Design, Simulation and Construction of a Test Rig for Organic Vapours

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Energy Department

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Motivation

Increase ORC turbine efficiencies via passage flow field investigation

⇒ Experimental investigation of ORC turbine passage flows

NO experimental data for flows within ORC turbine blade passages

- **Properties** $T_T, P_T, P, u, \alpha, \psi$
- **Independent** measurement of $P$ and $u$ field
  - direct measurement of $u$
    - consistency of thermodynamic models
      - e.g. $h(P_T, T_T) = h(P, T) + |u|^2/2$
- **Techniques**
  - total pressure probes & pressure taps ($P_T, P$)
  - thermocouples ($T_T$), LDV ($v$), Schlieren (shock waves)

limited investigation in industrial plants ⇒ TROVA (Test Rig for Organic Vapors)
Summary

→ Background on ORC

→ Design of the TROVA

→ Dynamic simulation of the TROVA

→ Construction of the TROVA

→ Conclusions
→ Background on ORC

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Background – ORC & turbine flow

Rankine cycle + organic working fluid – **M_m, complexity**

- Advantages on cycle, plant, operation → viable technology, low/med \( T, W_{el} \)
- Disadvantages on turbine flows – real-gas effects, low speed of sound
- limited knowledge of expansions (\( \eta_T \) – design tools)

**State of the art**

novel real-gas models (Span-Wagner) + CFD (\( \zeta \text{Flow} \)) , separate validations
Background – ORC & turbine flow

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  - limited knowledge of expansions ($\eta_T$ – design tools)

State of the art

novel real-gas models ($Span-Wagner$) + CFD ($\zeta Flow$), separate validations

➔ PROVIDE EXPERIMENTAL DATA ON FLOWS
TYPICAL OF ORC TURBINE PASSAGE
→ Background on ORC

→ Design of the TROVA

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→ Construction of the TROVA

→ Conclusions
Dedicated facility – Design

- Limits for investigation industrial ORC plants
- Controlled flow for calibration

TEST SECTION: planar **straight axis** convergent – divergent **nozzle**
quasi – 1D, isentropic expansion (no calibrated probes)

FLUIDS: Siloxanes & Hydrofluorocarbons – thermodynamics, safety
Siloxane **MDM** (high T) & HFC **R245fa** (low T)

OP COND: parameters \( A_t - P_{T,6}, T_{T6} - \beta_{max} - P_7 \)

CYCLE: Gas cycle vs Phase transition cycle
high **costs** for continuous operation
Dedicated facility – Design

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high **costs** for continuous operation

<table>
<thead>
<tr>
<th></th>
<th>$P_{T,6}$ (bar)</th>
<th>$T_{T,6}$ (°C)</th>
<th>$\beta$</th>
<th>$A_t$ (mm²)</th>
<th>$c_t$ (m/s)</th>
<th>$M_t$</th>
<th>$m$ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDM</td>
<td>25</td>
<td>310</td>
<td>25</td>
<td>314</td>
<td>63.6</td>
<td>1</td>
<td>6.25</td>
</tr>
<tr>
<td>R245fa</td>
<td>37</td>
<td>159.2</td>
<td>18.5</td>
<td>314</td>
<td>104.3</td>
<td>1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

\[ M_t = \frac{\sqrt{2 \left[ h_{T,6} - h(\alpha, s_6) \right]}}{c(\alpha, s_6)} \quad m = \rho_t A_t c_t \]
Dedicated facility – Design

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**MDM – gas cycle**

**MDM – ph. tr. cycle**
TROVA – A blow down facility

Closed loop – phase transition – batch operating facility

• ↓ power – ↑ energy exchange time: storage $P_{T,4} > P_{T,6}$ – limited test duration

• Unsteady nozzle flow: constant $P_{T,6}$ (MCV) – change in $b_{T,6}$ (HPV)
  $\rightarrow$ sequence of steady flows with transient operating conditions $P_{T,6}, T_{T,6}$
Closed loop – phase transition – batch operating facility

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→ sequence of steady flows with transient operating conditions $P_{T,6}, T_{T,6}$
Sizing procedure & results

EVALUATE HPV/LPV $V, P, T \rightarrow t_{min} \approx 20$ s

Iterative nozzle flow calculation – Lumped parameter – MDM, R245fa

- **Parameters setting** $V_{HPV}, V_{LPV}, P_{HPV}$
- **Initial conditions** nozzle flow operating conditions
- **Calculation** $t \rightarrow$ unsteady mass & energy bal. – vessels b.c. update
- **Calculation stop** $P_{T,5} = P_{T,6}$ or $\perp$ shock at exit
- **Parameters update** if $t_{ex} \leq t_{min}$
- **Safety check** $P_{max}$ for tanks connection
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3. **Calculation** $t \rightarrow$ unsteady mass & energy bal. – vessels b.c. update
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5. **Parameters update** if $t_{\text{ex}} \leq t_{\text{min}}$
6. **Safety check** $P_{\text{max}}$ for tanks connection

<table>
<thead>
<tr>
<th>MDM – Vessels design</th>
<th>HPV</th>
<th>LPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ (m$^3$)</td>
<td>1.0</td>
<td>5.6</td>
</tr>
<tr>
<td>$P_{\text{max}}$ (bar)</td>
<td>50.0</td>
<td>20.0</td>
</tr>
<tr>
<td>$T_{\text{max}}$ (°C)</td>
<td>400.0</td>
<td>400.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MDM – HPV conditions, tests</th>
<th>MDM</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{T,4(t=0)}$ (bar)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$T_{T,4(t=0)}$ (°C)</td>
<td>315</td>
<td>176.5</td>
</tr>
<tr>
<td>$t_{\text{ex}}$ (s)</td>
<td>12</td>
<td>28.5</td>
</tr>
</tbody>
</table>
Overview

HEATING SECTION
Overview

THROTTLING SECTION
Overview

TEST SECTION

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Overview

COOLING SECTION
Overview

COMPRESSSION SECTION
Overview

VACUUM SECTION
→ Background on ORC

→ Design of the TROVA

→ Dynamic simulation of the TROVA

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→ Conclusions
Dynamic simulation

Batch operation + control systems \(\rightarrow\) START-UP and TEST time

- **Processes to simulate:** heating – test – condensation
- **Batch simulation:** batch operation of the facility
- **Model approaches:** lumped parameter / 1D (plant) + 1D (nozzle)
- **Simulation tools:** Modelica (object-oriented language) + FluidProp
  
  - simple models \(\rightarrow\) complex model
  
  Fortran + FluidProp

- **Self-made library:** lack of component models – e.g. nozzle \(\rightarrow\) TestRig
Dynamic simulation

**Batch operation + control systems** → **START-UP** and **TEST** time

![Graph showing MDM, P7, Tcond, and R245fa](image)

**SELECTED CASES**

<table>
<thead>
<tr>
<th>MDM₁</th>
<th>MDM₂</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{T,4}$ (bar)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$T_{T,4}$ (°C)</td>
<td>315</td>
<td>311.4</td>
</tr>
<tr>
<td>$P_{T,6}$ (bar)</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>$T_{T,6}$ (°C)</td>
<td>310</td>
<td>276.9</td>
</tr>
<tr>
<td>$P_7$ (bar)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$T_{\text{cond}}$ (°C)</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
Models – Heating system

3 LEVELS

a. Control system model
b. Vessel model
c. Heating system model
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models – test system

from HPV
to LPV

HPV

LOSSES

PLENUM

MCV

TEST SECTION

LPV

Boiler

Losses

pressureTank

valueCompressi...

relativePressure

valveCompressi...

Plenum

Condenser

V=5.6

V=1

k=25

combustion1De

const

feedback

product

Control

gain

k=1e-5

D1

D2

D3

V4

V5

V6

SEEDING TANK

MAIN CONTROL VALVE

TEST SECTION

pp

Tt6 pt6

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POLITECNICO DI MILANO
Simulation results: heating & condensing systems

**FINAL CONDITIONS**

<table>
<thead>
<tr>
<th></th>
<th>MDM₁</th>
<th>MDM₂</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{T,4} ) (bar)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>( T_{T,4} ) (°C)</td>
<td>315</td>
<td>311.4</td>
<td>176.5</td>
</tr>
<tr>
<td>( \rho_{T,4} ) (kg/m³)</td>
<td>372.9</td>
<td>364.0</td>
<td>498.2</td>
</tr>
<tr>
<td>( t_{heating} ) (s)</td>
<td>25000</td>
<td>25000</td>
<td>10000</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>MDM₁</th>
<th>MDM₂</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{T,9} ) (bar)</td>
<td>0.012</td>
<td>0.012</td>
<td>2.51</td>
</tr>
<tr>
<td>( T_{T,9} ) (°C)</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>( P_{T,6} ) (bar)</td>
<td>25</td>
<td>10</td>
<td>37</td>
</tr>
<tr>
<td>( t_{cond} ) (s)</td>
<td>1000</td>
<td>1500</td>
<td>2000</td>
</tr>
</tbody>
</table>

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Simulation results: test

**FINAL CONDITIONS**

<table>
<thead>
<tr>
<th></th>
<th>MDM(_1)</th>
<th>MDM(_2)</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(_{T,4}) (bar)</td>
<td>25</td>
<td>17.7</td>
<td>37</td>
</tr>
<tr>
<td>T(_{T,4}) (°C)</td>
<td>308</td>
<td>302.5</td>
<td>158.1</td>
</tr>
<tr>
<td>P(_{T,9}) (bar)</td>
<td>2.27</td>
<td>4.44</td>
<td>8.33</td>
</tr>
<tr>
<td>T(_{T,9}) (°C)</td>
<td>275</td>
<td>277</td>
<td>104.8</td>
</tr>
<tr>
<td>P(_{T,6}) (bar)</td>
<td>25</td>
<td>10</td>
<td>37</td>
</tr>
<tr>
<td>M(_{\text{dis}}) (kg)</td>
<td>75</td>
<td>149</td>
<td>156</td>
</tr>
<tr>
<td>t(_{\text{ex}}) (s)</td>
<td>12</td>
<td>93</td>
<td>28.6</td>
</tr>
</tbody>
</table>
Simulation results: nozzle regimes

Lumped parameter dynamic simulation – Modelica

Different regimes in time

Quasi 1-D steady calculation at different $P_g$

Different regimes in space
Simulation results: nozzle regimes

Lumped parameter dynamic simulation – *Modelica*

**Different regimes in time**

![Graph showing pressure over time](image)

\[ \Gamma = 1 + \frac{\rho}{c} \left( \frac{\partial c}{\partial \rho} \right)_s < 1 \]

**Quasi 1-D steady calculation at different \( P_8 \)**

**Different regimes in space**

![Graph showing pressure and Mach number over space](image)
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Conclusions

- Experimental investigation on typical ORC turbine expansions → flow characterization – code validations
- Measurements in industrial ORC turbines: limits – needs of calibrated probes
- TROVA: bolw-down – phase transition facility
- Design & simulation → performance of proposed investigation
- Construction
- Conceived for ORC fluids/applications – other applications in real gases → real gases calibration tunnel

Developments

- Control + DAQ software
- Commissioning → TEST
Acknowledgements

• Profs Osnaghi, Dossena, Gaetani, Mr. Deponti, Matteo Pini, Emiliano Casati

• Prof. Mario Gaia & Turboden staff

• Alberto Guardone

• Prof. Piero Colonna, Teus van der Stelt

• Profs Gianfranco Angelino & Costante Invernizzi

• Manufacturers – Mr. Malavasi, Mr. Fermi
THANK YOU FOR YOUR ATTENTION