Two-phase chamber modelling of a twin-screw expander for Trilateral Flash Cycle applications

Giuseppe Bianchi¹, Stuart Kennedy³, Obadah Zaher², Savvas A. Tassou¹, Jeremy Miller², Hussam Jouhara¹

Milan, 13/09/2017
**I-ThERM** Project aim is to...

*Investigate, design, build and demonstrate innovative plug and play waste heat recovery solutions to facilitate optimum utilisation of energy in selected applications with high replicability and energy recovery potential in the temperature range 70°C – 1000°C*

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 680599.
The opportunity

EU-28 final energy consumptions (12350 TWh)

- Residential: 24.8%
- Industry: 25.9%
- Transport: 33.2%
- Other: 16.1%

theoretical WHR potential (918 TWh)

- HT: 30%
- LT: 51%
- MT: 19%

Map of EU 28 showing energy consumption levels:

- >20%
- 10%-20%
- 4.5%-10%
- 1.5%-4.5%
- <1.5%

[elaborations from Eurostat database + Forman et al. 2016]
**TFC vs ORC**

Single phase heat recovery
- High exergetic efficiency
- High mass flow rate

Two-phase expansion
- High isentropic efficiency
- Large density changes

Multi-phase heat recovery
- Compact heater (evaporator)
- Worse heat utilization

Single phase expansion
- Safer blade environment
- Realistic expansion ratios

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*G. Bianchi*

**Two-phase chamber modelling of a twin-screw expander for Trilateral Flash Cycle applications**
Outline

✓ Potential for low grade waste heat to power conversion through TFC systems

☐ Modelling approach

☐ Input data for twin-screw machines

☐ Test case

☐ Parametric analyses

☐ Next challenges
Modelling approach

- One-dimensional formulation of Navier-Stokes equations
- Staggered grid spatial discretization
- Leakage paths as orifices
- Thermo-physical properties from REFPROP® v9.1
- Explicit Runge-Kutta scheme

\[ \gamma = \gamma_{vap} x + \gamma_{liq} \left(1 - x\right) \]
# Input data

## Geometrical data from pre-processor or CAD drawings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Diameter</td>
<td>127 mm</td>
</tr>
<tr>
<td>Aspect Ratio (L/D)</td>
<td>1.65</td>
</tr>
<tr>
<td>Built-in Volume ratio</td>
<td>5</td>
</tr>
<tr>
<td>Male / Female rotor lobes</td>
<td>4/6</td>
</tr>
<tr>
<td>Suction / Discharge ports arrange</td>
<td>axial / axial</td>
</tr>
<tr>
<td>Revolution speed range</td>
<td>1500-6000 RPM</td>
</tr>
<tr>
<td>Tip speed range</td>
<td>10.01-40.06 m/s</td>
</tr>
<tr>
<td>Weight</td>
<td>220 kg</td>
</tr>
</tbody>
</table>

![Diagram](image)

- HP end wall
- male tip
- interlobe
- LP end wall
- female tip
- blow-hole

![Graph](image)

- Intake port
- cell #2
- High pressure End Wall
- expansion
- cell #1
- Female Tip
- Blow Hole
- Male Tip
- Interlobe
- Low pressure End Wall
- Exhaust port
GT-SUITE® model

Scaling procedure

\[ SF = \frac{360}{\Delta \alpha} = \frac{\omega_{\text{sim}}}{\omega_{\text{real}}} \]

\[ Z_{\text{sim}} = \text{ceil} \left( \frac{\Delta \alpha \cdot Z_{\text{male}}}{360} \right) \]

G. Bianchi

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## Test case – TATA Steel UK

<table>
<thead>
<tr>
<th>Stream</th>
<th>Flowrate (kg/s)</th>
<th>Inlet/max Pressure (bar)</th>
<th>Outlet/min Pressure (bar)</th>
<th>Inlet Temperature (°C)</th>
<th>Outlet Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste heat stream</td>
<td>10.39</td>
<td>4</td>
<td>3.5</td>
<td>70</td>
<td>24</td>
</tr>
<tr>
<td>R245fa stream</td>
<td>31.4</td>
<td>5.47</td>
<td>1.18</td>
<td>66</td>
<td>19</td>
</tr>
<tr>
<td>Condensing water stream</td>
<td>90.85</td>
<td>4</td>
<td>3.5</td>
<td>12</td>
<td>17</td>
</tr>
</tbody>
</table>

2MW thermal
design power output
120 kW electrical

pilot test rig (1:10) at Spirax Sarco UK
Simulation results

<table>
<thead>
<tr>
<th>Inlet pressure</th>
<th>Inlet quality</th>
<th>Revolution speed</th>
<th>Outlet pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 ( \text{bar}_a )</td>
<td>0.11</td>
<td>4070 RPM</td>
<td>1.3 ( \text{bar}_a )</td>
</tr>
</tbody>
</table>

Indicator diagram (p-V)

Quality-angle diagram

- Expansion at the intake (no shaft work)
- Under-expansion

Inlet duct

- \( \approx \) TFC heater outlet
- Closed volume
- Expansion range

Expander cell
Parametric analyses

Constant inlet quality upstream the expander
Variable revolution speed
Inlet pressure 8bar

Greater revolution speeds
- Increase the expansion in the manifold
- Lower the volumetric efficiency
- Increase the indicated power, but not proportionally
Parametric analyses (cont’d)

Constant revolution speed
Inlet quality is set upstream the expander
Inlet pressure 8bar

A greater inlet quality
• Lowers the mass flow rate
• Increases the volumetric efficiency
• Reduces the indicated power

\[ \eta_{vol} = \frac{m}{\rho_{suc} V_{suc} Z_{male} \omega_{real} / 60} \]

\[ P_{ind} = Z_{male} \frac{\omega_{real} \int pdV}{60} \]

(a) mass flow rate [kg/s]
(b) Indicated power [kW]

(b) - rev. speed 4000 RPM
- x = 0.04
- x = 0.11
- x = 0.30
Conclusions

- Potential of low grade heat to power conversion assessed
- Similarities and differences between TFC and ORC outlined
- Modelling procedure for twin-screw machines in GT-SUITÉ® developed
- A twin-screw expander for TFC applications modelled
  - Pre-expansion in the intake manifold highly affects the expander performance
  - Actual expansion ratio of the Trilateral Flash Cycle is significantly influenced by the expander operation
Next challenges

- Upscaling the prototype unit
- Testing in real industrial environment
  - Model setup on large size expanders
  - Validation
  - Transient modelling of the whole TFC system
Acknowledgements

www.itherm-project.eu

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www.foodenergy.org.uk
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