Response time characterization of ORC evaporators for dynamic regime analysis with fluctuating thermal power

The 4th International Seminar on ORC Power Systems

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Waste heat recovery
- Stationary sources
- Mobile sources

Exemplary profile of waste heat

Efficiency curve of ORC system
- Design Point
- Off-design condition
- No working zone

- Off-design conditions most of the time: poor efficiency
- Outside operating range: ORC downtimes

Introduction
Dynamic regime analysis
Response time characterization
Case Study
Future work and conclusions
Waste heat recovery
- Stationary sources
- Mobile sources

Exemplary profile of waste heat

Fluctuating thermal power input means that the ORC system often experiences transients

**ORC evaporator**: link between heat source and rest of components

**Dynamics of ORC** dominated by heat exchanger transients

**Evaporator intrinsic thermal inertia** affects the dynamic behavior of the ORC under fluctuating thermal power
ORC evaporator design for dynamic behavior

Standard methodology for heat exchanger design:

- Select type of hex according to application
- Find heat duty Q
- Assume h.t.c. $U \rightarrow$ LMTD
- Calculate heat transfer area $A$
- Select tube D, thickness, material and calculate # of tubes according to $A$
- Calculate film coefficients, compare to reqd. $U$
- Calculate pressure drops $\Delta p$ and compare to max
- Mechanical design

Include desired dynamic behavior of evaporator:

- Desired thermal inertia of hex

Introduction | Dynamic regime analysis | Response time characterization | Case Study | Future work and conclusions
Dynamic regimes and dynamic regime number

Thermal power input

Dynamic regime I
Quasi-steady

Dynamic regime II
Transient

Dynamic regime III
Quasi-constant

Heat input

Enthalpy increase evap.
Dynamic regimes and dynamic regime number

Define a characteristic response time of the evaporator $\tau_{ev}$

Period of fluctuation of the thermal power $T_{load}$

Dynamic regime number $\Gamma$: ratio of response time to period of load fluctuation

$\Gamma = \frac{\tau_{ev}}{T_{load}}$

How does the design parameters of the hex affect its response time?
Methodology for dynamic characterization

Finite volume 1-D model of evaporator:

For each 1-D cell:

Continuity equation: \( \frac{dM}{dt} = \frac{d(V \cdot \rho)}{dt} = V \cdot \left( \frac{\partial \rho}{\partial h} \frac{dh}{dt} + \frac{\partial \rho}{\partial p} \frac{dp}{dt} \right) = \dot{m}_{in} - \dot{m}_{out} \)

Energy equation: \( V \cdot \rho \cdot \frac{dh}{dt} - V \cdot \frac{dp}{dt} = \dot{m}_{in} \cdot h_{in} - \dot{m}_{out} \cdot h_{out} + \alpha_i \cdot A_{ht} \cdot (T_w - T) \)

Heat balance in wall: \( C_w M_w \frac{dT_w}{dt} = \dot{q}_o \cdot A_{ht} + \alpha_i \cdot A_{ht} \cdot (T - T_w) \)

Heat transfer correlations: 1p – Gnielinski, 2p - Shah
Generalization of results: Dimensionless parameters

Response time as function of dimensionless parameters:

\[
Ja_{lv} = \frac{C_{p,v}(T_v - T_{sat}) + C_{p,l}(T_{sat} - T_i)}{\Delta H_{vap}}
\]

\[
CapR = \frac{\rho_w C_w}{\rho_{tp\ avg} \cdot (\frac{\Delta H_{vap}}{T_{sat}})}
\]

- Geometric ratio(s)
  - 1) Geometry
  - +
  - 2) Fluid thermal state
  - +
  - 3) Wall material

Jakob number: relative ratio of sensible to latent heat transfer

Cap Ratio: ratio of wall heat capacity to a “relative heat capacity of fluid”
Summary of methodology

- Parametrization of $\tau_{ev}$ as function of dimensionless parameters
- From parametric points interpolate to build charts with “constant response” time curves
ORC evaporator response time charts

- **Ja = 0.400**
- **Ja = 0.870**

**Fixed parameters:**
- Area HT = 4m²
- Wall-th = 2mm
- q = 10 kW/m²
- Tsat = 450 K
- Fluid: MM

**HEX Geometry**

**Working fluid thermal state**

**HEX Wall material**

**CapR**

**D/L**
ORC evaporator response time charts

If we are interested in a response time slower or faster than 700 s, which area will that be?

The charts show “what it takes” in terms of design to achieve a desired dynamic response

Ja = 0.400

\[ \tau_{0.95} < 700 \text{s} \]

\[ \tau_{0.95} > 700 \text{s} \]
Dynamic regimes and dynamic regime number

Define a characteristic response time of the evaporator $\tau_{ev}$

**Dynamic regime number $\Gamma$:** ratio of response time to period of load fluctuation

$$\Gamma = \frac{\tau_{ev}}{T_{load}}$$

We know what it takes to design the evaporator for a certain thermal inertia.

To have a desired dynamic regime behavior with a given fluctuating heat input.

**Dynamic regime I**
*Quasi-steady*
$\Gamma < 1$

**Dynamic regime II**
*Transient*
$1 < \Gamma < 10$

**Dynamic regime III**
*Quasi-constant*
$\Gamma > 10$
Case study – Billet reheating furnace waste heat

Discrete Fourier Analysis
Frequency components

T: characteristic period of load (half-wave)
f: frequency component (full-wave)

Response time characterization of ORC evaporators for dynamic regime analysis with fluctuating thermal power

T = 274 s
T = 960 s
T = 2194 s
T = 290 s
T = 290 s
T = 138 s

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Case study – Billet reheating furnace waste heat

We can choose a combination of design variables for a desired dynamic regime depending on our thermal power profile

$$\Gamma = \frac{T_{0.95}}{T}$$
Case study – Billet reheating furnace waste heat

<table>
<thead>
<tr>
<th>Characteristic time $\tau_{0.95}$</th>
<th>Evaporator A</th>
<th>Evaporator B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>MM</td>
<td>MM</td>
</tr>
<tr>
<td>Heat transfer area</td>
<td>4 m$^2$</td>
<td>4 m$^2$</td>
</tr>
<tr>
<td>$D/L$</td>
<td>0.0199</td>
<td>0.0022</td>
</tr>
<tr>
<td>$Ja_w$</td>
<td>41.28</td>
<td>24.92</td>
</tr>
<tr>
<td>Wall material</td>
<td>Steel</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>2 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Fluid mass flow</td>
<td>0.25 kg/s</td>
<td>0.25 kg/s</td>
</tr>
<tr>
<td>Sat temperature</td>
<td>177 °C</td>
<td>177 °C</td>
</tr>
<tr>
<td># of parallel tubes</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

$\Gamma = \frac{\tau_{0.95}}{\tau}$

$\Gamma = 3.05$  
$\Gamma = 0.38$  
$\Gamma = 0.38$  
$\Gamma = 2.88$

Evap A

$\Gamma = 0.87$  
$\Gamma = 0.87$

Evap B

$\Gamma = 0.46$  
$\Gamma = 0.06$

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\[ \Gamma < 1 \]
Quasi steady regime

\[ 1 < \Gamma < 10 \]
Transient regime

\[ \Gamma < 1 \] everywhere
Quasi-steady regime
Case study – Billet reheating furnace waste heat

- Evaporator A can effectively filter out some of the variability of the heat
- Less deviation from a design point - “Thermal flywheel”
- Evaporator B reacts faster to changes
Current and future work

- Diameter
- Wall thickness

Consideration of secondary fluid cooling (properties of air)
Step changes of mass flow/temperature

Fig. Finned Tubes (Yang, 2015)

Fig. Louvered Fins (Mastrullo, 2015)
Concluding remarks

- Methodology to include dynamic behavior of ORC evaporator at design stage
- Response time charts as function of design decision variables: geometry, wall material, fluid
- Case study: evaporator selection that can reduce variability of heat
- Very simple geometry – method is to be extended to more realistic and complex geometries

Applications:
- Dampening to decrease inefficiencies of ORC related to off-design conditions
- Feasability of direct evaporation (no thermal oil loop) to reduce size of system on mobile applications
- Design “desired” dynamic behavior of ORC for control
Thank you for your attention!

Q & A

Acknowledgements: This research is part of the ICER collaborative project between NTU Singapore and TUM Germany
Response Time charts

*Additional slides*
Comparison of resp times for two dif. Fluids with the same fixed parameters. (area, heat flux) → Toluene shows relatively shorter response times
ORC evaporator response time charts

Comparison of response times for two different fluids with the same fixed parameters (area, heat flux) → Toluene shows relatively shorter response times.

If we are interested in a response time slower or faster than 700 s, which are will that be?

The charts show “what it takes” in terms of design to achieve a desired dynamic response.

*Additional slides
Extension to more complex geometries: Finned tubes evaporator

Key parameter to vary: diameter of tubes
- Diameter
- Wall thickness

Investigation of response time, fixed UA, variable D (int)
Case 1: Variable diameter and N serial tubes
Case 2: Variable diameter and N parallel tubes
Case 3: Variable diameter and length
Case 4: “Fixed” int. diameter, variable thickness

Base geometry (Yang, 2015)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N serial tubes</td>
<td>9</td>
</tr>
<tr>
<td>N parallel tubes</td>
<td>20</td>
</tr>
<tr>
<td>Tube length</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Diameter (int)</td>
<td>20 mm</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>2.5 mm</td>
</tr>
</tbody>
</table>

Base thermal boundaries

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow flue gas</td>
<td>3 kg/s</td>
</tr>
<tr>
<td>Temperature flue gas</td>
<td>350 °C</td>
</tr>
<tr>
<td>Inlet sub-cooling</td>
<td>10 °C</td>
</tr>
<tr>
<td>Outlet superheating</td>
<td>1 °C</td>
</tr>
<tr>
<td>Working fluid</td>
<td>R245fa</td>
</tr>
<tr>
<td>Evap pressure</td>
<td>30 bar</td>
</tr>
</tbody>
</table>

Same UA means same amount of heat is being transferred for the same inlet conditions of both fluids

*Additional slides
Extension to more complex geometries: Finned tubes evaporator

*Additional slides*
Extension to more complex geometries: Finned tubes evaporator
Next: comparison of thermal inertia with louvered fins heat exchanger

Finned tubes ORC evap
Base geometry - Yang, 2015

Louvered fins ORC evap
Base geometry - Mastrullo, 2015

Comparison variables:
- N parallel tubes – N tubes
- N serial tubes – Length
- Length – N ports
- Thickness - Thickness

Compare to the same boundary conditions

- Convenient, both papers take practically the same values of mass flow and temperature of the heat source
- How to compare geometries?
  - Hydraulic diameter - very different ranges, characteristics
  - Equivalent “macro” dimensions: Aspect ratio of gas side path

*Additional slides
Louvered fins evaporator – dynamic characterization with changes in geometry and step change in gas mass flow

*Additional slides