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An experimental and numerical analysis of the performances of a Wankel steam expander

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Expander devices for ORC power plants…

Available technologies:

Scroll and vane devices: P < 10 kW

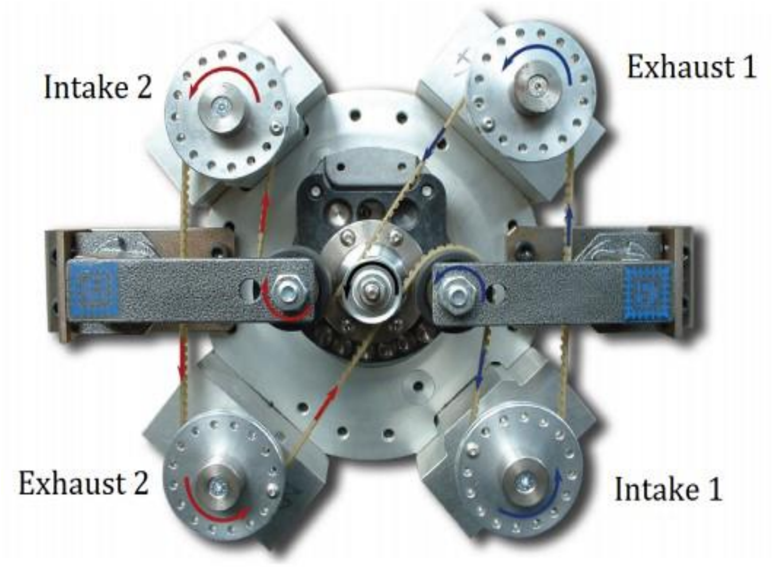
Screw devices : 25 < P < 100 kW

Reciprocating devices: 25 < P < 100 kW

Turbines: P > 1 MW

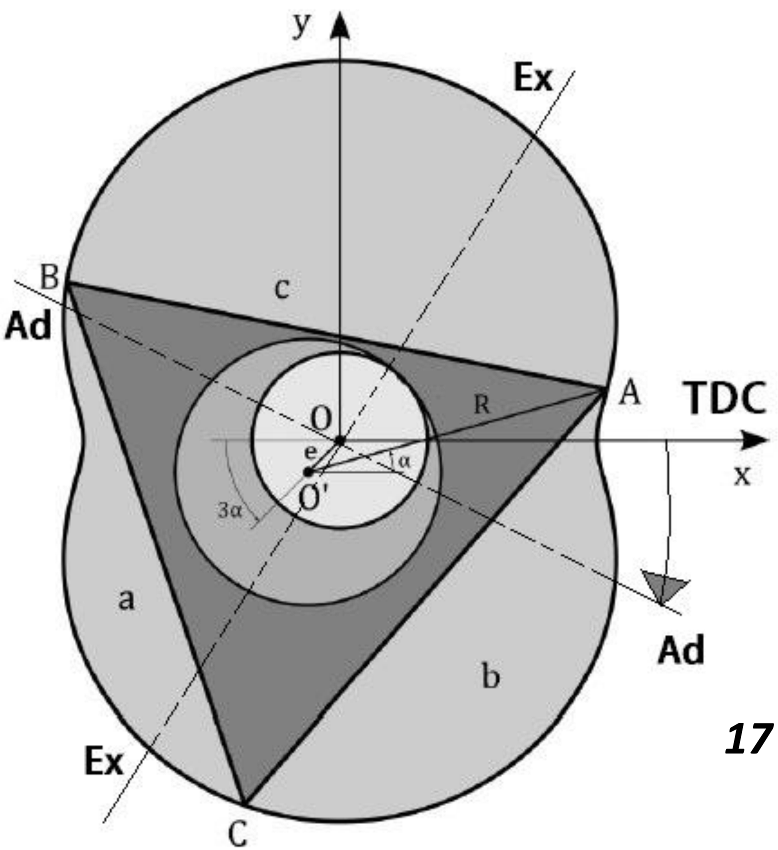
The Wankel expander

A rotary device for power between 10 and 50 kW



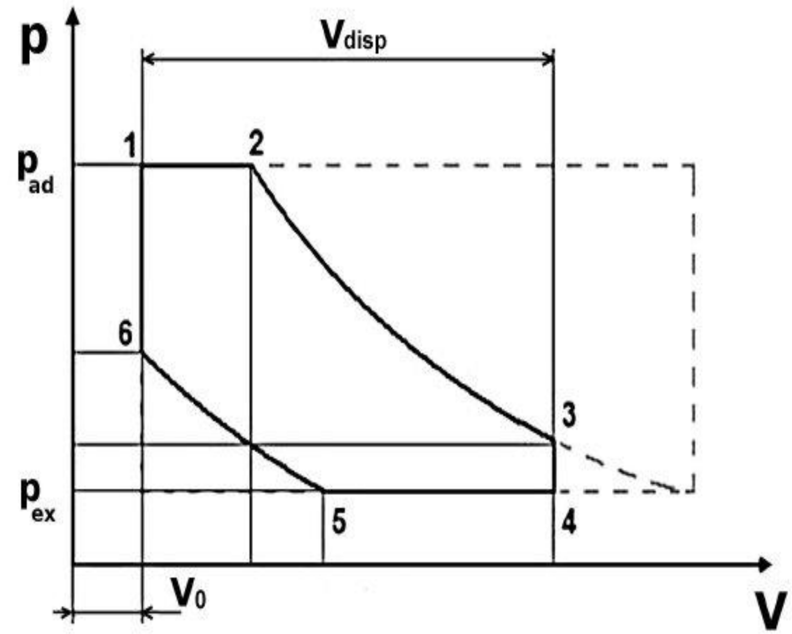
Parameter	Value
Displacement	3.16 *10-4 m^3
Eccentricity	1.205 *10-2 m
Volume ratio	12.7
Admission grade	0.4
Recompression grade	0.3

The Wankel expander



17 deg.

115 deg.



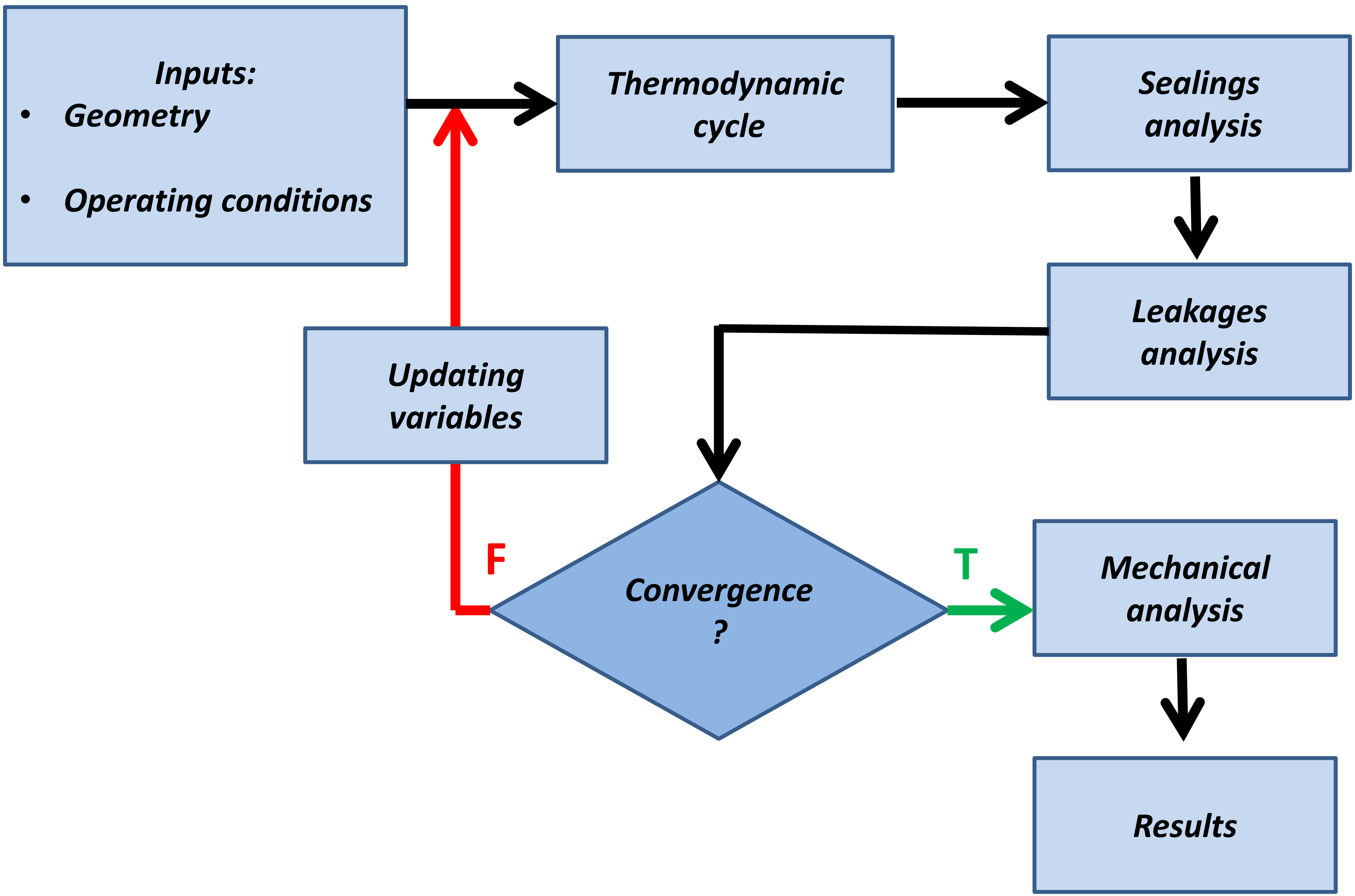
A complete thermodynamic cycle is between 0 and 180 degrees of rotor!

The numerical model of the Wankel expander

Analysis of:

- ***Mechanical losses (bearings, belts, pulleys, gears);***
- ***Thermal losses & Leakages;***
- ***Modeling in Matlab®***

The numerical model of the Wankel expander

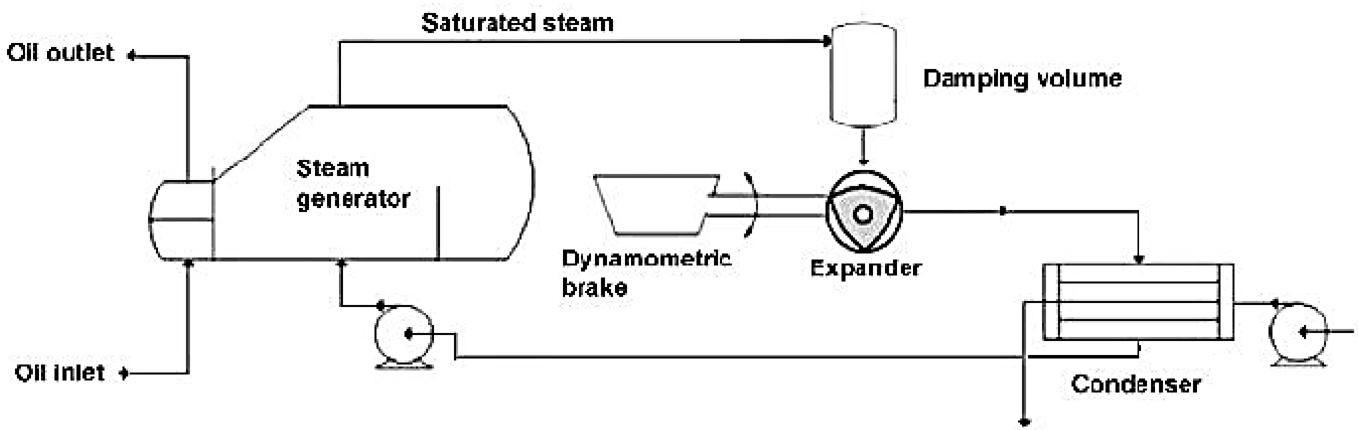


The numerical model of the Wankel expander

Other details:

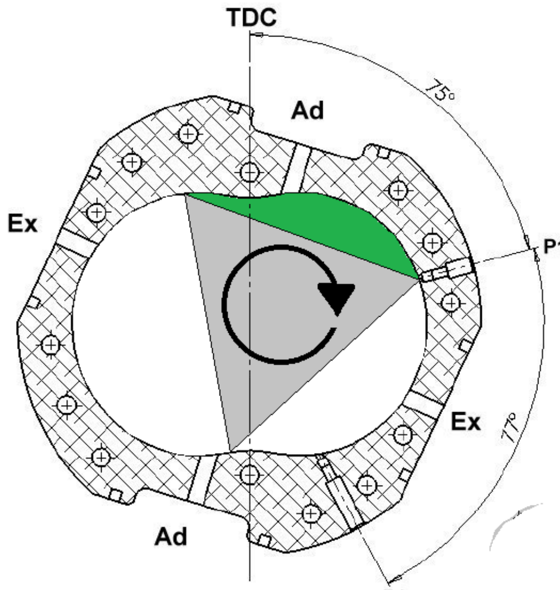
- *The process was performed for each angular position;*
- *Small angular increments to get restrained pressure drops;*
- *Convergence condition: $p(180\ \text{deg.}) - p(0\ \text{deg.}) < 0.001$ bar*

The experimental plant

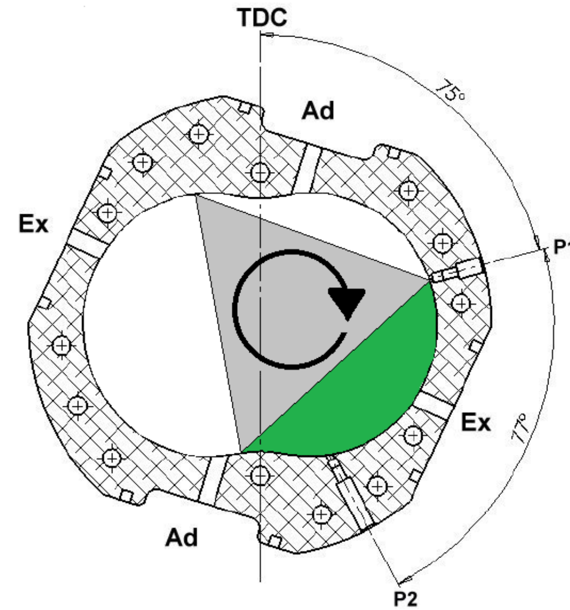


- ***Thermal source: biomass;***
- ***Steam pressure: 5,6,7 barA;***
- ***Condensing pressure: 0,75 barA ;***
- ***Damping volume of 50L to reduce pressure fluctuations;***
- ***Operating speed: 1000,2000,3000 rpm.***

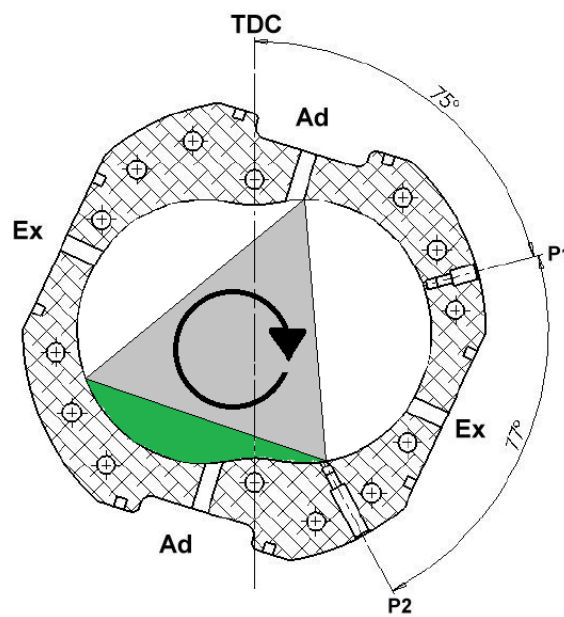
Cycle acquisition process



1: acquisition start



2: overlapping



3: acquisition stop

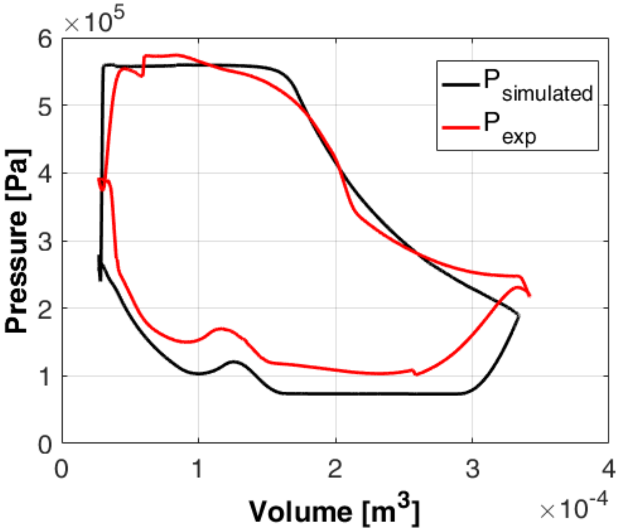
Cycle acquisition process: post processing

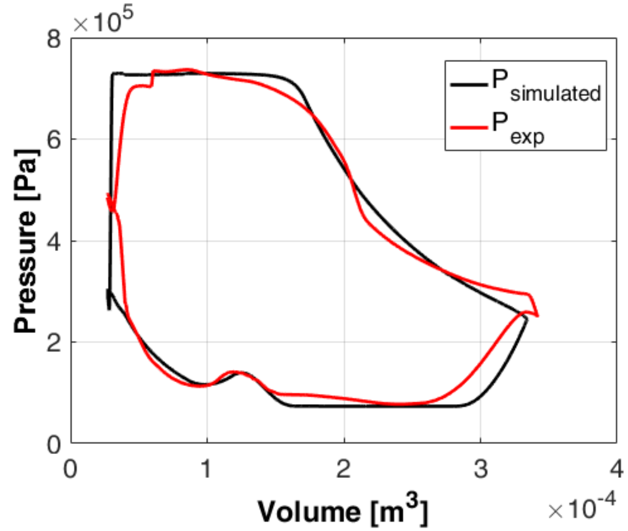
Evaluation of the experimental error:
100 cycles/test for every test

For each test:

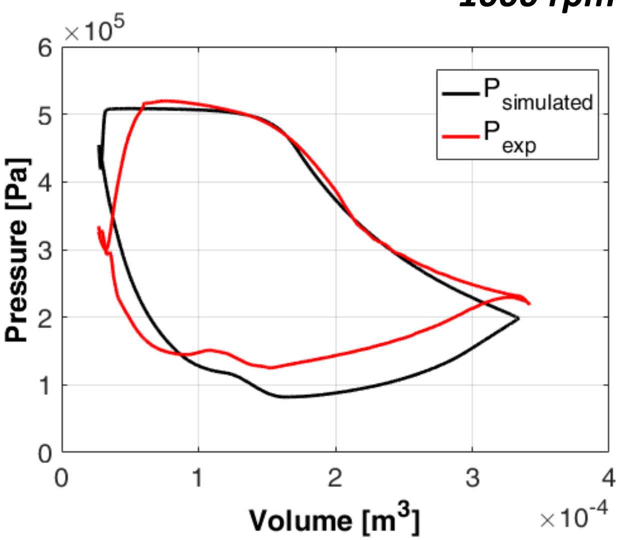
- ***The average percentage difference between the pressure data in the same cycle position <15%;***

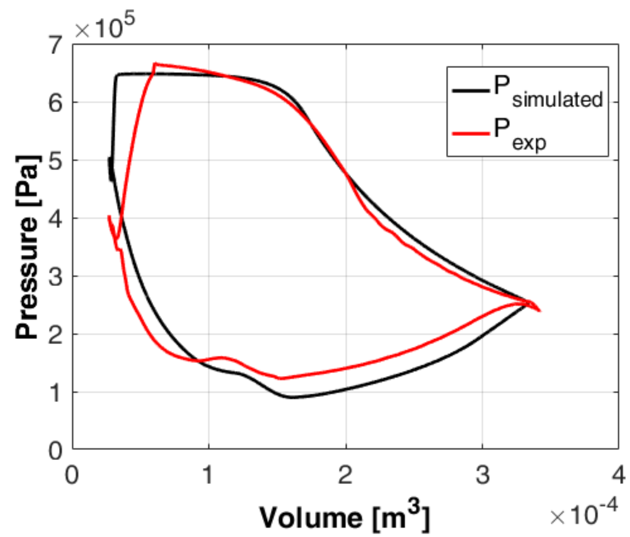
Predicted vs experimental indicated cycle





1000 rpm 5barA (left) and 7barA (right)

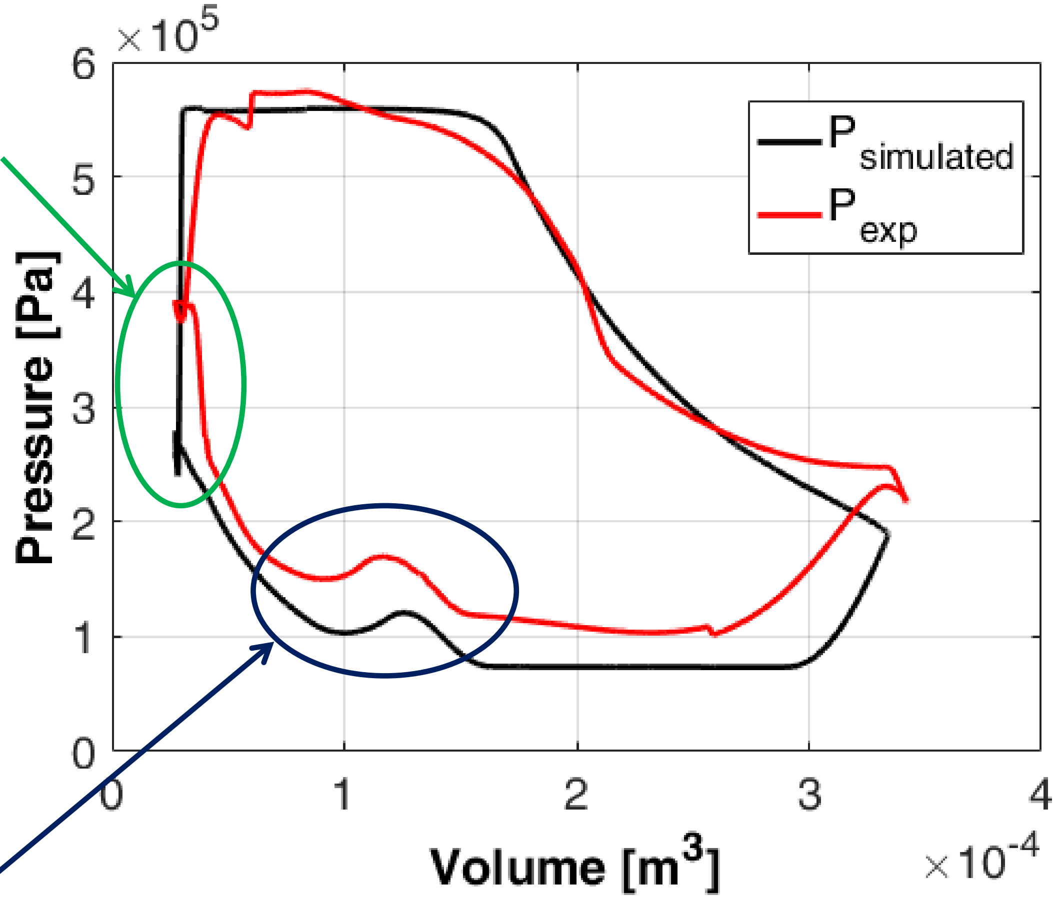




3000 rpm 5barA (left) and 7barA (right)

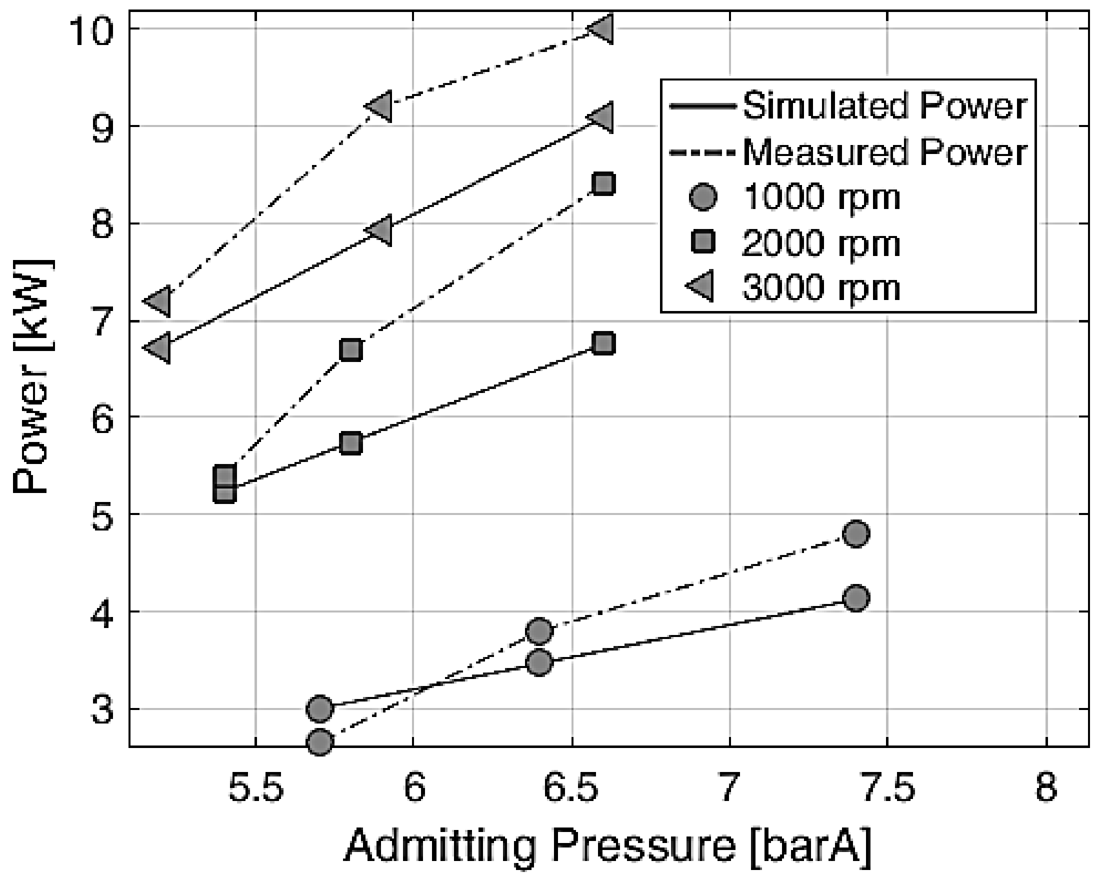
Captured effects

Opening of the valve

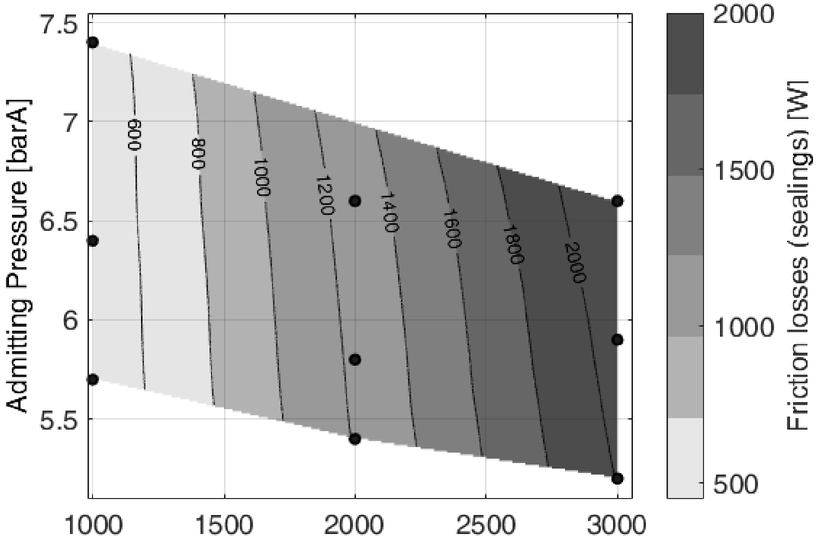


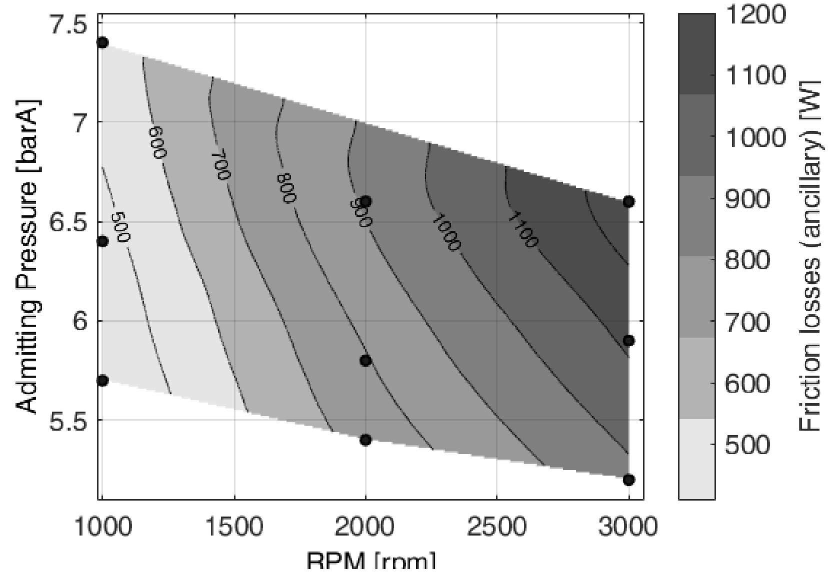
Presence of a stator duct (possible leakages)

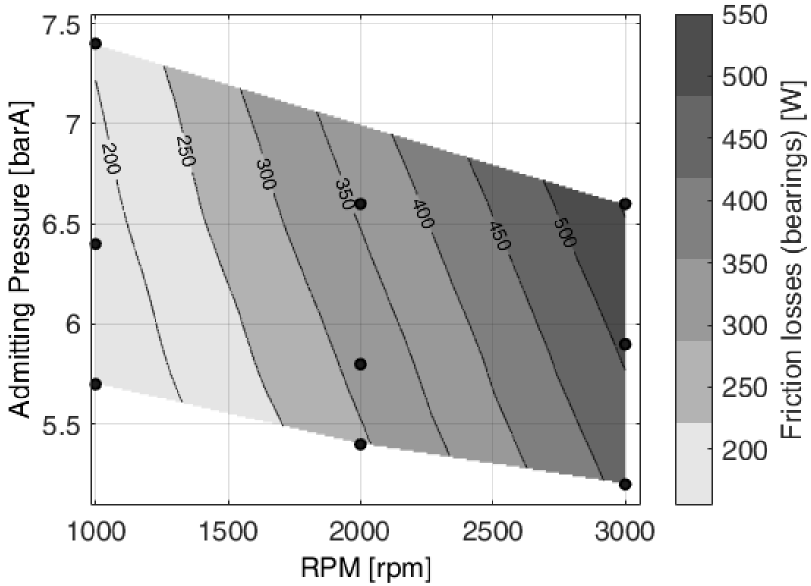
Numerical vs experimental results

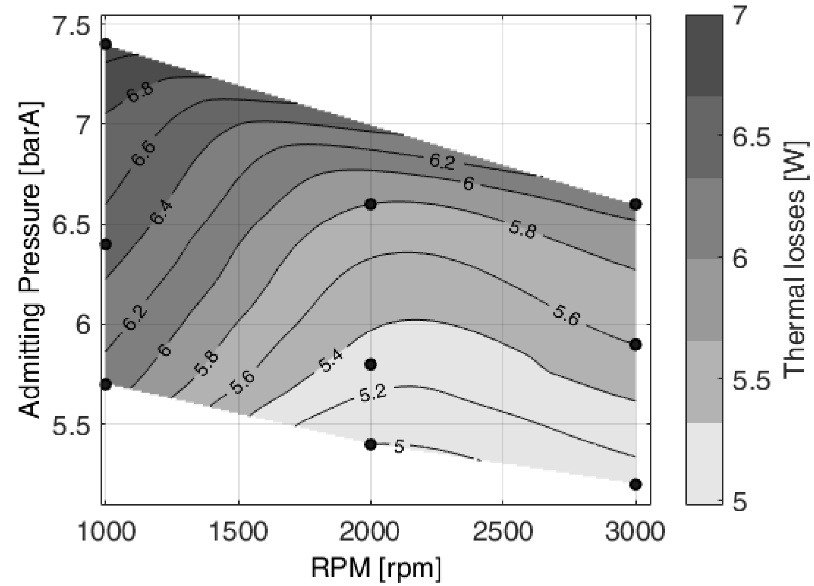


Power losses









Power losses

- ***The effects due to the rise of rotating speed were :***

✓ ***The increase of the mechanical power losses of the several parts of the expander;***

✓ ***The prevailing effect is the rise of mechanical consumption;***

✓ ***A counterbalancing between the increase of heat exchange coefficient and the residence time of the fluid in the operating chamber.***

- ***The increase of admitting pressure was:***

✓ ***Not so relevant for the amount of mechanical losses;***

✓ ***The same of increasing the live steam temperature, (increase of thermal losses).***

Conclusions (1/2)

- ***A comparison between the experimental and simulated data of a Wankel expander was shown;***
- ***A numerical model of the device was created in Matlab® ;***
- ***Three different values of rotating speed (1000,2000,3000 rpm) and three values of inlet pressure (5,6,7 barA) were considered;***
- ***The condensing pressure was kept at 0,75 barA;***

Conclusions (2/2)

- *The prediction of the real performances was reliable (the average difference between the measured and simulated pressure was below 15%);*
- *The amount of rotating speed deformed the shapes of the indicated cycle in the predicted as well as real case;*
- *The rise of the rotating speed increased the mechanical losses;*
- *Thermal losses grew with the admitting pressure.*

General informations:

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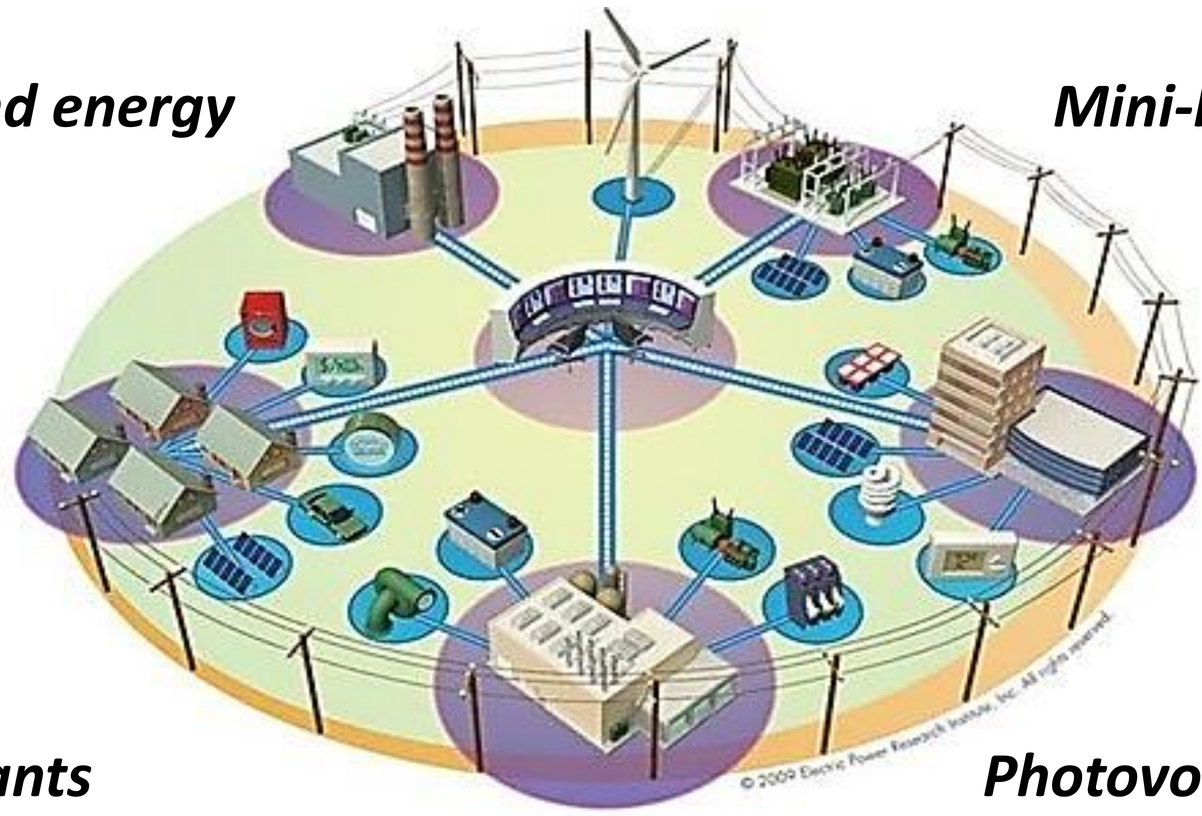
Appendices

A possible solution for the future…

Micro-generation

Micro-wind energy ***Mini-hydro energy***



ORC plants ***Photovoltaic plants***

The ORC process: the energy sources…

A suitable technology to exploit low grade heat sources…

Biomasses

Solar energy

Geothermal energy

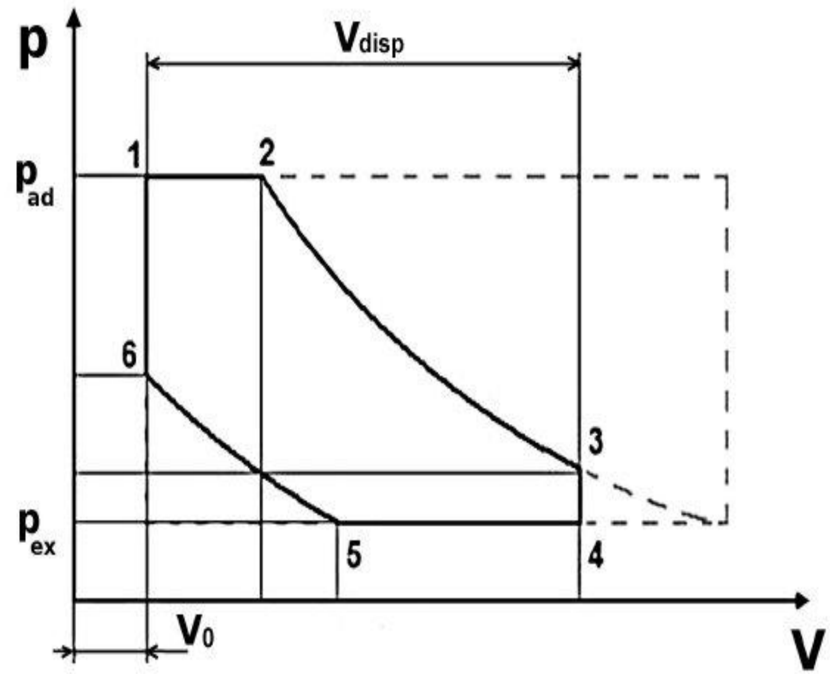
Waste heat recovery

General Theory

$$Admission\ grade = \frac{V_2 - V_1}{V_{disp}}$$

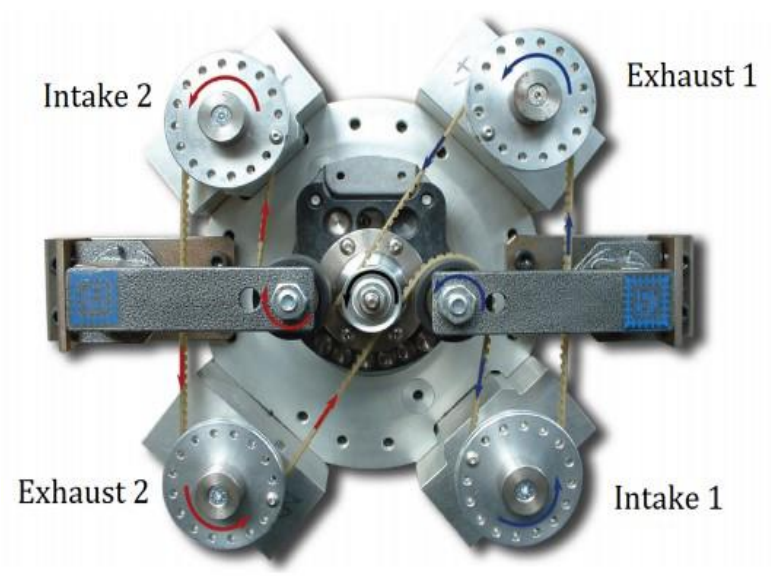
$$Recompression\ grade = \frac{V_5 - V_6}{V_{disp}}$$

$$Volume\ ratio = \frac{V_0 + V_{disp}}{V_0}$$



The Wankel expander

A rotary device for power between 10 and 50 kW



Parameter	Value
Number of rotors	1
Displacement	3.16 *10-4 m^3
Eccentricity	1.205 *10-2 m
Equivalent crank	1.905*10-2 m
Volume ratio	12.7
Admission grade	0.4
Recompression grade	0.3

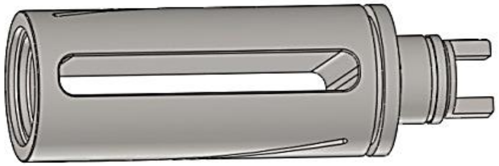
The Wankel expander

From the engine to the prototype…

New stator case

Original shaft

New Rotor



Rotating valves

The numerical model of the Wankel expander

Key aspects of the modeling:

- ***Stationary analysis;***
- ***O.D.E. solver:*** ***Euler method (predictor-corrector approach);***
- ***Mechanical analysis:*** ***rigid body and balance equations;***
- ***Analysis of leakages:*** ***ideal gas modelling;***
- ***Thermal exchanges:*** ***Electrical analogy with correlation for a Wankel engine.***

Cycle acquisition process: instrumentation

- ***2 piezo-electric sensors (Kistler 6052C) with direct access to the chamber;***
- ***A Kistler 5064A1 charge amplifier;***
- ***Encoder Elcis 38Q: trigger for TDC and clock for each angular position;***
- ***SCHENCK W 130 engine test bench;***
- ***Data acquisition system:***

- ✓ ***NI 9174 chassis;***
- ✓ ***Pressure acquisition: NI9223 board ;***
- ✓ ***Encoder acquisition: NI9174 board.***

Piezo electric sensors Kistler 6052C :

- *Measuring range between 0 and 250 bar;*
- *Sensitivity 20pC/bar and linearity < 0.3 %/FSO;*
- *Operating temperature range: between -20 and 350°C;*
- *Housing: M4x0.35 housing and the hole depth allowed the direct access to the expansion chamber;*

The Kistler 5064A1 Charge amplifier :

- ***2 channels;***
- ***Measuring range (resolution<0,1%):***
  - ✓ ***Without offset pC: ±100… ±50000;***
  - ✓ ***With offset pC: ±162… ±50000 ;***
- ***Error (0….60°C) < ± 0,5%;***
  - ✓ ***Typical value: < ± 0,2%.***
- ***Output Voltage: between 0 and ± 10 V;***
- ***Output current: between 0 and ± 2mA;***
- ***Output impedance: 10Ω.***

The Elcis 38Q encoder:

- ***Maximum error between two consecutive wavefronts of two channels is MAX ± 25°e (electric degree);***

- ***Maximum division error of ± 45°e, randomly measured between two wavefronts of different channels;***

- ***Error in a rotating encoder is not cumulative, because it does not increase when shaft rotates more than one revolution.***

The SCHENCK W 130 engine test bench

- ***Power: 130 kW;***
- ***Max speed: 10000 rpm;***
- ***Max torque: 400 Nm;***
- ***Precision:***
  - ✓ ***for the rotation : ± 3 rpm;***
  - ✓ ***for the torque: ± 0,5% of the full scale ;***
- ***Precision of the indication of the extent:***
  - ✓ ***for the rotation : ± 1 revolution;***
  - ✓ ***for the torque: ± 0,2% of the full scale .***

Results and discussion

Other effects described by the numerical model:

- ***Presence of leaks (e.g. effect of stator ducts);***
- ***Pressure disturbs (e.g. the curl due to opening valve);***
- ***This effects were less important with the increase of the operating speed.***

Results and discussion

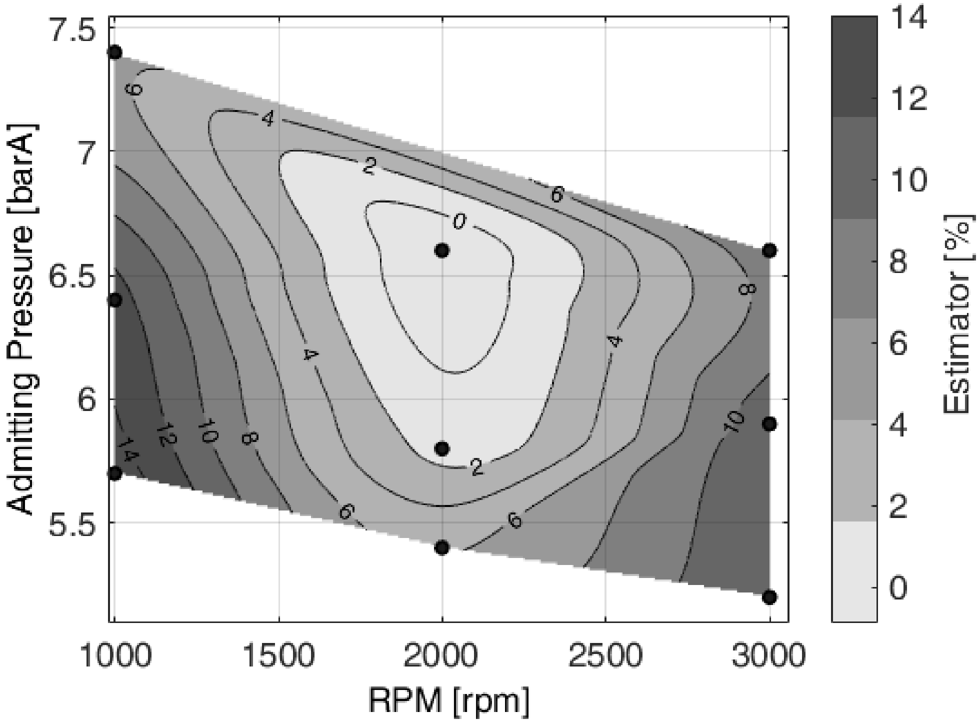
Effects due to the increase of rotating speed:

- ***Shape deformation of the measured and predicted indicated cycles;***
- ***Increase of pressure losses through valves;***
- ***Pressure differences due to an unsteady flow in the real operating conditions (variation of discharge coefficient);***
- ***This effect was greater for the exhaust valve because of the low density of the fluid.***

Numerical and experimental results

Rotational speed	Admitting Pressure	$Power_{sim}$	$Torque_{sim}$	$Power_{exp}$	$Torque_{exp}$
[rpm]	[barA]	[kW]	[N m]	[kW]	[N m]
1000	5.7	3.0	29	2.7	26
	6.4	3.5	33	3.8	36
	7.4	4.1	39	4.8	46
2000	5.4	5.2	25	5.4	26
	5.8	5.7	27	6.7	32
	6.6	6.8	33	8.4	40
3000	5.2	6.7	21	7.2	23
	5.9	7.9	25	9.2	29
	6.6	9.1	29	10.0	32

Numerical vs experimental results



Estimator E:

$$E = 1 - \frac{L_{sim}}{L_{exp}}$$

L_{sim}***: Simulated work***

L_{exp}***: Experimental work***