Improved scroll expander model for exhaust heat recovery

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EXOES

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EXOES
at a glance
Latest project

Demo vehicle tested in 2017 (shown at EORCC last year) thanks to a collaborative project with Faurecia and Renault Trucks
Component development

2012: Inlet valves & materials
2013: Swashplate architecture & lubricant
2014: Double acting pistons
2016: Single acting piston
Expander model description

**Presentation based on EVE-T 3 design**

**Literature:**

– University of Liège: Vincent Lemort, Leonardo Cutini, Arnaud Legros
– Ian Bell, Thesis [1]
– J. E. McCullough [2]

<table>
<thead>
<tr>
<th>EVE-T3 Datasheet</th>
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<tr>
<td>Speed range (RPM)</td>
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<tr>
<td>Shaft power range</td>
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<tr>
<td>Eff. Is. efficiency range</td>
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<tr>
<td>Size</td>
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<tr>
<td>Weight w/o coupling</td>
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<tr>
<td>Working fluid</td>
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<tr>
<td>Oil circulation rate</td>
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<td>Expansion ratio</td>
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<td>Displacement</td>
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Scroll expander modelling

Improvement of a scroll model

• Original model from University of Liège:
  – Matlab based model (linked with Coolprop)

• The scroll model includes:
  – Geometry description, incl. tip & inlet port
  – Conservation of energy and mass
  – Leakage
  – Mechanical model
  – Heat transfers

• We added / improved:
  – Leakages, mechanics and heat transfers
  – “double pocket” description

END

Convergence ?

No

Yes

END

Inputs

Geometry calc.

Thermodynamic calculation

Mechanical calculation

Heat transfer calculation

END
• Chamber volume calculated according to [1]
Flank leakages
Tip seal & flank leakages

- Flank leakages: nozzle equation (perfect gas)

\[
\dot{M}_{flk} = h_{flk} \cdot e_{leak} \sqrt{2P_h \rho_h \frac{\gamma}{\gamma - 1} \left[ \left( \frac{P_{thr}}{P_h} \right)^2 - \left( \frac{P_{thr}}{P_h} \right)^{\frac{\gamma+1}{\gamma}} \right]}
\]

Flank leakage areas
Tip seal leakages
Tip seal & flank leakages

• Tip seal leakages: Hagen-Poiseuille equation

\[ L_{\text{tip}} = r_b \left( \frac{1}{2} (\varphi_{\text{max}}^2 - \varphi_{\text{min}}^2) - \varphi_0 (\varphi_{\text{max}} - \varphi_{\text{min}}) \right) \]  

\[ \dot{M}_{\text{tip}} = L_{\text{tip}} h_{\text{tip, leak}} \sqrt{\frac{2D_h \cdot \rho \cdot \Delta P}{f \cdot t}} \]
Tip seal leakages

Curve length for tip leakages

Corresponding arcs
Rotation angle: 225°
Mechanical model

*Mandatory for a scroll design*

- Loads on the mobile scroll calculation [1]
- Loads on the bearings
- Heat losses correlations

**Expander kinematics**

**Tangential & radial forces representation**
Heat transfer

• Heat transfer in the control volume [1]
  – Between the fluid and the scroll wrap and the base plate.
  – Linear drop of wall temperature from inlet to exhaust
  – Base plate temperature calculated function of wall temperature

• Heat transfers in the housing [1]
  – Between fluid exhaust and supply, spirals, housing, ambient air
  – Lumped housing temperature
  – Integration of the energy of the mechanical losses

\[ \dot{Q}_{spirals} - \dot{Q}_{amb} - \dot{W}_{loss} + \dot{Q}_{ex} + \dot{Q}_{su} = 0 \]
Simulation results

Scroll calculation for truck ethanol ORC

• Inputs:
  – Ethanol 95.5%wg
  – 3,600 rpm
  – 20°C Superheat
  – Exhaust press. 1 BarA

• Outputs:
  – Mechanical power
  – Mass flow
  – Isentropic efficiency
SCROLL NOSE TIP & INLET PORT OPTIMIZATION
Scroll nose tip and inlet port are key for a high performing expander

- Accurate nose modeling to withstand mechanical stress
- Detailed leak model on the tip seal

Different scroll tip nose thicknesses [1]  FEA - Nose stress  Nose tip seal

Simulation and FEA needed to find a tradeoff between efficiency and mechanical strength
Problem to be solved:

– Dissymmetric chamber → Supply process too optimistic
– Vibrations

Supply port position @ 180°

Supply port position @ 240°
Geometric decomposition

- Resolution proposition
  - Geo. decomposition of the first pocket
  - Central pocket at supply pressure

Single pocket model @330°

Double pocket model @330°
“Double pocket” concept

Simulation results

• Results:
  – Better design of supply process
  – Pressure difference negligible if supply process well designed

• Inputs:
  – Ethanol 95.5%wg
  – 3,600 rpm
  – 20°C Superheat
  – Supply press. 20 BarA
  – Exhaust press. 1 BarA

Example of a non optimized supply process
“Double pocket” concept

Simulation results

• Results:
  – Better design of supply process
  – Pressure difference negligible if supply process well designed

• Inputs:
  – Ethanol 95.5%wg
  – 3,600 rpm
  – 20°C Superheat
  – Supply press. 20 BarA
  – Exhaust press. 1 BarA

Example of an optimized supply process
“Double pocket” concept

Simulation results

Net Isentropic efficiency comparison

- Single pocket
- DP with optimization
- DP w/o optimization

Working fluid mass flow

Impossible to optimize the expander mass flow & mechanical power without double pocket model.
Conclusion

• Exoès developed a scroll expander model with double pocket decomposition which allows a:
  – Better supply process prediction
  – Better mass flow prediction / mechanical power prediction

• Coupling with FEA tool is mandatory for an efficient design

• Next step: Model calibration with experimental data
Conclusion

Thank you for your attention

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References


NRB: Needle Roller Bearing
CRB: Cylindrical Roller Bearing
TB: Thrust Bearing
OB: Orbiting Bearing
ro: orbiting radius
D: distance
Ftg: Tangential force
Frg: Radial force
ANNEXES
Scroll positions

Rotation angle: 0°  Rotation angle: 90°  Rotation angle: 180°  Rotation angle: 270°
“Double pocket” concept

Simulation results

• Volume repartition in the first chamber

Volume repartition in the first chamber

1st pocket volume decomposition

Crank angle [°]

V [cm^3]

- First pocket
- After opening
- Sum
- Reference
Conservation of Energy and Mass

Very standard description

– Mass conservation:

\[ m_{i+1} = m_i + m_{su} + m_{ex} + m_{leaks} \]

– Energy conservation:

\[ m_{i+1} \cdot U_i = m_i \cdot U_i + (m_{su} + m_{leak,i,su}) \cdot h_{su} + (m_{ex} + m_{leaks,i,ex}) \cdot h_i + Q_i - P \cdot dV \]
• Inputs:
  – Ethanol 95.5%wg
  – 3,600 rpm
  – 20°C Superheat
  – Psu: 20 BarA
  – Pex: 1 BarA