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PERFORMANCE OF A SMALL-SCALE ORGANIC RANKINE CYCLE SYSTEM USING A REGENERATIVE FLOW TURBINE: A SIMULATION ANALYSIS

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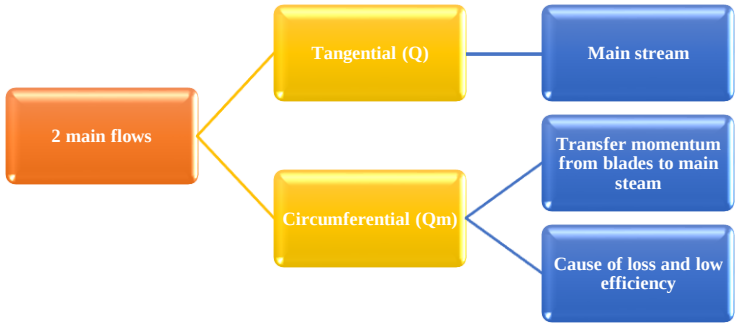
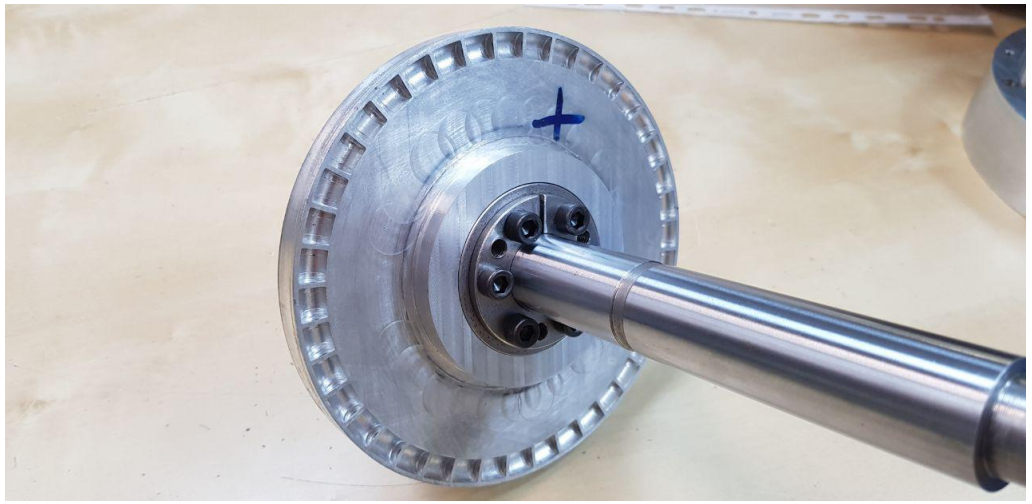
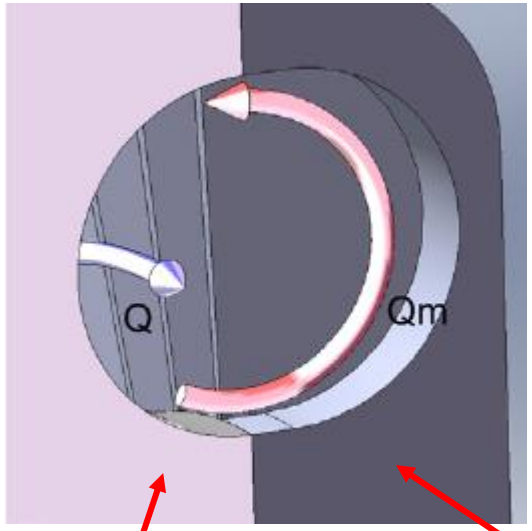


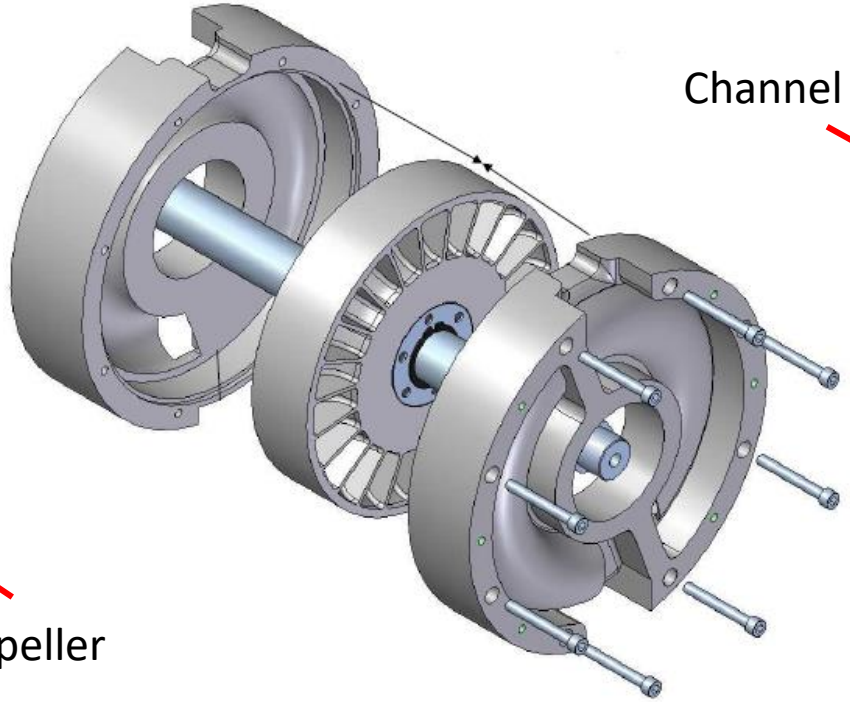
Present RFT prototype



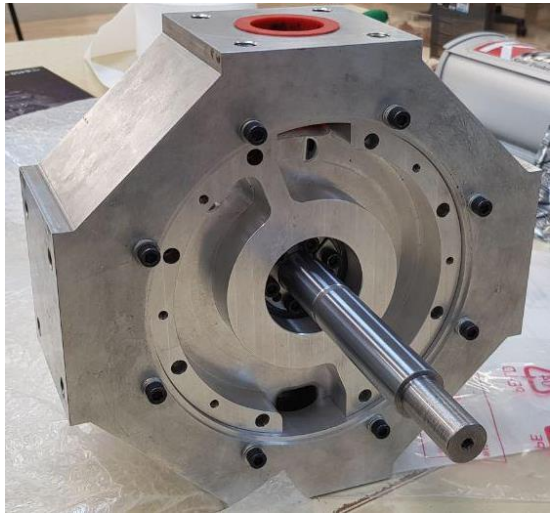


Channel

Impeller



Channel



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A low cost, reliable expander for small-scale ORC units?

A possibility is introduced here:
Regenerative flow (RF) turbo-machines, also known with other names such as peripheral, side channel, tangential, vortex, and turbulence turbo-machines

- **RF turbo-machines**
  - **Advantages**
    - **High heads in low flow rates** → suitable for lubrication, control, filtering and booster systems
    - **Low speeds**
    - **Can work with highly variable flow rates** → suitable for vehicles, gas pipelines
    - **Can work with 2-phase flow** → suitable to operate with hot or volatile liquids as pump, or in small-scale cryogenic cycles as compressors
    - **low maintenance**
    - **Low cost** → suitable for small-scale plants
    - **Compact & reliable**
  - **disadvantages**
    - **Low Efficiency** →

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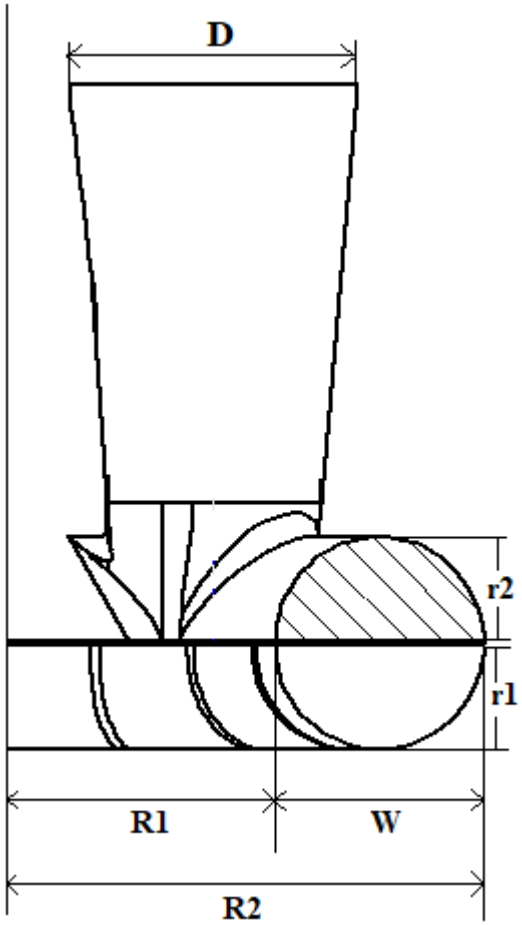
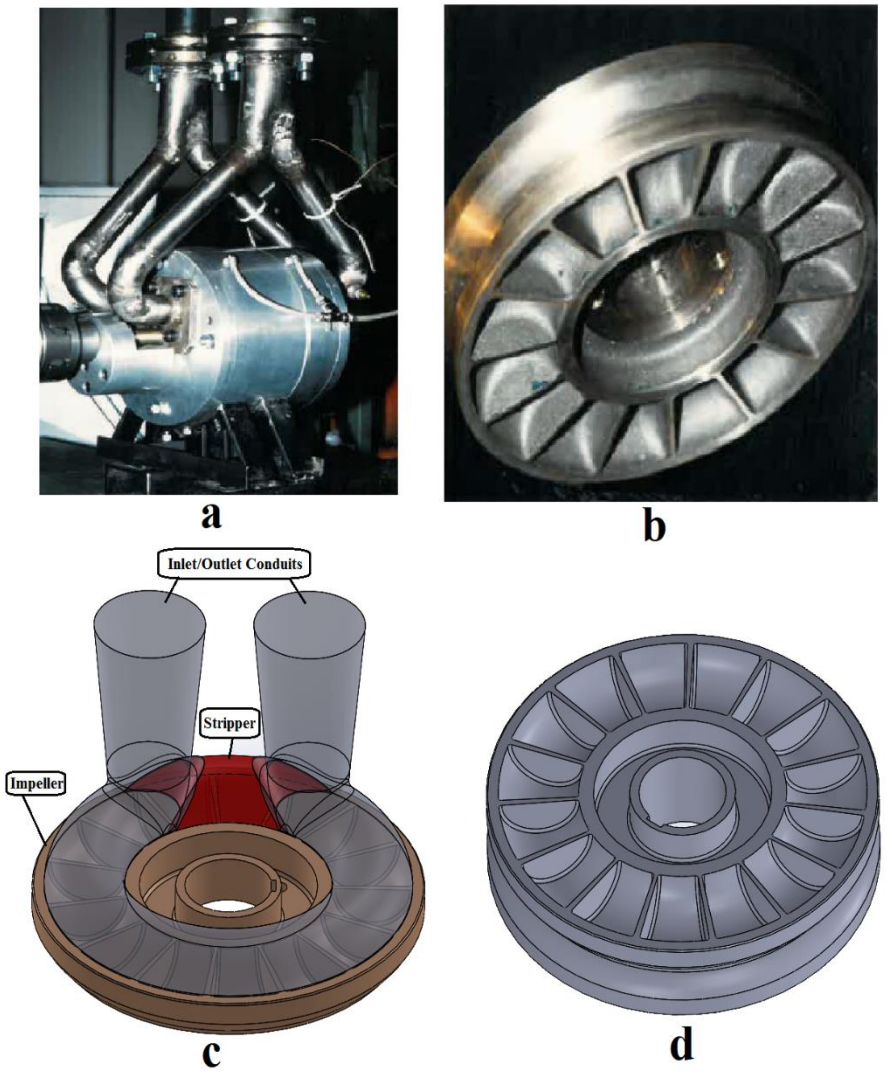
Geometry of CFD

Normalized dimensions of the RFT

D/W	R1/W	R2/W	r2/W	r1/W	$(\pi D_m)/(n \cdot W)$
1.388	1.292	2.292	0.5	0.5	0.75





Experimental apparatus (a and b) [1], and 3D model (c and d)

[1] Fabio Balducci, Carlo M. Bartolini. INDAGINE SPERIMENTALE SUL CAMPO FLUIDODINAMICO INTERNO ALLE TURBINE A CANALE PERIFERICO. Energy department. University of Ancona, Ancona, Italy, 1992. pp. 110-3.

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Simulation of RFT with **air**

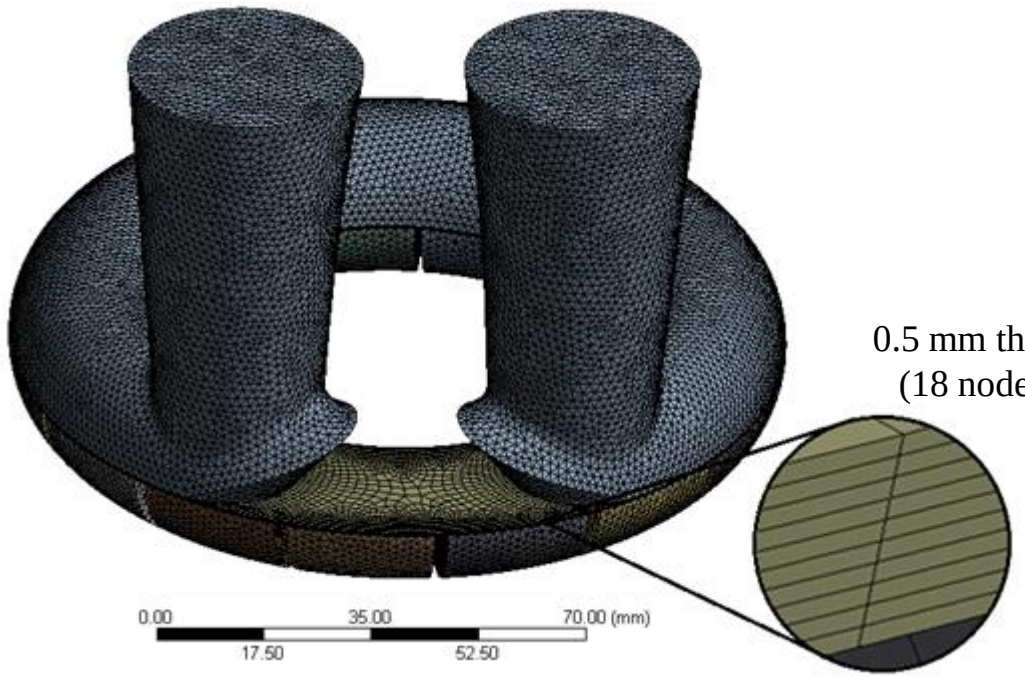
Assumptions:

- Steady state
- Ideal gas density model
- Sutherland three-coefficient model for viscosity
- Negligible axial and radial leakage
- Adiabatic machine

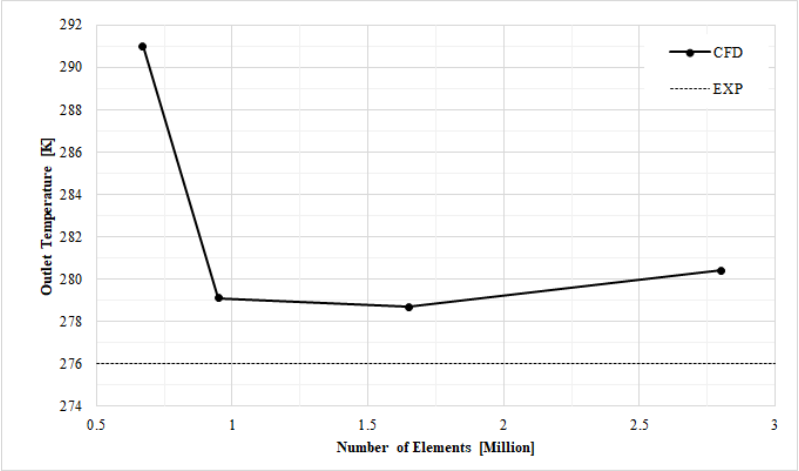
CFD Model:

- RSM_BSL model
- MRF model (Frozen Rotor)
- Pressure-velocity coupling scheme: PISO
- Pressure discretization scheme: PRESTO!
- Inlet BC: Mass flow & Temperature
- Outlet BC: Pressure & Temperature

Mesh domain



0.5 mm thickness
(18 node/mm)



Variation of the outlet temperature with mesh density

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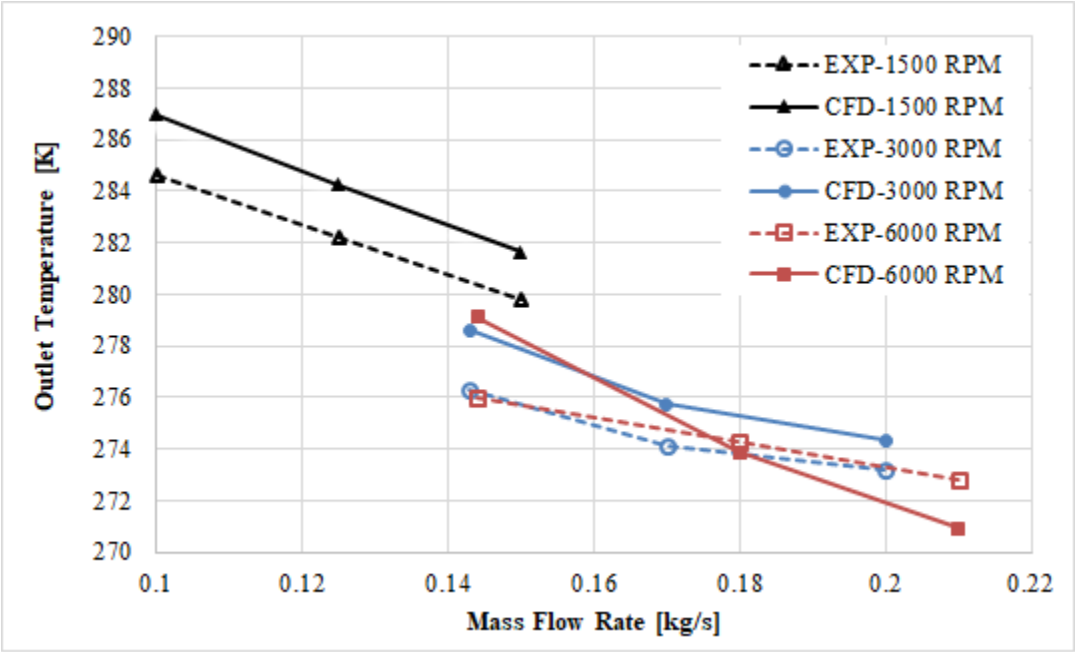
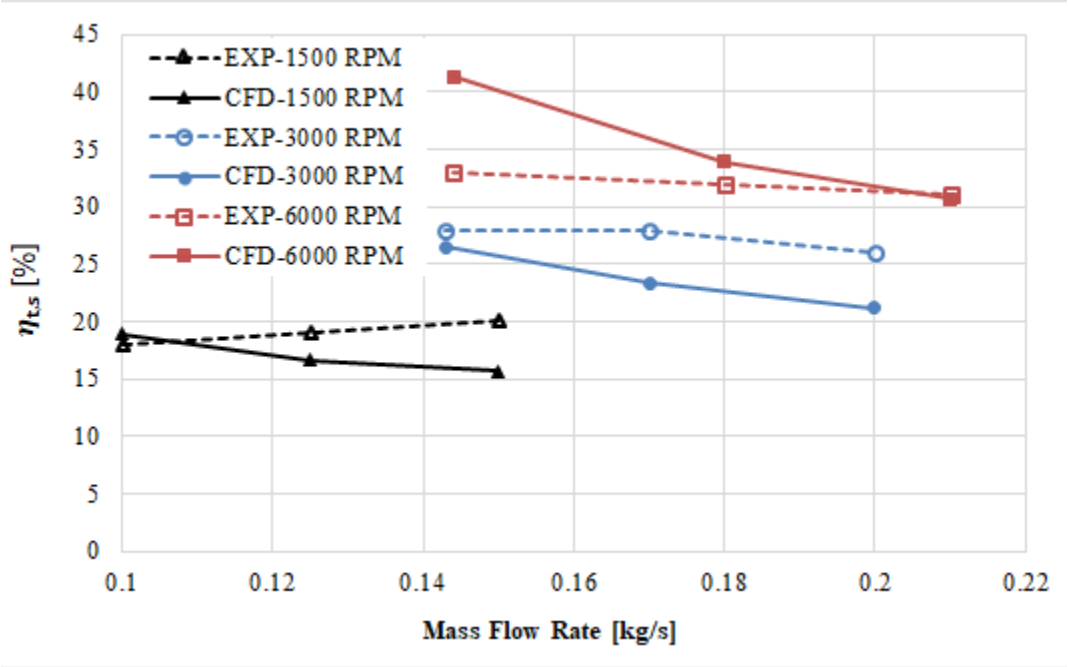
Model **Validation** with experimental data [1] (**air**)





Comparison of outlet temperature (left) and isentropic efficiency (right) between CFD results and experimental data [1]

[1] Fabio Balducci, Carlo M. Bartolini. INDAGINE SPERIMENTALE SUL CAMPO FLUIDODINAMICO INTERNO ALLE TURBINE A CANALE PERIFERICO. Energy department. University of Ancona, Ancona, Italy, 1992. pp. 110-3.

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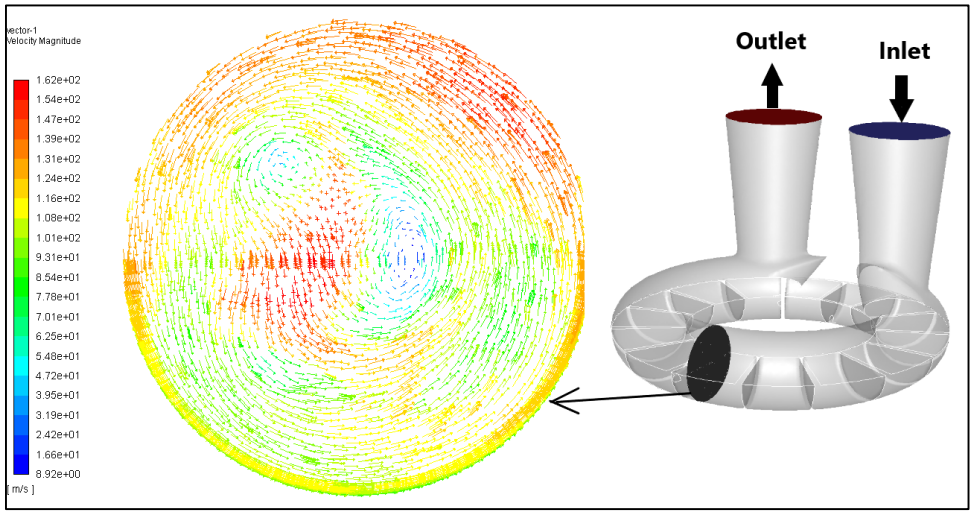
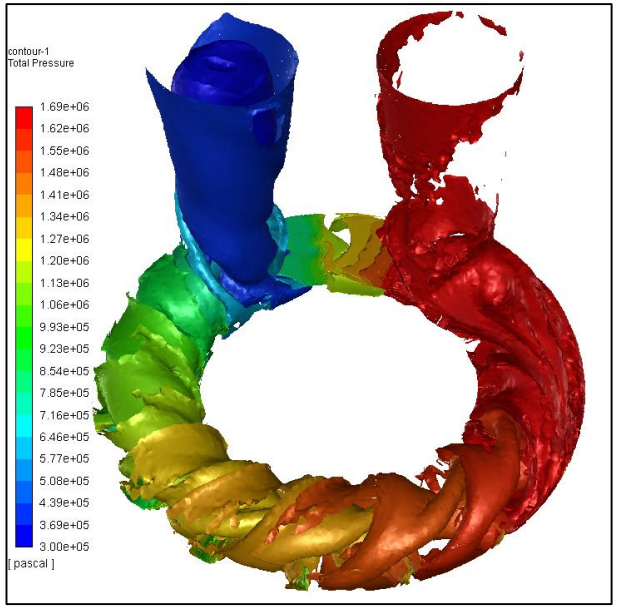
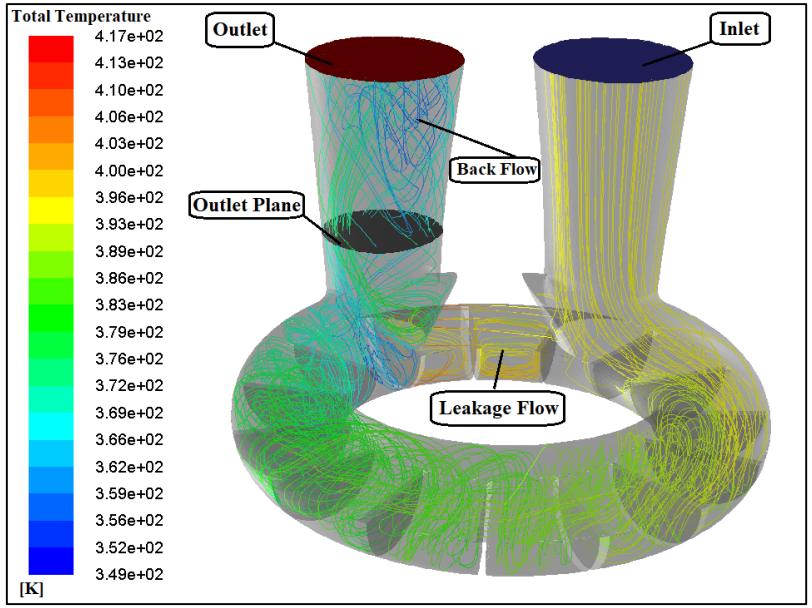
Flow Visualization (**air**)



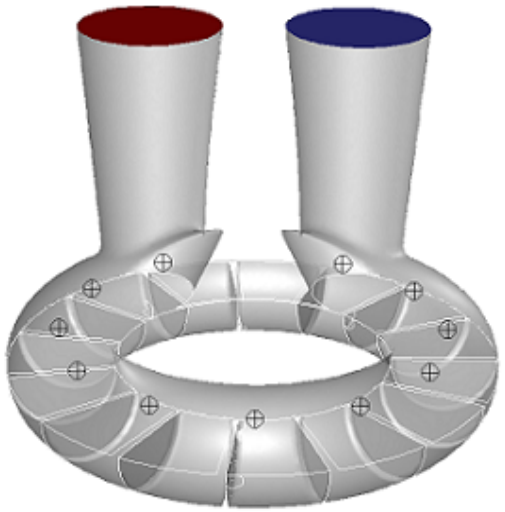
Velocity vectors in a typical cross section plane in the channel



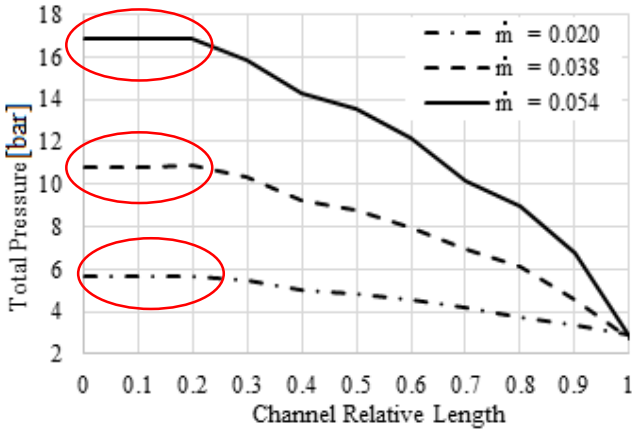
Iso-pressure surfaces



Streamlines colored by the total temperature of the flow



(a)



(b)

a) position of sample points along the channel, b) Variations of total pressure along the channel at 3000 RPM (BM=0.08) and different flow rates

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Simulation of RFT with **R245fa**

Same geomnetry, mesh and model settings of the model with air, except for density:

- Peng-Robinson real gas model for density
- BC temperarture and pressures similar to a typical ORC unit
- The range of the mass flow rate is determined from CFD results of the RFT considering the maximum suction pressure 20 bar (equivalent of PR of about 6.5)

Boundary conditions of the CFD model

Inlet BCs		**Outlet BCs**		**RPM**
Mass flow (kg/s)	Temperature (°C)	Pressure (bar)	Temperature (°C)	
0.3-0.9	120	3	90	1500, 3000, 6000

Total-to-static isentropic efficiency

$$\eta_{t,s} = W_{act}/W_{is} = (h_{01}-h_{02})/(h_{01}-h_{2s})$$

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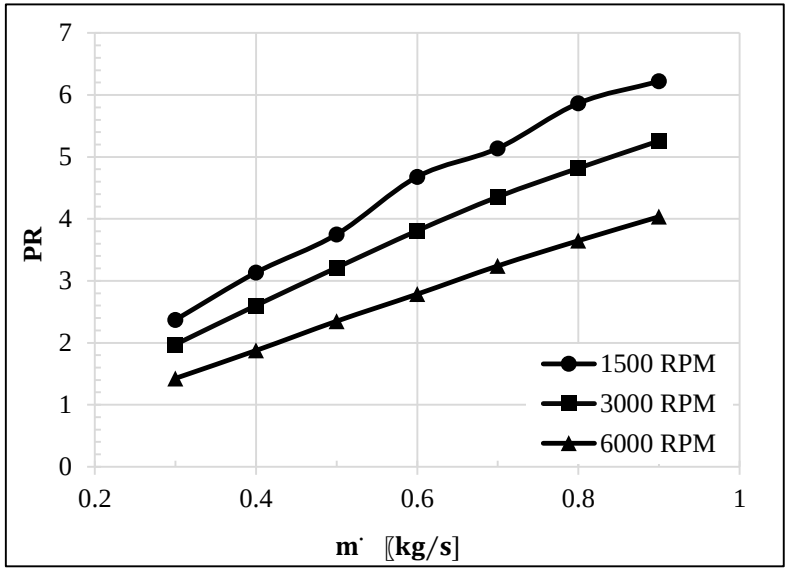
Simulation of RFT with **R245fa**

Total pressure ratio (PR)

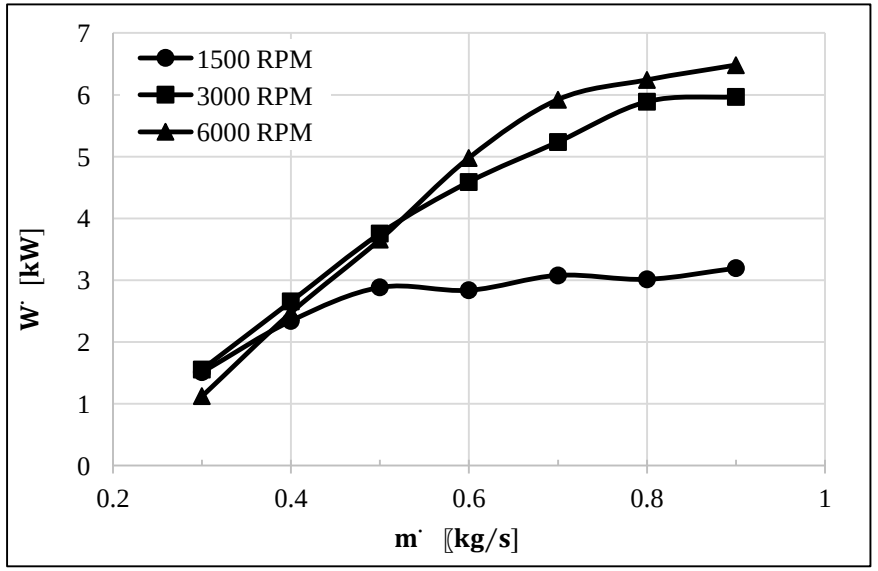
- Linaer increase of PR with mass flow rate
- The PR is higher at the lower rotational speed, in contrast to traditional turbines → due to void effect in the channel



The total pressure ratio by the mass flow rate in different RPMs

Output power

- The power of the RFT increases almost linearly with an increment of the mass flow rate up to a certain point



Output Power by mass flow rate in different RPMs

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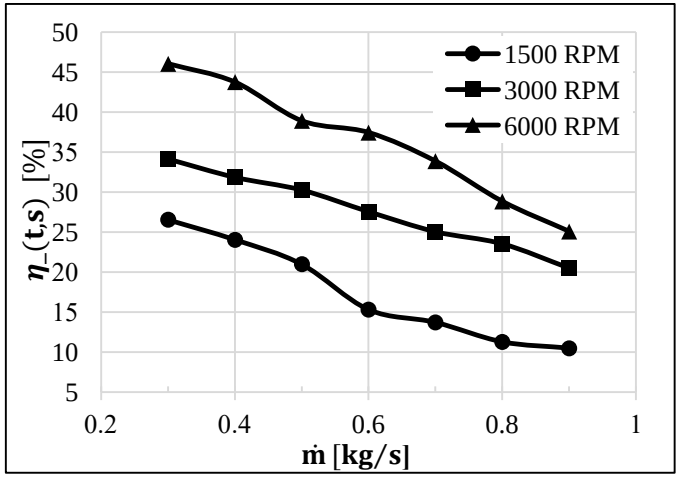
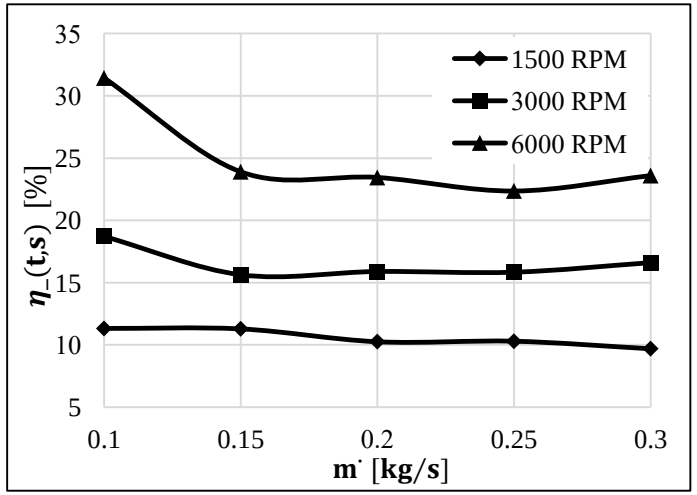
Simulation of RFT with **R245fa**

Total-to-static isentropic efficiency

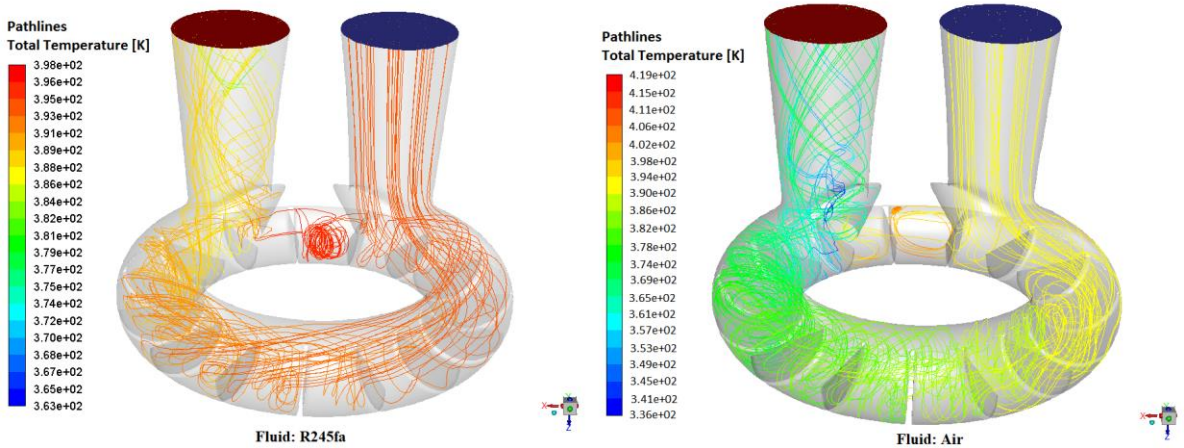
- Relatively low isentropic efficiency compared to commercially available positive displacement expanders or dynamic turbines
- Higher isentropic efficiency working with R245fa compared to air → due to higher molecular weight of R245fa → weaker swirl → less losses



Isentropic efficiency by the mass flow rate (**R245fa**)



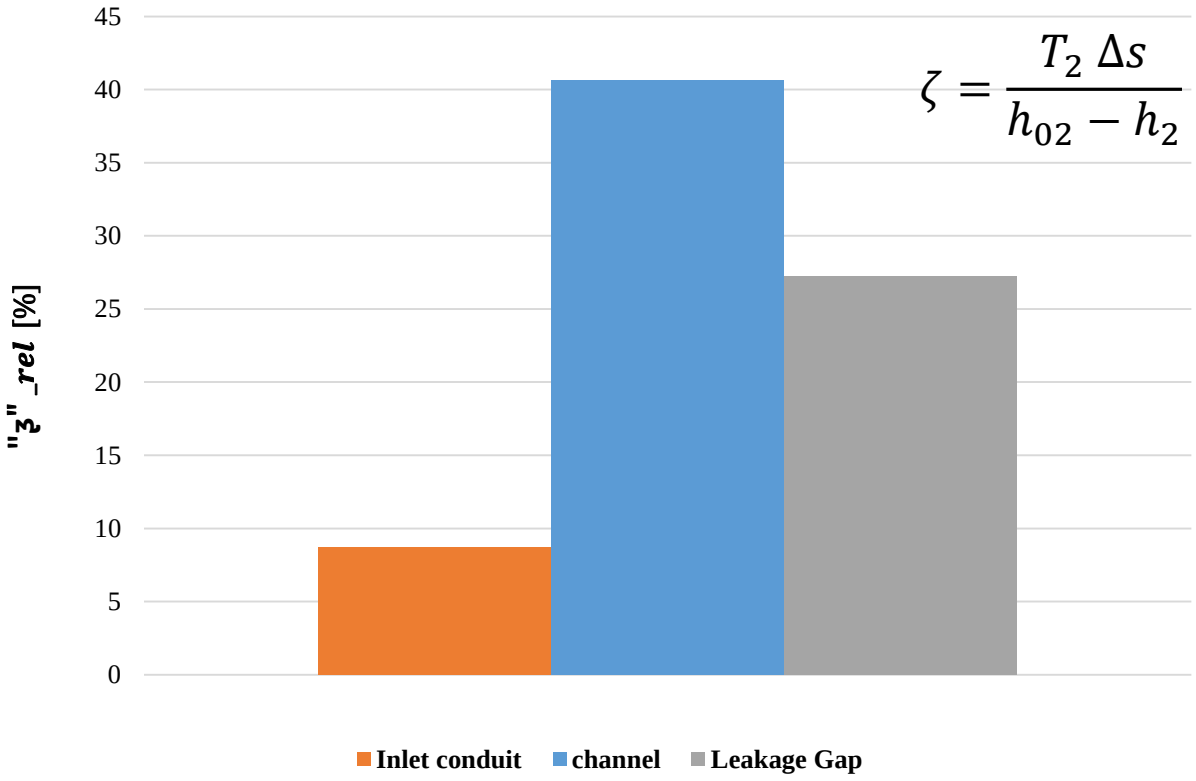
Isentropic efficiency by the mass flow rate (**Air**)

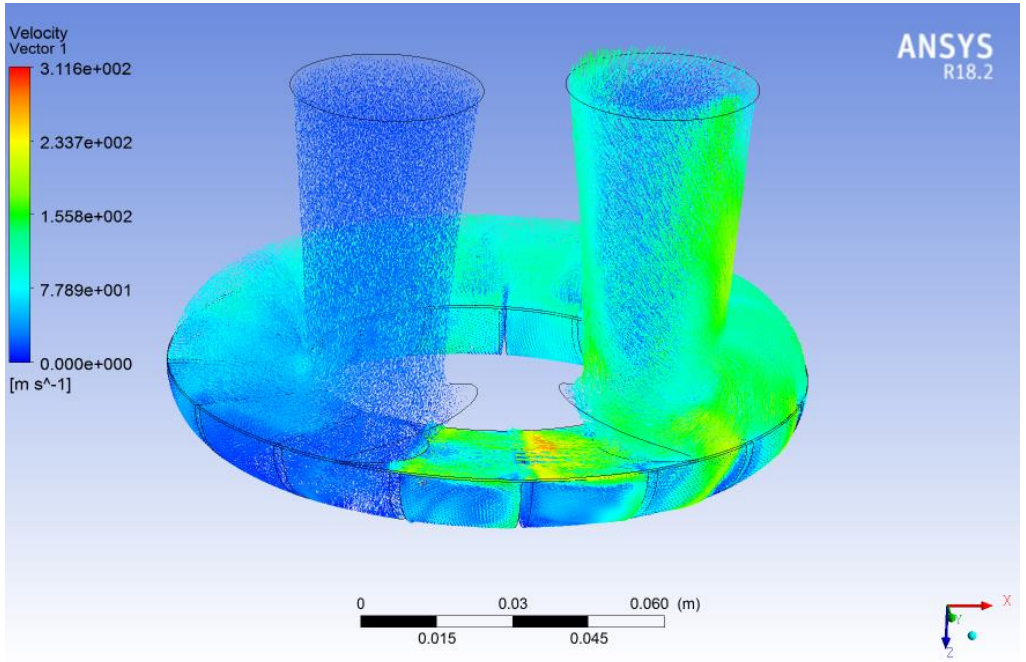


Streamlines colored by the total temperature at 6000 RPM & $\dot{m}$ = 0.3 kg/s for R245fa and air

The entropy loss coefficient is a non-dimensional number representing the loss in the isentropic efficiency For the sake of comparison, the relative entropy loss coefficient has been used, which is the ζ calculated in each zone divided to the total ζ calculated from the inlet boundary of the RFT to the outlet plane.

$$\zeta = \frac{T_2\,\Delta s}{h_{02} - h_2}$$





Relative entropy loss coefficient in three zones at 3000 RPM (BM=0.08) & 0.3 kg/s ($\dot{m}$=0.054)

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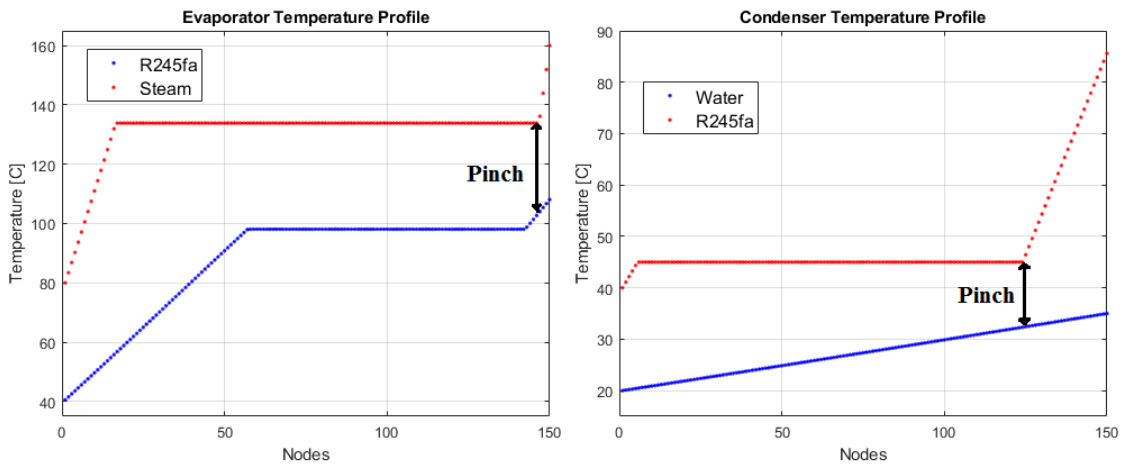
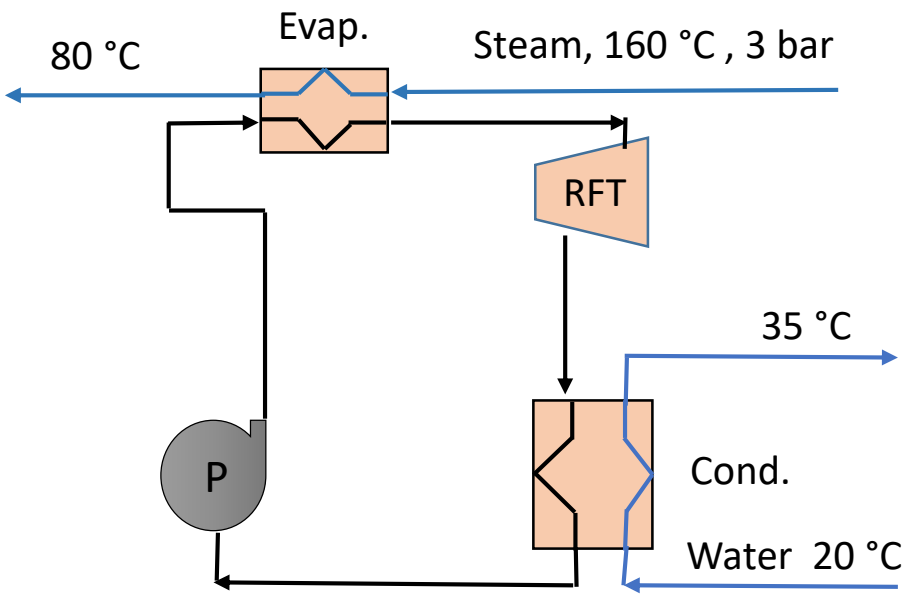
Simulation of **ORC** with **R245fa**

The temperature difference between the inlet of the cooling fluid and the saturation temperature of the organic working fluid in the condenser is considered 25 °C. The mass flow rate of the R245fa is an input to the model whilst the isentropic efficiency of the RFT and its pressure ratio (PR) are obtained from the CFD results. Minimum allowable temperature pinch is assumed 10 °C for both evaporator and condenser



Temperature distribution in the heat exchangers of the ORC unit at $\dot{m}$ = 0.8 kg/s, P_{cond} = 2.94 bar & P_{evap} = 12 bar



Performance of the ORC system

$\dot{m}_{ORC} = 0.6\ kg/s$		$\dot{m}_{ORC} = 0.8\ kg/s$	
P_{evap}	9 bar	P_{evap}	12 bar
$\dot{W}_{pump}$	0.39 kW	$\dot{W}_{pump}$	0.78 kW
$\dot{W}_{RFT,el}$	4.69 kW	$\dot{W}_{RFT,el}$	6.27 kW
$\eta_{net,el}$	3.2 %	$\eta_{net,el}$	2.9 %

Design parameters of the ORC system

Organic Fluid	R245fa
Pump isentropic efficiency	75%
Pump mechanical efficiency	96%
Electrical generator efficiency	97%
Sub-cooling at the pump inlet	5 ˚C
Super-heating in the evaporator	10 ˚C

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- **The PR of the RFT decreases with RPM, thus confirming the peculiarity of this type of expander.**
- **The isentropic efficiency of the RFT achieves a peak of more than 45%, explained via a less swirl showed in the CFD results has been found.**
- **The output power increases with the mass flow rate almost linearly, but up to a certain limit.**
- **The net electrical efficiency of the ORC unit is around 3%, at the highest RPM of the RFT.**
- **The range of the mass flow rate that can be elaborated by the RFT is higher than the one with volumetric expanders but its isentropic efficiency, despite being increased using R245fa, is still low.**
- **Low manufacturing costs and high reliability of RFTs can be highlighted further compared to turbo-machines working in this range of mass flow rates. Nevertheless, a re-engineering of the design of the RFT must still be performed to reduce the main losses, especially the leakage flow through the clearance gap between the stripper body and blade tips.**

We acknowledge S.TRA.TE.G.I.E. srl (www.strategiesrl.com) for its support in the design of the expander

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