Charge-sensitive methods for the off-design performance characterization of organic Rankine cycle (ORC) power systems

by

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Organic Rankine Cycle (ORC)

1 → 2: Compression
2 → 3: Evaporation
3 → 4: Expansion
4 → 1: Condensation

CONTEXT & MOTIVATIONS
ORC application fields

ORC applications

- low-grade heat
- small-capacity

CONTEXT & MOTIVATIONS
ORC application fields

CONTEXT & MOTIVATIONS

ORC applications ➔ Off-design operation
Off-design performance modelling
Off-design performance modelling

**Inputs:**
- ORC boundary conditions
- Components specifications

**Context & Motivations**
- Heat source supply conditions
- Heat sink supply conditions

Variables:
- $N_{pp}$
- $N_{exp}$
Off-design performance modelling

**Inputs:**
- ORC boundary conditions
- Components specifications

**Outputs:**
- Working fluid (WF) mass flow rate
- WF states along the cycle
Off-design performance modelling

**Inputs:**
- ORC boundary conditions
- Components specifications

**Outputs:**
- Working fluid (WF) mass flow rate
- WF states along the cycle
- All energy transfers

\[ Q_{ev}, h_{ev,su}, P_{ev,su}, h_{exp,su}, P_{exp,su}, h_{cd,su}, P_{cd,su}, h_{pp,su}, P_{pp,su}, \dot{m}_{wf}, W_{pp}, W_{exp} \]
Off-design performance modelling

**CONTEXT & MOTIVATIONS**

- **Inputs:**
  - ORC boundary conditions
  - Components specifications

- **Outputs:**
  - Working fluid (WF) mass flow rate
  - WF states along the cycle
  - All energy transfers

**N variables ⇔ N equations:**
- Energy balances → N - 1 equations
Off-design performance modelling

CONTEXT & MOTIVATIONS

**Inputs:**
- ORC boundary conditions
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**Outputs:**
- Working fluid (WF) mass flow rate
- WF states along the cycle
- All energy transfers

N variables $\Leftrightarrow$ N equations:
- Energy balances $\rightarrow$ N - 1 equations
  - Need 1 assumption ($\Delta T_{sc,cd,ex}$)

$\Delta T_{sc,cd,ex}$

\[ \Delta T_{sc,cd,ex} \rightarrow N - 1 \text{ equations} \]
Off-design performance modelling

N variables $\Leftrightarrow$ N equations:

- Energy balances $\rightarrow$ N - 1 equations

Need 1 assumption ($\Delta T_{sc,cd,ex}$)

Inputs:
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- Components specifications

Outputs:
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Off-design performance modelling

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- Energy balances \( \rightarrow N - 1 \) equations

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**CONTEXT & MOTIVATIONS**

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N variables $\Leftrightarrow$ N equations:
- Energy balances $\rightarrow$ N - 1 equations
- Mass balance $\rightarrow$ 1 equation

\[ \sum_{j=1}^{N} M_j = M_{ORC} \quad \text{Total charge is constant !!!} \]
Off-design performance modelling

N variables $\leftrightarrow$ N equations:
- Energy balances $\Rightarrow$ N - 1 equations
- Mass balance $\Rightarrow$ 1 equation

$\sum_{j=1}^{N} M_j = M_{ORC}$ $\longleftarrow$ Total charge is constant !!!

Inputs:
- ORC boundary conditions
- Components specifications
  + total charge ($M_{ORC}$)
- Working fluid (WF) mass flow rate

Outputs:
- WF states along the cycle
- All energy transfers
  + charge distribution ($M_j$)

TRUE OFF-DESIGN MODEL ONLY IF CHARGE-SENSITIVE
Goal of this thesis

Predict off-design performance of ORC with fully validated charge-sensitive models

Thesis objectives

ORC off-design modelling

HVAC systems

Theoretical only

Energy aspects only

Experimental validation

Charge-sensitive method

CONTEXT & MOTIVATIONS
Presentation outline

I. Context and motivations

II. Experimental investigations

III. Modelling developments

IV. Applications of the simulation tools

V. Conclusions and perspectives
II. EXPERIMENTAL INVESTIGATIONS
Test rig description

Main specifications

- 2kWe with R245fa as working fluid
- Scroll expander + diaphragm pump
- POE lubricant in free circulation
- Two BPHEXs (EV + REC)
- A fin coil air-cooled condenser
- Liquid receiver
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Example of LC calibration:

![Graph showing LC calibration](image-url)

**Legend:**
- : flexible pipe
- : rigid pipe
- : holding clamp
- : load cell
**Test rig description** (on-line charge measurement)

**Main specifications**
- 2kWe with R245fa as working fluid
- Scroll expander + diaphragm pump
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- A fin coil air-cooled condenser
- Liquid receiver

**Example of LC calibration:**

- Advantages:
  - Non-intrusive
  - Fast

- Drawbacks:
  - Limited accuracy
  - Not sensitive to the fluid nature

- R245fa + POE
Test rig description (on-line charge measurement)

Main specifications
- 2kWe with R245fa as working fluid
- Scroll expander + diaphragm pump
- POE lubricant in free circulation
- Two BPHEXs (EV + REC)
- A fin coil air-cooled condenser
- Liquid receiver

EXPERIMENTAL INVESTIGATIONS

**Diagram:**
- LC: Liquid cooler
- HEX: Heat exchanger
- LR: Liquid receiver

Legend:
- : flexible pipe
- : rigid pipe
- : holding clamp
- : load cell
Test rig description  (IR imaging of the condenser)
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Test rig description (IR imaging of the condenser)
Experimental campaign

- 6 control variables: $M_{\text{dot,htf}}$, $T_{su,htf}$, $N_{cd}$, $N_{pp}$, $N_{exp}$, $M_{wf}$

- No control strategy $\rightarrow$ non-optimal point, full-load, part-load

- 300 h of tests / 330 steady-state points

- Complete post-treatment (dual data reconciliation)
Charge distribution analysis

\[ M = V \cdot \bar{\rho} \]

\[ \rho(T, P) \]

\[ \alpha \cdot \rho_v + (1 - \alpha) \cdot \rho_l \]

EXPERIMENTAL INVESTIGATIONS
Charge distribution mechanisms

**Liquid receiver**

\[ M_{LR,1} < M_{LR,2} \]

M related to the liquid level

**Heat exchanger**

\[ M_{HEX,1} < M_{HEX,2} \]

M related to the temperature profile:
- inlet/outlet subcooling and superheating
- temperature differences between the fluids

\[ A = \frac{\dot{Q}}{U \Delta T} \]
Charge distribution mechanisms

T-s diagram

Charge inventory

Condenser profile (IR)

Charge inventory:
- AUX: 6%
- REC: 4%
- EV: 30%
- CD: 43%
- LR: 17%

Condenser profile (IR):
- Temperature: 55°C - 25°C
- Position: 11K
- Two-phase region
- Liquid region
Charge distribution mechanisms

**T-s diagram**

- Charge inventory:
  - 6% AUX
  - 4% REC
  - 30% EV
  - 43% CD
  - 17% LR

**Condenser profile (IR)**

- Two-phase: Vap.
- Liquid: 11K

- Two-phase: Vap.
- Liquid: 5K

**Position**
Charge distribution mechanisms

**Impact of increasing the charge only:**

M1:

- EV → No impact
- LR → First absorber
- CD → Second absorber

M2:

M3:

M4:

M5:

M6:
Charge distribution mechanisms

Scenario 1
Charge distribution mechanisms

\[ x_{cd,ex} = 0 \]
Charge distribution mechanisms

\[ x_{cd,ex} = 0 \]
Charge distribution mechanisms

$x_{cd,ex} = 0$

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

Scenario 2

$x_{cd,ex} = 0$

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

\[ x_{cd,ex} = 0 \]

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

\[ x_{cd,ex} = 0 \]

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

\[ x_{cd,ex} = 0 \]

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

$\chi_{cd,ex} = 0$

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

\[ \Delta T_{cd,ex} > 0 \]
\[ x_{cd,ex} = 0 \]

LR totally flooded
Liquid zone in CD

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

Scenario 3

\[ \Delta T_{cd,ex} > 0 \]
\[ x_{cd,ex} = 0 \]

LR totally flooded
Liquid zone in CD

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

- **LR totally flooded**: Liquid zone in CD
  - $\Delta T_{cd,ex} > 0$
  - $x_{cd,ex} = 0$

- **LR partially filled**: No liquid zone in CD
Charge distribution mechanisms

Δ\(T_{cd,ex} > 0\)  \(\Rightarrow\) LR totally flooded

\(\Delta x_{cd,ex} = 0\)  \(\Rightarrow\) LR partially filled

Liquid zone in CD

No liquid zone in CD
Charge distribution mechanisms

- **LR totally flooded**: Liquid zone in CD
- **LR partially filled**: No liquid zone in CD

Mathematical expressions:
- $\Delta T_{cd,ex} > 0$
- $x_{cd,ex} = 0$
Charge distribution mechanisms

\[ \Delta T_{cd,ex} > 0 \]

\[ x_{cd,ex} = 0 \]

LR totally flooded
Liquid zone in CD

LR partially filled
No liquid zone in CD
Charge distribution mechanisms

- LR totally flooded: Liquid zone in CD
  - $\Delta T_{cd,ex} > 0$
  - $x_{cd,ex} = 0$
- LR partially filled: No liquid zone in CD
  - $x_{cd,ex} > 0$
- LR totally empty: Pump cavitation
  - WF not fully condensed!

EXPERIMENTAL INVESTIGATIONS
III. MODELLING DEVELOPMENTS
Modelling developments

- Speed vs. accuracy → 0D/1D semi-empirical
- Matlab 2015a + CoolProp
- Open-access library (ORCmKit)
Modelling developments

- Speed vs. accuracy $\rightarrow$ 0D/1D semi-empirical
- Matlab 2015a + CoolProp
- Open-access library (ORCmKit)

- Fluid / flow properties
- Component-level models
- System-level models
**Fluid / flow properties**

R245fa/POE liquid mixture

Pure R245fa vapour

Oil enriched liquid

---

**R245fa/POE mixture composition model**

\[
\begin{align*}
\hat{h}_{mix} &= \frac{\zeta_{wf} \kappa_{oil}(1 - \kappa_{oil})}{1 - \zeta_{wf} - \kappa_{oil} + \zeta_{wf} \kappa_{oil}} \hat{h}_{wf,l} + \cdots \\
&\quad + \frac{(1 - \zeta_{wf} - \kappa_{oil})(1 - \kappa_{oil})}{1 - \zeta_{wf} - \kappa_{oil} + \zeta_{wf} \kappa_{oil}} \hat{h}_{wf,v} + \kappa_{oil}\hat{h}_{oil}
\end{align*}
\]
Fluid / flow properties

R245fa/POE liquid mixture

Pure R245fa vapour
Oil enriched liquid

R245fa/POE mixture composition model

Void fraction model

\[ M = V \bar{\rho} \]

\[ \rho_l (1 - \bar{\alpha}) + \rho_v \bar{\alpha} \]

\[ \bar{\alpha} = \frac{1}{1 + \frac{1 - x}{x} \left( \frac{\rho_v}{\rho_l} \right) S} \]

\[ h_{mix} = \frac{\zeta_{wf} k_{oil} (1 - \kappa_{oil})}{1 - \zeta_{wf} - \kappa_{oil} + \zeta_{wf} k_{oil}} h_{wf,l} \]

\[ \ldots + \frac{(1 - \zeta_{wf} - \kappa_{oil})(1 - \kappa_{oil})}{1 - \zeta_{wf} - \kappa_{oil} + \zeta_{wf} k_{oil}} h_{wf,v} + \kappa_{oil} h_{oil} \]
**Fluid / flow properties**

R245fa/POE liquid mixture

Pure R245fa vapour

Oil enriched liquid

R245fa/POE mixture composition model

Void fraction model

\[ h_{mix} = \frac{\zeta_{wf} K_{oil}(1 - K_{oil})}{1 - \zeta_{wf} - K_{oil} + \zeta_{wf} K_{oil}} h_{wf,l} \]

\[ \cdots + \frac{(1 - \zeta_{wf} - K_{oil})(1 - K_{oil})}{1 - \zeta_{wf} - K_{oil} + \zeta_{wf} K_{oil}} h_{wf,v} + K_{oil} h_{oil} \]
Fluid / flow properties

R245fa/POE mixture composition model

$$h_{mix} = \frac{\zeta_{wf} K_{oil}(1 - K_{oil})}{1 - \zeta_{wf} - K_{oil} + \zeta_{wf} K_{oil}} h_{wf,l} \ldots$$

$$\ldots + \frac{(1 - \zeta_{wf} - K_{oil})(1 - K_{oil})}{1 - \zeta_{wf} - K_{oil} + \zeta_{wf} K_{oil}} h_{wf,v} + K_{oil} h_{oil}$$

Void fraction model

$$M = V \bar{\rho}$$

$$\rho_l (1 - \bar{\alpha}) + \rho_v \bar{\alpha}$$

$$\bar{\alpha} = \frac{1}{1 + \frac{1 - x}{x} \left( \frac{\rho_v}{\rho_l} \right) S}$$

$$M_{oil} = (1 - \zeta_{wf}) (1 - \bar{\alpha}) \rho_l V$$

$$M_{wf} = [\bar{\alpha} \rho_v + (1 - \bar{\alpha}) \zeta_{wf} \rho_l] V$$

R245fa/POE liquid mixture

Pure R245fa vapour

Oil enriched liquid
Component modelling
Component modelling

Heat exchangers:

- 1D moving boundary
  \[ \text{find } \dot{Q} \text{ i.e. } \sum A_i = A_{HEX} \]

- General, robust and versatile:
  - Single- / multi-phase heat transfers
  - Counter- / cross-flow configurations
  - Symmetric / asymmetric surface area
  - Heat transfer transition (dry-out and wet-desuperheating)
  - Advanced discretization
  - Secondary resistances (fooling, conduction)
  - Fluid composition (pure, mixture, incompressible)
  - Heat source inversion
Component modelling

Heat exchangers:

Convective Heat Transfer Coefficients (CHTC)
Component modelling

Heat exchangers:

Why are the CHTCs so important?

- Impact heat transfer ($\dot{Q}_{HEX}$)
  \[ U_i = \left( \frac{1}{H_{h,i}} + \frac{1}{H_{c,i}} \right)^{-1} \]

- Impact zones distribution
  \[ A_i = \frac{\dot{Q}_i}{U_i \Delta T_i} \]

CHTCs ↔ Charge
Heat exchangers:

CHTCs identification method:

1. Selection of SoA correlations ($Nu = f(Re, Pr)$)

2. Fitting comparison in terms of
   a) Heat transfer predictions
   b) Charge/zone distribution predictions

3. Refinement of the best candidates, i.e.

$$Nu^*_j = c_j \cdot Nu_j$$

$$\min_{c_j} \text{RMSE}_\dot{Q} + \text{RMSE}_{M/A_i}$$
Component modelling

Mechanical components:

- Expander
- Pump

Similar of expander +
Component modelling

Pipelines:
- Pressure drops + ambient losses → easy
- Charge and oil retention → more complex
Liquid receiver:

- if $x = 0$ → partially filled (two-phase)
- if “$x < 0$” → filled of subcooled liquid
- if $0 < x < 1$ → filled of saturated vapour
- if “$x > 1$” → filled of superheated vapour
ORC modelling

MODELS PARAMETERS


INPUTS

\( N_{\text{exp}} \)
\( N_{\text{pp}} \)
\( T_{\text{amb}} \)
\( \dot{m}_{\text{htf, h}} \)
\( T_{\text{htf, h, su}} \)
\( P_{\text{htf, h, su}} \)
\( \dot{m}_{\text{htf, c}} \)
\( T_{\text{htf, c, su}} \)
\( P_{\text{htf, c, su}} \)
\( M_{\text{wf}} \)
\( K_{\text{oil}} \)

OUTPUTS

\( \dot{m}_{\text{wf}} \)
\( \{ P_{\text{wf, i}}, T_{\text{wf, i}}, h_{\text{wf, i}} \} \)
\( \{ \dot{W}_{i}, \dot{Q}_{i} \} \)
\( M_{i} \)

Off-design

(+ charge-sensitive)

(+ lubricant-sensitive)

ORC model
**MODELLING DEVELOPMENTS**

**ORC modelling**

**MODELS PARAMETERS**


**INPUTS**

- $N_{\text{exp}}$
- $N_{\text{pp}}$
- $T_{\text{amb}}$
- $T_{\text{htf,h}}$
- $T_{\text{htf,c}}$
- $P_{\text{htf,h}}$
- $P_{\text{htf,c}}$
- $M_{\text{wf}}$
- $K_{\text{oil}}$

**OUTPUTS**

- $\dot{m}_{\text{wf}}$
- $P_{\text{wf,i}}$
- $T_{\text{wfi,i}}$
- $h_{\text{wf,i}}$

**MODELS**

1. **PP**
   - $M_{\text{pp}}$
   - $P_{\text{pp,ex}}$
   - $N_{\text{pp}}$
   - $P_{\text{pp,su}}$
   - $h_{\text{pp,su}}$

2. **EV**
   - $M_{\text{ev}}$
   - $P_{\text{ev,ex}}$
   - $P_{\text{ev,su}}$
   - $h_{\text{ev,su}}$
   - $h_{\text{ev,ex}}$

3. **REC**
   - $M_{\text{rec}}$
   - $P_{\text{rec,ex}}$
   - $P_{\text{rec,su}}$
   - $h_{\text{rec,ex}}$
   - $h_{\text{rec,su}}$

4. **CD**
   - $M_{\text{cd}}$
   - $P_{\text{cd,ex}}$
   - $P_{\text{cd,su}}$
   - $h_{\text{cd,ex}}$
   - $h_{\text{cd,su}}$

5. **EXP**
   - $M_{\text{exp}}$
   - $P_{\text{exp,ex}}$
   - $P_{\text{exp,su}}$
   - $h_{\text{exp,ex}}$
   - $h_{\text{exp,su}}$

6. **Pipe**
   - $M_{\text{pipes}}$
   - $\Delta P$

**Parameters**

- $M_{\text{wf,2}} = M_{\text{pp}} + M_{\text{rec}} + M_{\text{ev}} + M_{\text{exp}} + M_{\text{recc}} + M_{\text{cd}} + M_{\text{LR}} + \Sigma_{i} M_{\text{pipes,i}}$

**Equations**

- $M_{\text{wf,2}} = M_{\text{pp}} + M_{\text{rec}} + M_{\text{ev}} + M_{\text{exp}} + M_{\text{recc}} + M_{\text{cd}} + M_{\text{LR}} + \Sigma_{i} M_{\text{pipes,i}}$

**Diagram**

- Flowchart showing the interaction between different models and parameters.
Model validation (inner state)
Model validation (energy flows)
Model validation (charge inventory)

**REC [kg]**

- Simulated charge vs. Exp. charge
- X=Y line
- ±15% range

**EV [kg]**

- Simulated charge vs. Exp. charge
- X=Y line
- ±15% range

**CD [kg]**

- Simulated charge vs. Exp. charge
- X=Y line
- ±15% range

**AUX [kg]**

- Simulated charge vs. Exp. charge
- X=Y line
- ±15% range

**LR [kg]**

- Simulated charge vs. Exp. charge
- X=Y line
- ±15% range

**ΔT_{sc} [K]**

- Simulated vs. Exp. charge
- X=Y line
- ±5K range
IV. APPLICATIONS OF THE SIMULATION TOOLS
Example of applications

- Off-design sensitivity mapping
- Cavitation detection
- Full- and part-load performance optimization
- Optimal charge selection and LR sizing
Example #1: Cavitation detection

• Pump cavitation = vapour bubbles within pump → really bad!

\[
\frac{P_{pp,su} - P_{sat}(T_{pp,su})}{g \rho_{pp,su}} < NPSH_r
\]
Example #1: Cavitation detection

- Pump cavitation = vapour bubbles within pump $\rightarrow$ really bad!
- Detectable with charge-sensitive model (no guess on $\Delta T_{sc,cd,ex}$)

No hypothesis here
Example #1: Cavitation detection

- Pump cavitation = vapour bubbles within pump → really bad!
- Detectable with charge-sensitive model (no guess on $\Delta T_{sc, cd, ex}$)
- Example: decrease of charge in the system
Example #2: Optimal charge and LR size

1. Define off-design operational range

2. Full-load performance mapping while imposing $\Delta T_{sc,cd,ex}$

Seek for optimal control in order to maximize $\dot{W}_{net}$
Example #2: Optimal charge and LR size

1. Define off-design operational range

2. Full-load performance mapping while imposing $\Delta T_{sc, cd, ex}$
   - Seek for optimal control in order to maximize $\dot{W}_{net}$
   - Build a charge requirement mapping
Example #2: Optimal charge and LR size

1. Define off-design operational range
2. Full-load performance mapping while imposing $\Delta T_{sc,cd,ex}$
3. Optimal charge assessment

$$M_{ORC} = \max(M_{FL,j})$$
Example #2: Optimal charge and LR size

1. Define off-design operational range
2. Full-load performance mapping while imposing $\Delta T_{sc,cd,ex}$
3. Optimal charge assessment $\rightarrow M_{ORC} = \max(M_{FL,j})$
4. Minimum LR volume $\rightarrow V_{LR} = \frac{M_{ORC} - M_{\text{min}}}{\rho_{l,min}}$

APPLICATIONS OF THE SIMULATION TOOLS

$M_{ORC} = \max(M_{FL,j})$

$V_{LR} = \frac{M_{ORC} - M_{\text{min}}}{\rho_{l,min}}$

$\min(M_{FL,j})$
Example #2: Optimal charge and LR size

1. Define off-design operational range

2. Full-load performance mapping while imposing $\Delta T_{sc,cd,ex}$

3. Optimal charge assessment $\rightarrow M_{ORC} = \max(M_{FL,j})$

4. Minimum LR volume $\rightarrow V_{LR} = \frac{M_{ORC} - M_{\text{min}}}{\rho_{l,\text{min}}}$

$M_{\text{min}}$ Full-load only

$M_{ORC} = 9.3 \text{ kg}$

$\min(M_{FL,j})$
Example #2: Optimal charge and LR size

1. Define off-design operational range

2. Full-load performance mapping while imposing $\Delta T_{sc,cd,ex}$

3. Optimal charge assessment

4. Minimum LR volume

\[ V_{LR} = \frac{M_{ORC} - M_{min}}{\rho_{l, min}} \]

APPLICATIONS OF THE SIMULATION TOOLS

\[
M_{ORC} = \max(M_{FL,j})
\]

\[
M_{min} = \min(M_{PL,j}) \\
\approx \min(M_{FL,j} - M_{ev,j})
\]

\[
M_{ORC} = 9.3 \, \text{kg}
\]
V. CONCLUSIONS AND PERSPECTIVES
Overall summary

- Modelling library in Matlab (ORCmKit)
- Components + whole systems
- Semi-empirical approaches (0D/1D)
- Robust and versatile

**ORC off-design modelling**

- **Charge-sensitive method**
  - Direct OLM method
  - Intrinsic charge inventory
  - Mechanisms of charge transfers

- **Experimental validation**
  - 2kWe ORC test rig
  - 330 SS pts database
  - Full operating ranges
  - Reconciled data

- **Lubricant-sensitive**
  - Miscibility impact on performance rating
  - Modelling framework for POE/R245fa
5 lessons to remember

1. True off-design models MUST be charge-sensitive.

2. The charge distribution is related to spatial occupation of the liquid/vapour phases.

3. The master is the evaporator. The low-pressure components are slaves.

4. Any knowledge on the charge inventory (or the zones distribution) can help to characterize the convective heat transfer coefficients.

5. Charge-sensitive models are not mandatory, but they are useful.
Perspectives

- Extend to other architectures/technologies
  - Other fluids, shell&tube HEX, turbines, external LR, etc.
  - QCV method vs. OLM method
  - If lubricant in free circulation, direct measurement of oil fraction

- Need further investigations on fundamental aspects
  - Convective heat transfer coefficients
  - Hydraulics in BPHEX (oil retention, void fraction, etc.)
  - WF/lubricant miscibility data

- Extend to dynamic simulations
Thanks for your attention
Any questions?

(Hopefully, future Dr)
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