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

M. Francesconi, G. Caposciutti, M. Antonelli

University of Pisa
Expander devices for ORC power plants...

Available technologies:

*Scroll and vane devices: $P < 10 \text{ kW}$*

*Screw devices: $25 < P < 100 \text{ kW}$*

*Reciprocating devices: $25 < P < 100 \text{ kW}$*

*Turbines: $P > 1 \text{ MW}$*
The Wankel expander

A rotary device for power between 10 and 50 kW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>$3.16 \times 10^{-4}$ m$^3$</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$1.205 \times 10^{-2}$ m</td>
</tr>
<tr>
<td>Volume ratio</td>
<td>12.7</td>
</tr>
<tr>
<td>Admission grade</td>
<td>0.4</td>
</tr>
<tr>
<td>Recompression grade</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The Wankel expander

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

Inputs:
- Geometry
- Operating conditions

Thermodynamic cycle

Sealings analysis

Leakages analysis

Updating variables

Convergence?

Mechanical analysis

Results
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: \( p(180 \text{ deg.}) - p(0 \text{ deg.}) < 0.001 \text{ bar} \)
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:

• *Ph.D. Marco Francescon*
i

• *marco.francescon@for.unipi.it*

• *+39 050 2217137*

• *Largo Lucio Lazzarino, 56122 Pisa, Italy*
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rotors</td>
<td>1</td>
</tr>
<tr>
<td>Displacement</td>
<td>3.16 *10^{-4} m^3</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>1.205 *10^{-2} m</td>
</tr>
<tr>
<td>Equivalent crank</td>
<td>1.905*10^{-2} m</td>
</tr>
<tr>
<td>Volume ratio</td>
<td>12.7</td>
</tr>
<tr>
<td>Admission grade</td>
<td>0.4</td>
</tr>
<tr>
<td>Recompression grade</td>
<td>0.3</td>
</tr>
</tbody>
</table>
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** \( \text{MAX} \pm 25^\circ_e \) (electric degree);

- **Maximum division error of** \( \pm 45^\circ_e \), 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

<table>
<thead>
<tr>
<th>Rotational speed [rpm]</th>
<th>Admitting Pressure [barA]</th>
<th>( \text{Power}_{\text{sim}} ) [kW]</th>
<th>( \text{Torque}_{\text{sim}} ) [N m]</th>
<th>( \text{Power}_{\text{exp}} ) [kW]</th>
<th>( \text{Torque}_{\text{exp}} ) [N m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>5.7</td>
<td>3.0</td>
<td>29</td>
<td>2.7</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>3.5</td>
<td>33</td>
<td>3.8</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>7.4</td>
<td>4.1</td>
<td>39</td>
<td>4.8</td>
<td>46</td>
</tr>
<tr>
<td>2000</td>
<td>5.4</td>
<td>5.2</td>
<td>25</td>
<td>5.4</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
<td>5.7</td>
<td>27</td>
<td>6.7</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>6.8</td>
<td>33</td>
<td>8.4</td>
<td>40</td>
</tr>
<tr>
<td>3000</td>
<td>5.2</td>
<td>6.7</td>
<td>21</td>
<td>7.2</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>7.9</td>
<td>25</td>
<td>9.2</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>9.1</td>
<td>29</td>
<td>10.0</td>
<td>32</td>
</tr>
</tbody>
</table>
Numerical vs experimental results

Estimator $E$:

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

$L_{sim}$: Simulated work

$L_{exp}$: Experimental work