation of CFD process

Is the machine suitable?

Scroll Test Bench

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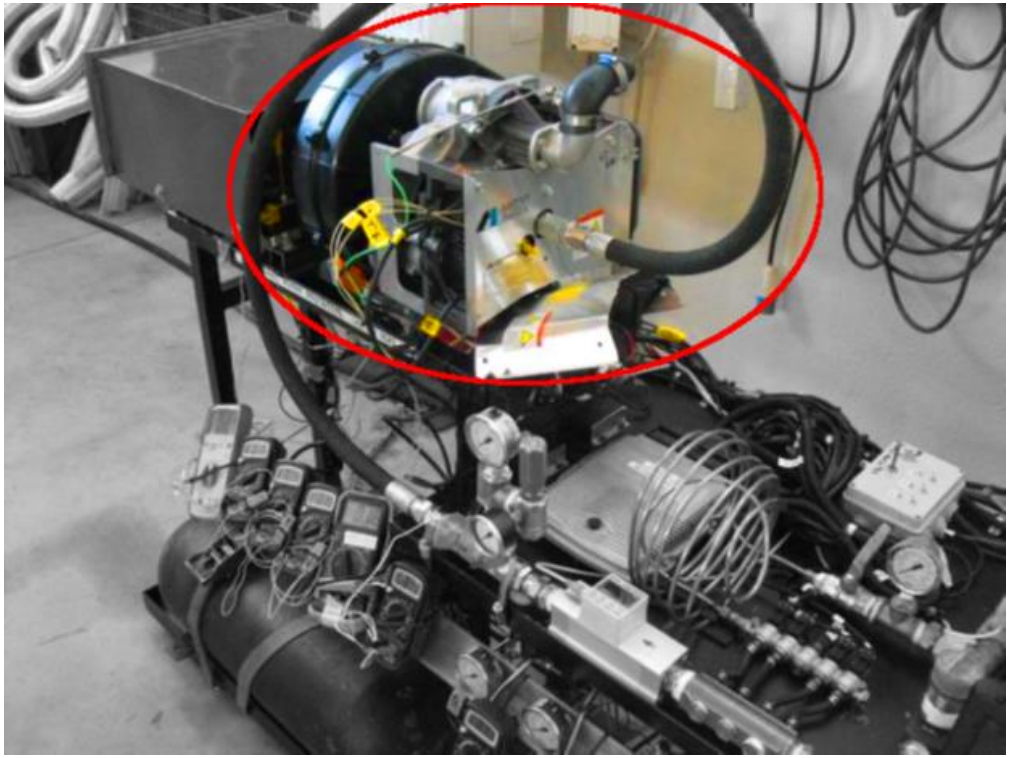

Pressure Transducers (± 0.5 % FS)

Temperature (A-class Pt100 probes)

Mass flow (± 1.8 % FS)

Load Cell (± 0.05 % FS)

Rotational speed

DAQ (± 1 K, ± 1 % R)

Operating conditions:

- Air
- p_{IN}: 7.5 bar
- T_{IN}: 292.15 K
- N: 400 rpm – 2400 rpm

Experimental Results

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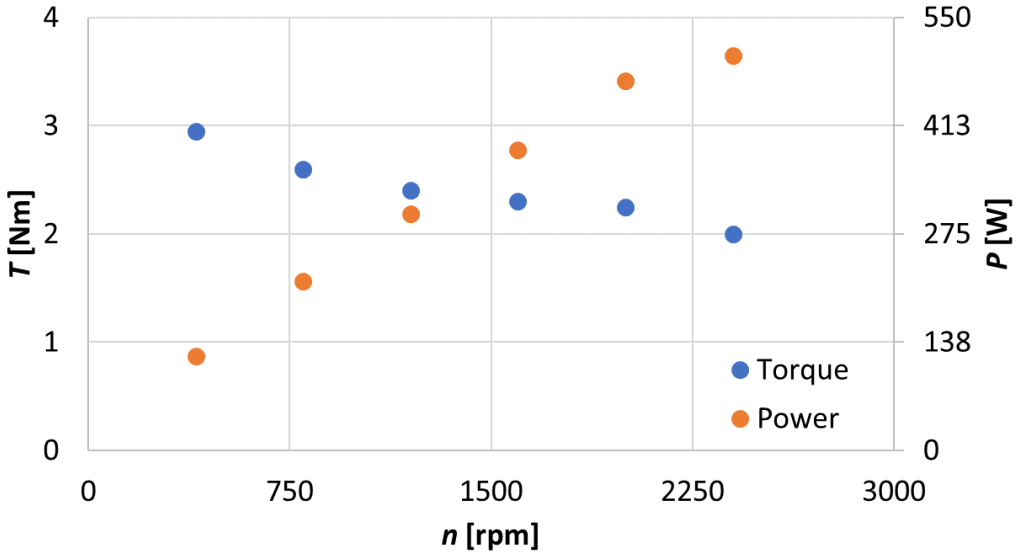

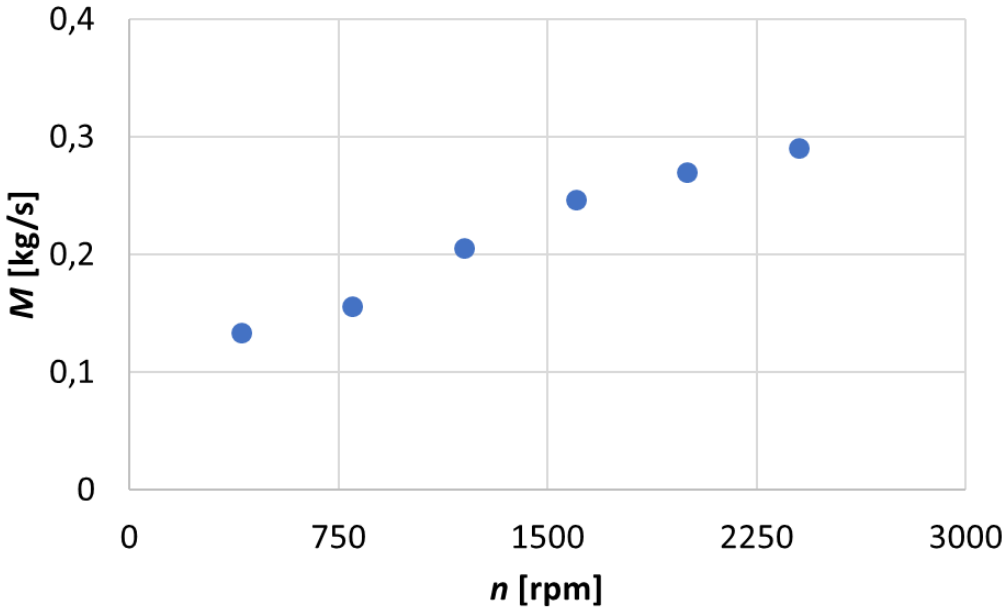

Trends were consistent with expectations

Off-the-shelf machine

Experimental campaign

Validation of CFD process

Is the machine suitable?

Model virtualization

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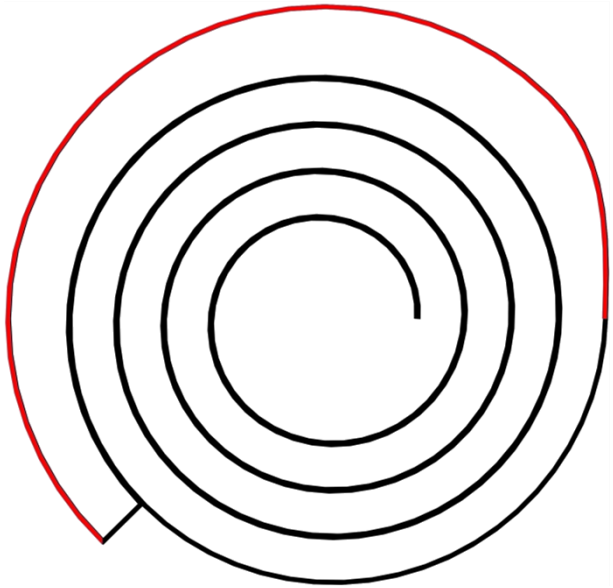
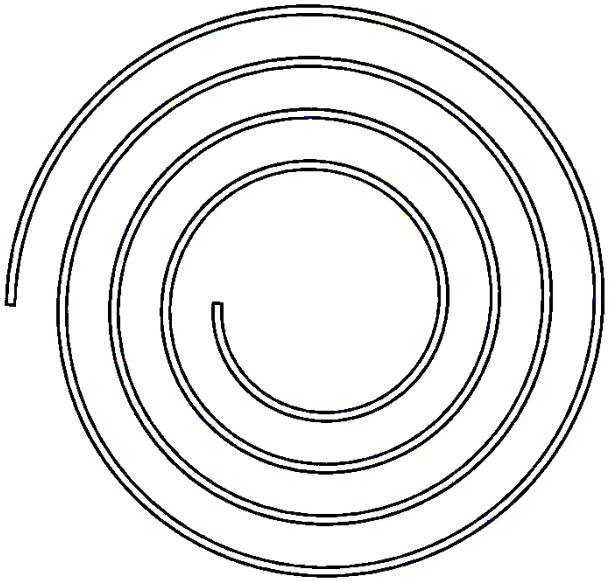
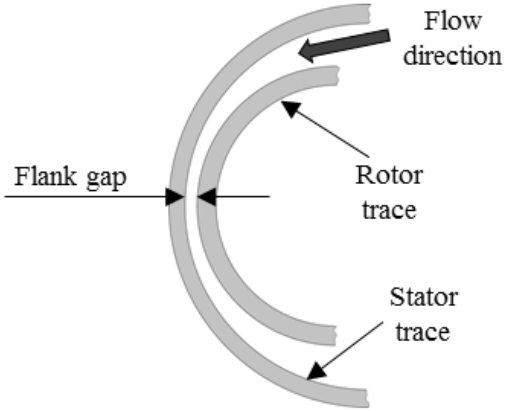
R.E. procedure





Numerical approach



Orbiting geometry with narrow **gaps**

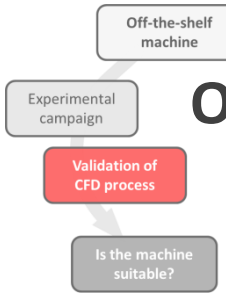
Overset mesh approach

Great effort to generate a good quality mesh

- Polyhedral elements at the core
- Prismatic cell layers on moving walls

Number of mesh elements $> 21 \cdot 10^6$

Quality > 0.2



Overset grid

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Two independent grids are used to discretize the computational domain

Moving grid has to:

- Follow the domain geometry modification by means of a rigid body motion
- Exchange information with fixed grid by means of several local “interfaces” (donor and acceptor cells)

To establish the connectivity between the grids, a two-step Overset Assembly process takes place:

1- Hole-cutting, which determines which cells are active, inactive, or acceptor cells

2- Donor Search, which ensures that donor cells are found for each acceptor cell

In a scroll machine, this process is <u>not</u> trivial!

Overset strategy applied to scroll

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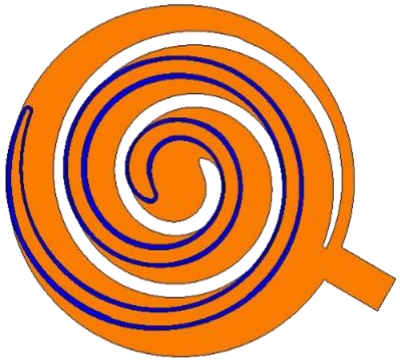
All points
(background and overlapping grid)



Active points
(called field point)

Hole points
(related to inactive cells)

Receptor (acceptor) points
(data interpolation with the overset cells)

Overset grid – 3

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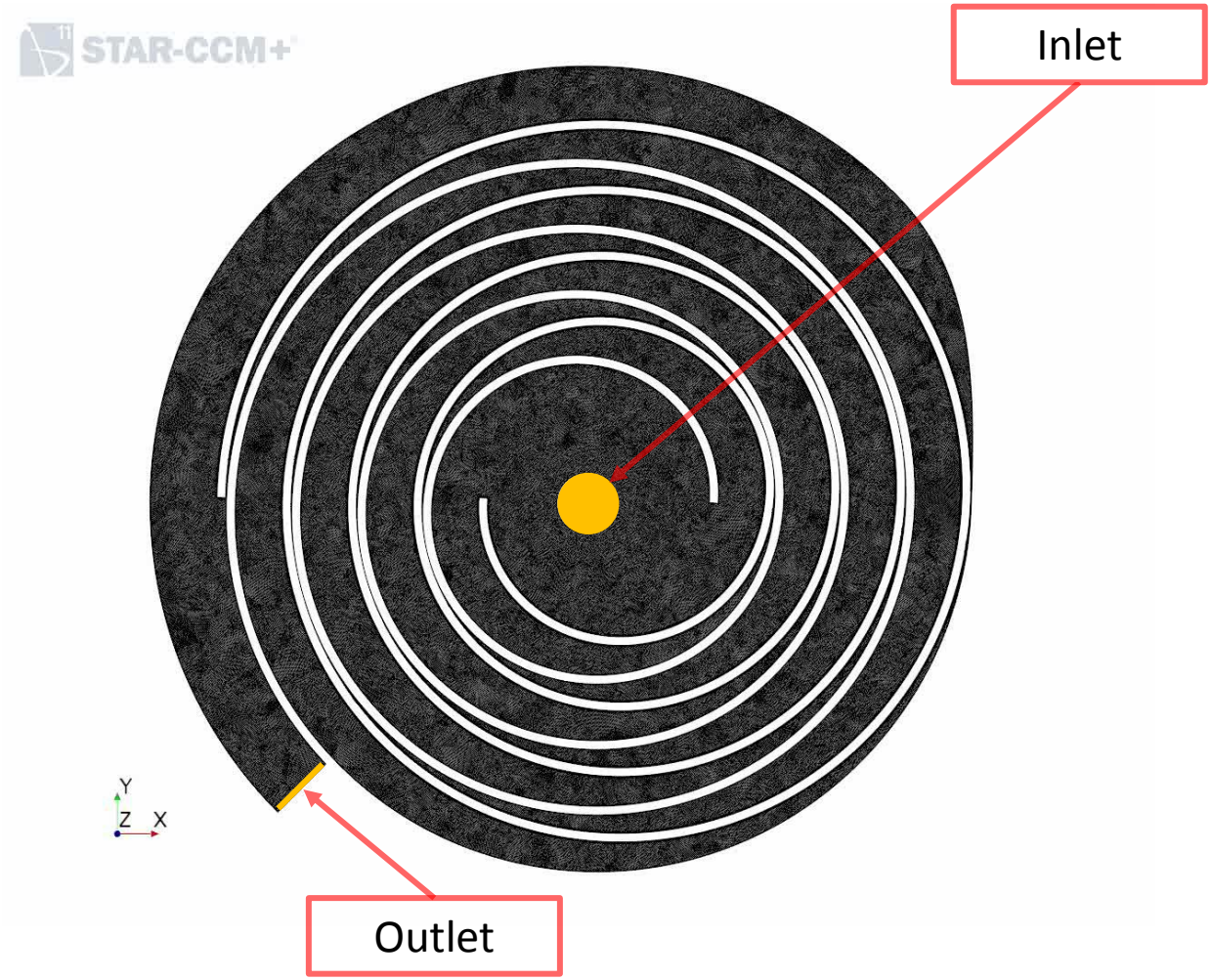

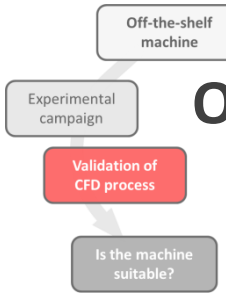

Overset grid – 4

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The **element quality** in the **gaps** is **completely defined**
(after the grid generation, each cells remains the same)

The **grid morphology** remains the **same**
(no element deformation is needed)

Matching between the Background and overset grid is **critical**
(5 elements with similar size at least)

Two numerical domains at least (background + overset)
(each moving object needs its overset grid)

Numerical model

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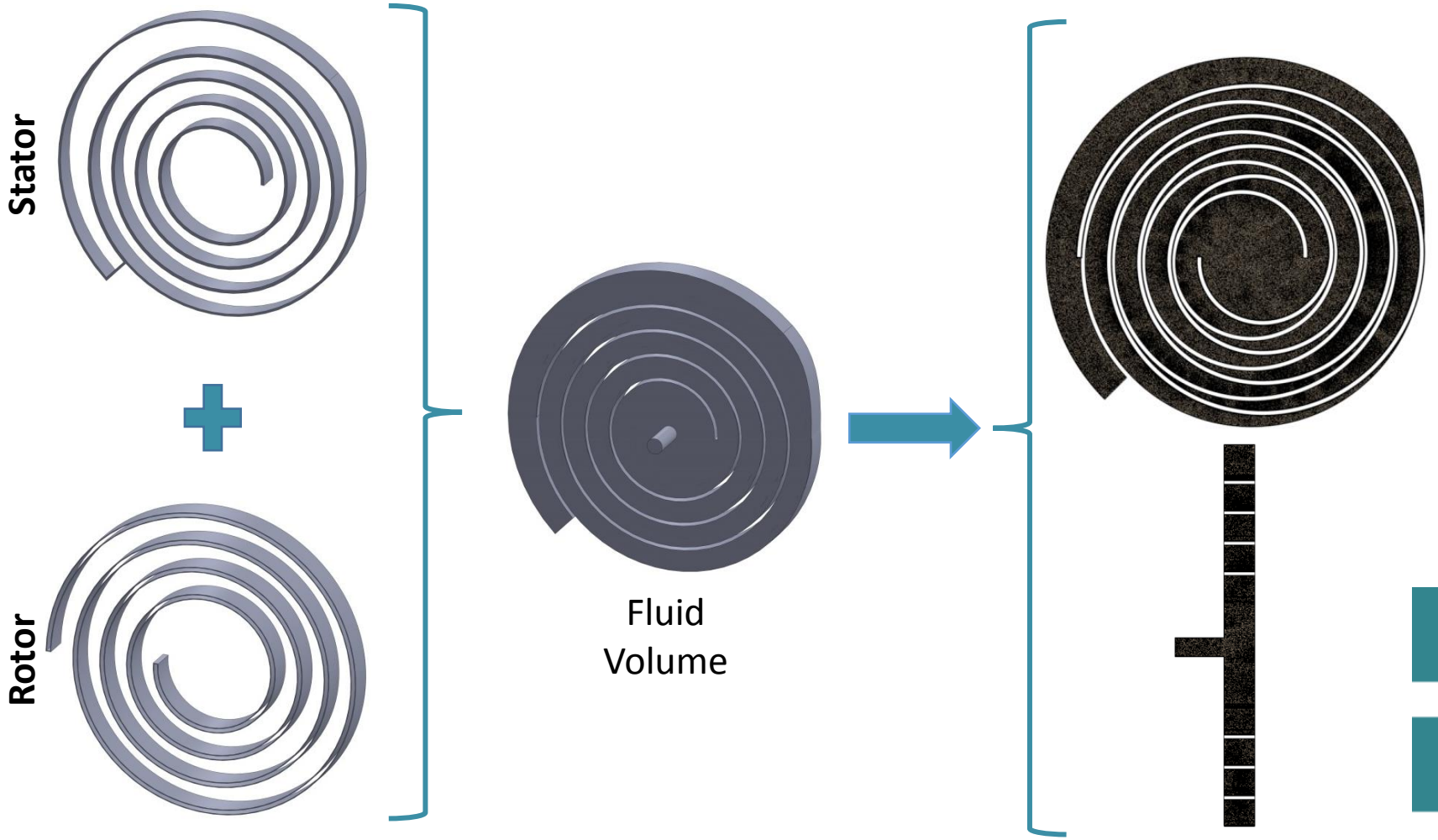

Off-the-shelf machine

Experimental campaign

Validation of CFD process

Is the machine suitable?

Numerical model

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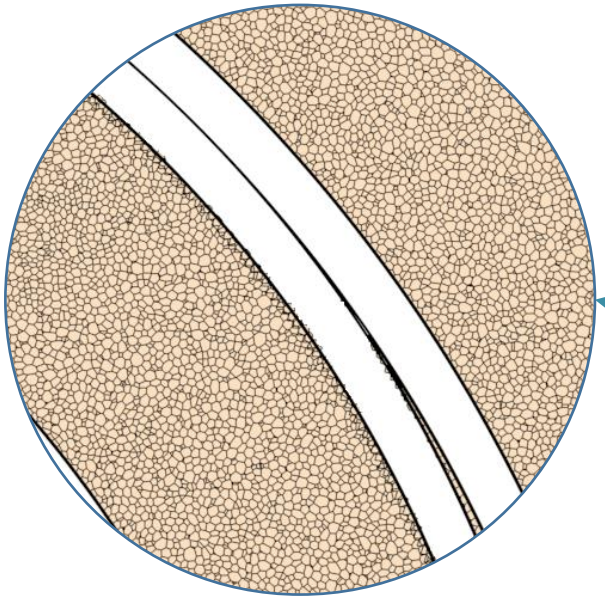

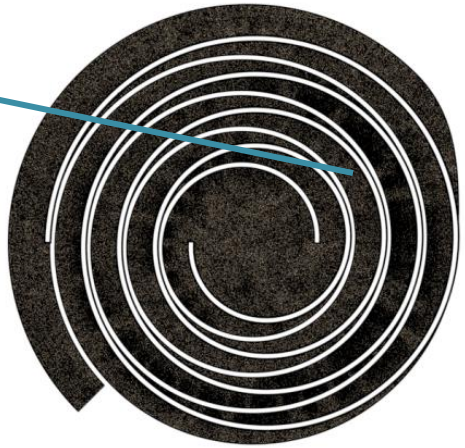

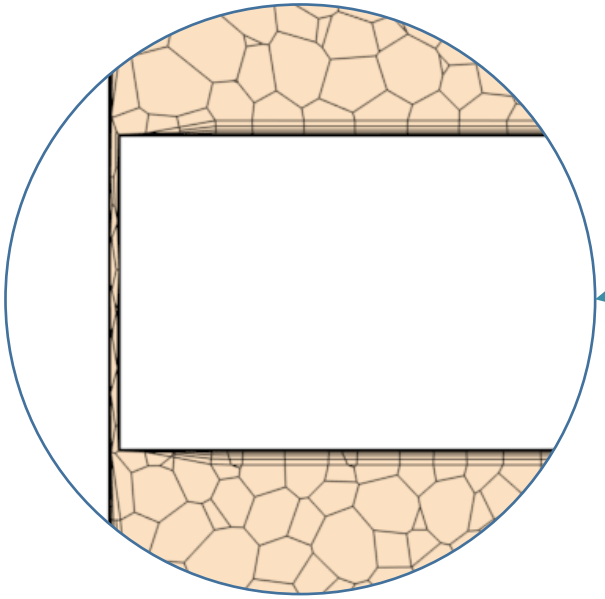

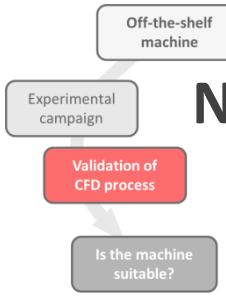

Numerical model - Air

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- Siemens STAR-CCM+ 11.02
- Flow: Compressible, 3D
- Gas: Air as a real gas
- Real gas model: Redlich-Kwong
- Turbulence model: 2nd order Realizable k-ε, two-layer y^+ wall treatment
- Temporal discretization: 1st order, $5 \cdot 10^{-6} s$ time-step
- Boundary conditions:
  - Inlet pressure: $7{,}5\ bar$
  - Inlet temperature: $292{,}15\ K$
  - Outlet pressure: $1{,}01\ bar$
  - Walls thermal specification: adiabatic.

CFD: Air – Pressure

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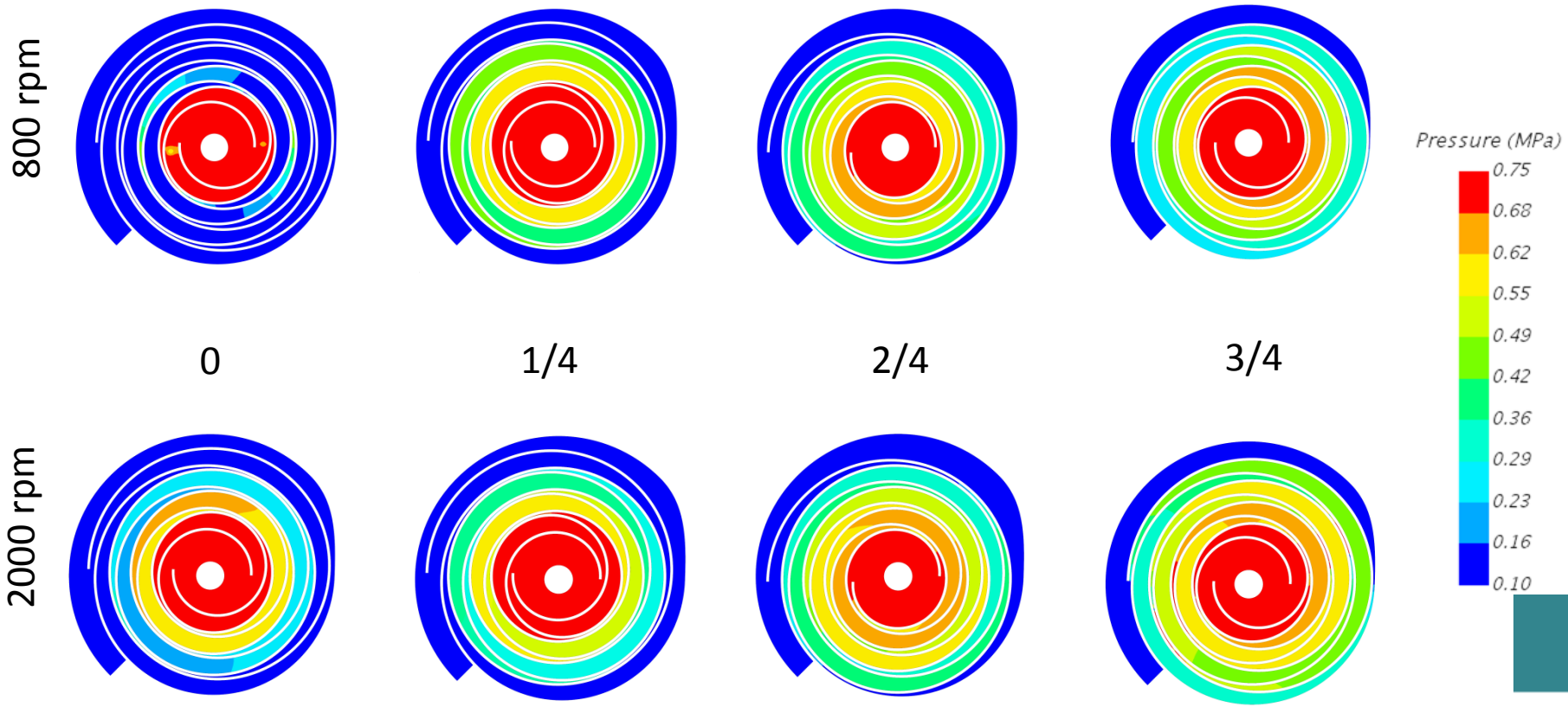
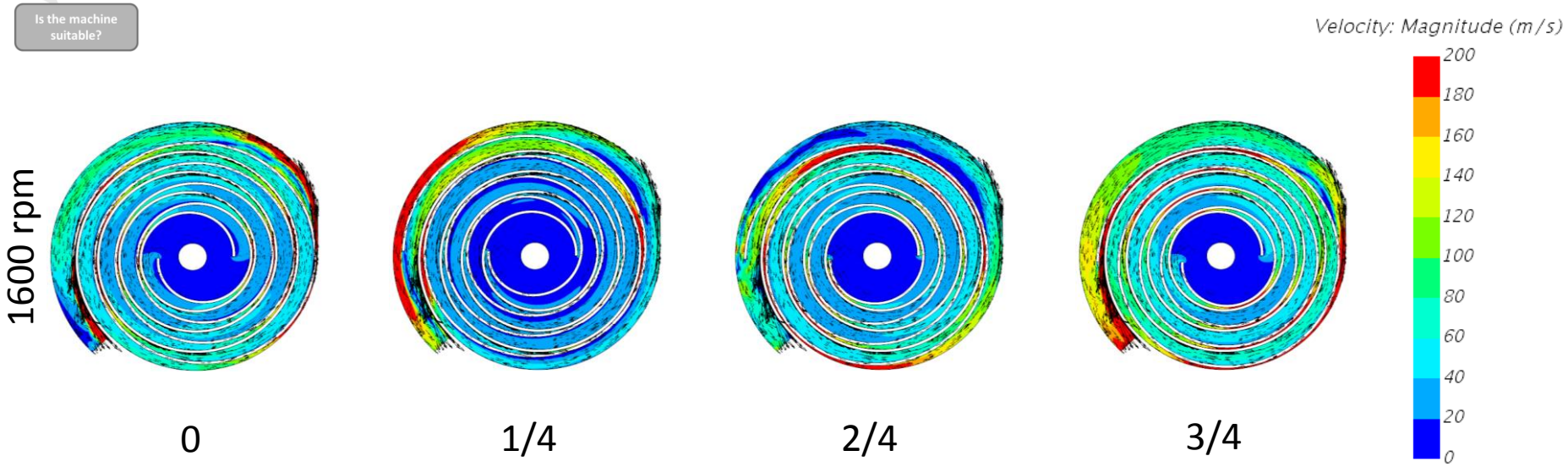


CFD: Air – Volume flow



Off-the-shelf machine

Experimental campaign

Validation of CFD process

Is the machine suitable?

CFD: Air – Volume flow

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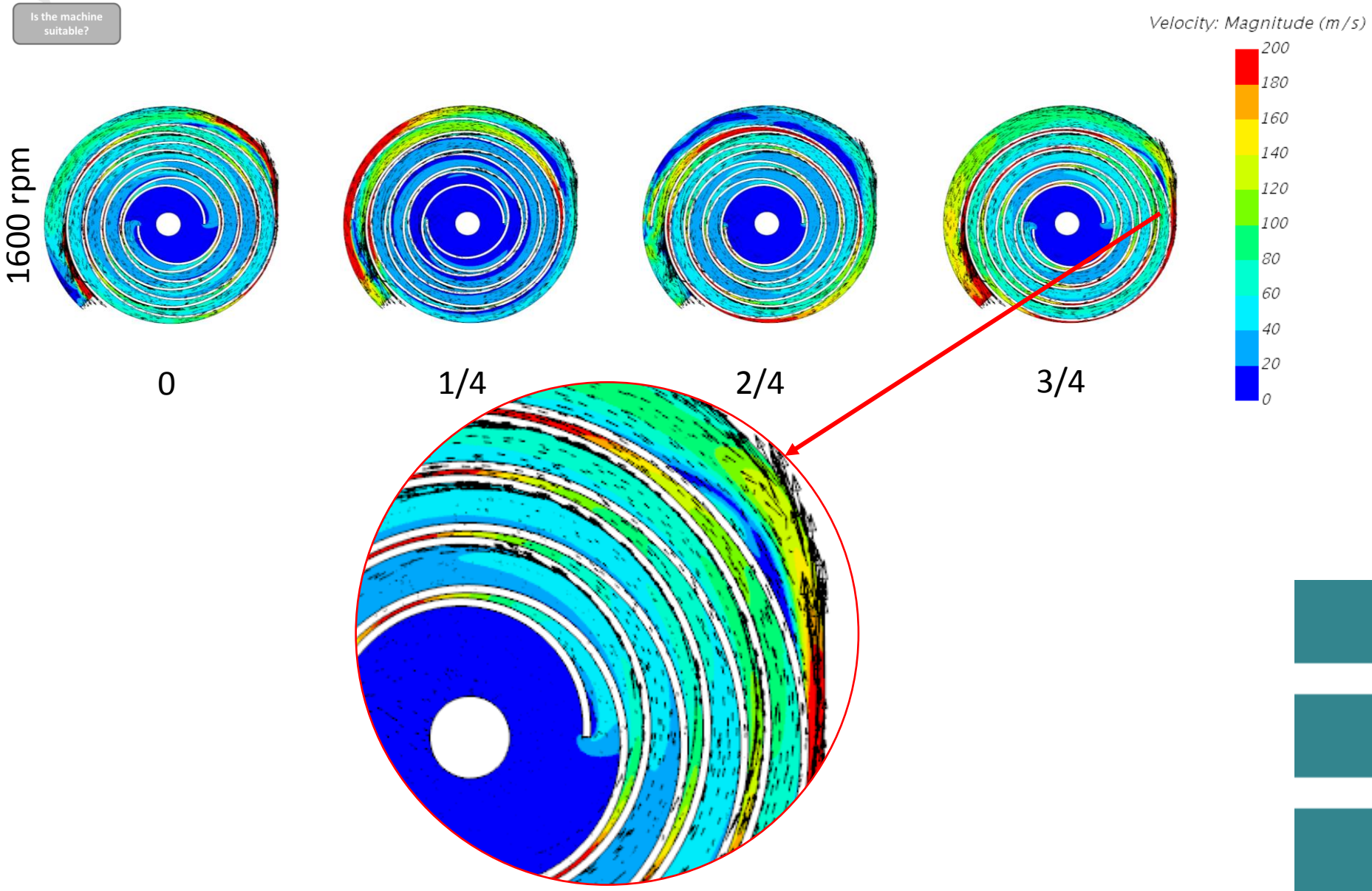

CFD: Air – Volume flow – 2

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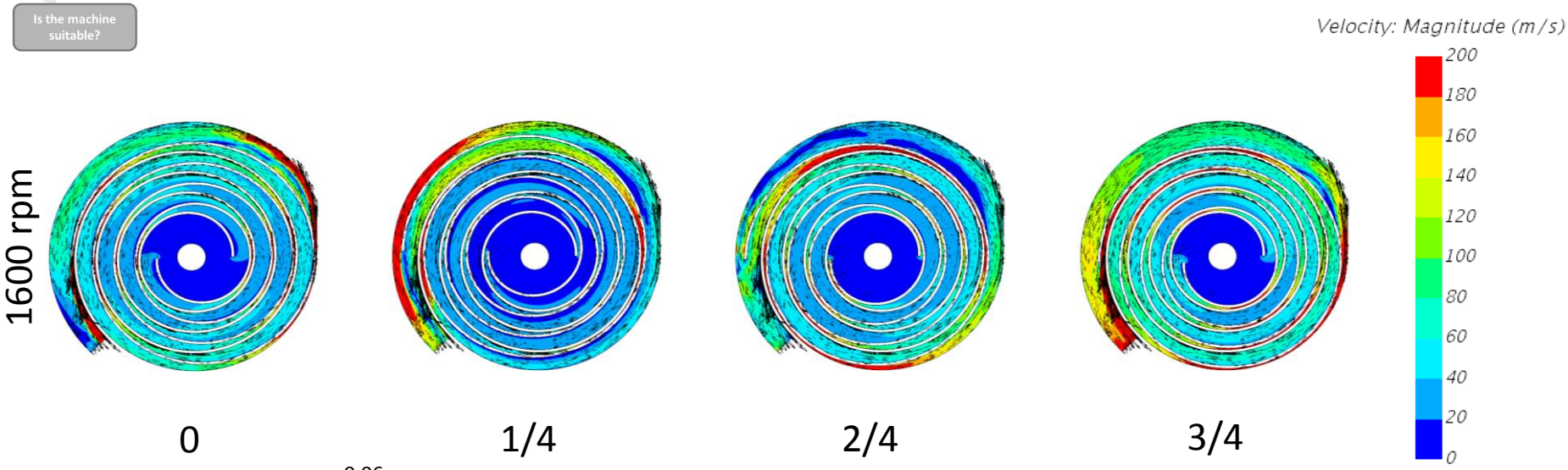

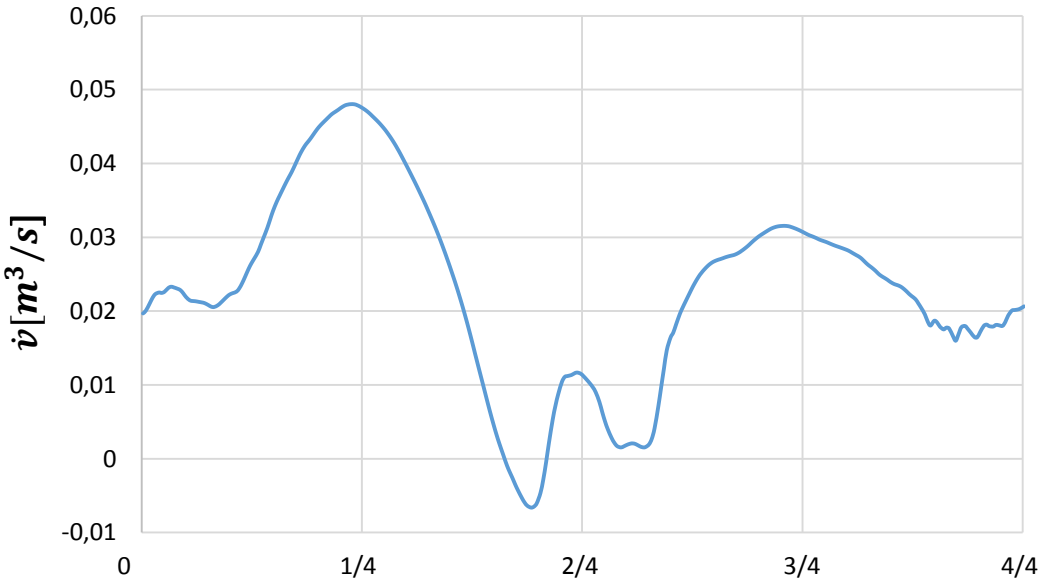

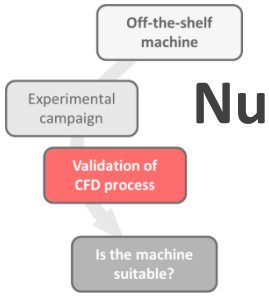

Numerical vs Experimental results

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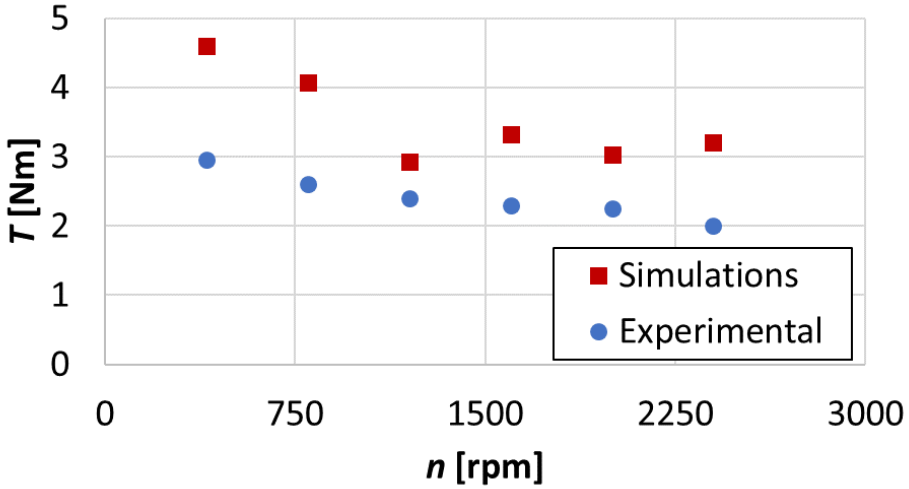

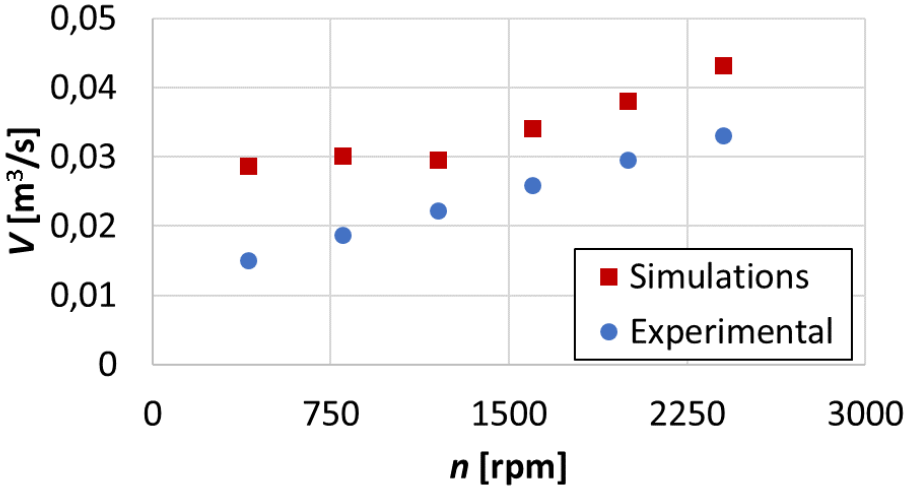

Numerical vs Experimental results

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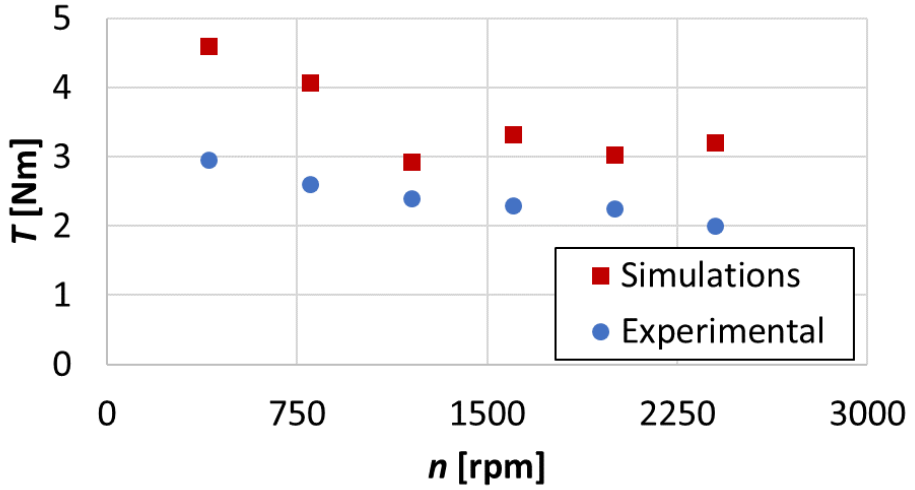

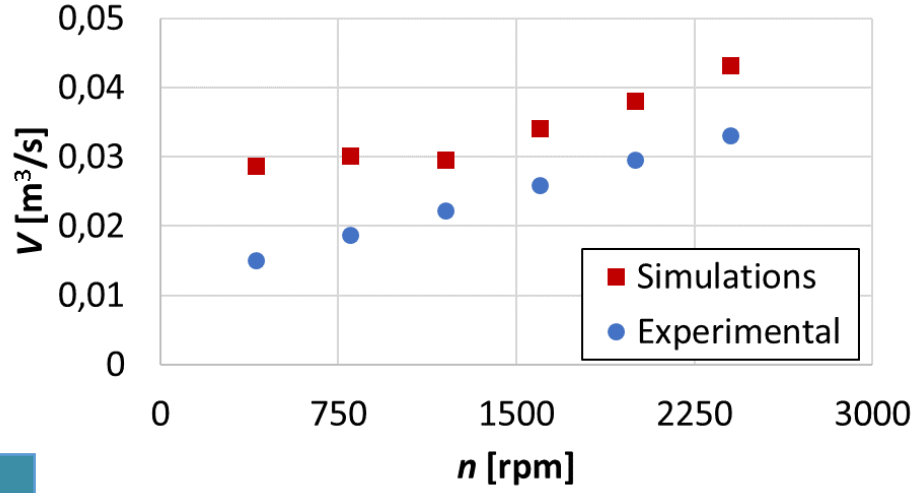

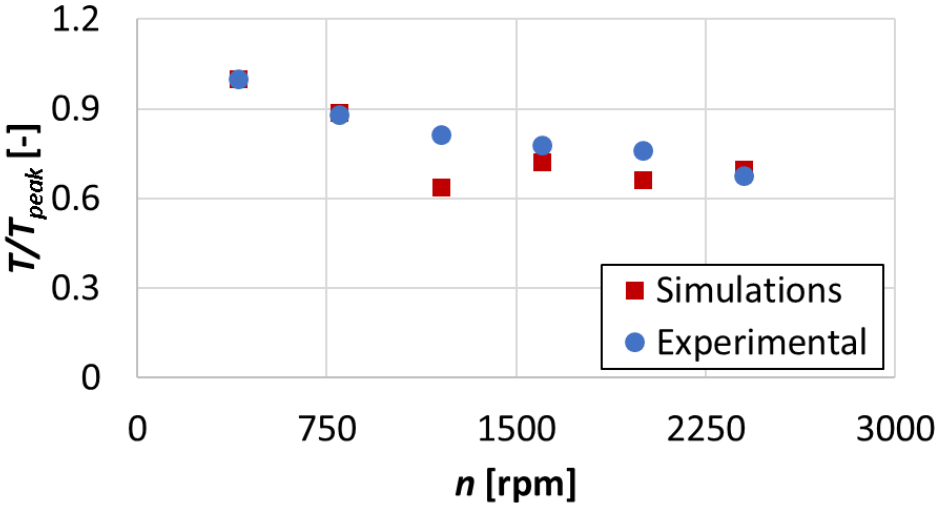

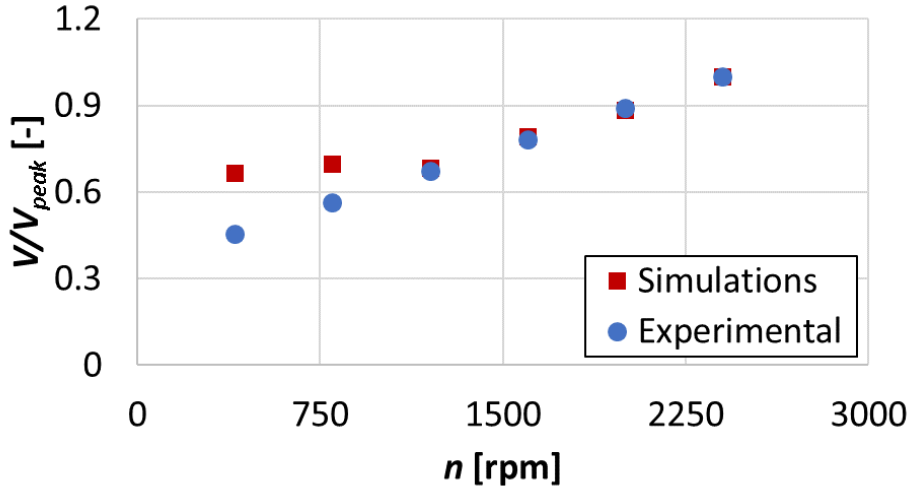

Off-the-shelf machine

Experimental campaign

Validation of CFD process

Is the machine suitable?

Application to an actual ORC system

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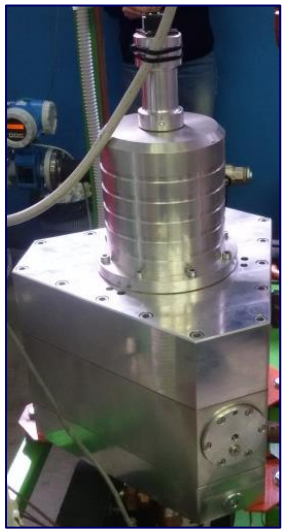
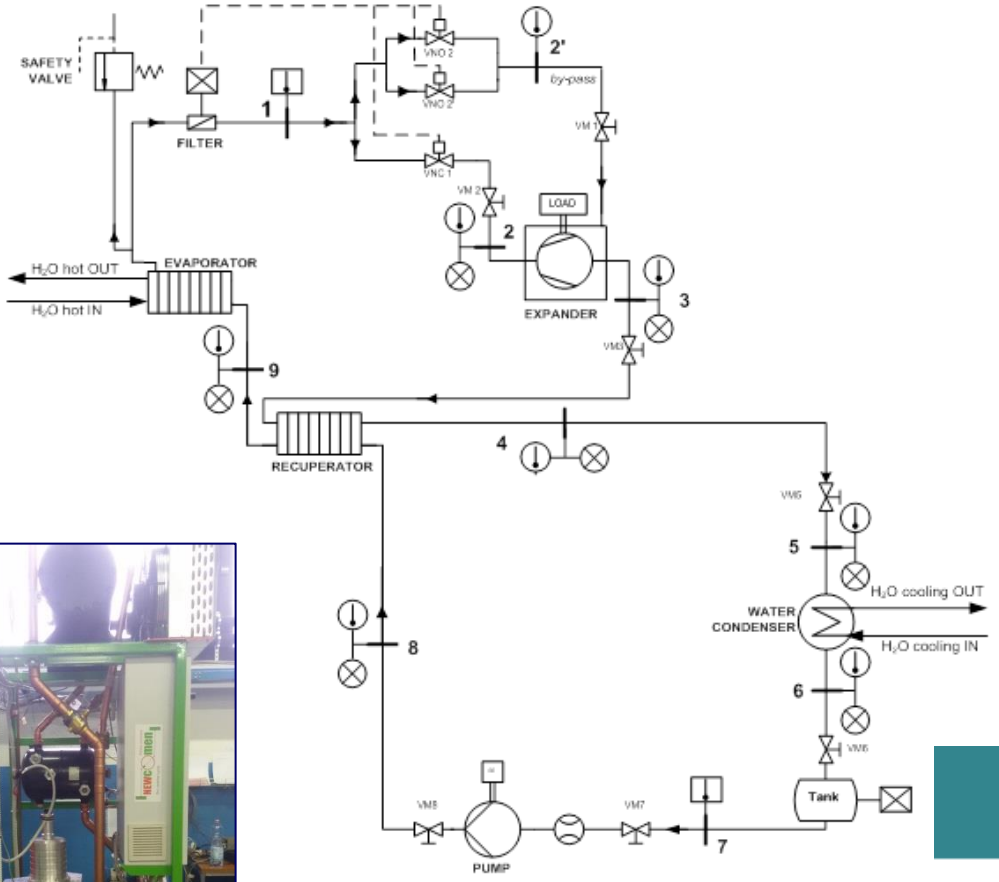


Actual expander:

Piston



Off-the-shelf machine

Experimental campaign

Validation of CFD process

Is the machine suitable?

Numerical model with R134a

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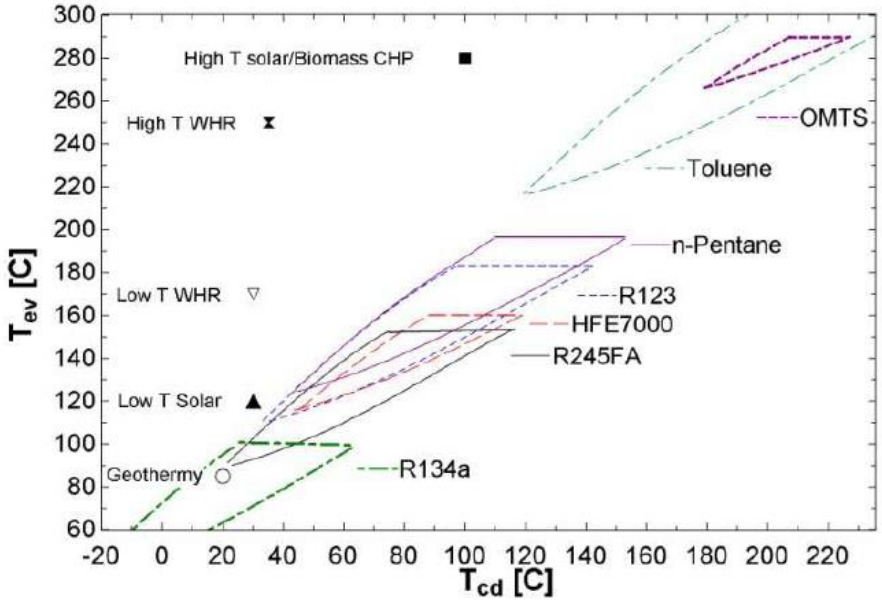
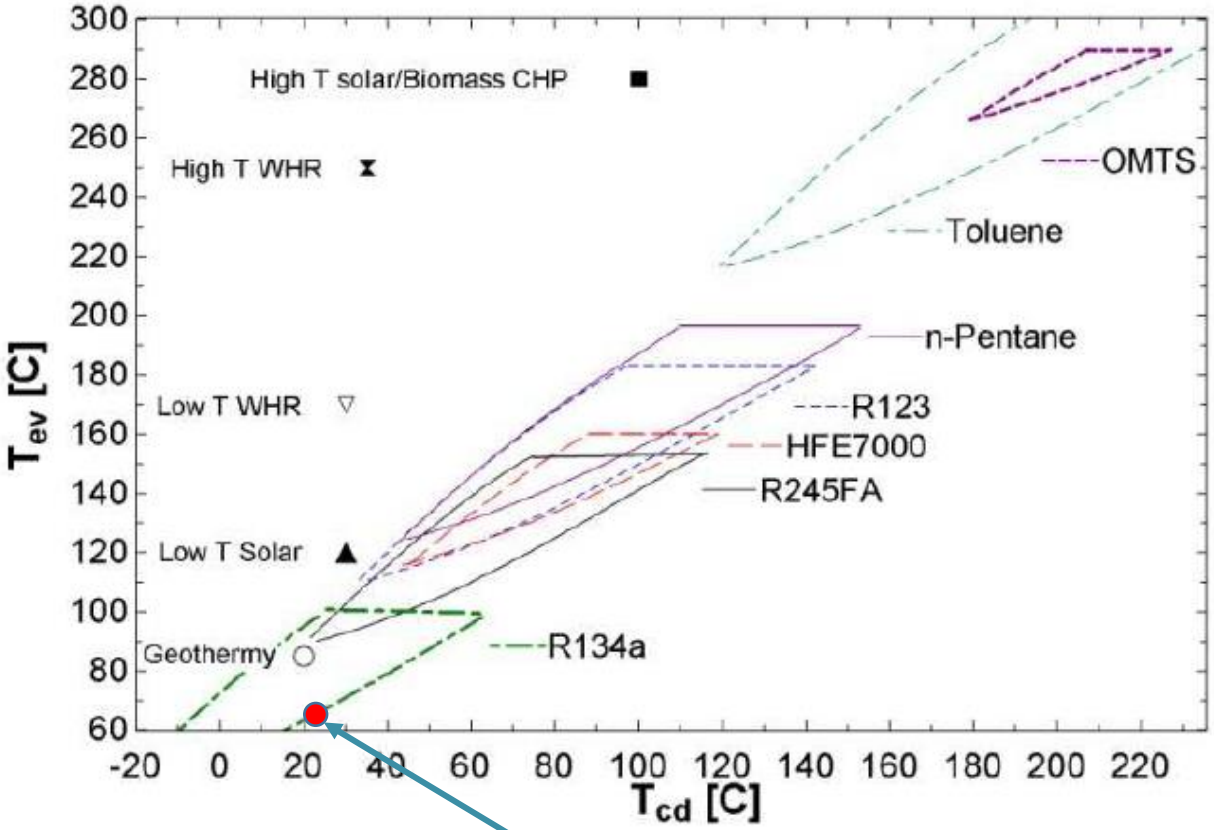
Which machine is suitable for actual operating conditions?

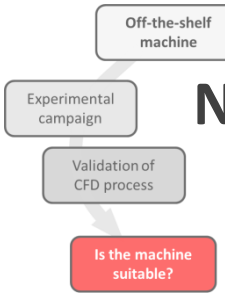


Quoilin et al. "Working fluid selection and operating maps for Organic Rankine Cycle expansion machines." *Purdue*. 2012.

Numerical model with R134a



Our cycle

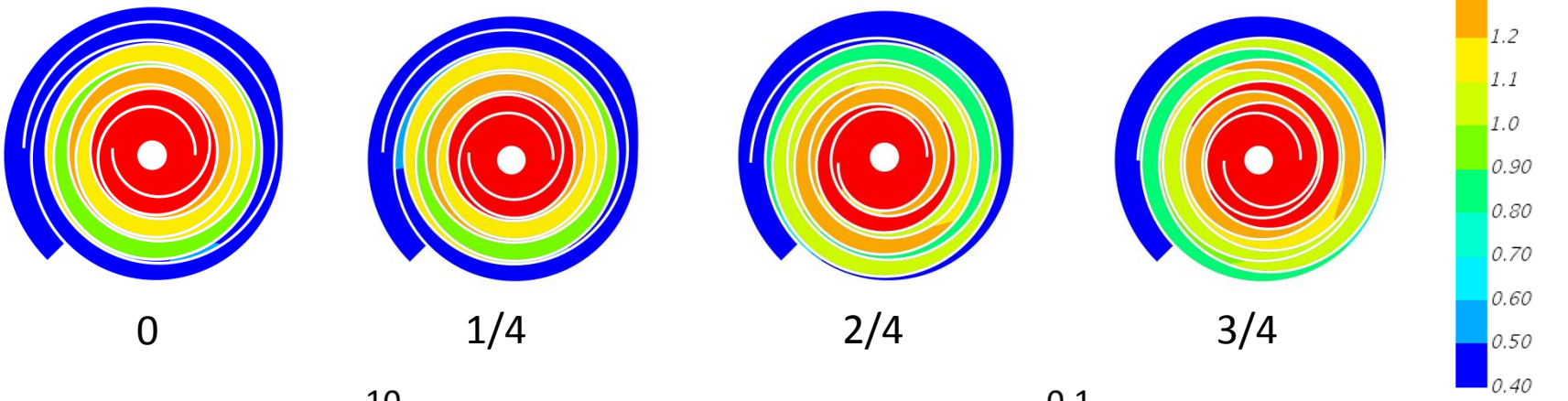


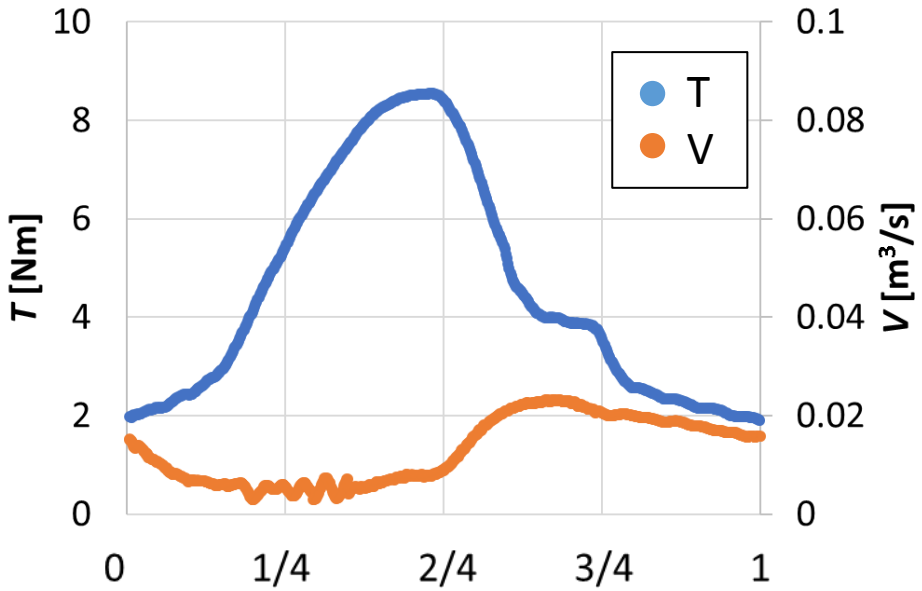
Numerical model – R134a

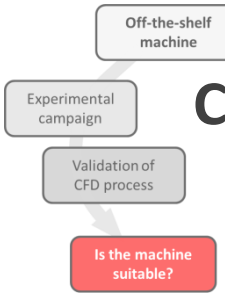
Department of Engineering Ferrara

- Siemens Star-CCM+ 11.02
- Compressible, 3D, Finite Volume Solver
- Temporal discretization: 1st order, $1 \cdot 10^{-6} s$ time-step
- Gas: R134a
- Real gas model: Redlich-Kwong
- Turbulence model: 2nd order Realizable k-ε, two-layer y^+ wall treatment
- Boundary conditions:
  - Inlet pressure: $13{,}9\ bar$
  - Inlet temperature: $338\ K$
  - Outlet pressure: $4{,}00\ bar$
  - Walls thermal specification: adiabatic.

CFD: R134a


Pressure (MPa)
1.4
1.3
1.2
1.1
1.0
0.90
0.80
0.70
0.60
0.50
0.40
0
1/4
2/4
3/4


T
V
T [Nm]
V [m³/s]
10
8
6
4
2
0
0.1
0.08
0.06
0.04
0.02
0
0
1/4
2/4
3/4
1



Conclusions

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- CFD analysis was able to capture flow and torque trends, while calculated values showed a certain deviation when compared to the measured ones
  - → Great influence of gaps and their modeling
    - Better results can be obtained by reducing gaps width in the model
      - → Greater computational effort
- CFD analysis showed fluctuations in the output torque and volume flow for the real gas expansion case
  - → Vibrations and noise are critical for household equipment

Future development

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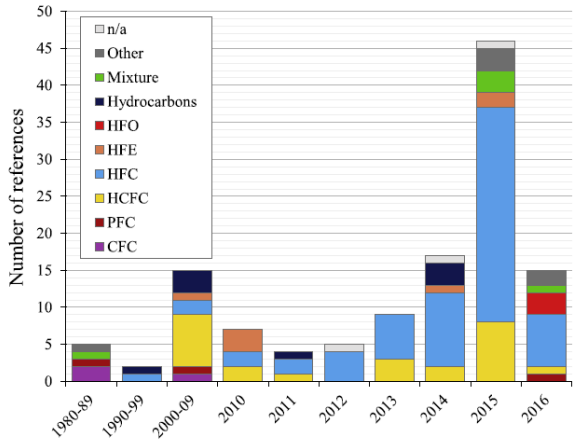
- Numerical simulations of the pump

- Expander and pump performance for different working fluids (current issue)

  → Maximize cycle efficiency



- Study of different types of expanders as cycle components

  → Single-screw expander

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Thank you

4th International seminar on ORC Power Systems

ORC 2017
13 - 15 September
MILANO, Italy