PhD defense

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

by

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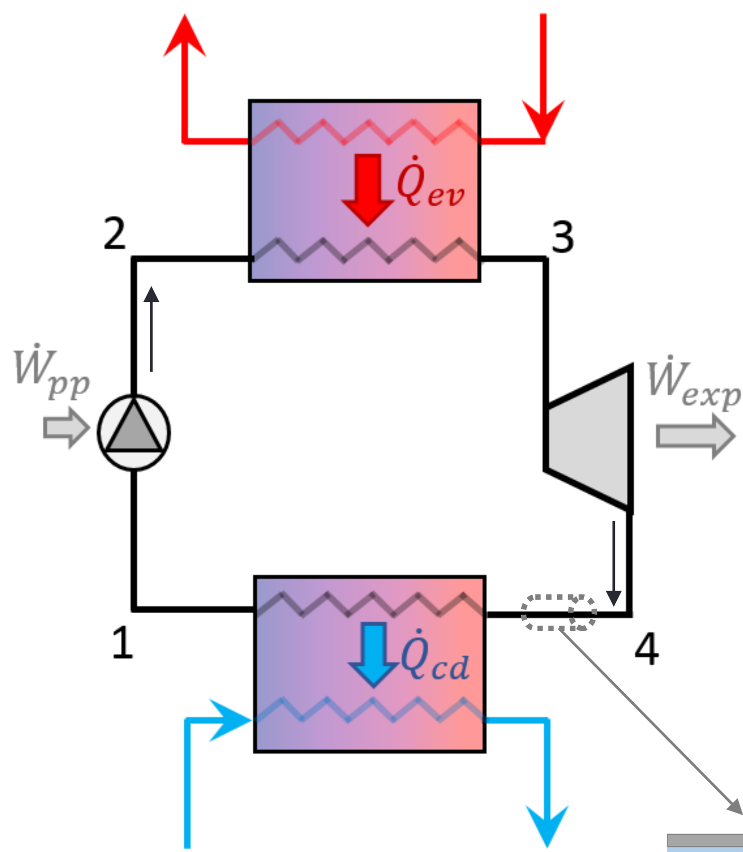
Organic Rankine Cycle (ORC)

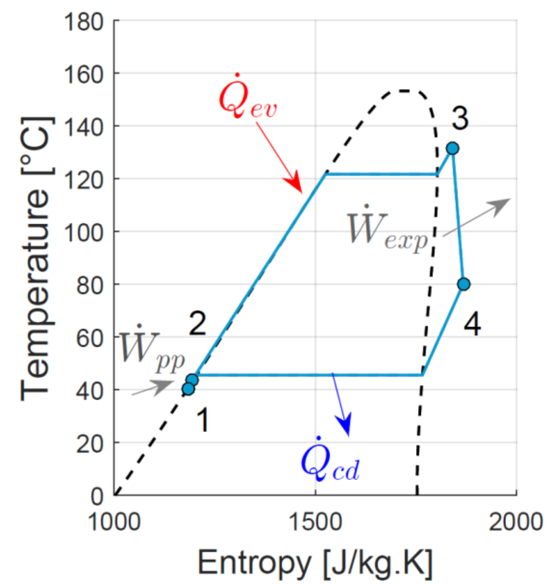
1→2: compression

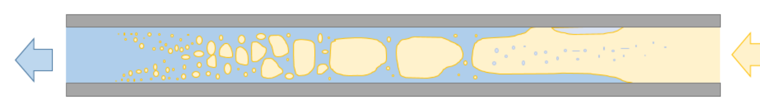
2→3: evaporation

3→4: expansion

4→1: condensation

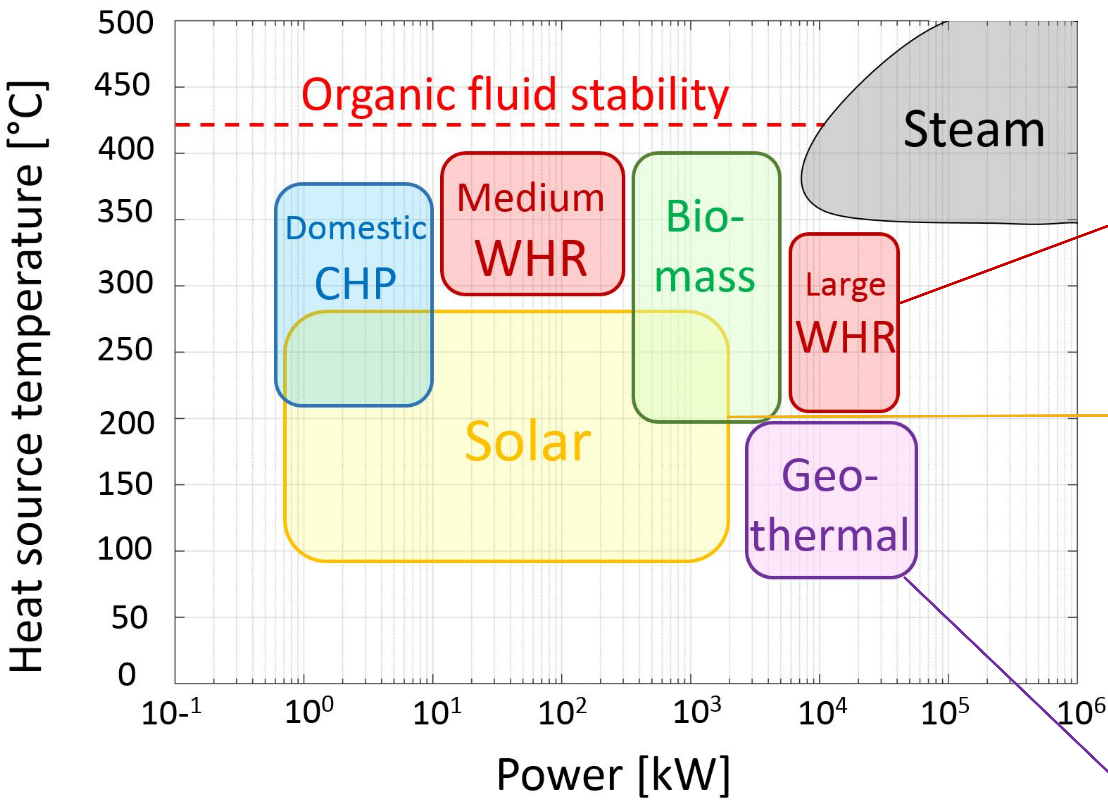






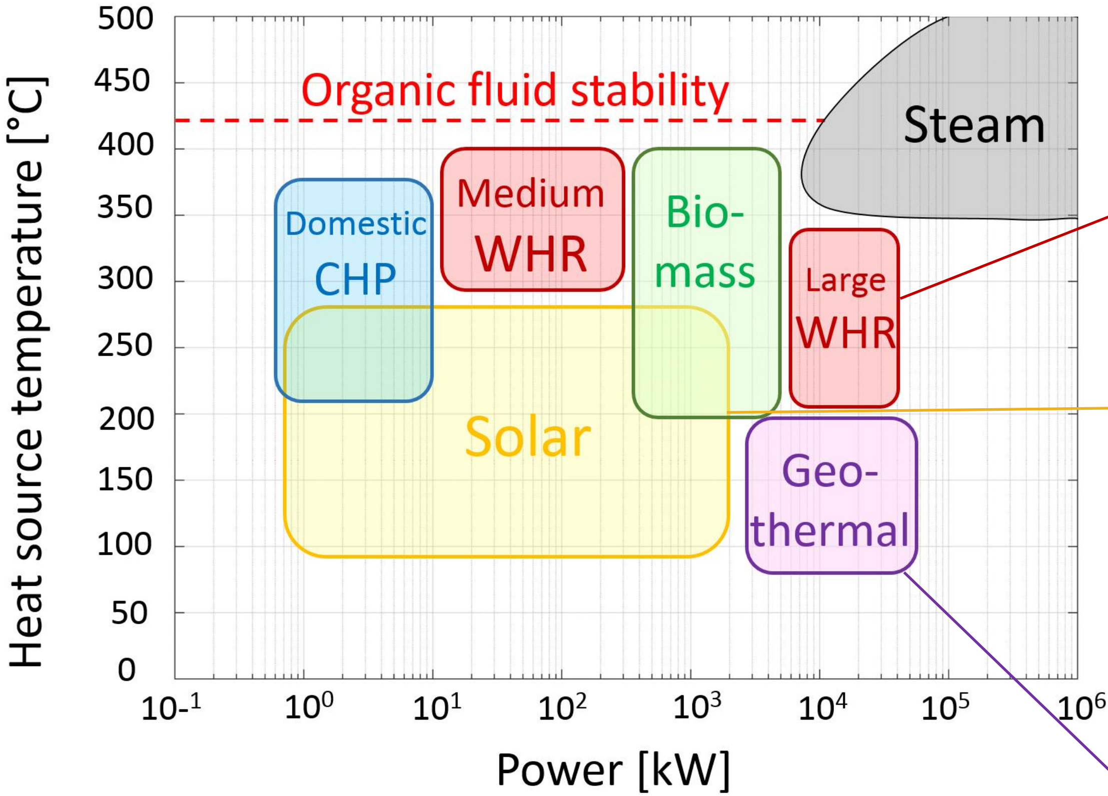
~~Water~~ → Organic fluid

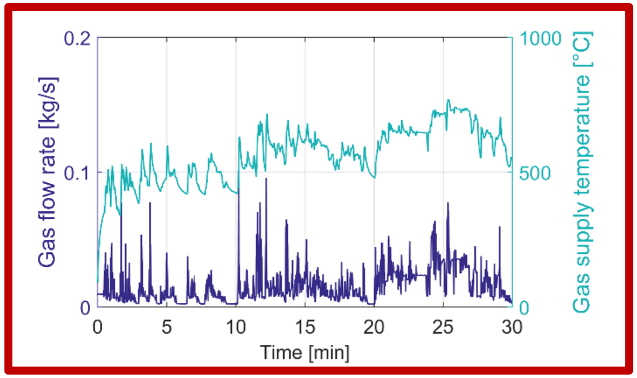
ORC application fields

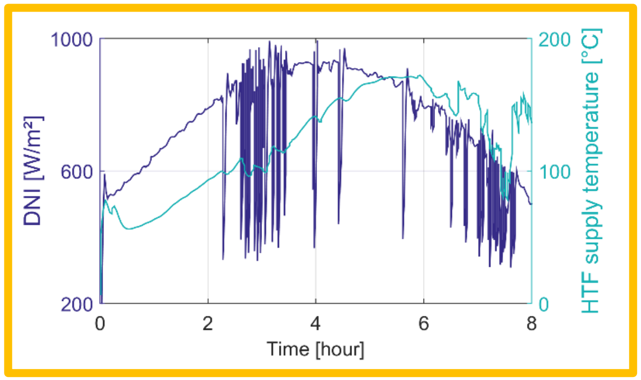


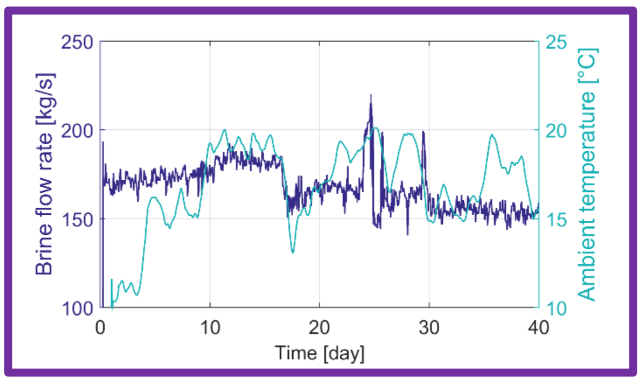
ORC applications
- low-grade heat
- small-capacity

ORC application fields



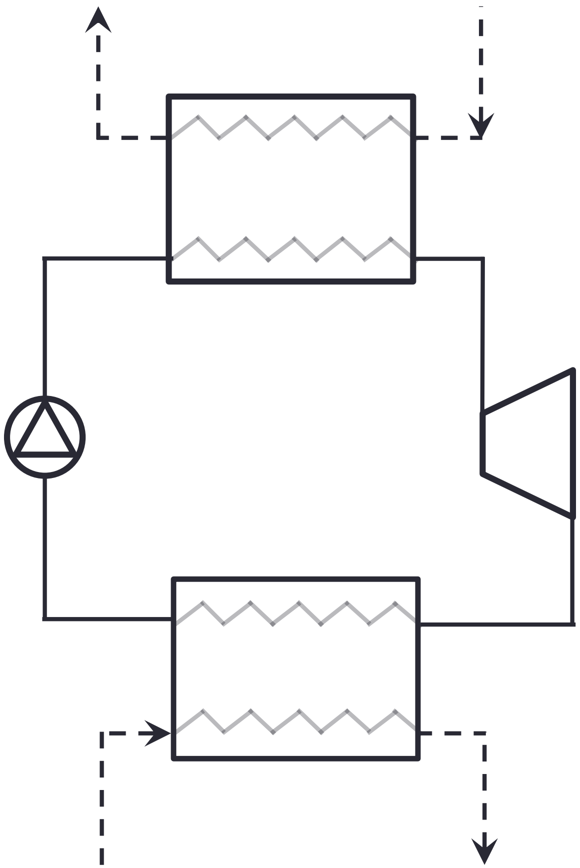






ORC applications ⟹ <u>Off-design operation</u>

Off-design performance modelling



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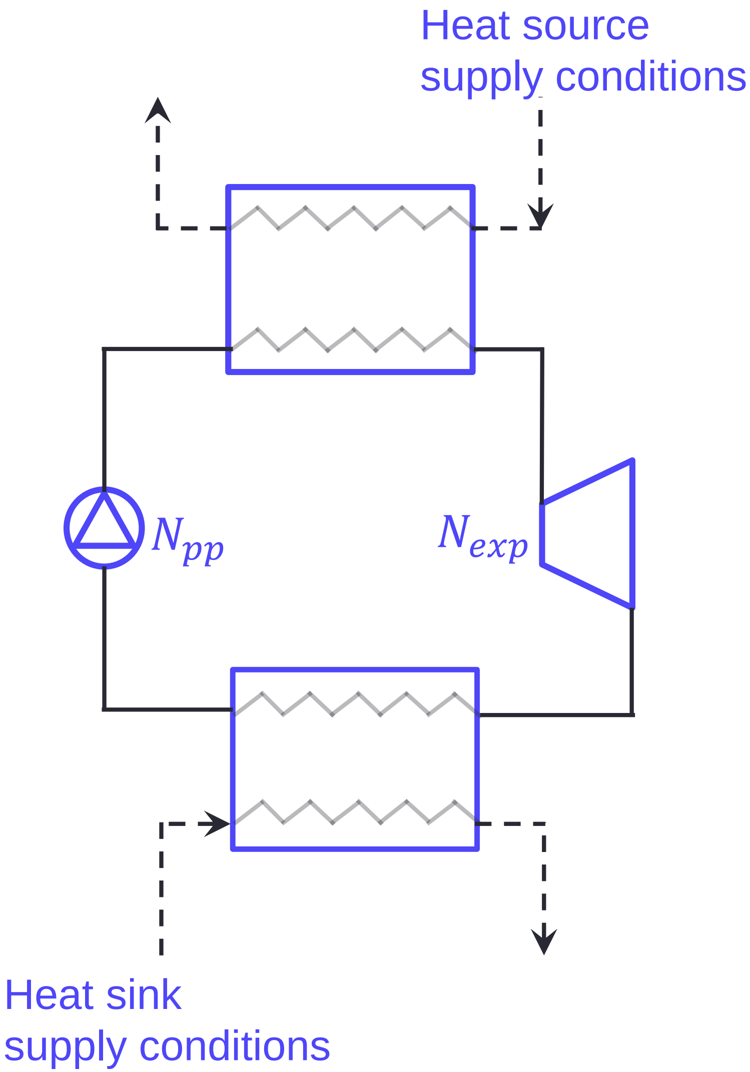

Inputs: ORC boundary conditions; Components specifications

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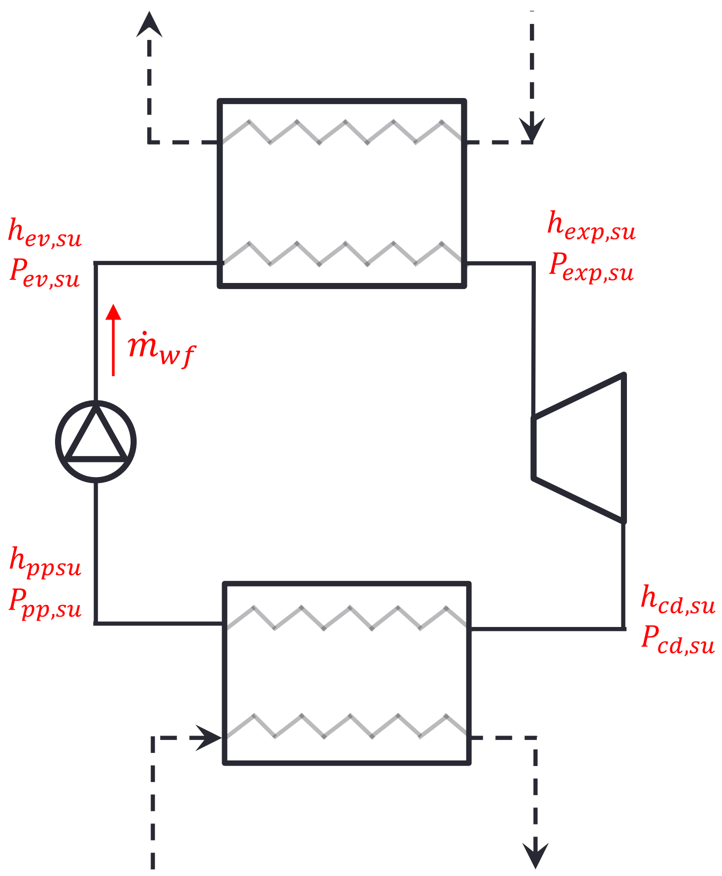

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Outputs: Working fluid (WF) mass flow rate; WF states along the cycle

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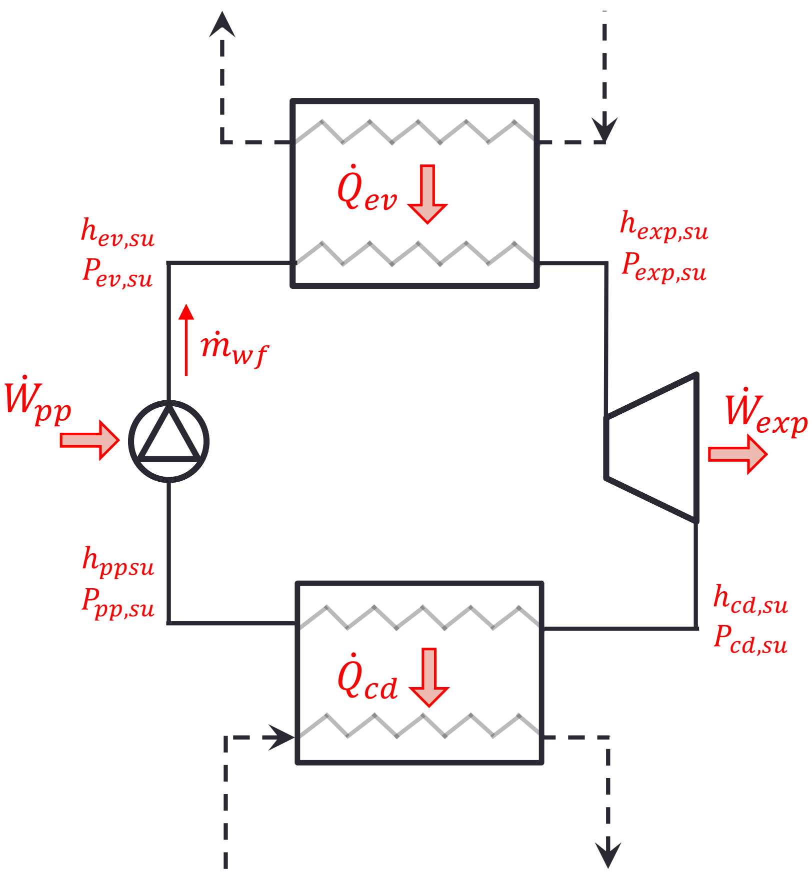

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Outputs:
- Working fluid (WF) mass flow rate
- WF states along the cycle
- All energy transfers

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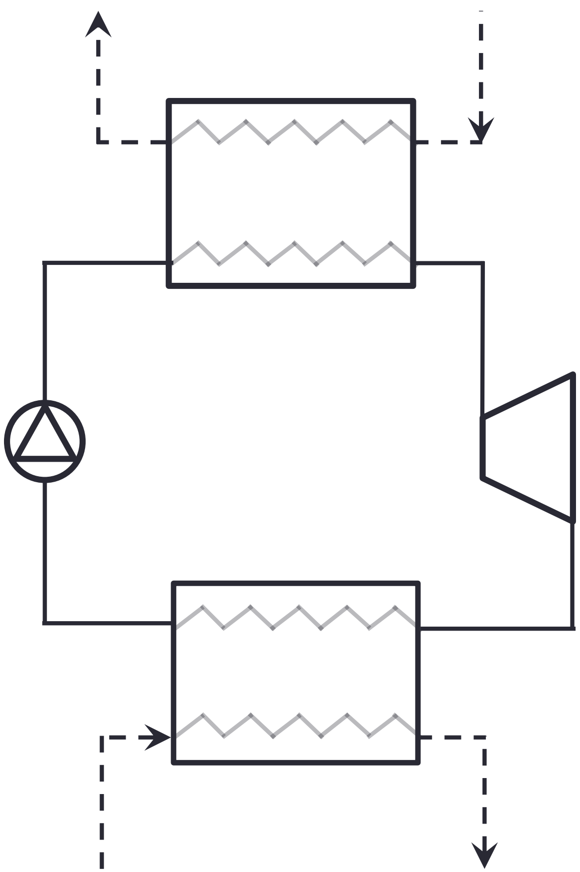

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N variables ⇔ N equations:

- Energy balances → N - 1 equations

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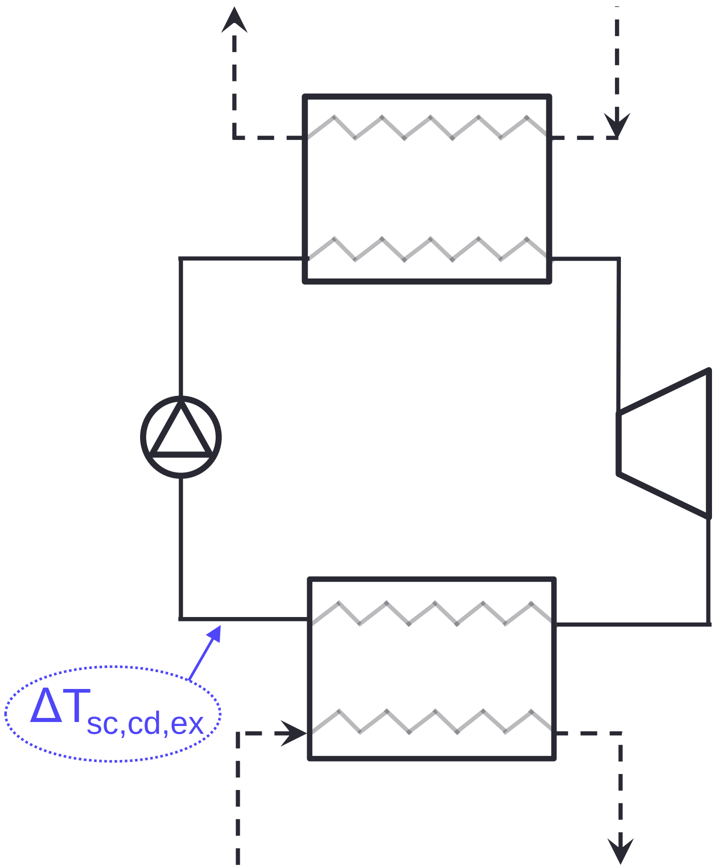

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  - ↳ Need 1 assumption ($\Delta T_{sc,cd,ex}$)

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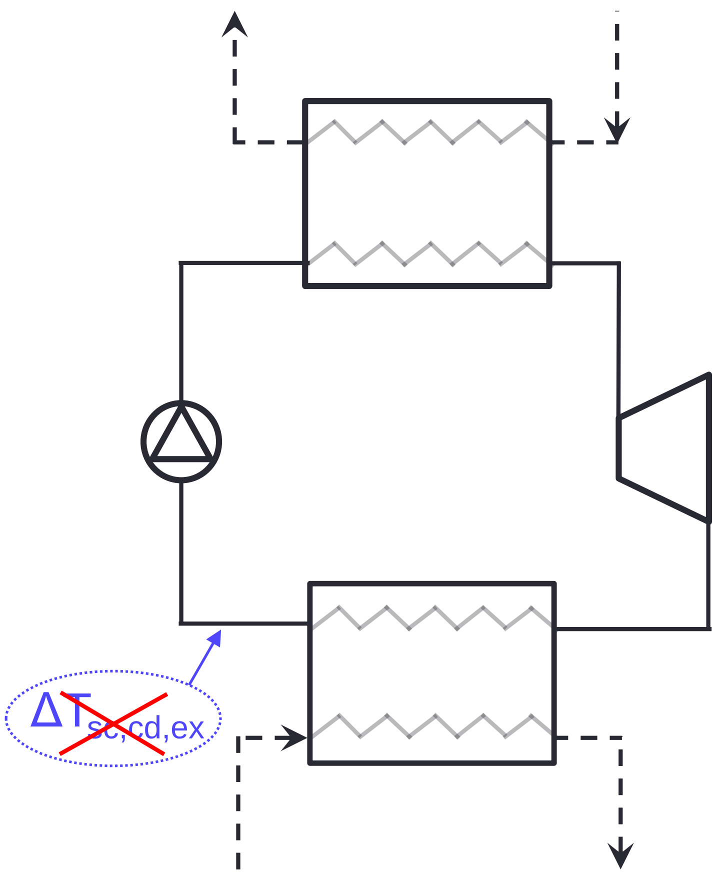

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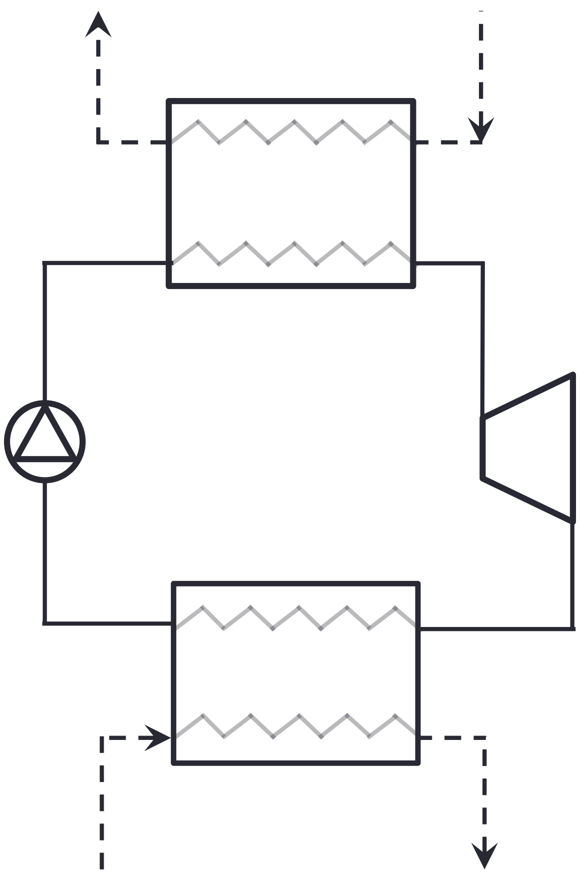

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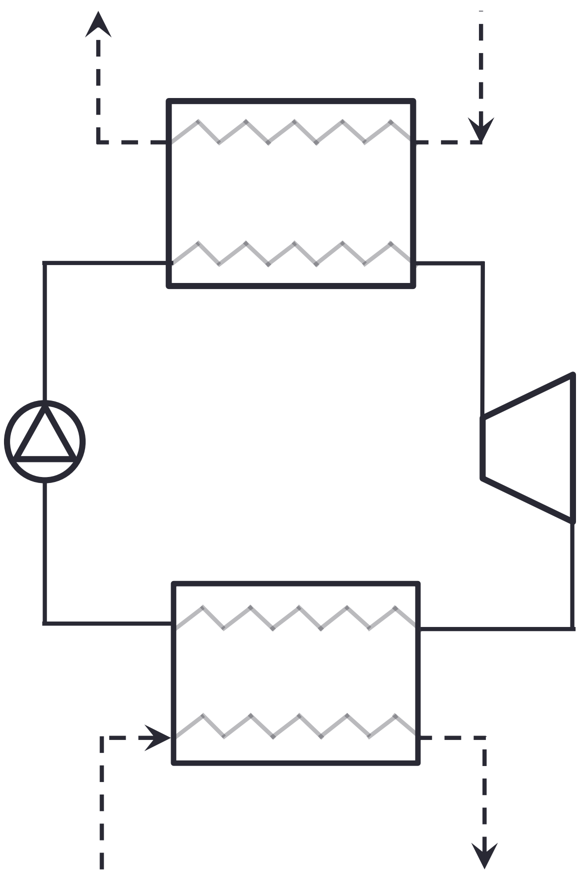

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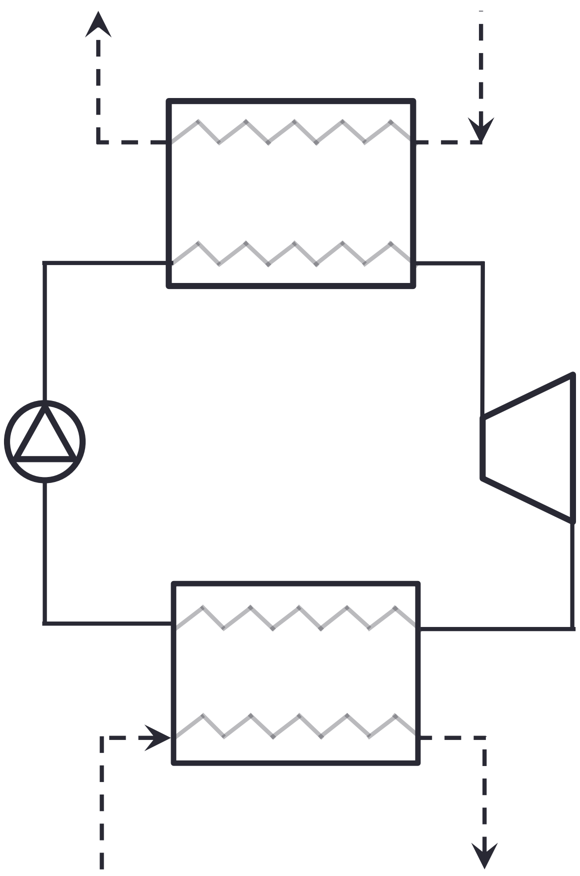

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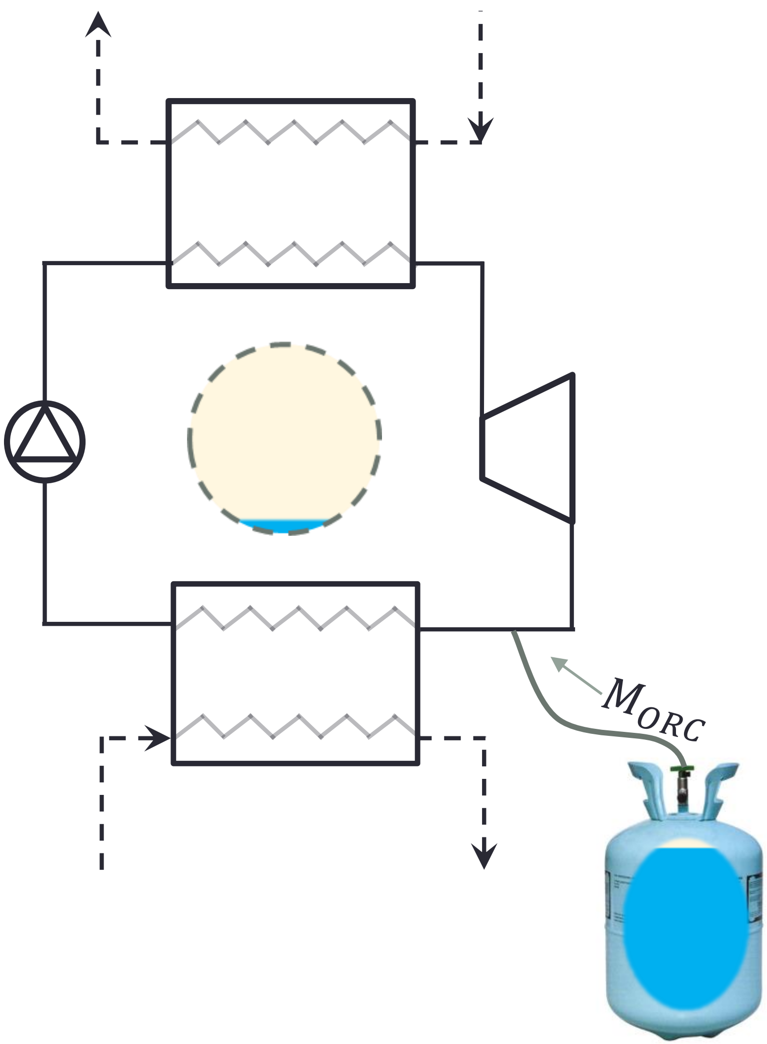

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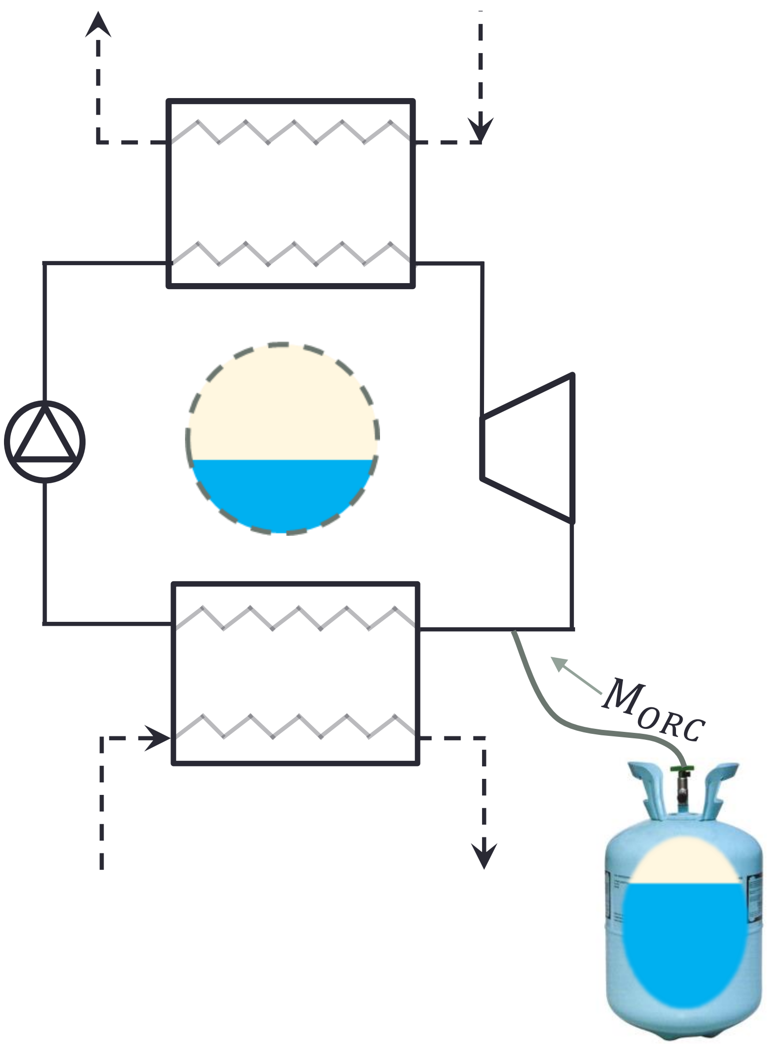

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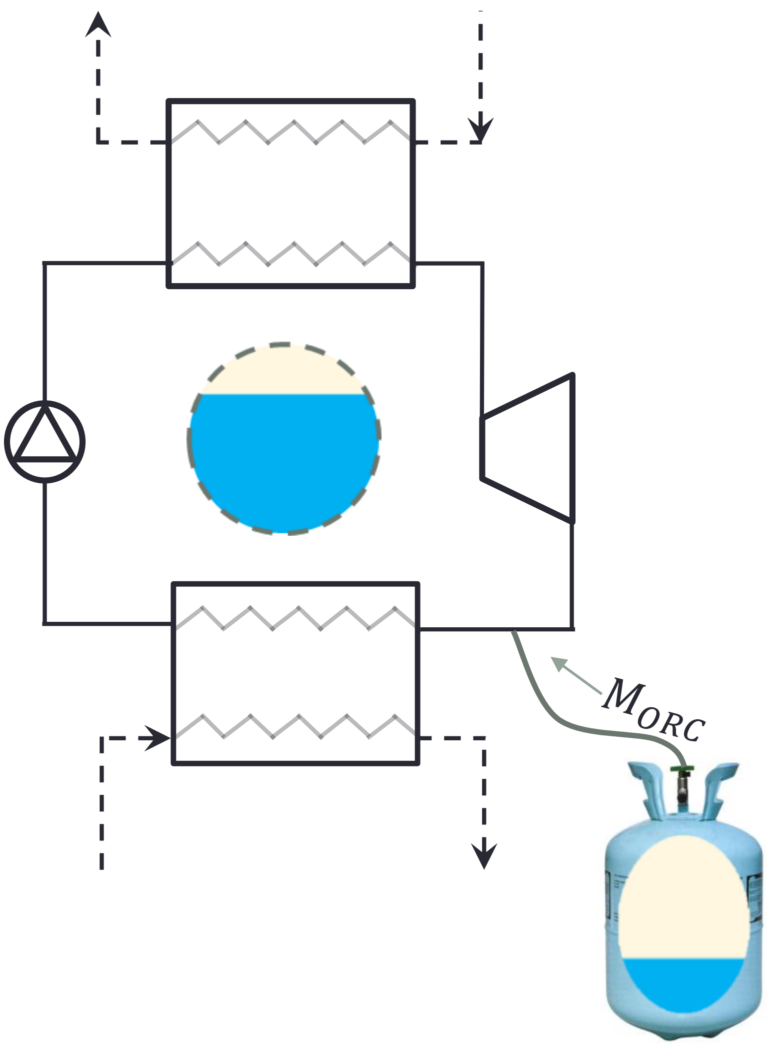

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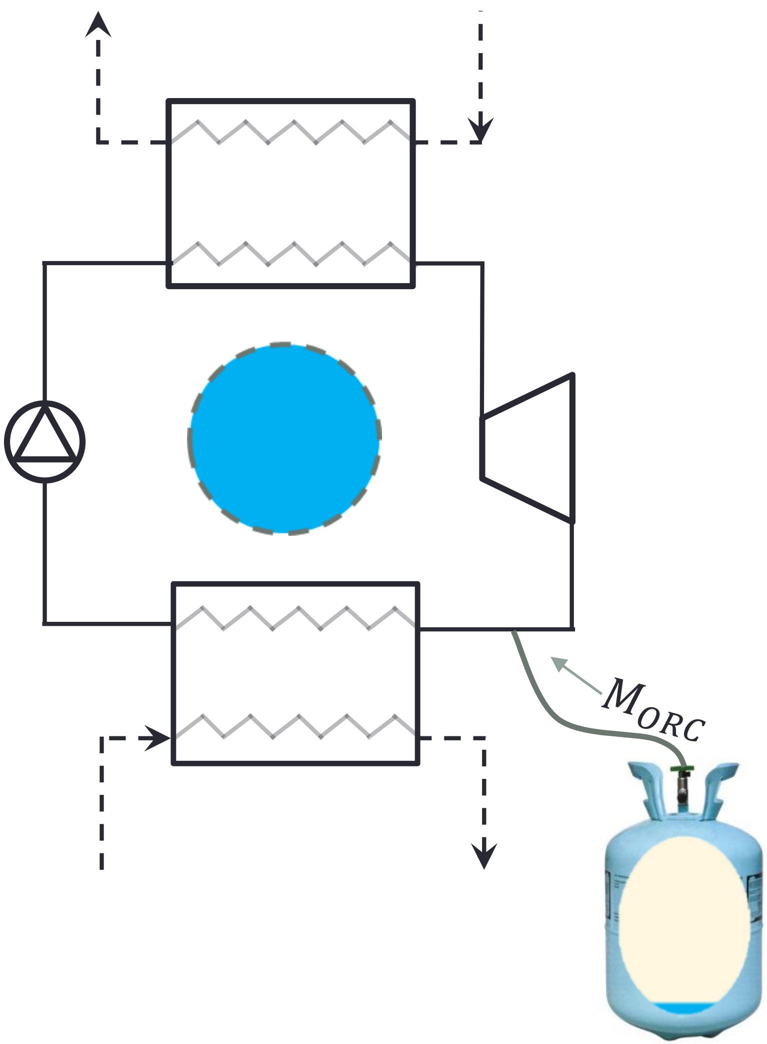

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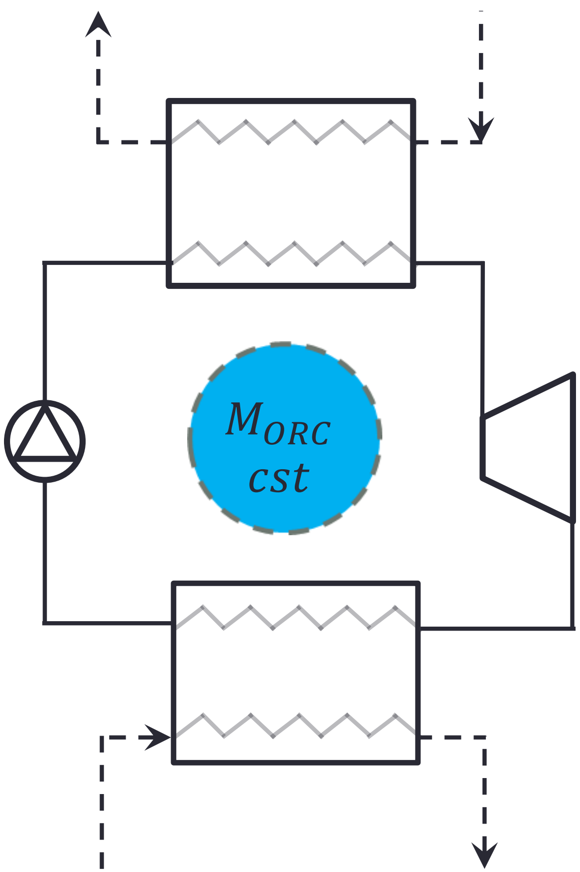

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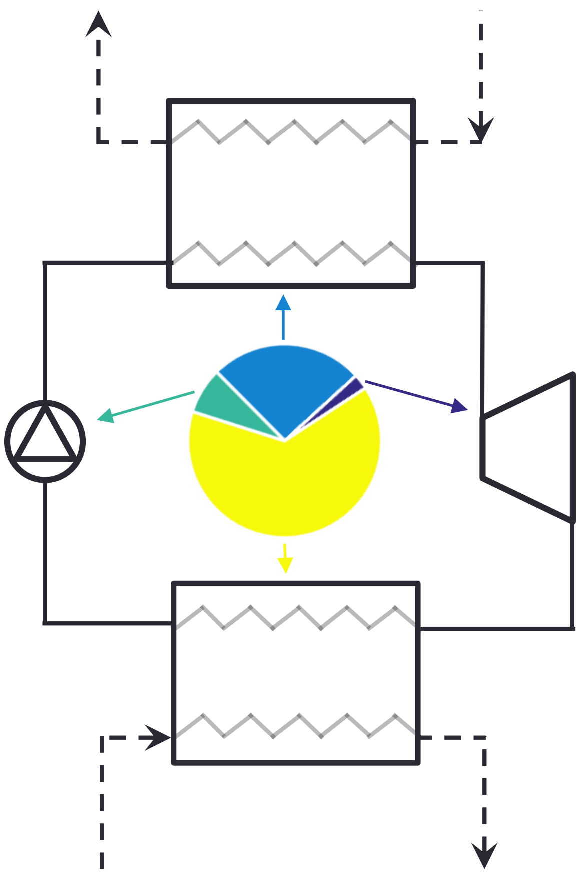

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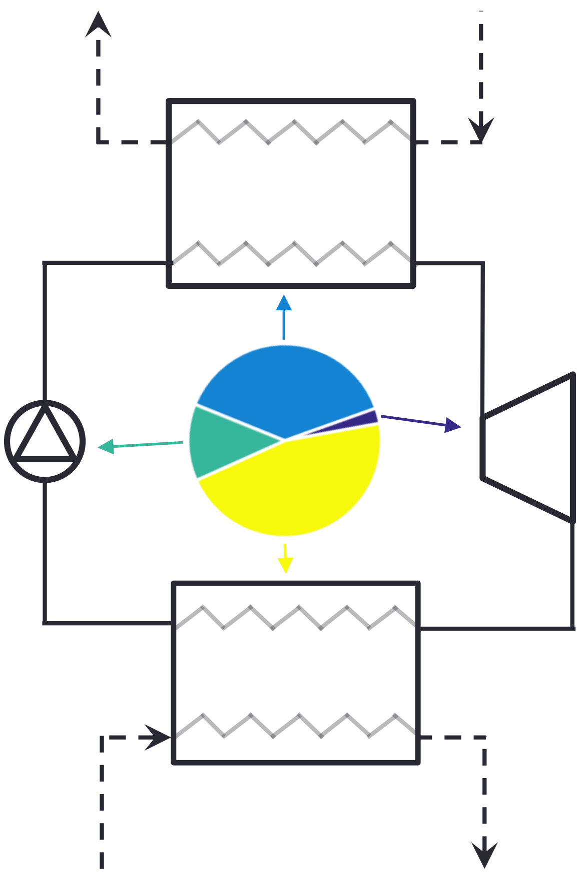

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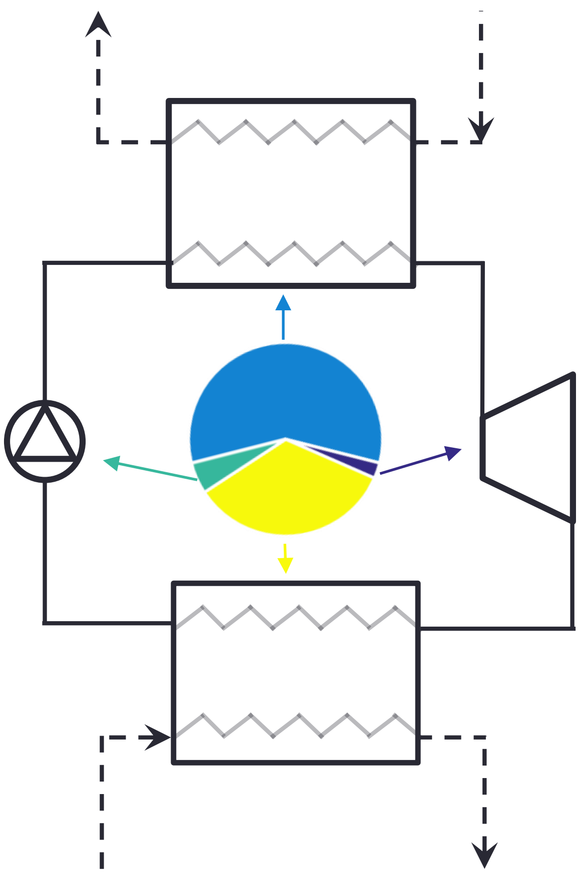

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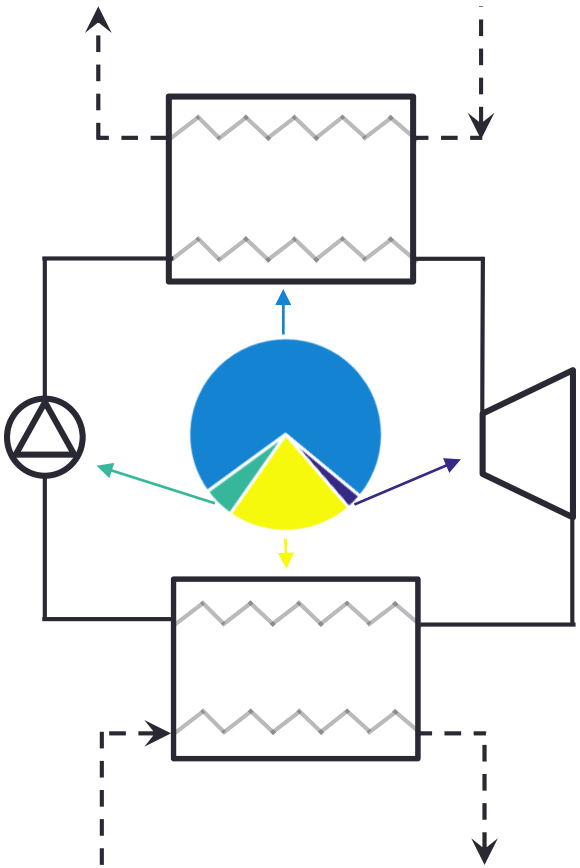

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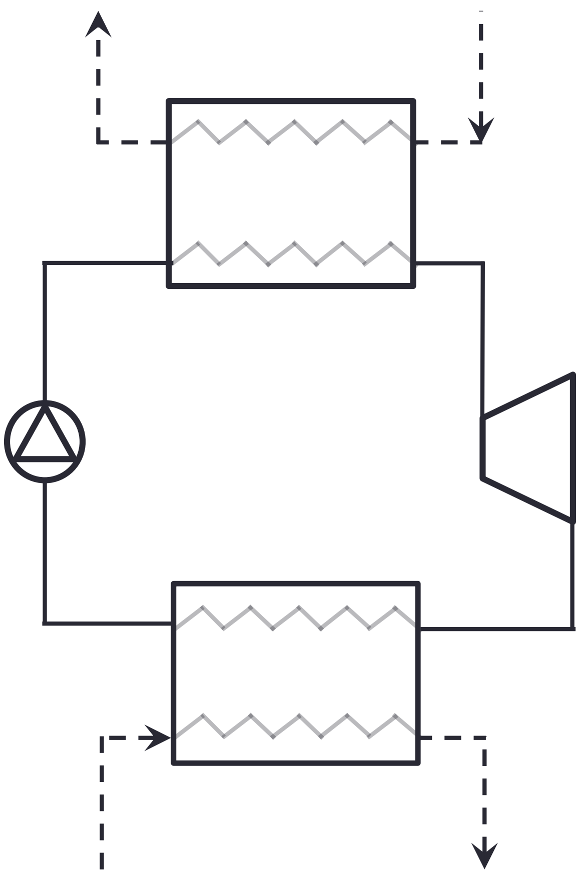

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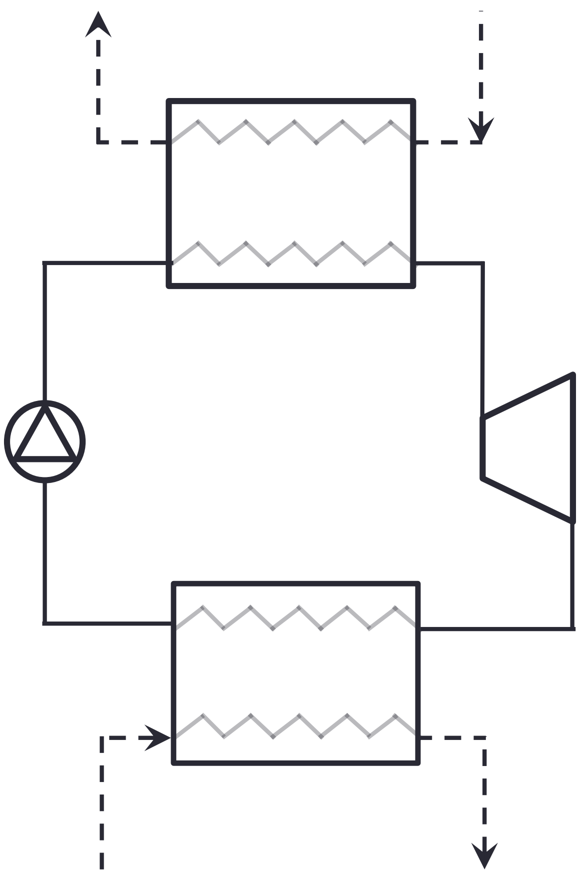

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N variables ⬄ N equations:

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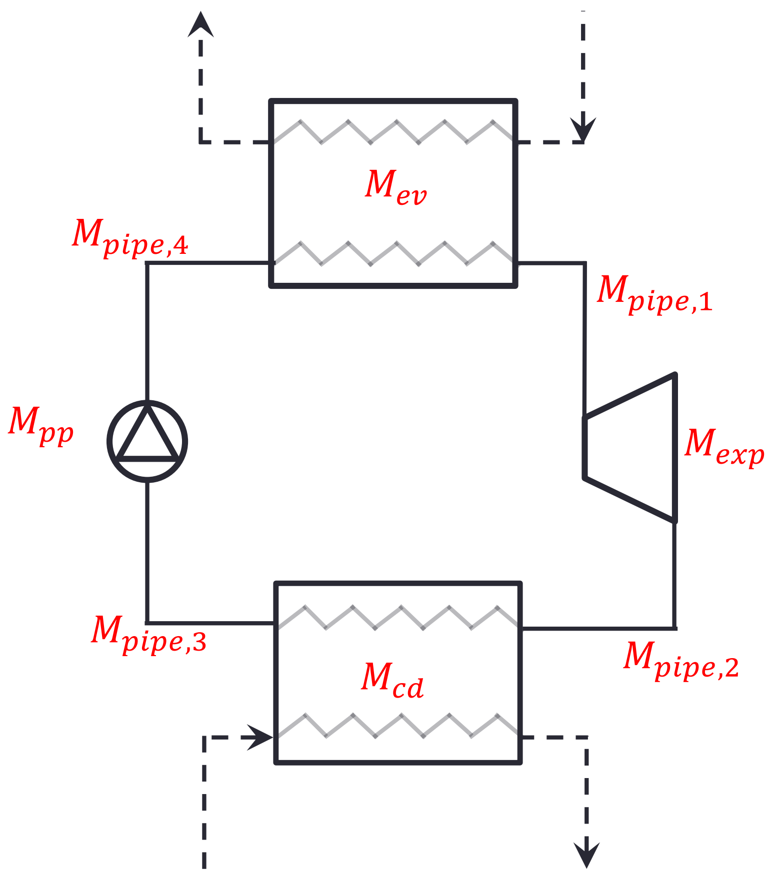
- Mass balance → 1 equation

$$\sum_{j=1}^{N} M_j = M_{ORC}$$

Total charge is constant !!!

Off-design performance modelling



Inputs: ORC boundary conditions
Components specifications

+ total charge (M_{ORC})

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

+ charge distribution (M_j)

N variables ⇔ N equations:

- Energy balances → N - 1 equations
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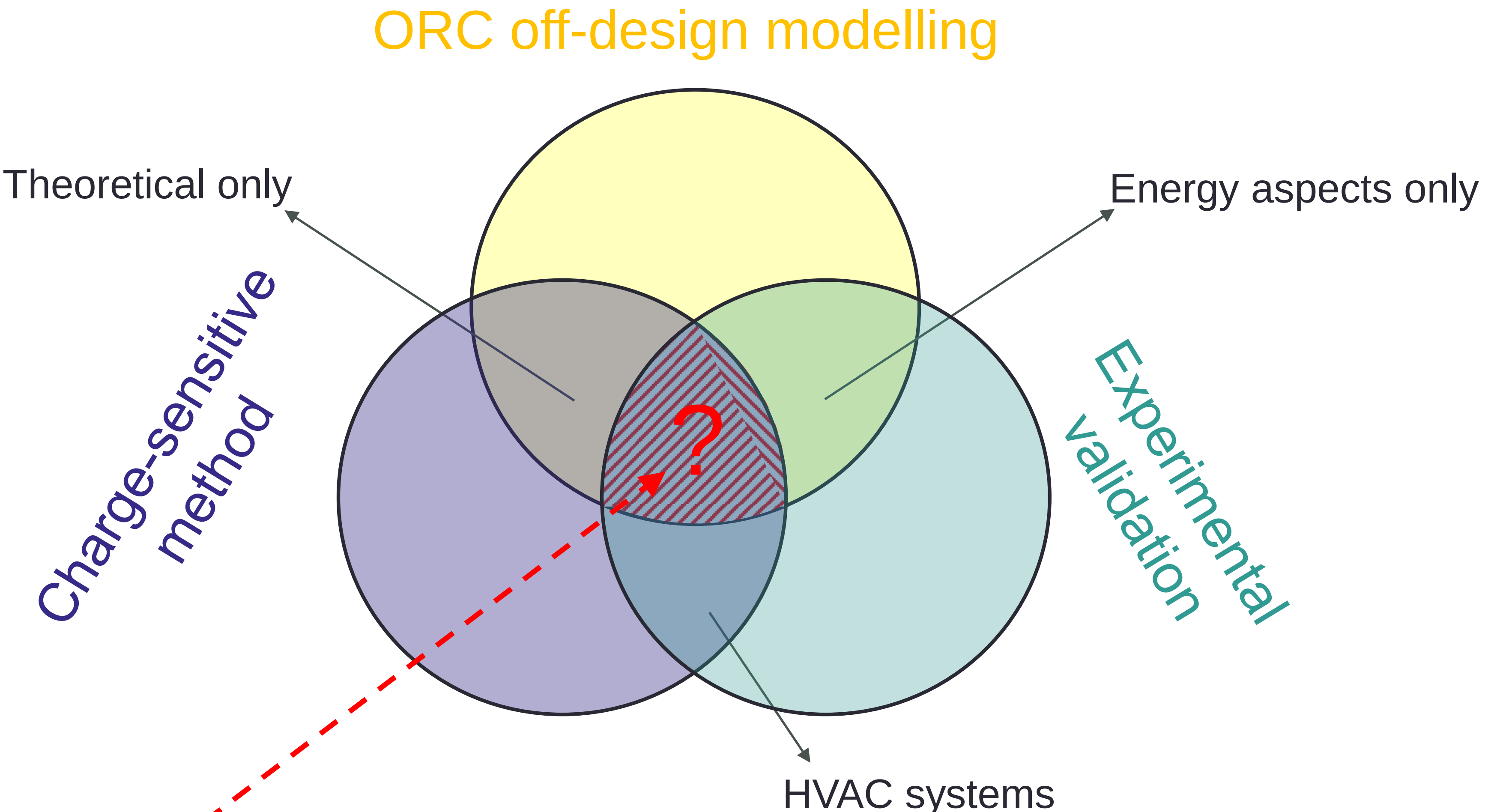
$$\sum_{j=1}^{N} M_j = M_{ORC}$$

Total charge is constant !!!

TRUE OFF-DESIGN MODEL ONLY IF CHARGE-SENSITIVE

Thesis objectives



Goal of this thesis { Predict off-design performance of ORC with fully validated charge-sensitive models

Presentation outline

I. Context and motivations

II. Experimental investigations

III. Modelling developments

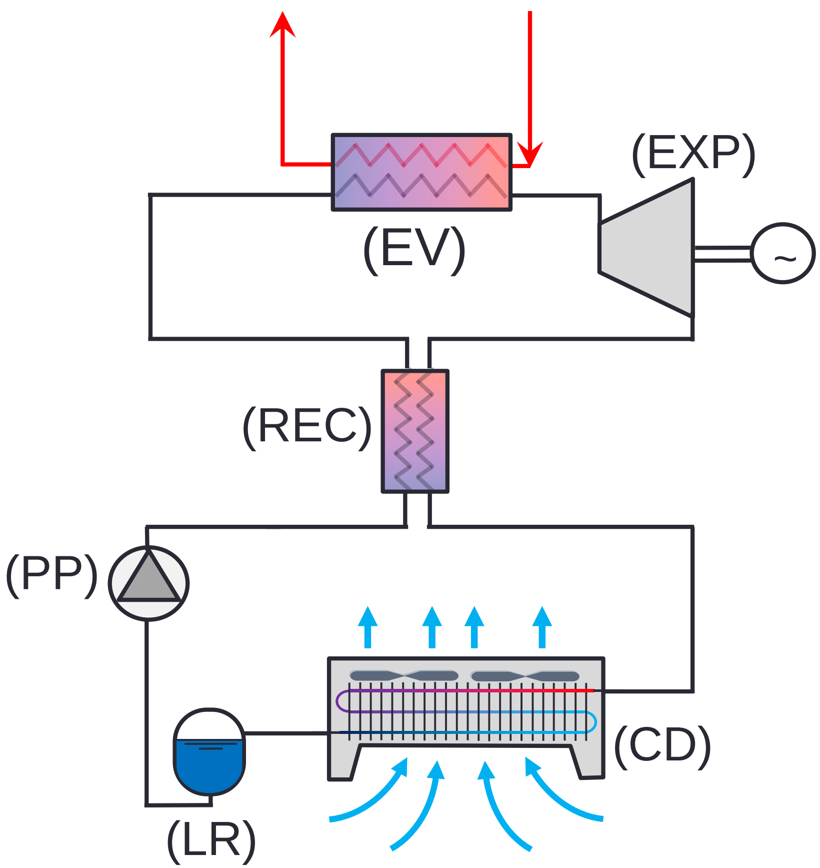
IV. Applications of the simulation tools

V. Conclusions and perspectives

II.

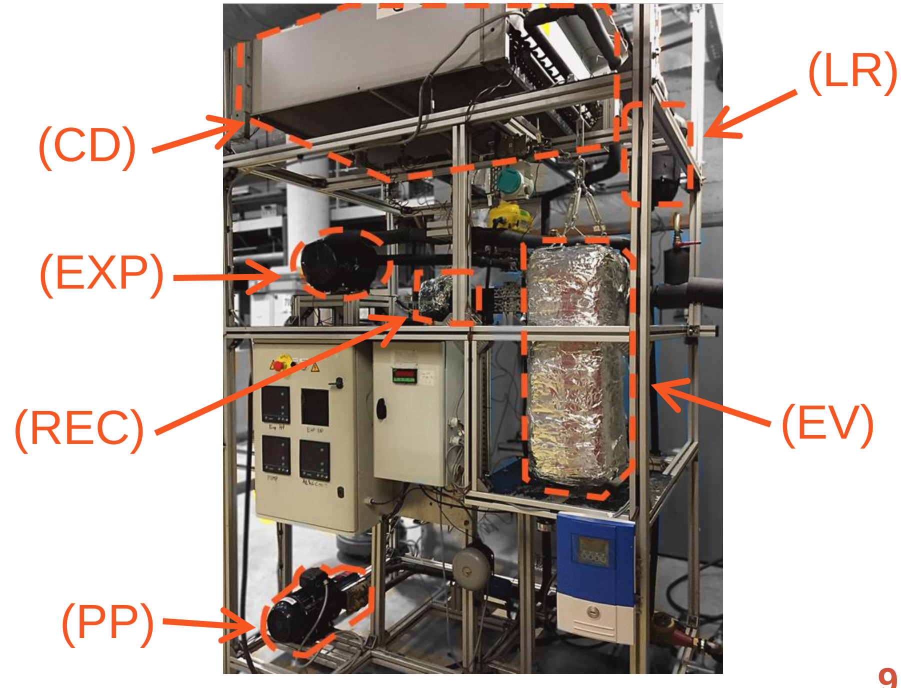
EXPERIMENTAL INVESTIGATIONS

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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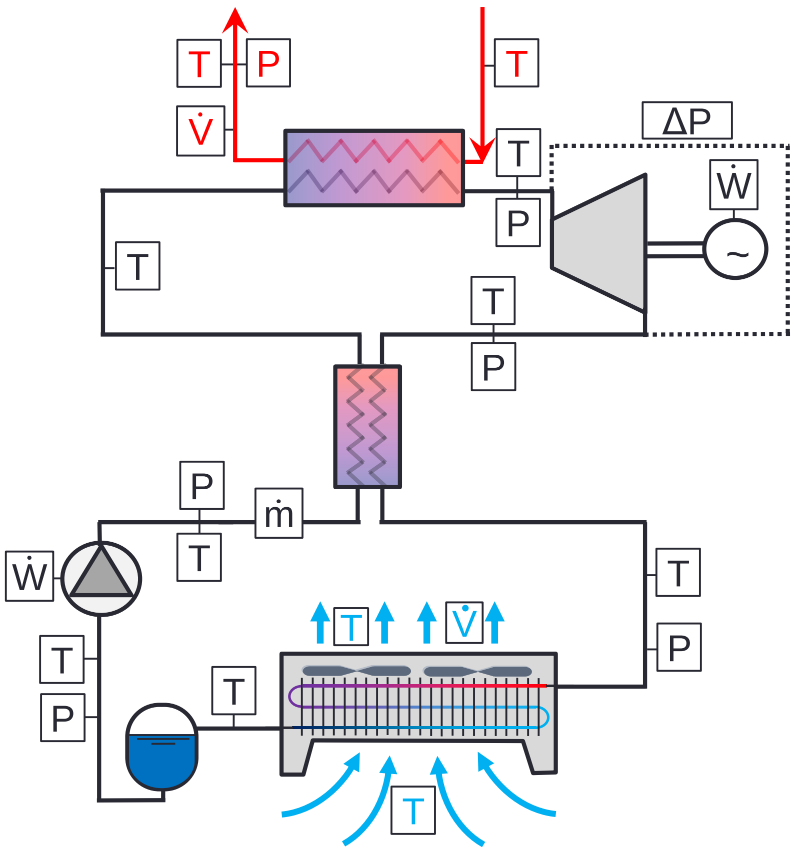

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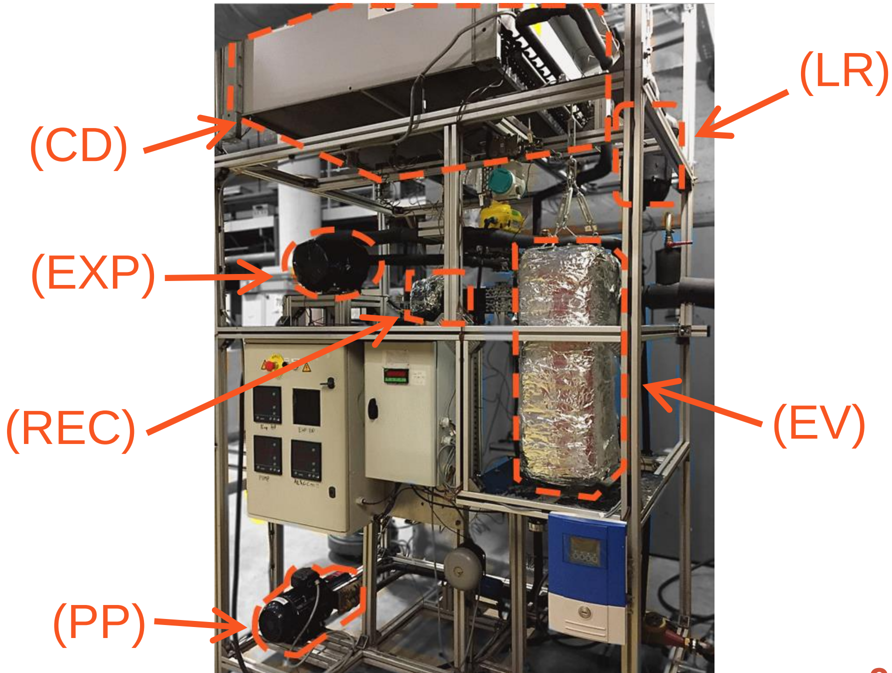
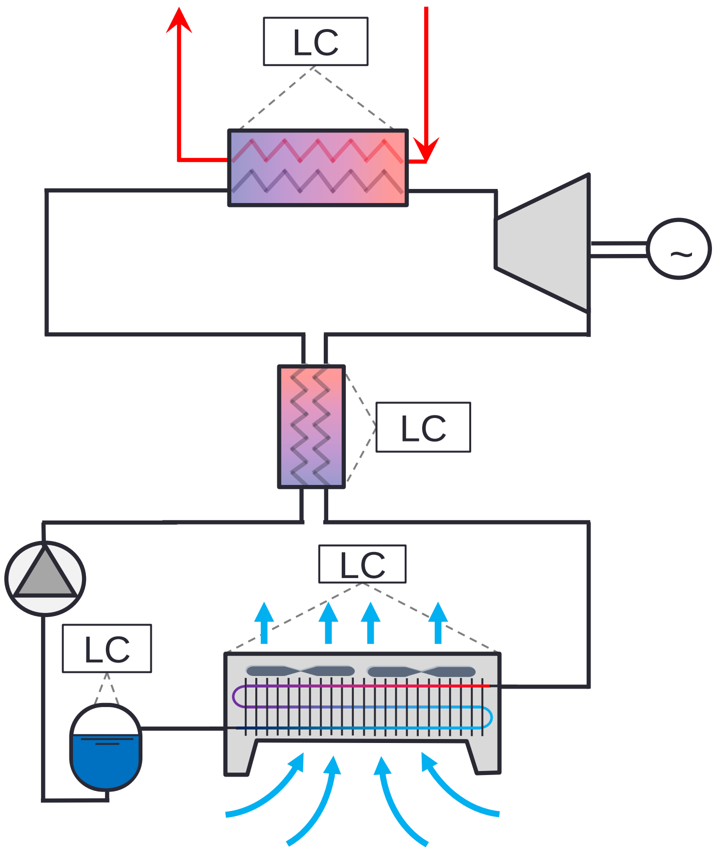


Test rig description (on-line charge measurement)



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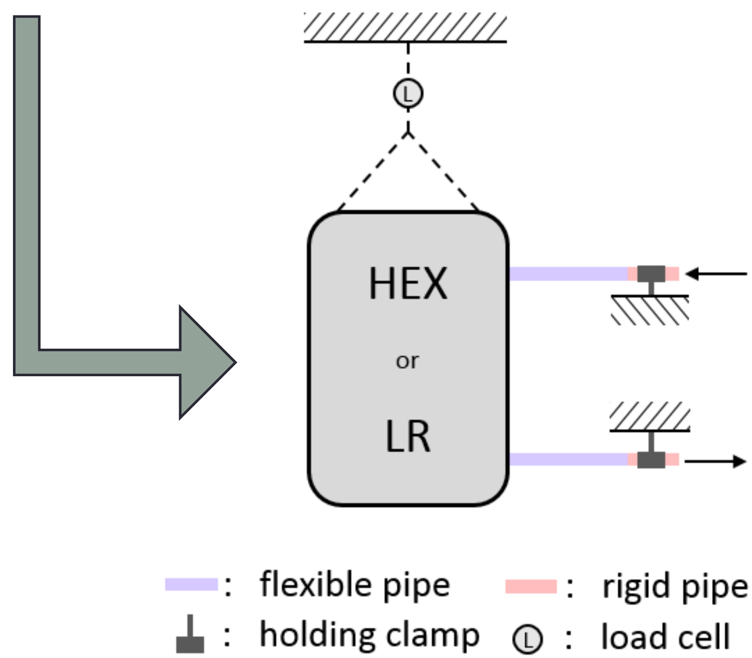

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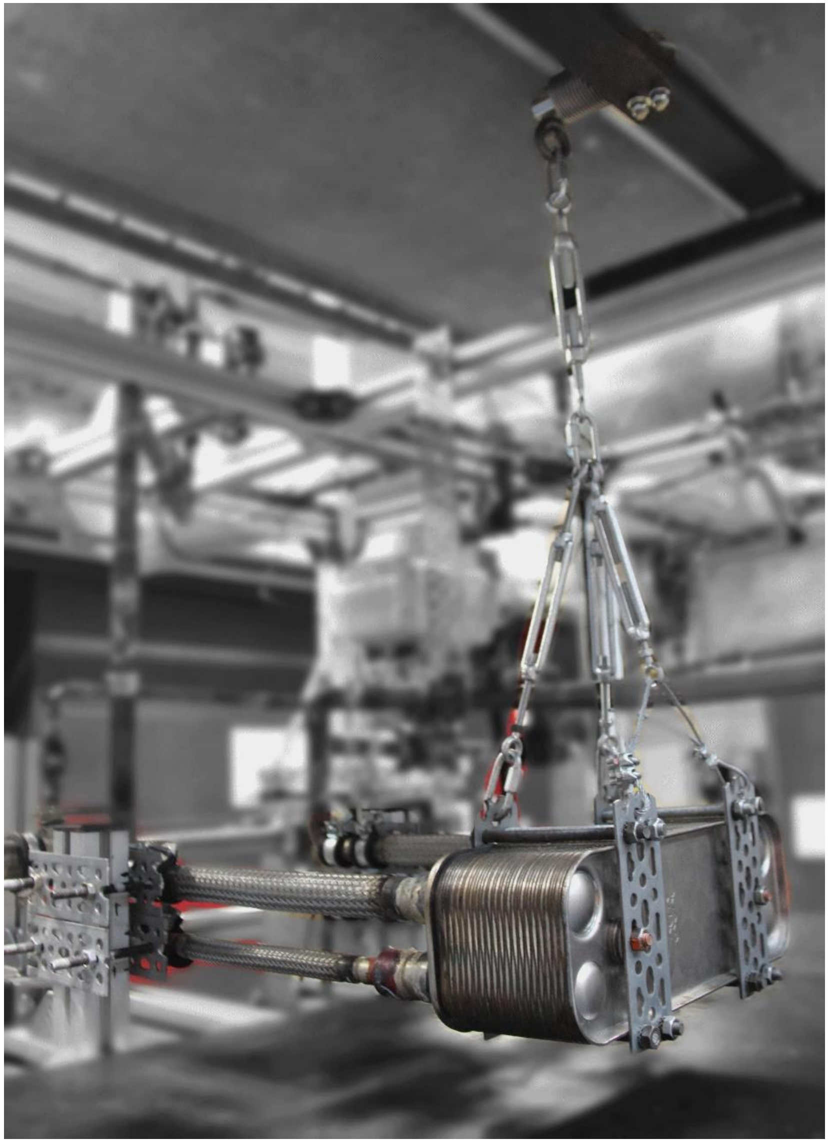

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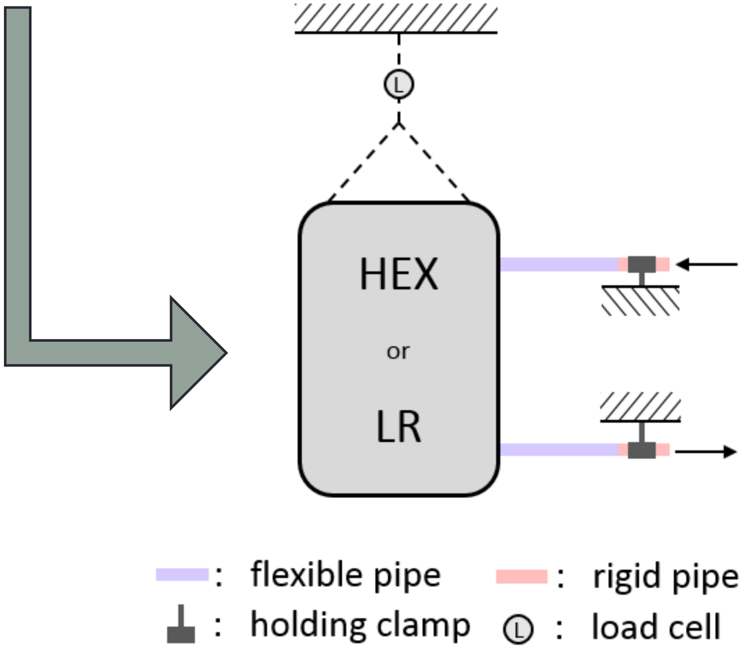

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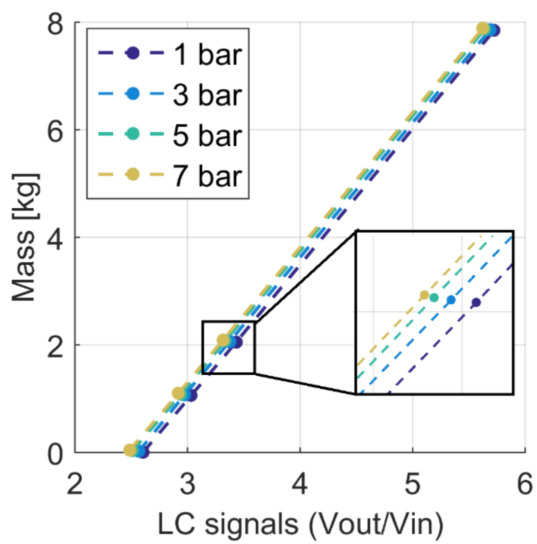
Example of LC calibration:



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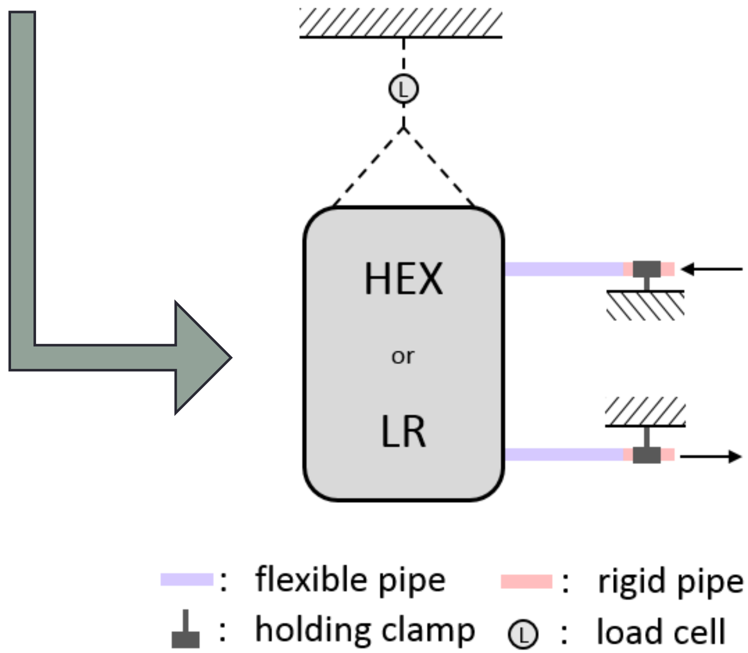

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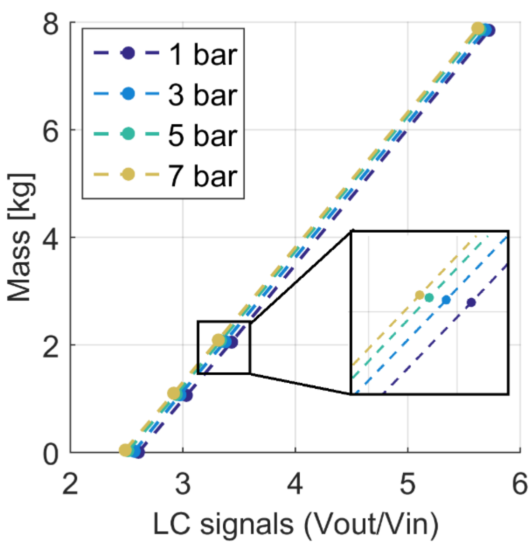

Advantages

Non-intrusive

Fast

Drawbacks

Limited accuracy

Not sensitive to the fluid nature

R245fa + POE

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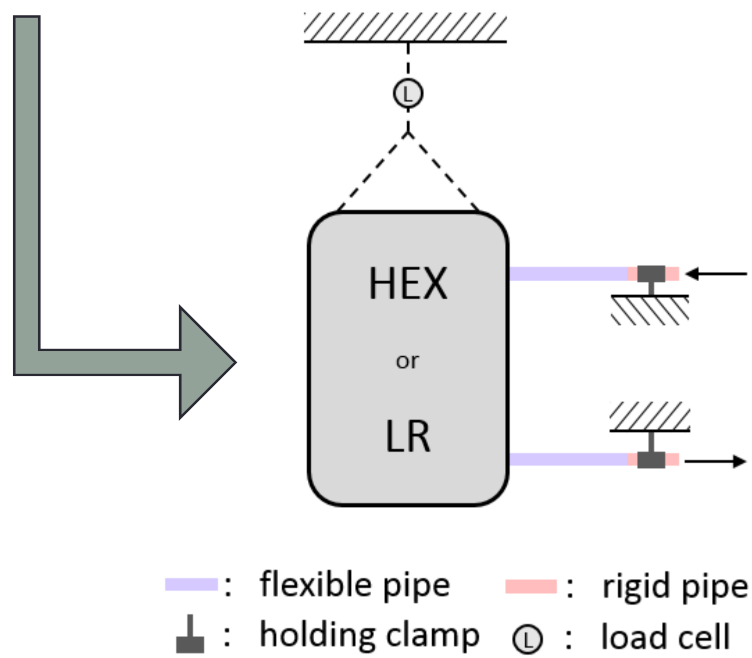

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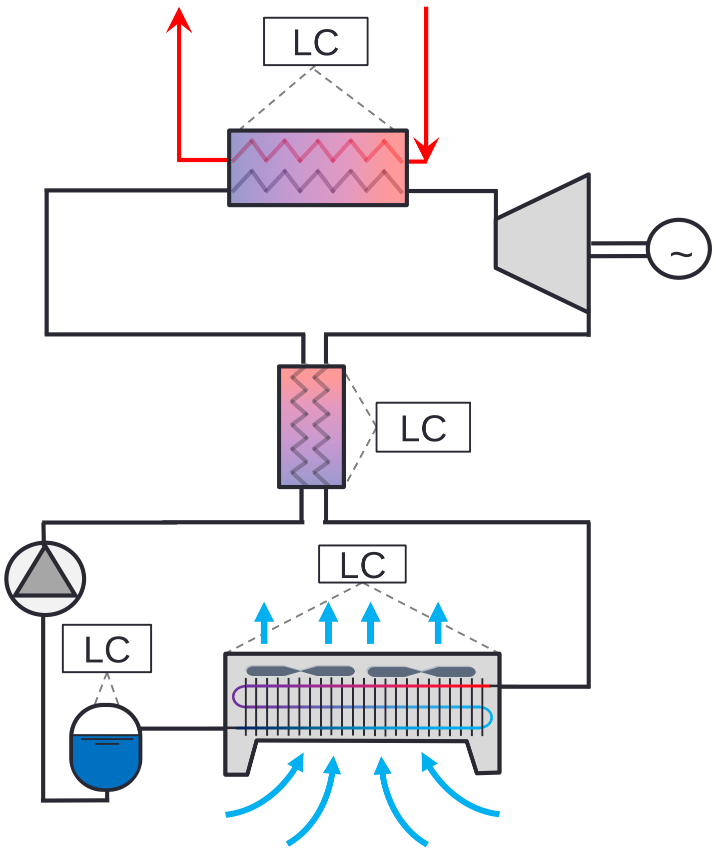

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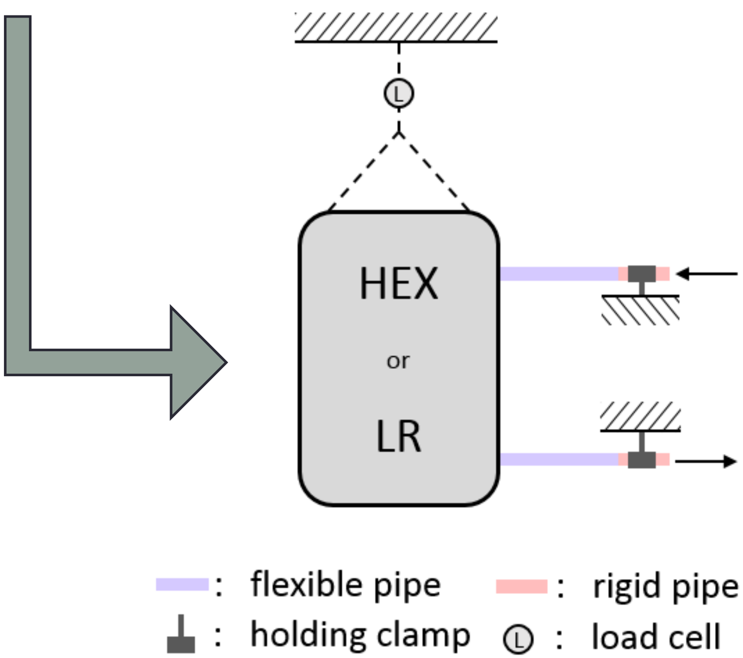

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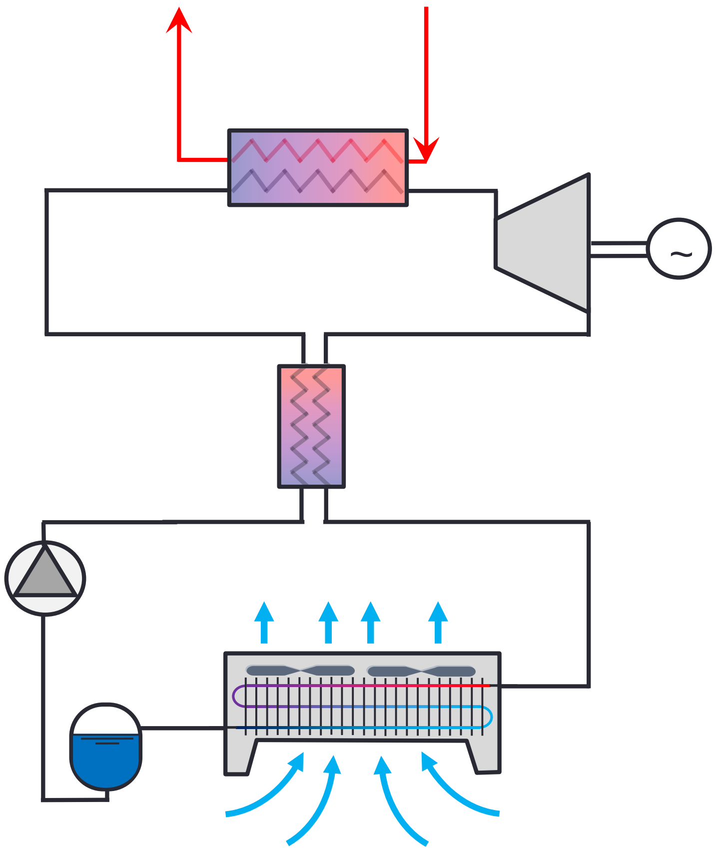

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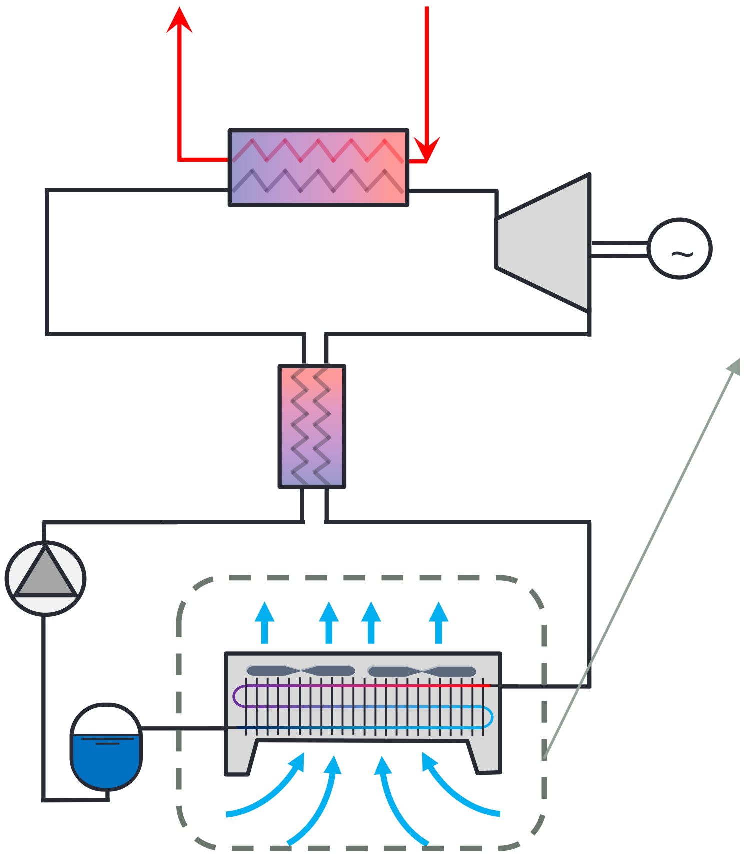

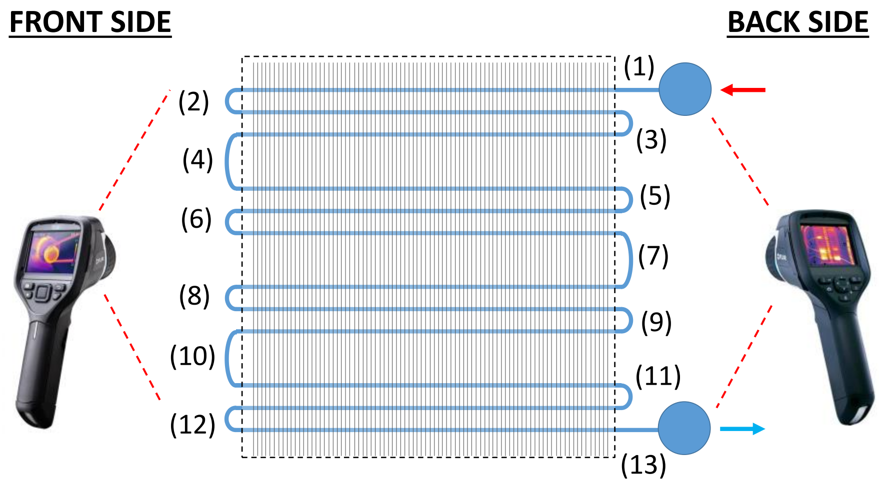

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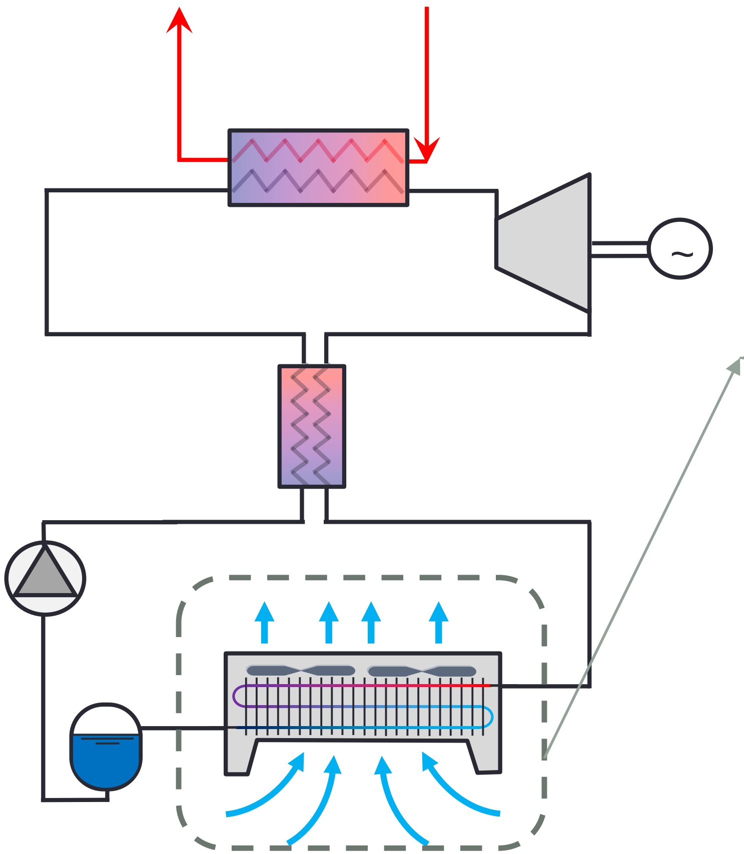

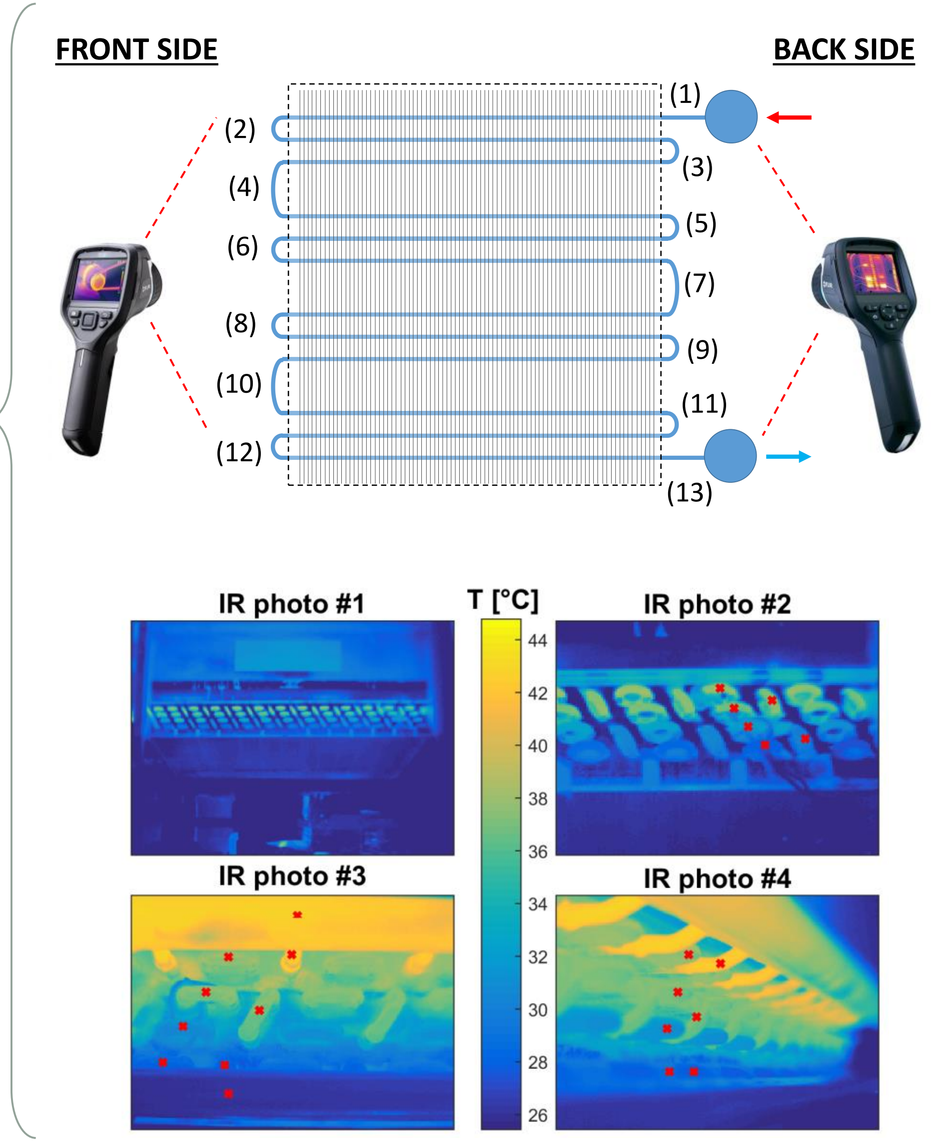

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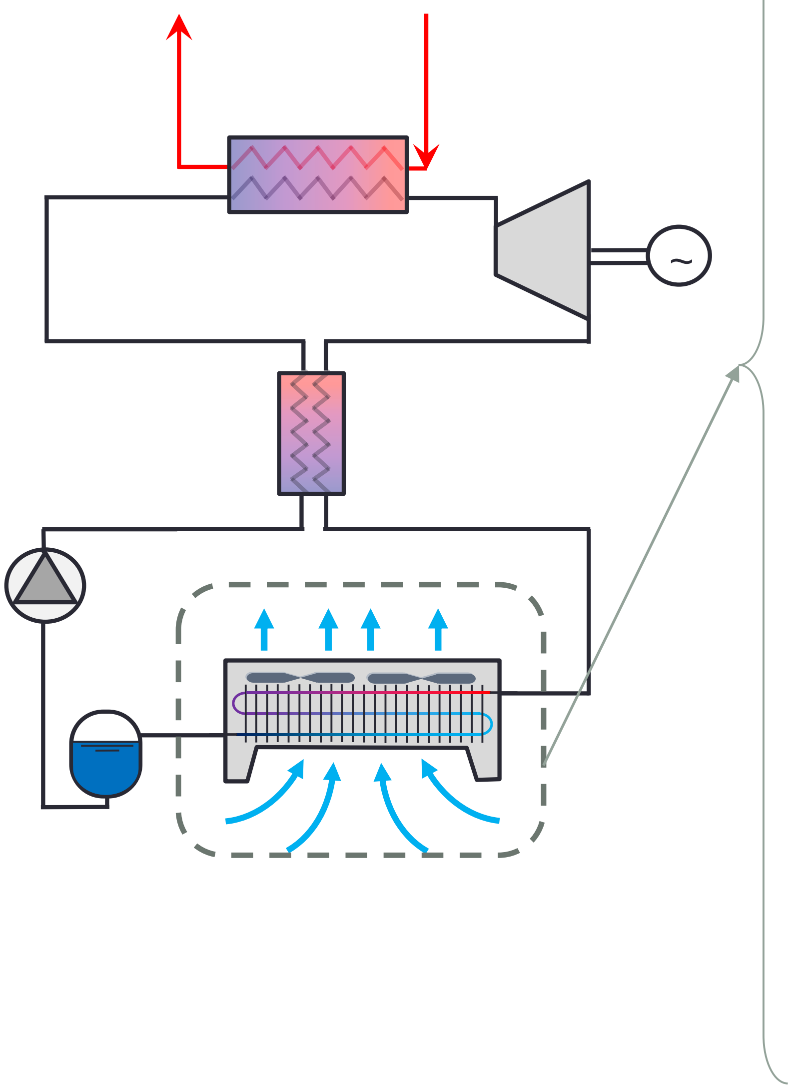
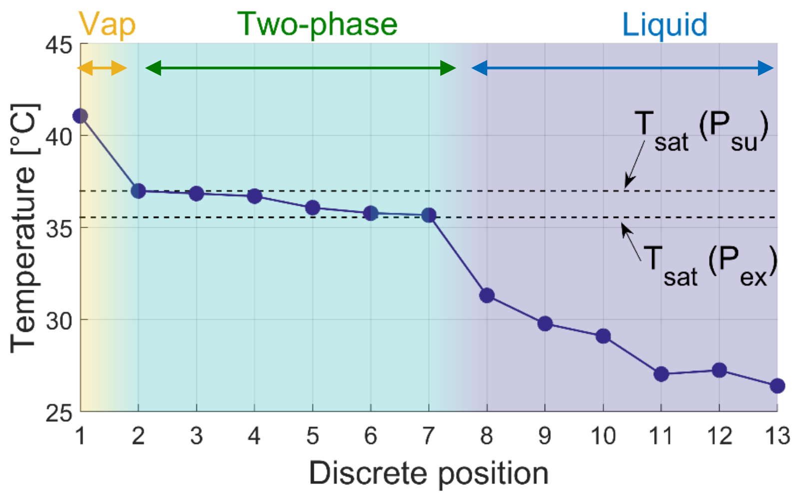
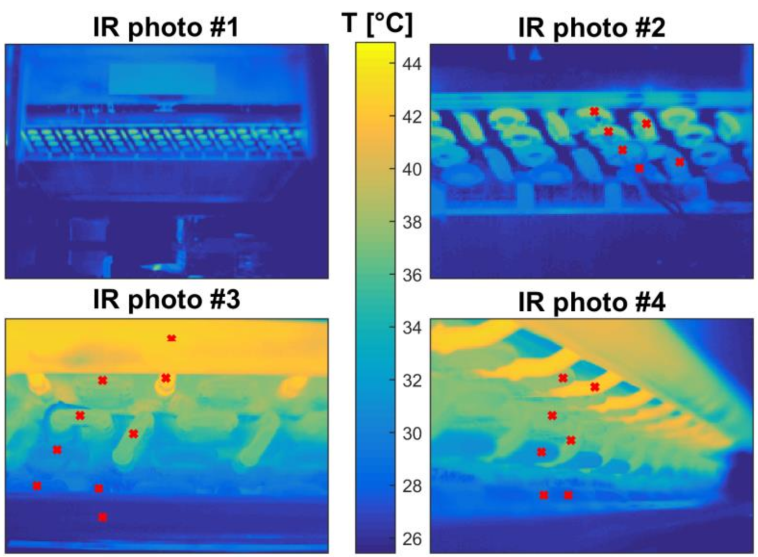






Experimental campaign

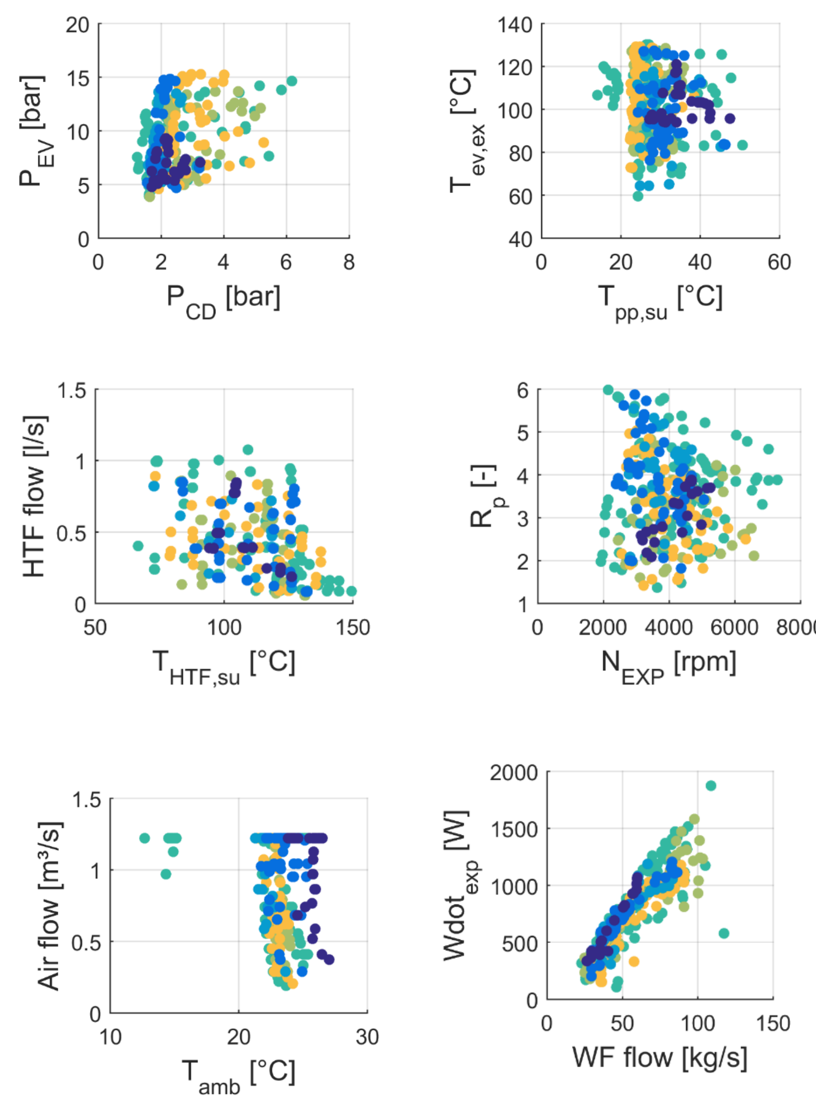
- 6 control variables: $M_{dot,htf}$, $T_{su,htf}$, N_{cd}, N_{pp}, N_{exp} , **M_{wf}**

14kg	20kg	28kg
17kg	25kg	31kg

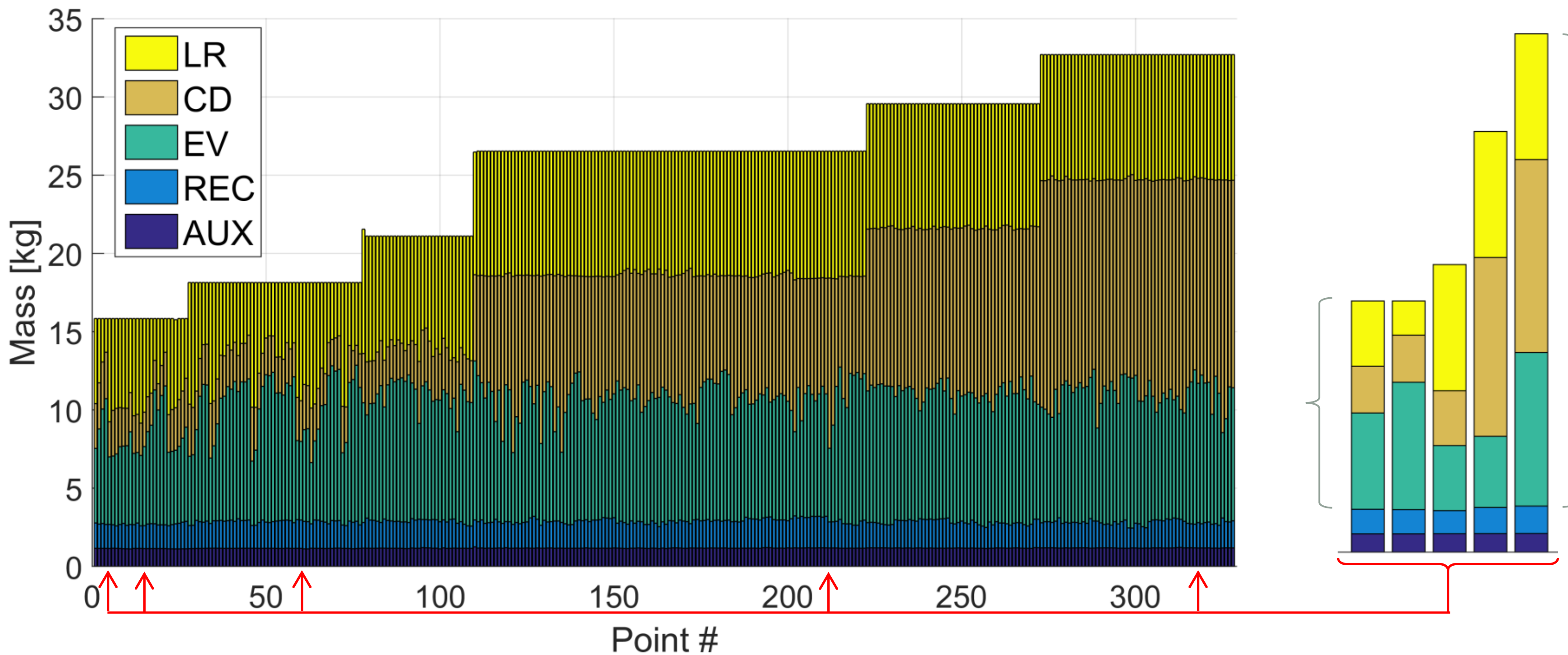
- No control strategy → non-optimal point, full-load, part-load

- 300 h of tests / 330 steady-state points

- Complete post-treament (dual data reconciliation)



Charge distribution analysis



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

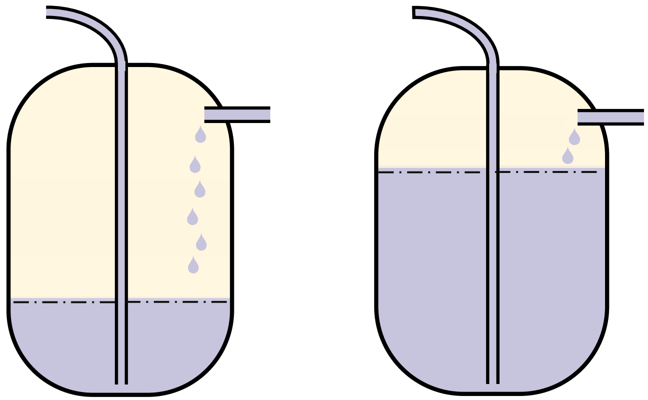
Single-phase only: $\rho(\bar{T},\bar{P})$

Multiple-phase: $\alpha.\rho_v + (1-\alpha).\rho_l$

Charge transfers ⇔ Liquid and vapor phases redistribution

Charge distribution mechanisms

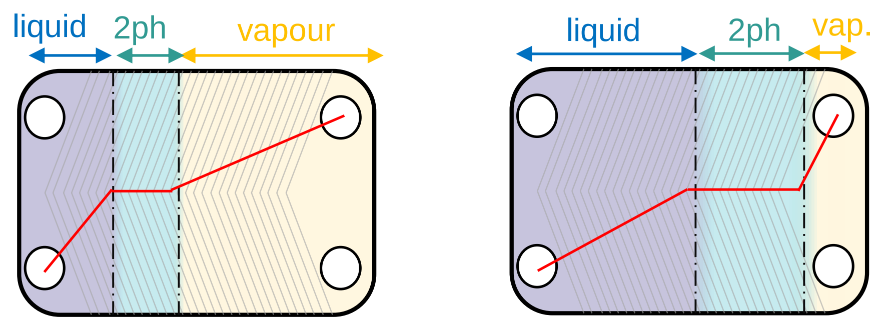
Liquid receiver



$$M_{LR,1} < M_{LR,2}$$

M related to the liquid level

Heat exchanger



$$M_{HEX,1} < M_{HEX,2}$$

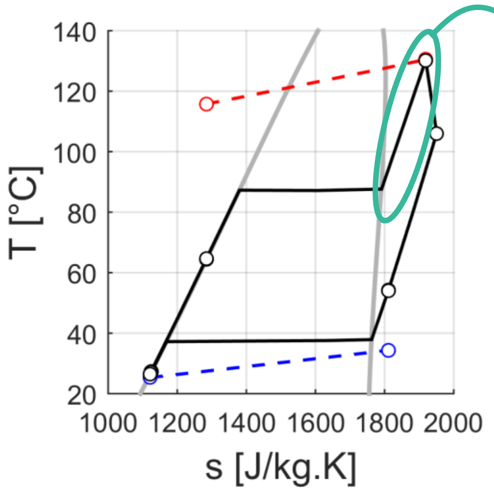
M related to the **temperature profile**:

- inlet/outlet subcooling and superheating
- temperature differences between the fluids

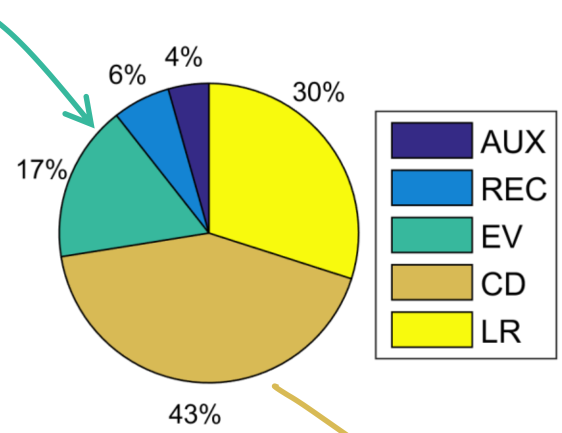
$$A = \frac{\dot{Q}}{U\,\Delta T}$$

Charge distribution mechanisms

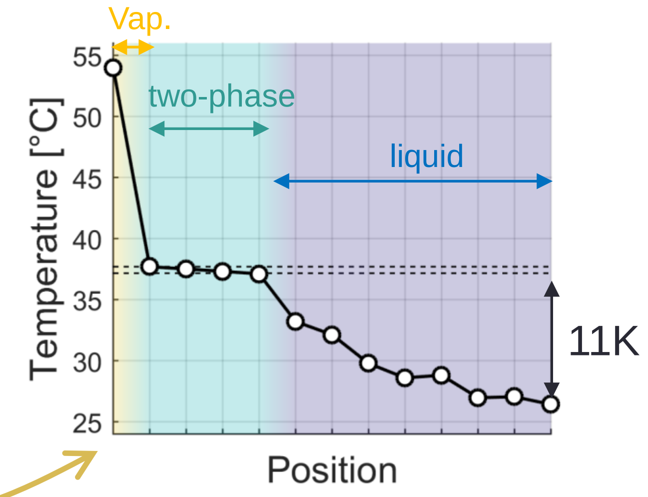
T-s diagram



Charge inventory

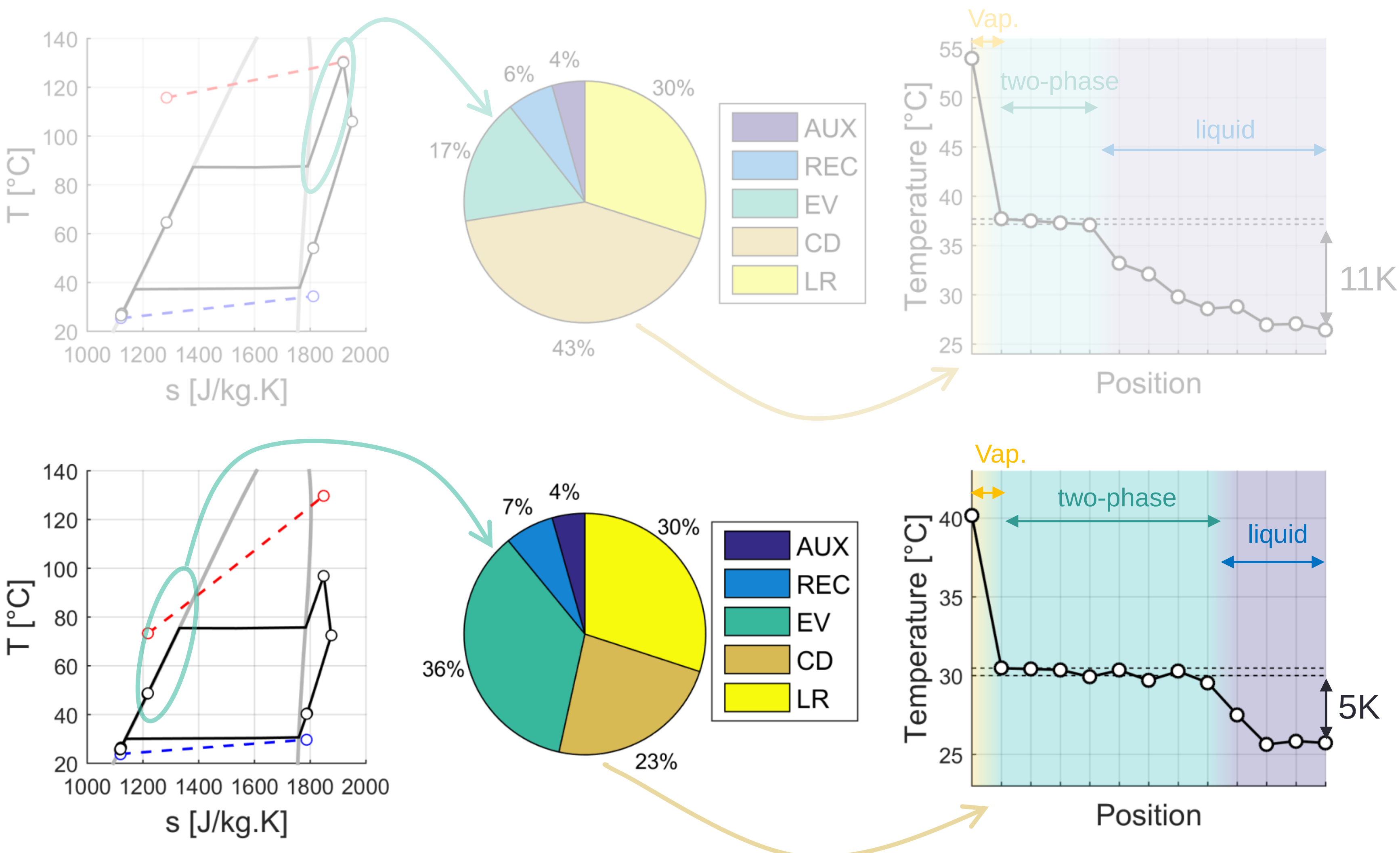


Condenser profile (IR)



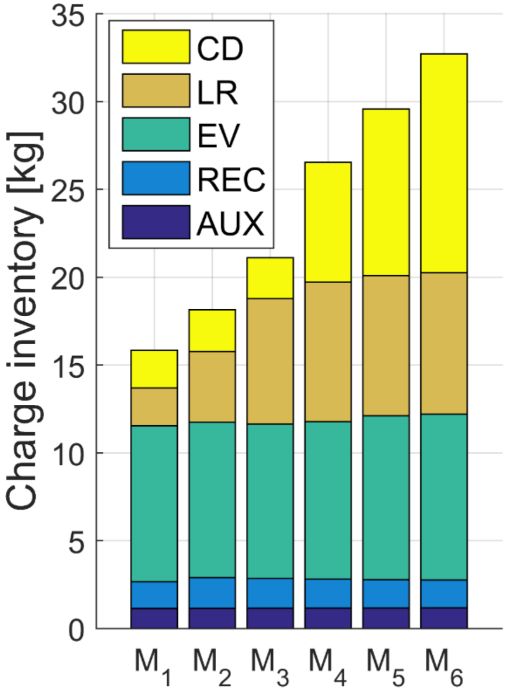
Charge distribution mechanisms

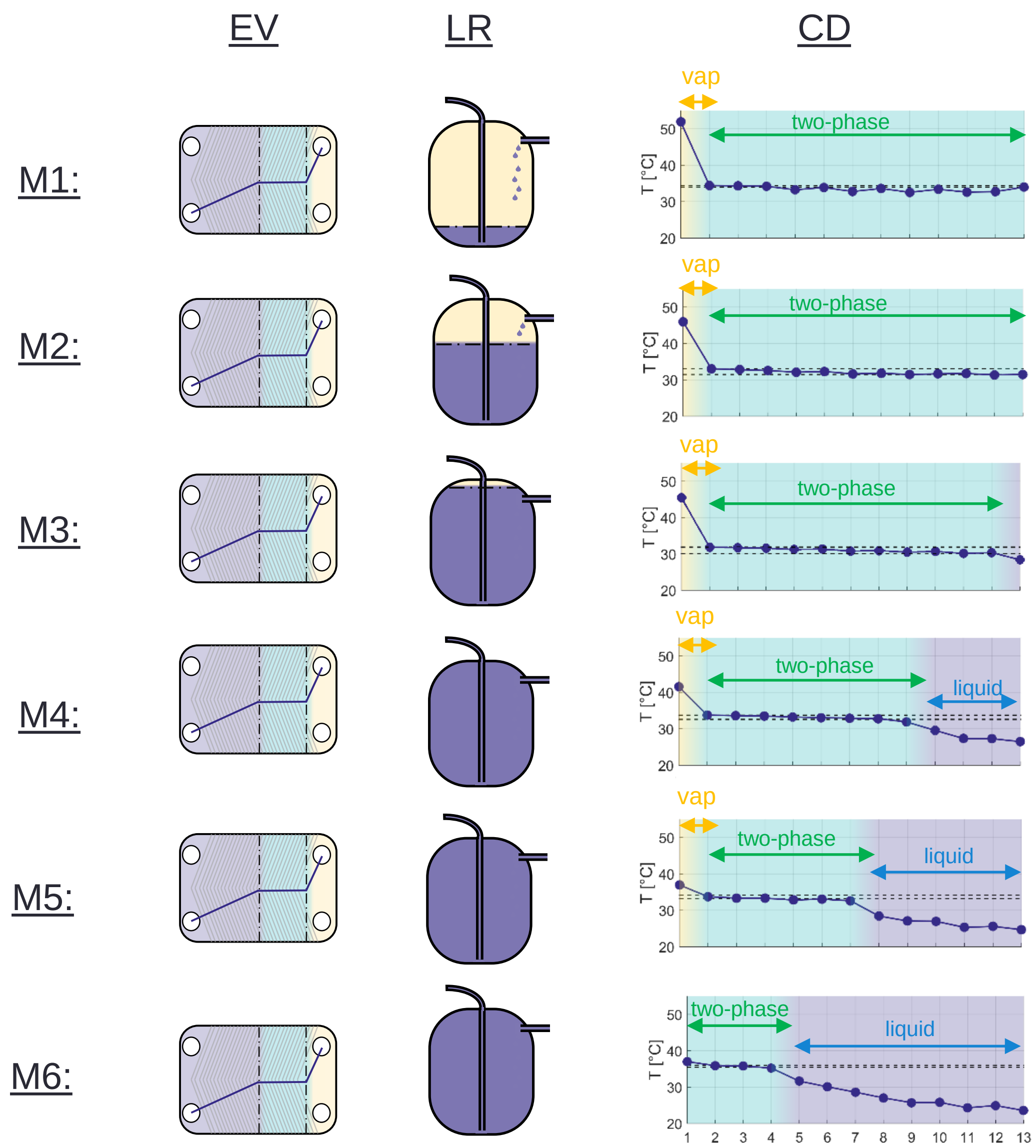
T-s diagram | Charge inventory | Condenser profile (IR)



Charge distribution mechanisms

Impact of increasing the charge only:





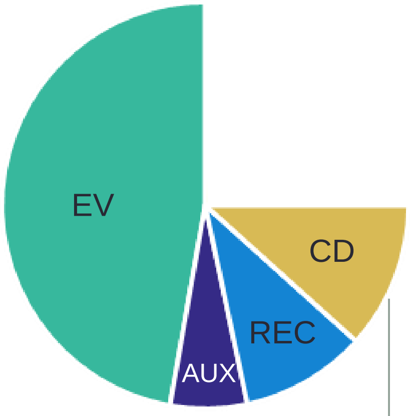
EV → No impact

LR → First absorber

CD → Second absorber

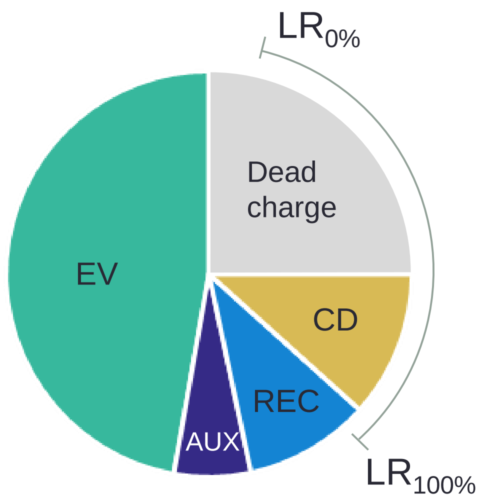
Charge distribution mechanisms

Charge distribution mechanisms



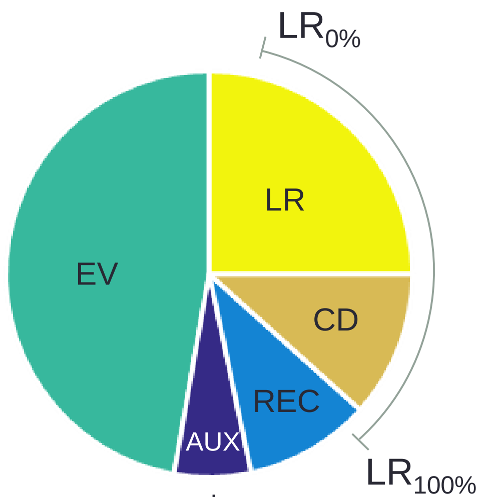
$$x_{cd,ex} = 0$$

Charge distribution mechanisms



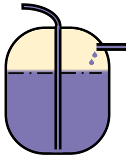
$$x_{cd,ex} = 0$$

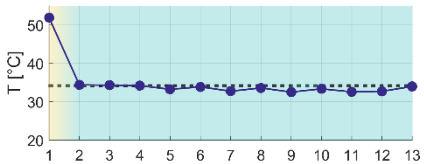
Charge distribution mechanisms



$$x_{cd,ex} = 0$$

LR partially filled
No liquid zone in CD





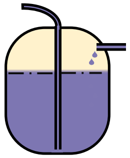
☺

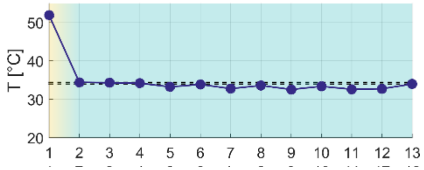
Charge distribution mechanisms

Scenario 2

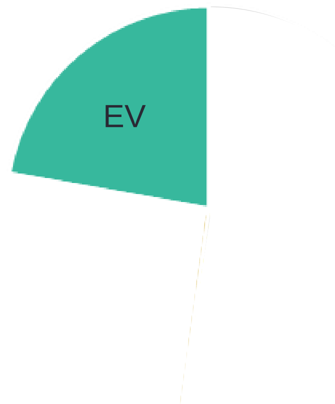
$x_{cd,ex} = 0$

LR partially filled
No liquid zone in CD



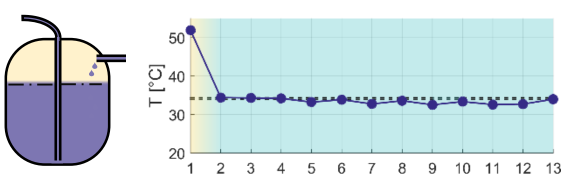


Charge distribution mechanisms

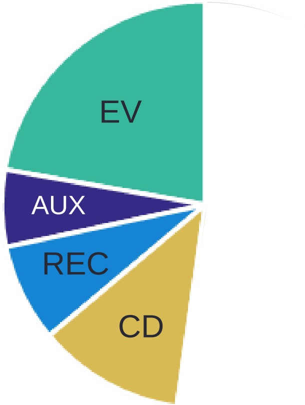


$$x_{cd,ex} = 0$$

LR partially filled
No liquid zone in CD

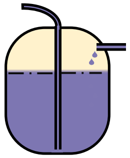


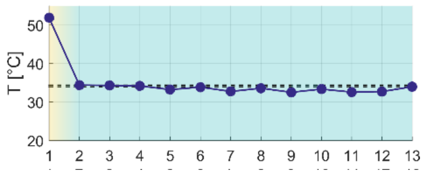
Charge distribution mechanisms



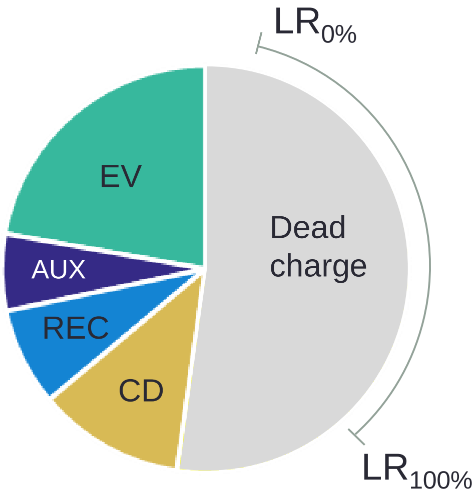
$x_{cd,ex} = 0$

LR partially filled
No liquid zone in CD



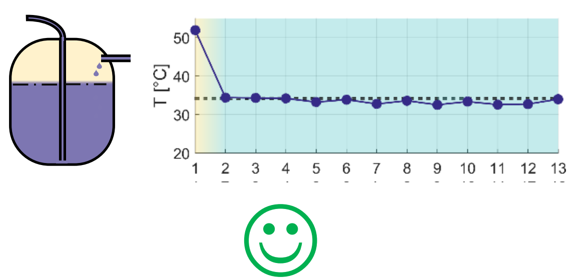


Charge distribution mechanisms

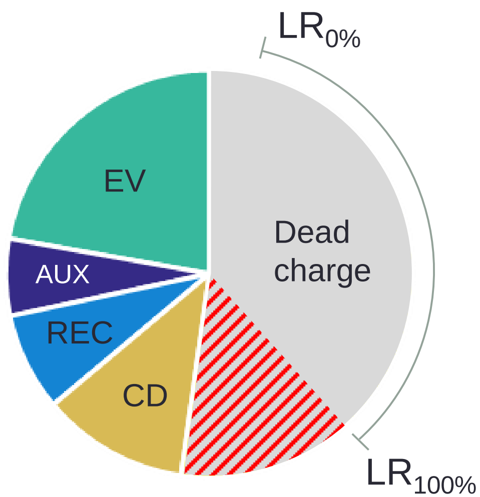


$x_{cd,ex} = 0$

LR partially filled
No liquid zone in CD

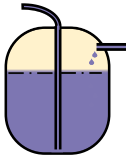


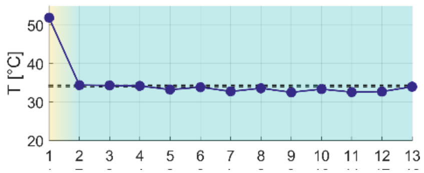
Charge distribution mechanisms



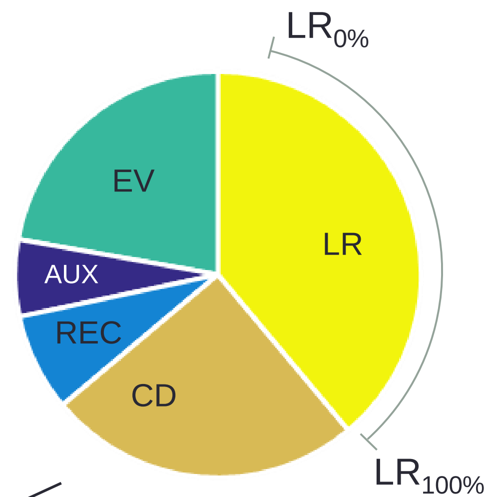
$x_{cd,ex} = 0$

LR partially filled
No liquid zone in CD





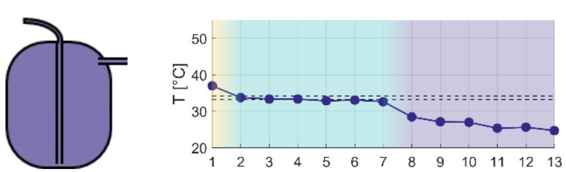
Charge distribution mechanisms



$\Delta T_{cd,ex} > 0$

$x_{cd,ex} = 0$

LR totally flooded
Liquid zone in CD



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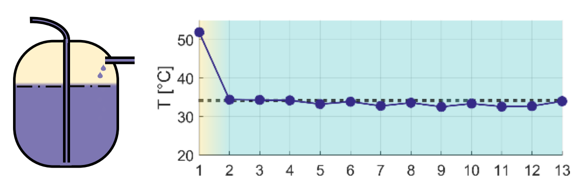
LR partially filled
No liquid zone in CD



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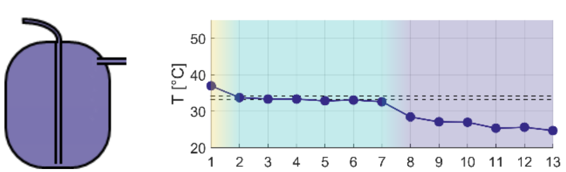
Charge distribution mechanisms

Scenario 3

$\Delta T_{cd,ex} > 0$

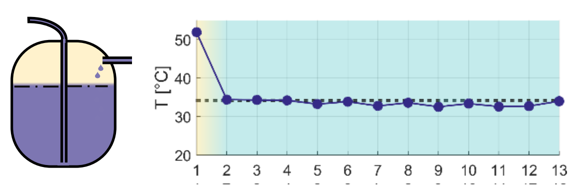
$x_{cd,ex} = 0$

LR totally flooded
Liquid zone in CD



☹

LR partially filled
No liquid zone in CD



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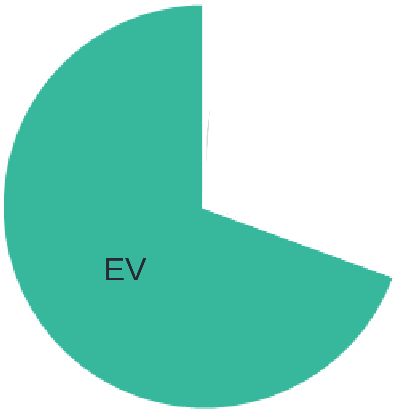
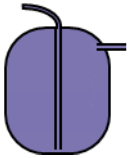
Charge distribution mechanisms

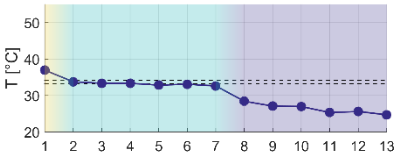


$\Delta T_{cd,ex} > 0$

$x_{cd,ex} = 0$

LR totally flooded
Liquid zone in CD





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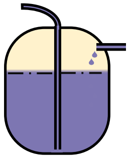
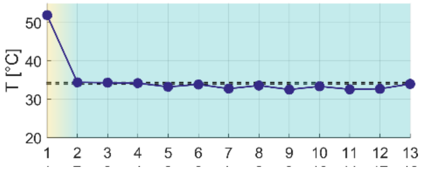
LR partially filled
No liquid zone in CD





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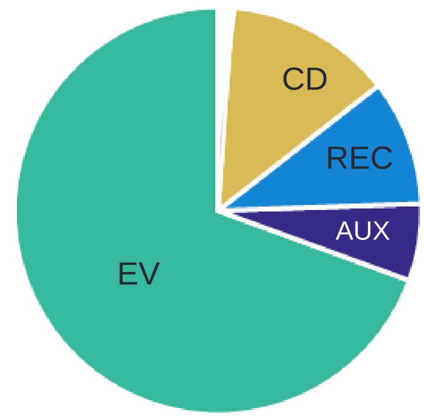
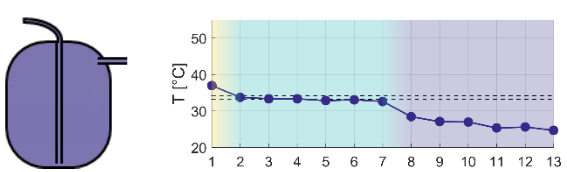
Charge distribution mechanisms



$\Delta T_{cd,ex} > 0$

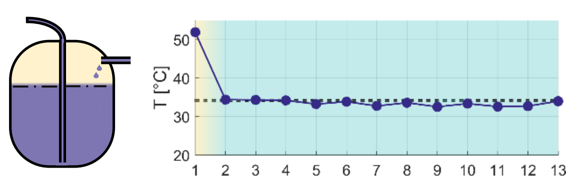
$x_{cd,ex} = 0$

LR totally flooded
Liquid zone in CD



☹

LR partially filled
No liquid zone in CD



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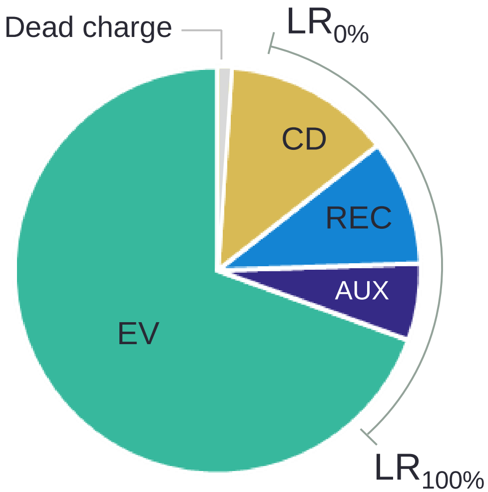
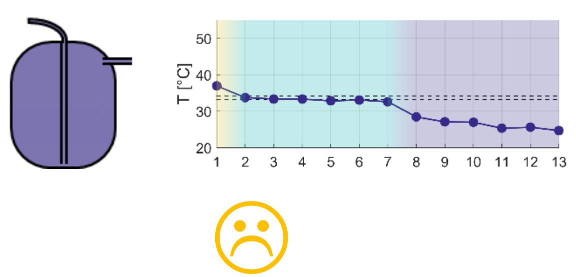
Charge distribution mechanisms



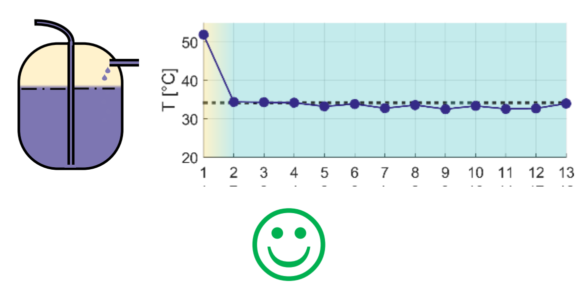
$\Delta T_{cd,ex} > 0$

$x_{cd,ex} = 0$

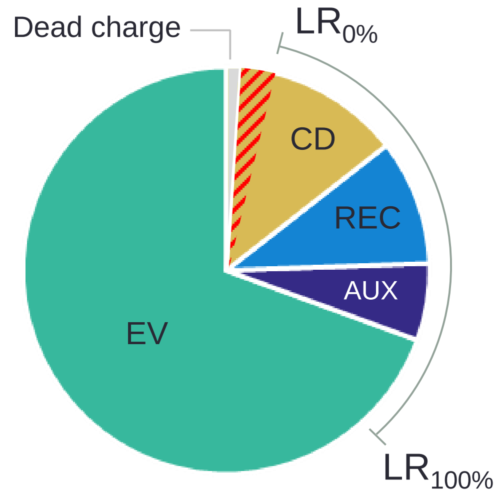
LR totally flooded
Liquid zone in CD



LR partially filled
No liquid zone in CD



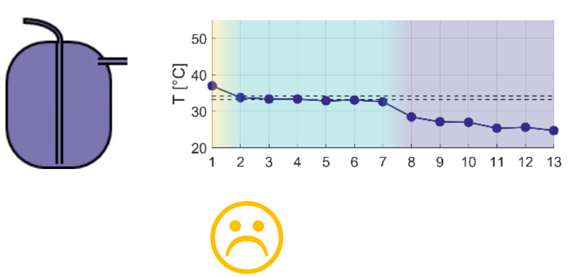
Charge distribution mechanisms



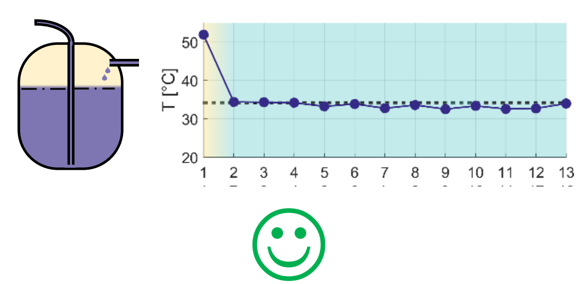
$\Delta T_{cd,ex} > 0$

$x_{cd,ex} = 0$

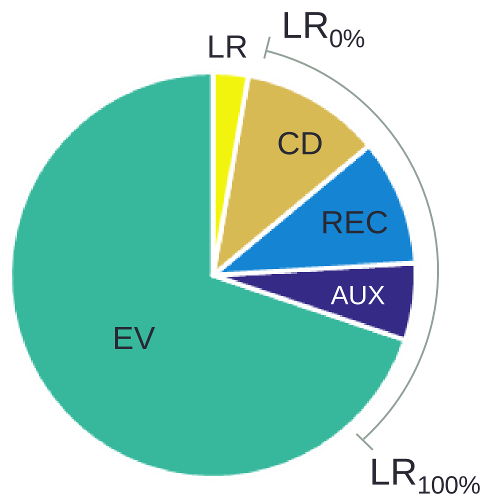
LR totally flooded
Liquid zone in CD



LR partially filled
No liquid zone in CD

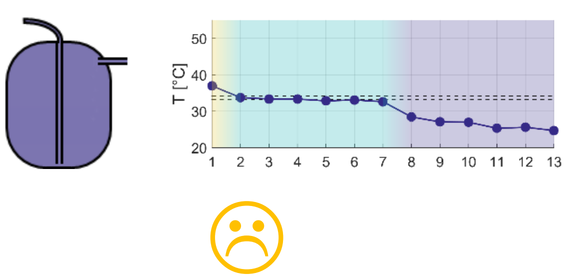


Charge distribution mechanisms

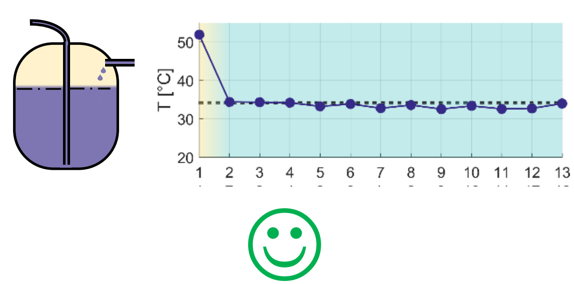


$\Delta T_{cd,ex} > 0$ $\quad$ $x_{cd,ex} = 0$ $\quad$ $x_{cd,ex} > 0$

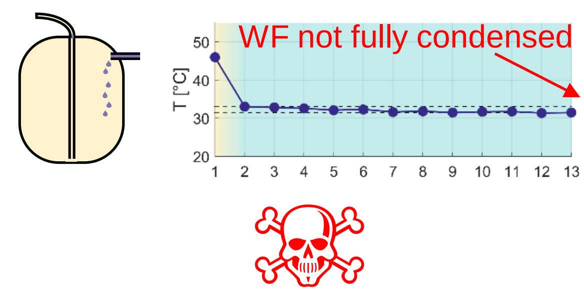
LR totally flooded
Liquid zone in CD



LR partially filled
No liquid zone in CD



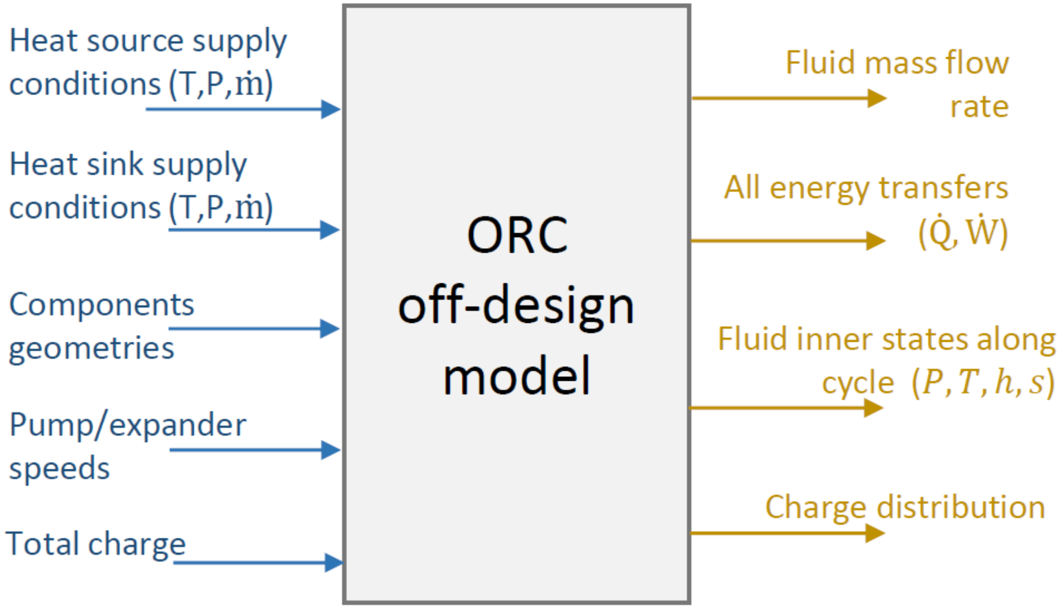
LR totally empty
Pump cavitation



III.

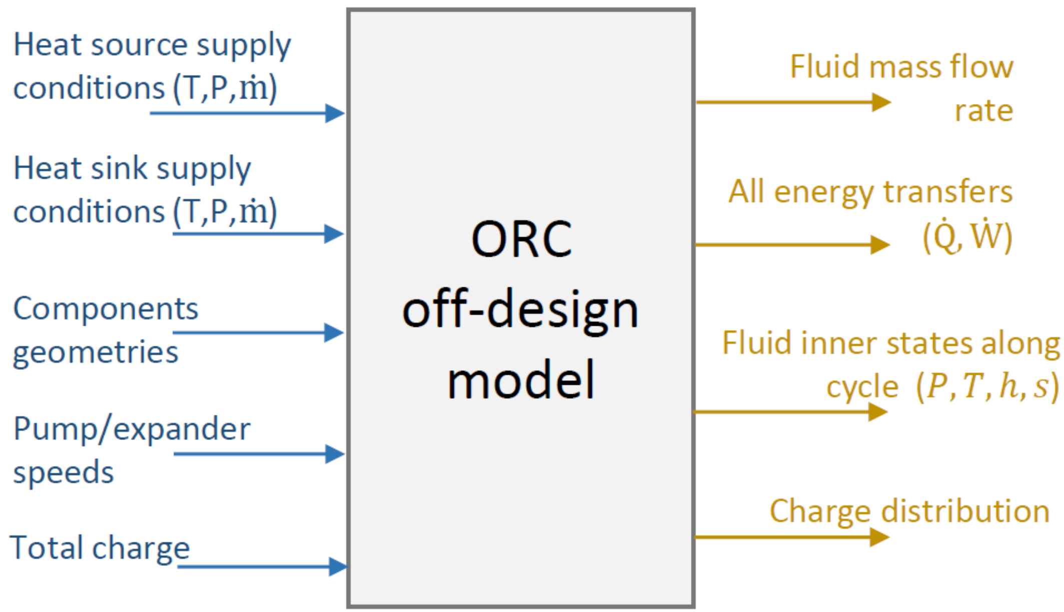
MODELLING DEVELOPMENTS

Modelling developments



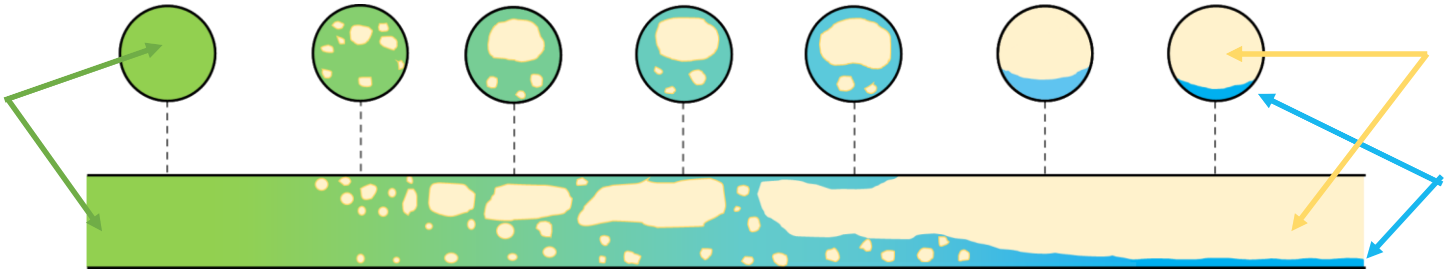
- Speed vs. accuracy → 0D/1D semi-empirical
- Matlab 2015a + CoolProp
- Open-access library (ORCmKit)

Modelling developments

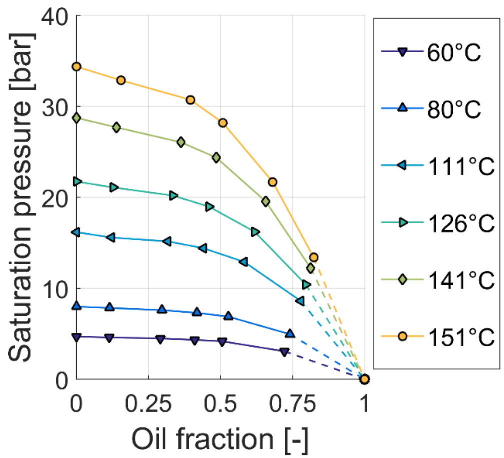


- Speed vs. accuracy → 0D/1D semi-empirical
- Matlab 2015a + CoolProp
- Open-access library (ORCmKit) → Fluid / flow properties; Component-level models; System-level models

Fluid / flow properties



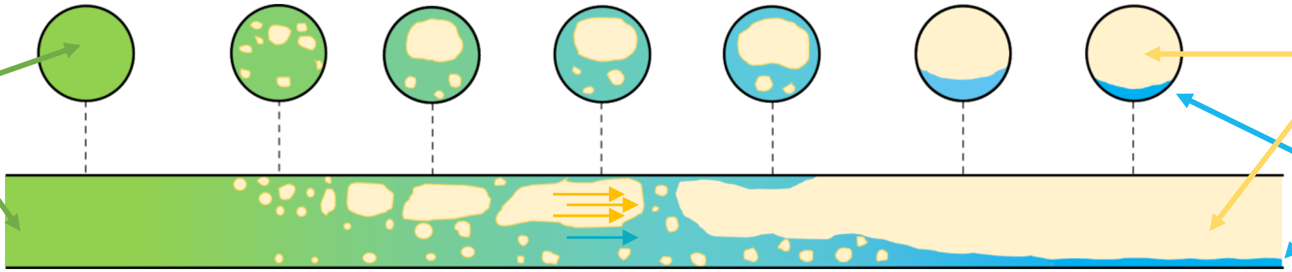
R245fa/POE mixture composition model



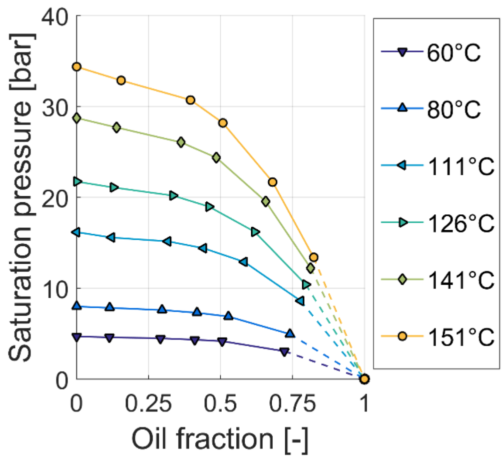
$$h_{mix} = \frac{\zeta_{wf}\kappa_{oil}(1-\kappa_{oil})}{1-\zeta_{wf}-\kappa_{oil}+\zeta_{wf}\kappa_{oil}} h_{wf,l} \cdots$$

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

Fluid / flow properties



R245fa/POE mixture composition model



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

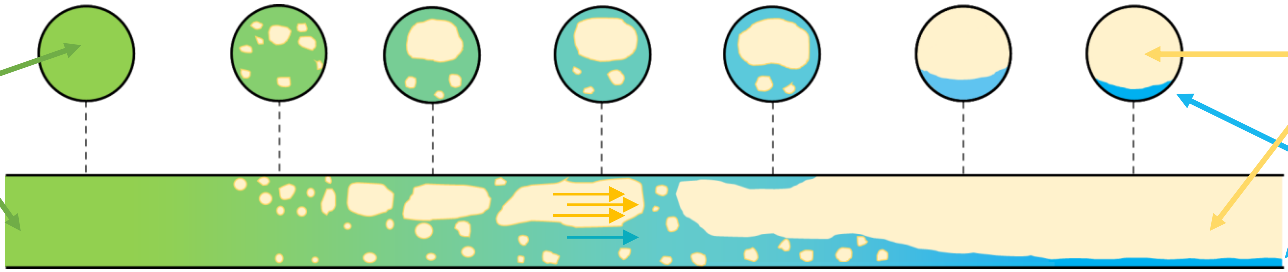
$$\cdots + \frac{(1-\zeta_{wf}-\kappa_{oil})(1-\kappa_{oil})}{1-\zeta_{wf}-\kappa_{oil}+\zeta_{wf}\kappa_{oil}} h_{wf,v} + \kappa_{oil} h_{oil}$$

Void fraction model

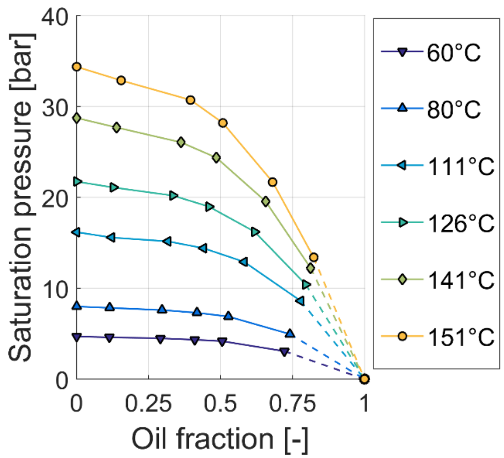
$$M = V \underbrace{\bar{\rho}}_{\rho_l(1-\bar{\alpha})+\rho_v\bar{\alpha}}$$

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

Fluid / flow properties



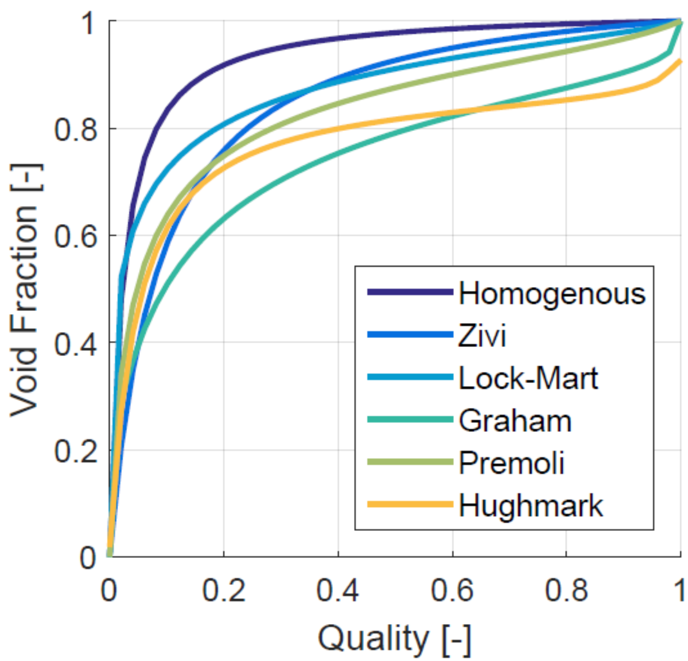
R245fa/POE mixture composition model



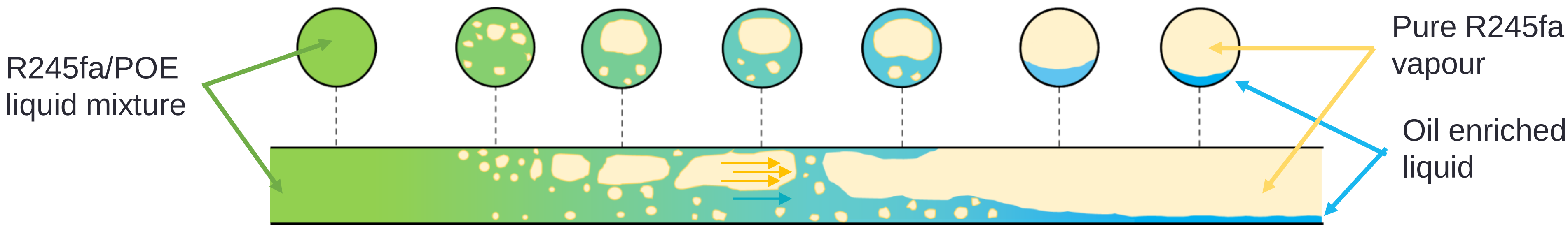
$$h_{mix} = \frac{\zeta_{wf}\kappa_{oil}(1-\kappa_{oil})}{1-\zeta_{wf}-\kappa_{oil}+\zeta_{wf}\kappa_{oil}} h_{wf,l} \cdots$$

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

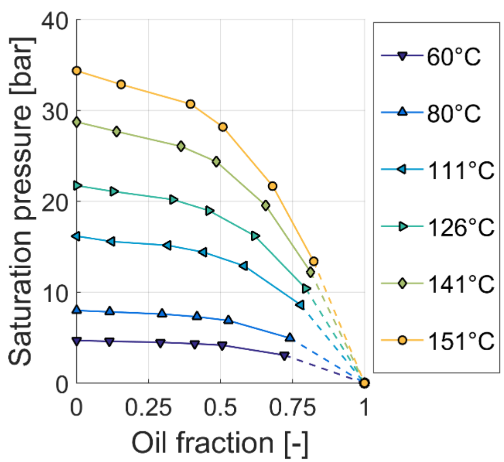
Void fraction model



Fluid / flow properties



R245fa/POE mixture composition model



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

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

Void fraction model

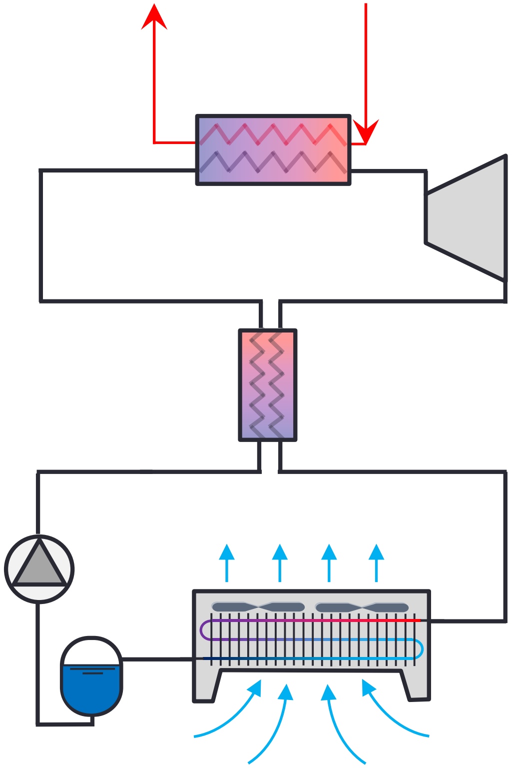
$$M = V \underbrace{\bar{\rho}}_{\rho_l (1-\bar{\alpha}) + \rho_v \bar{\alpha}}$$

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

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

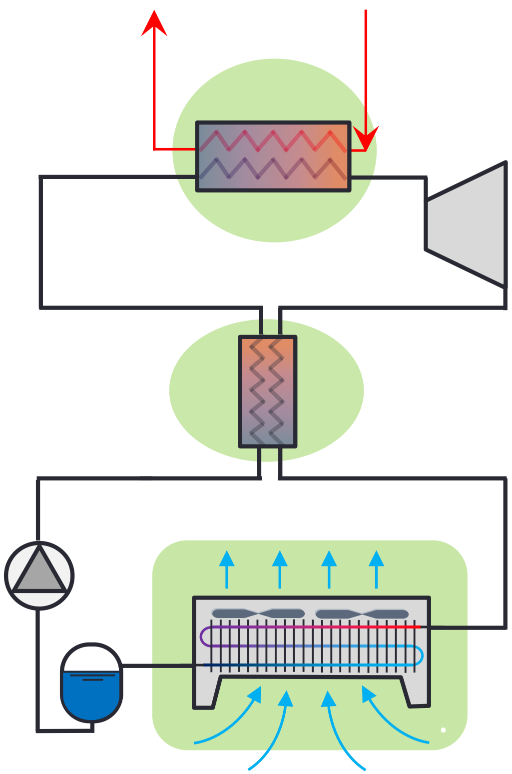
$$M_{wf} = \left[\bar{\alpha}\ \rho_v + (1-\bar{\alpha})\ \zeta_{wf}\ \rho_l\right] V$$

Component modelling



Component modelling

Heat exchangers:



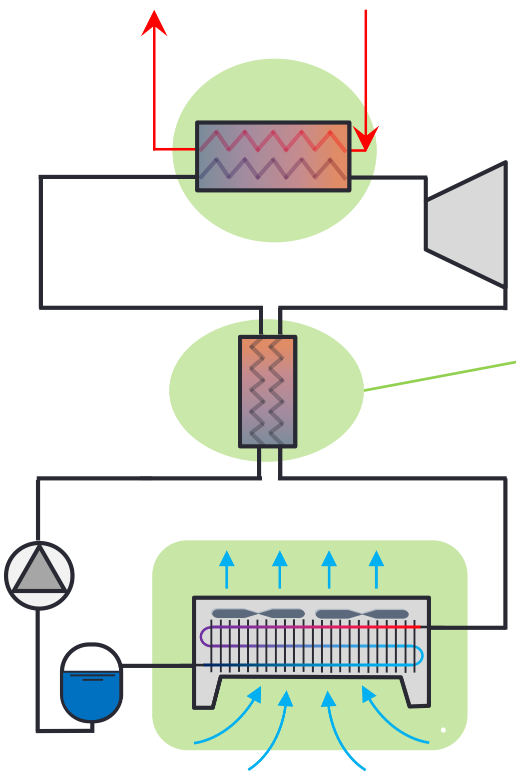
- 1D moving boundary

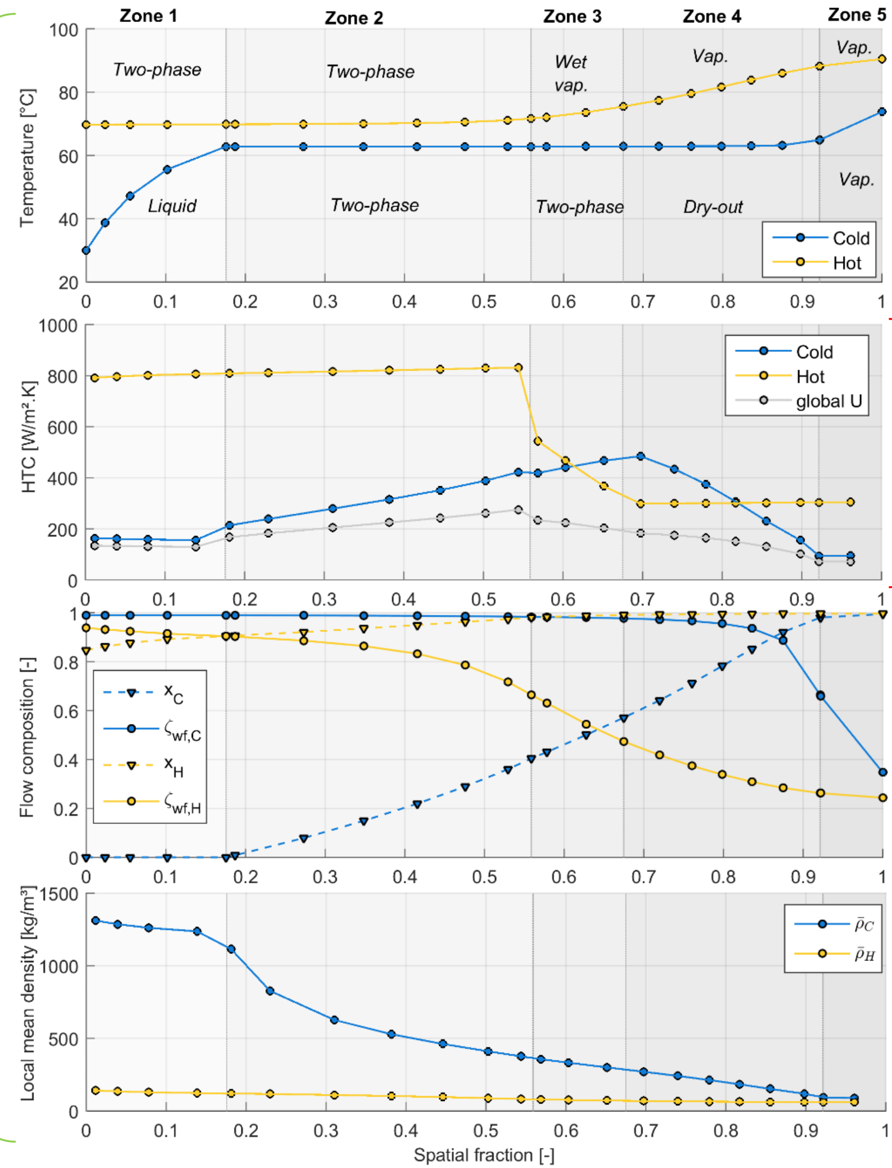
  ↳ find $\dot{Q}$ i.e. $\sum A_i = A_{HEX}$

- 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:



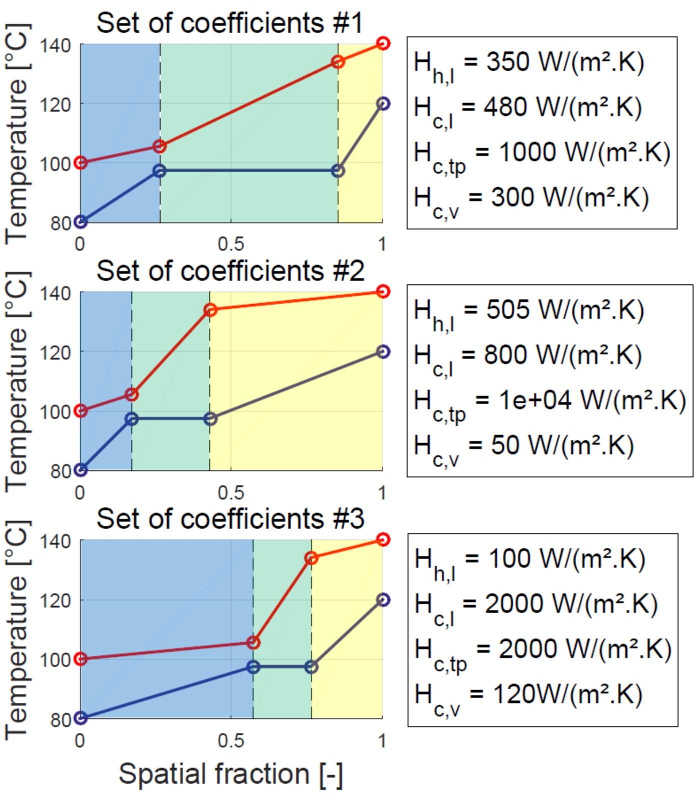


Convective Heat Transfer Coefficients

(CHTC)

Component modelling

Heat exchangers:



Why are the CHTCs so important?

Impact heat transfer ($\dot{Q}_{HEX}$)

$$U_i = \left(\frac{1}{H_{h,i}} + \frac{1}{H_{c,i}}\right)^{-1}$$

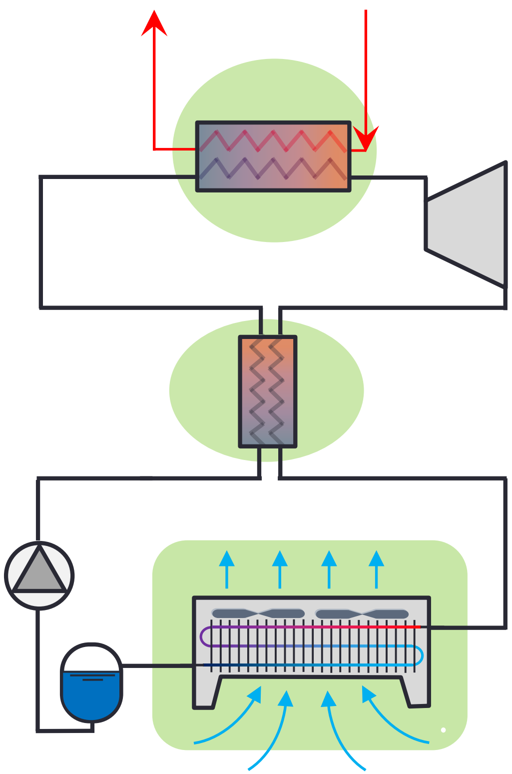
Impact zones distribution

$$A_i = \dot{Q}_i / U_i \Delta T_i$$

CHTCs ⇄ Charge

Component modelling

Heat exchangers:



CHTCs identification method:

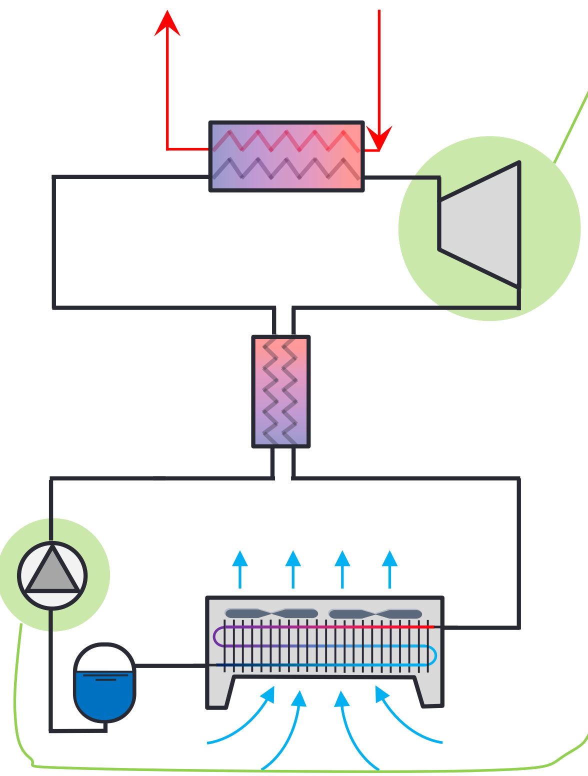
1. Selection of SoA correlations ($Nu = f(Re, Pr)$)
2. Fitting comparison in terms of
   a) Heat transfer predictions
   b) Charge/zone distribution predictions
3. Refinement of the best candidates, i.e.

$$Nu_j^* = c_j \,.\, Nu_j$$

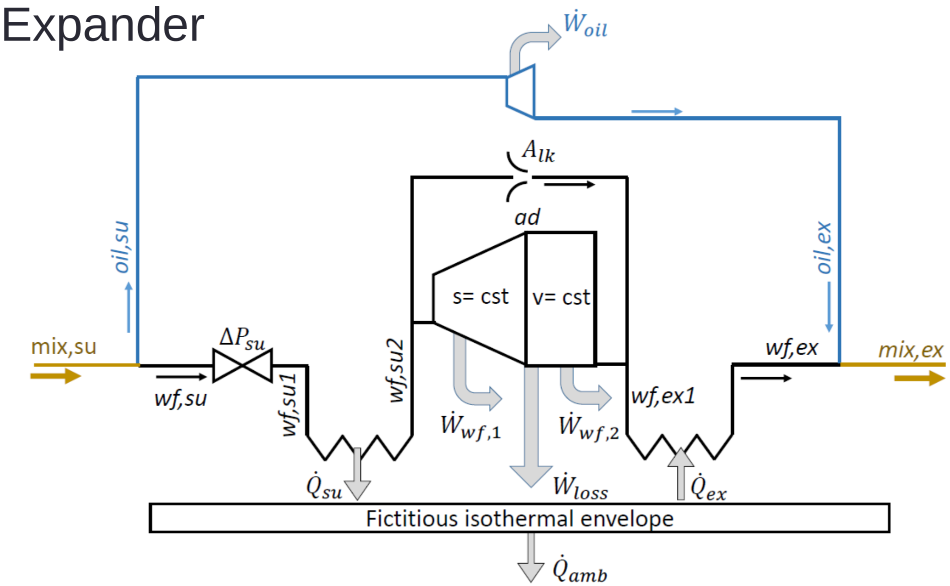
$$\min_{c_j} \; RMSE_{\dot{Q}} + RMSE_{M/A_i}$$

Component modelling

Mechanical components:

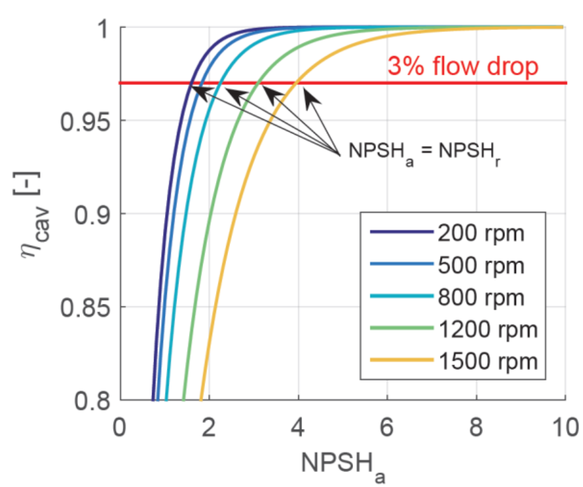


- Expander



- Pump

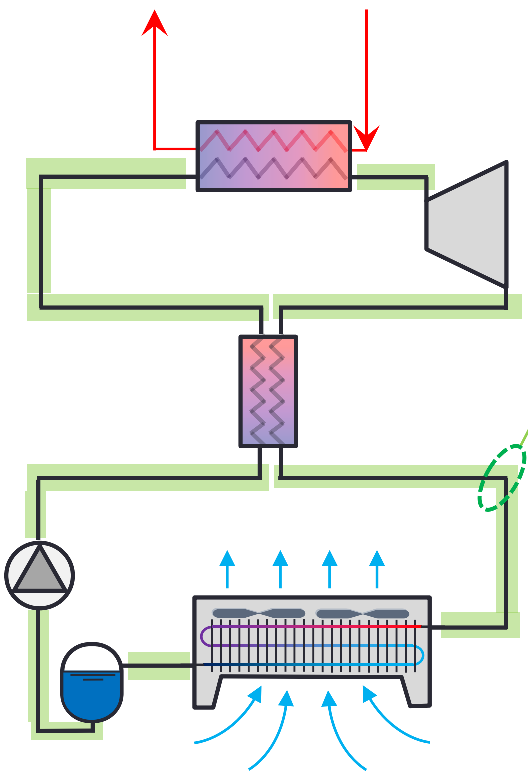
Similar of expander +

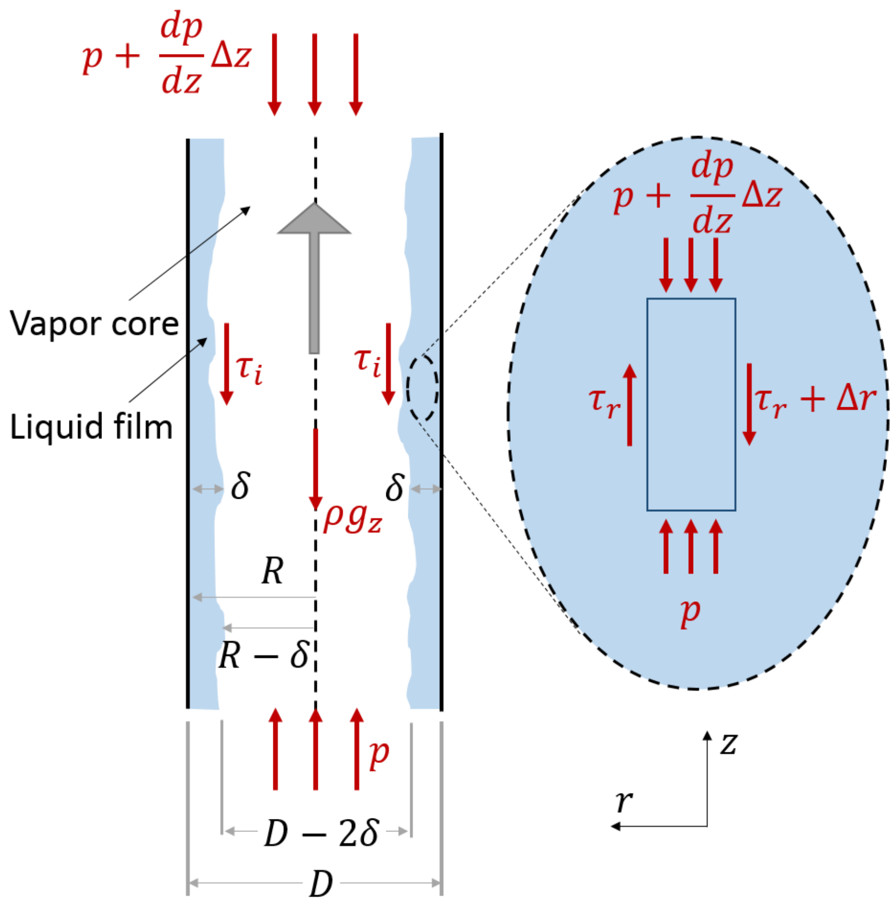


Component modelling

<u>Pipelines:</u>

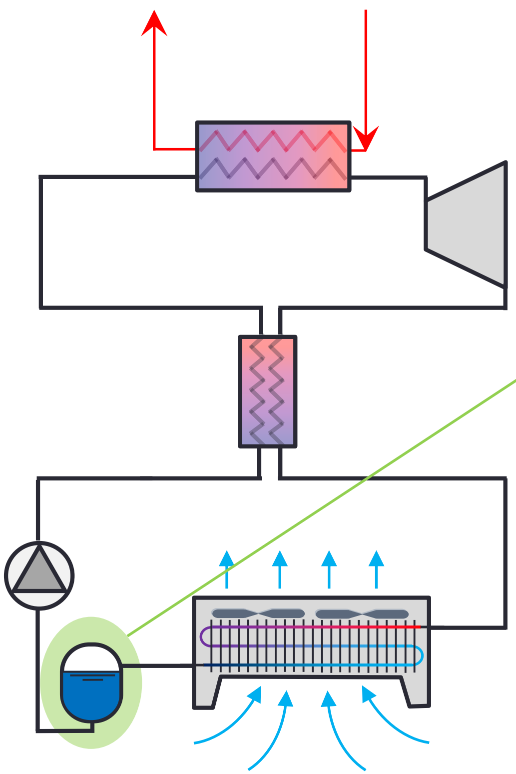
- Pressure drops + ambient losses → easy
- Charge and oil retention → more complex

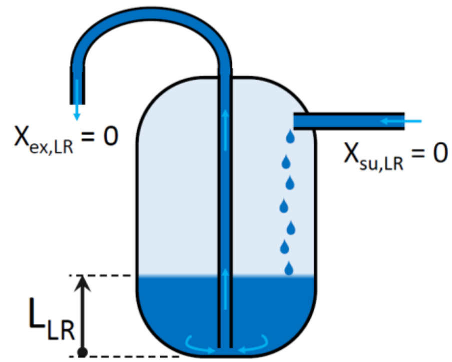


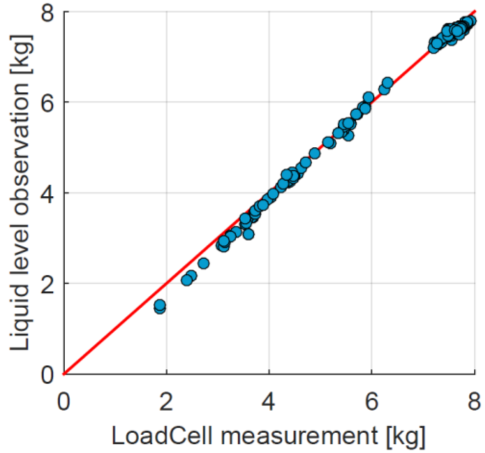


Component modelling

Liquid receiver:







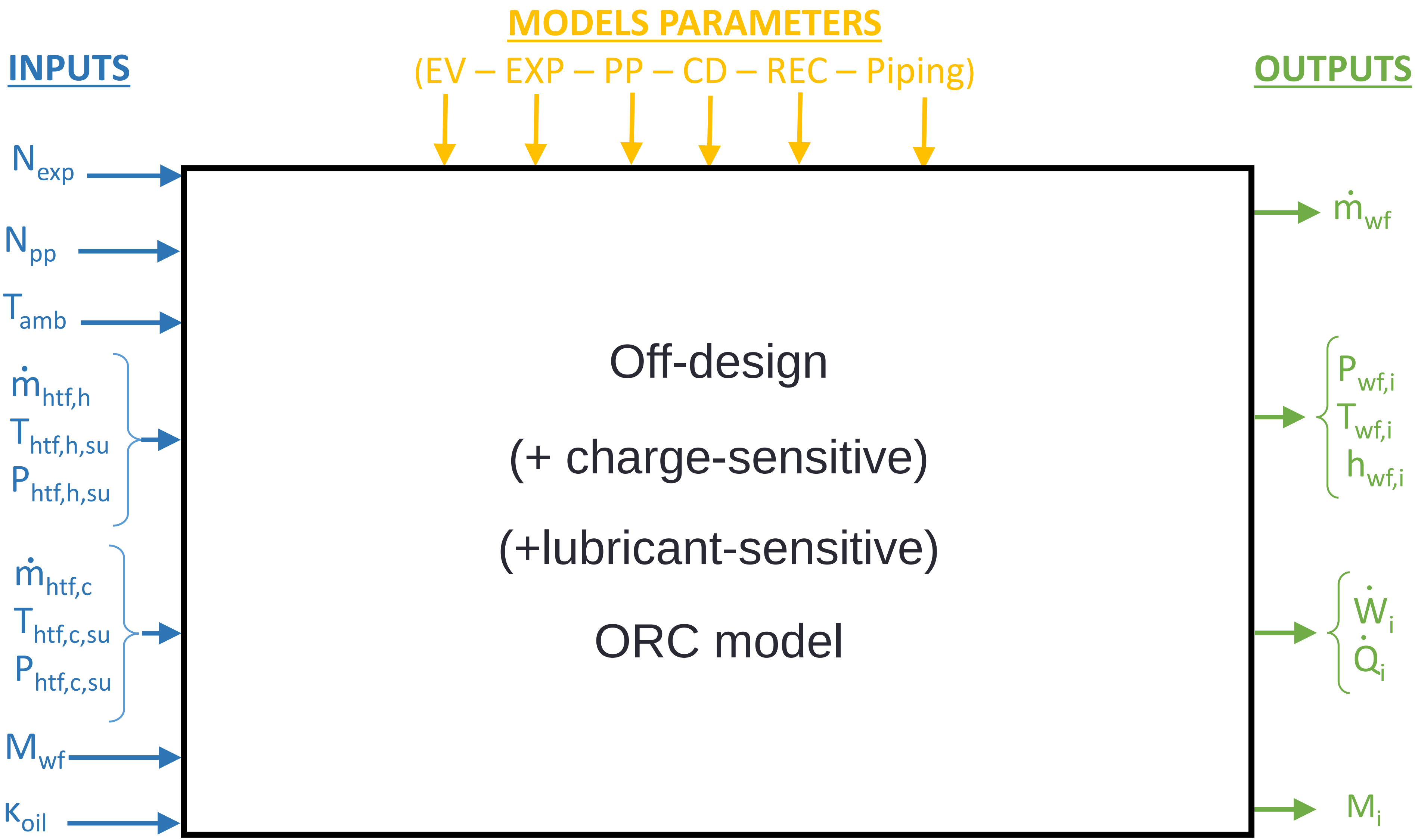
if x = 0 → partially filled (two-phase)

if “x < 0” → filled of subcooled liquid

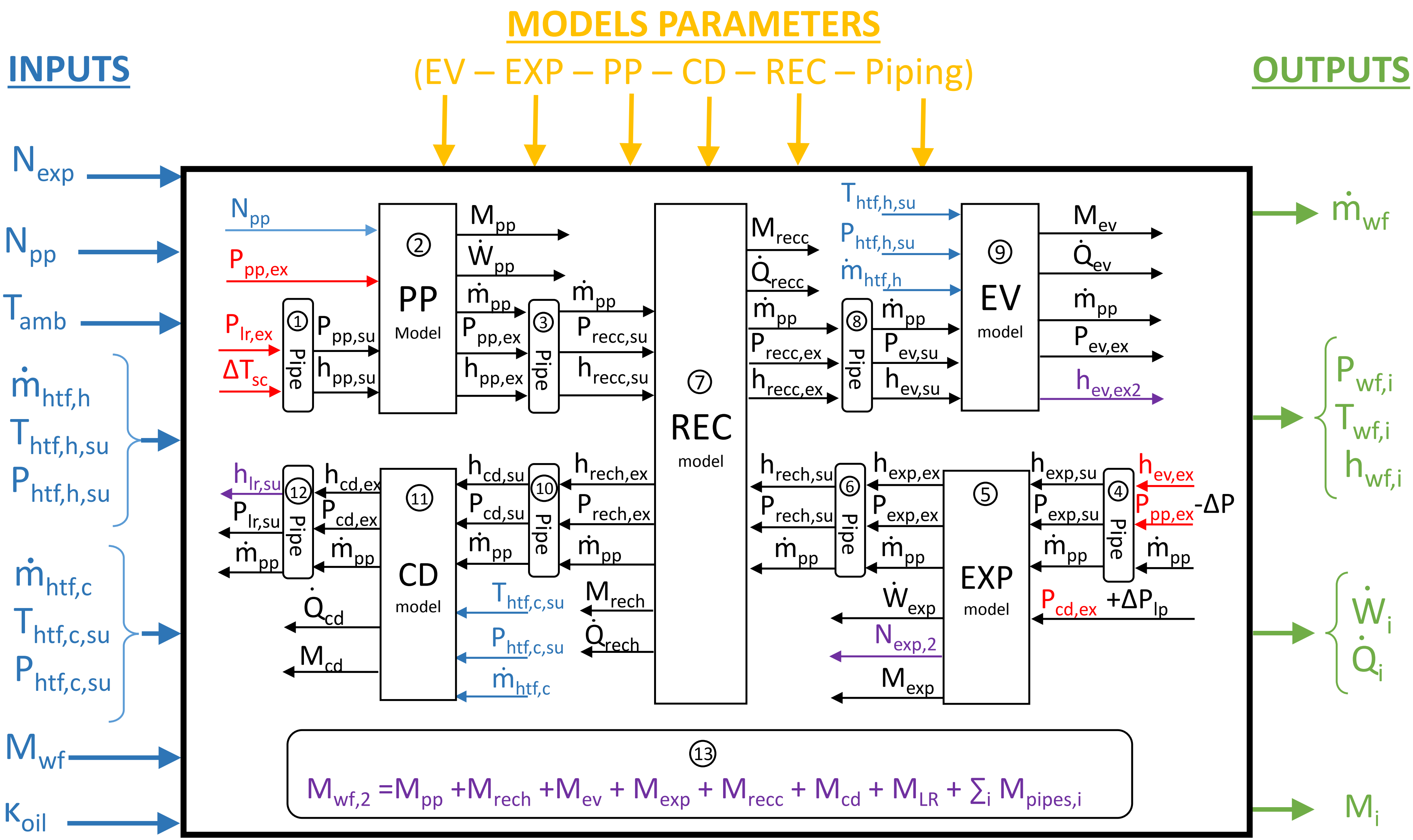
if 0<x<1 → filled of saturated vapour

if “x>1” → filled of superheated vapour

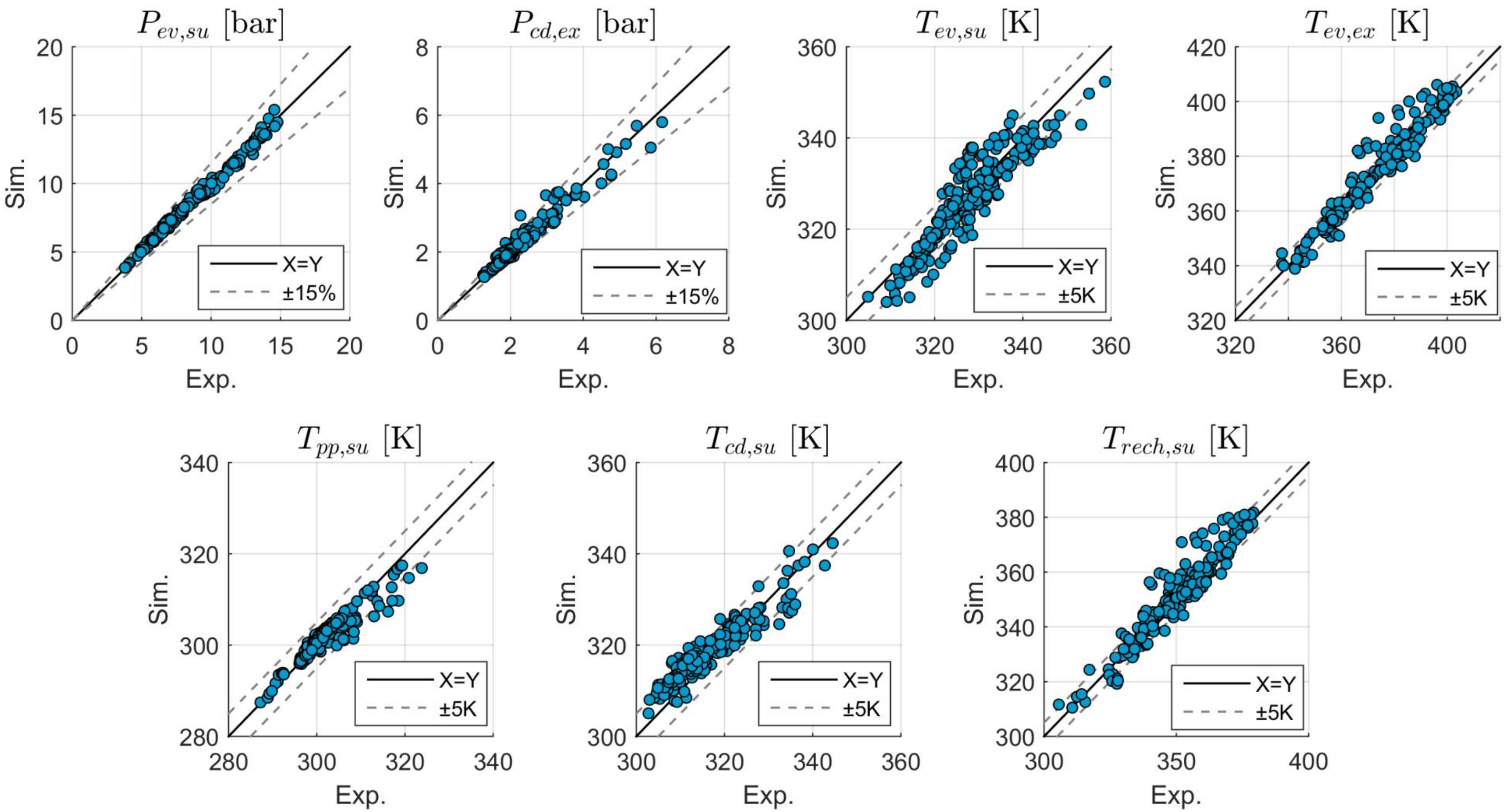
ORC modelling



ORC modelling

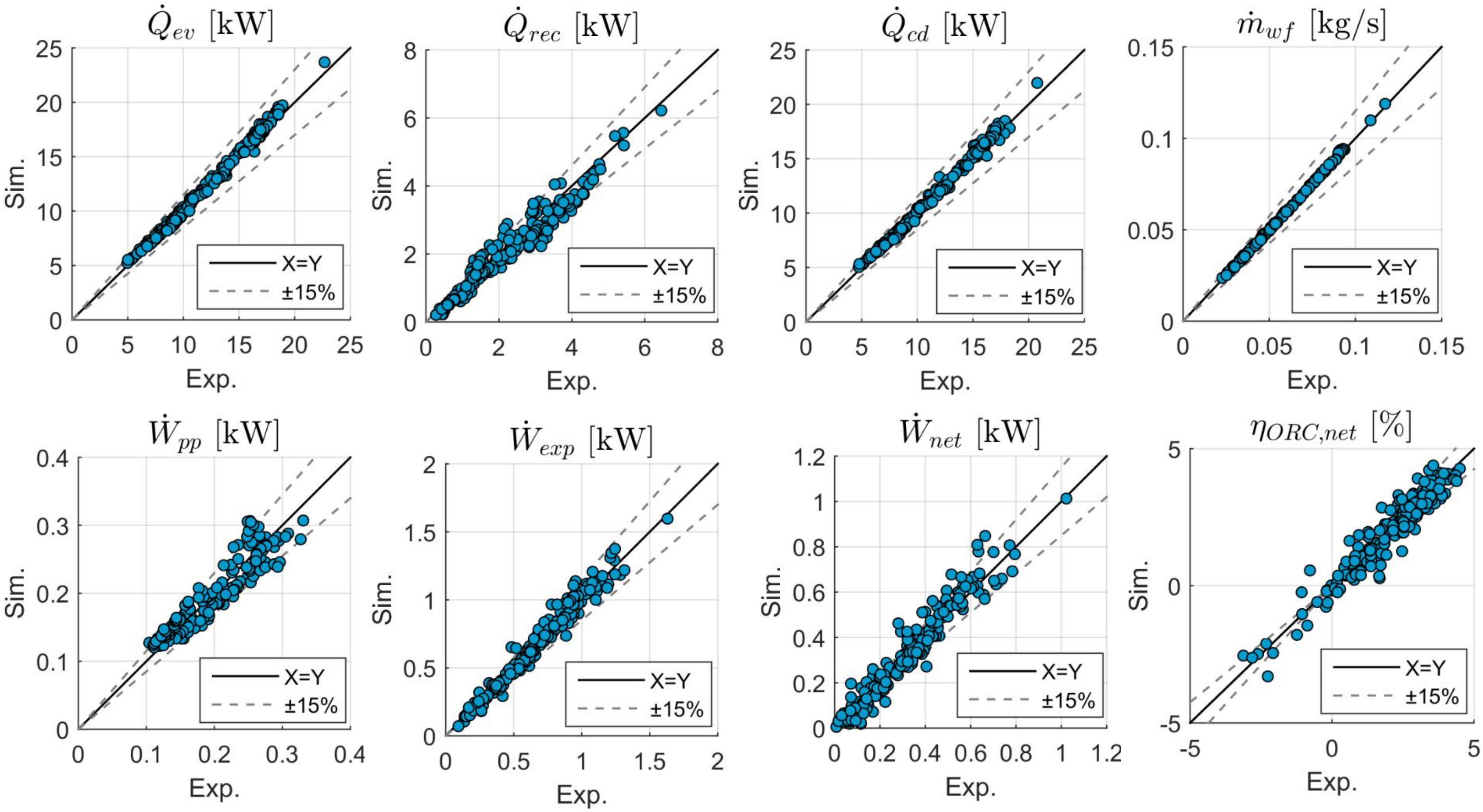


Model validation (inner state)

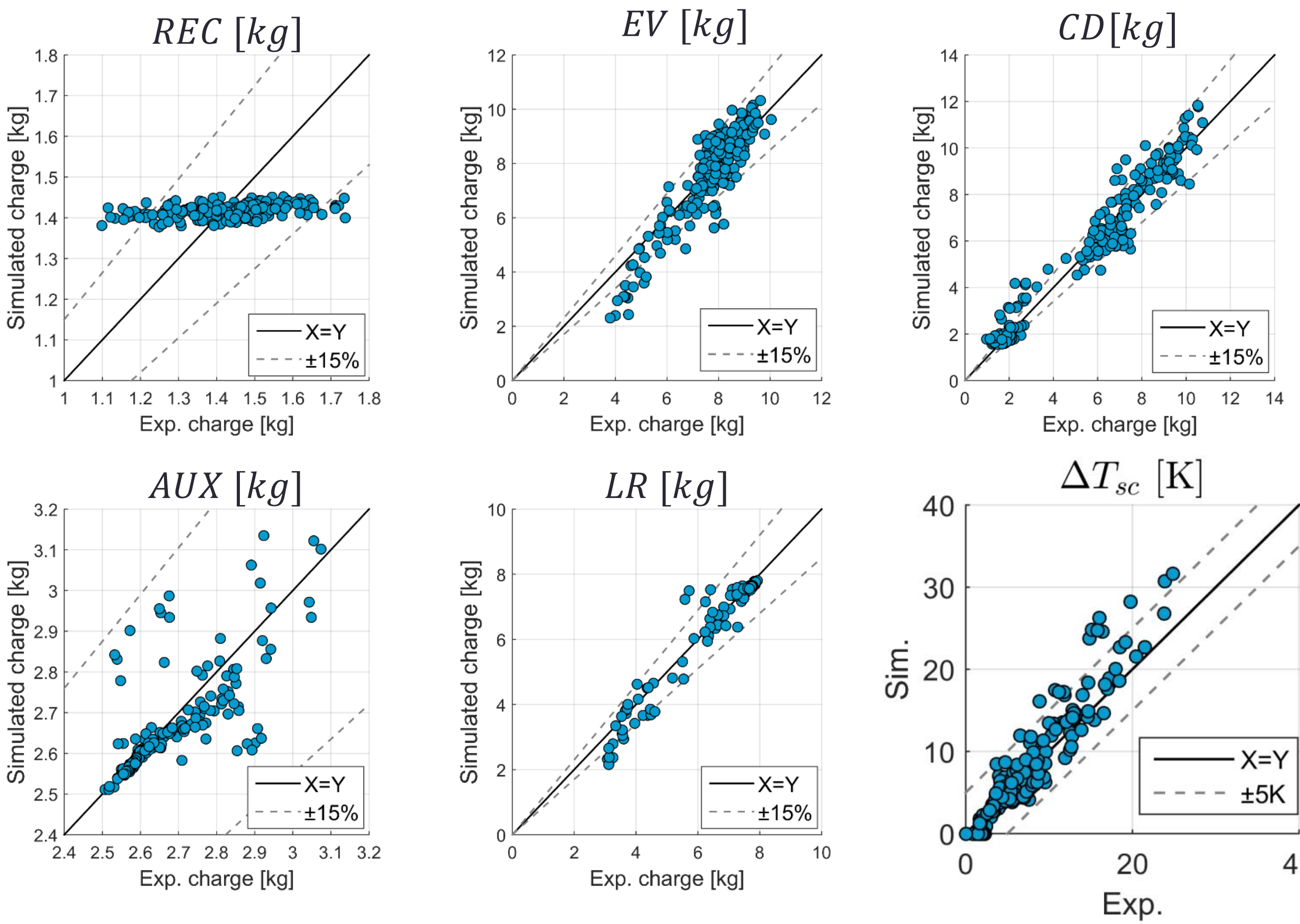


☺ ...

Model validation (energy flows)



Model validation (charge inventory)



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

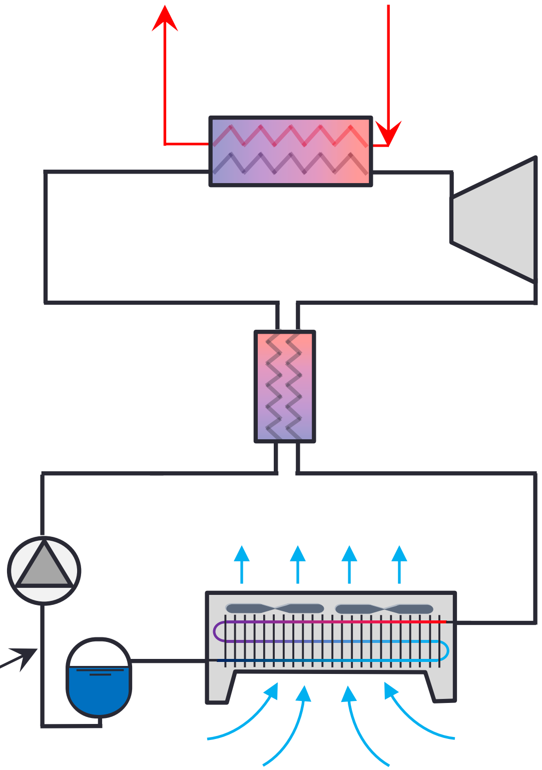
Example #1: Cavitation detection

- 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

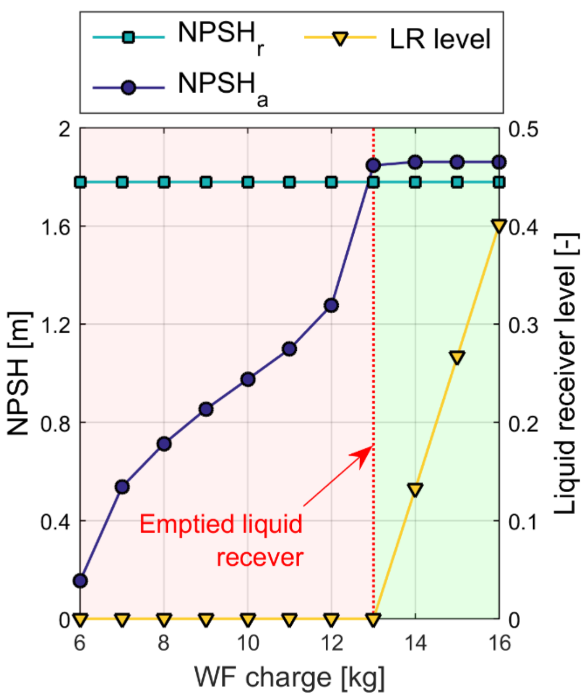
- Pump cavitation = vapour bubbles within pump → really bad !
- Detectable with charge-sensitive model (no guess on $\Delta T_{sc,cd,ex}$)

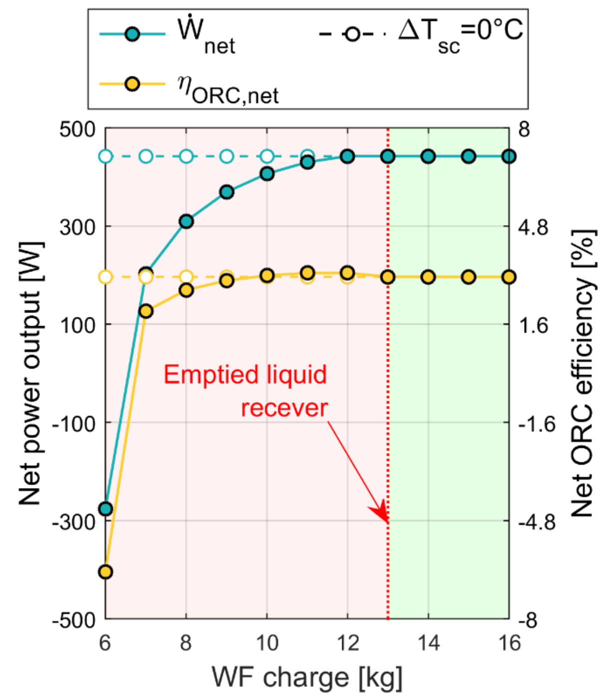


No hypothesis here

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



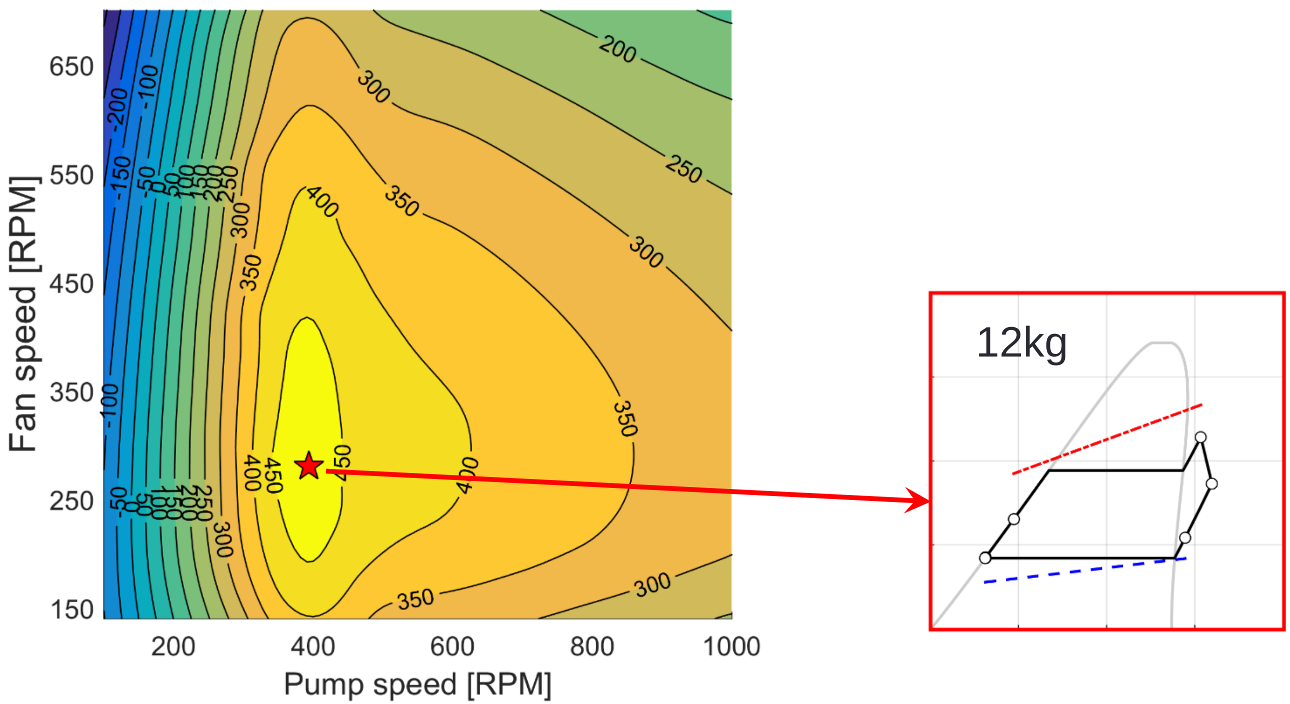


Example #2: Optimal charge and LR size

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 $\dot{W}_{net}$



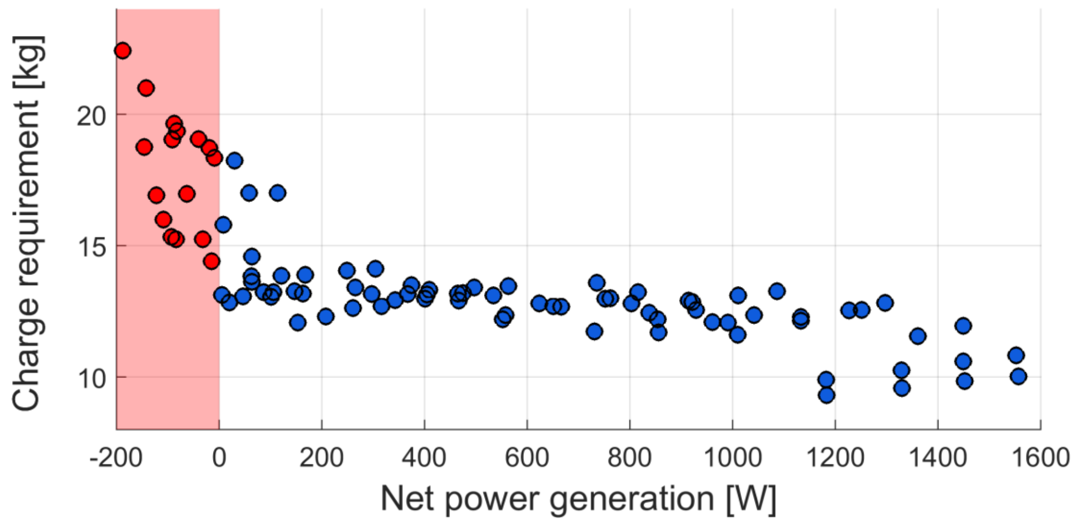
Example #2: Optimal charge and LR size

1. Define off-design operational range

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

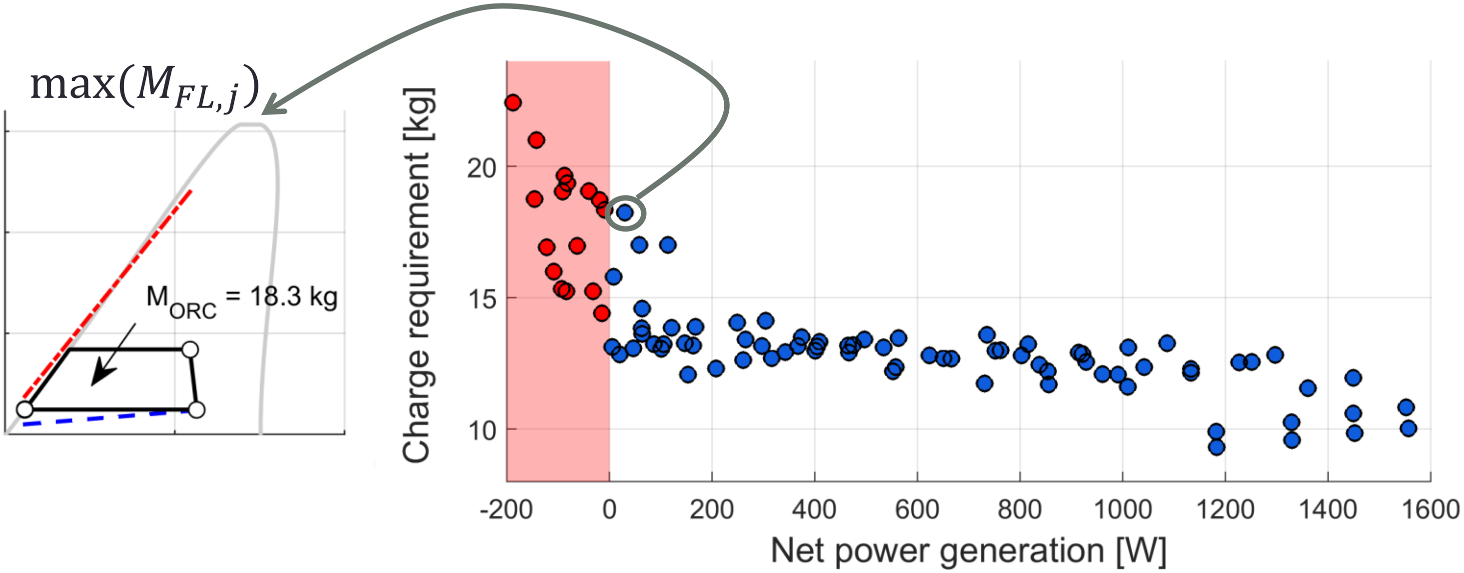
   Seek for optimal control in order to maximize $\dot{W}_{net}$

   Build a charge requirement mapping



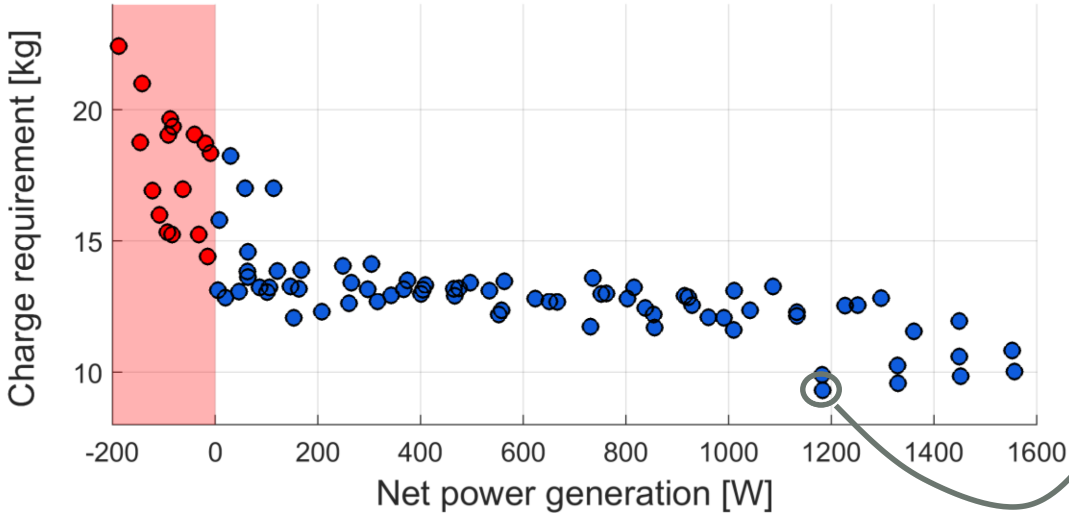
Example #2: Optimal charge and LR size

1. Define off-design operational range
2. Full-load performance mapping while imposing $\Delta T_{sc,cd,ex}$
3. Optimal charge assessment $\longrightarrow$ $M_{ORC} = \max(M_{FL,j})$



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 $\longrightarrow$ $M_{ORC} = \max(M_{FL,j})$
4. Minimum LR volume $\rightarrow V_{LR} = \dfrac{M_{ORC} - M_{min}}{\rho_{l,min}}$

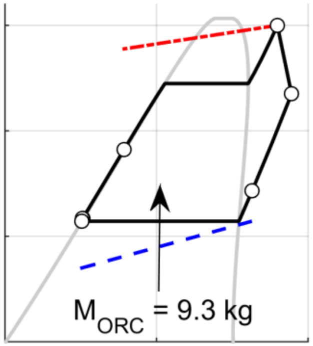


$\min(M_{FL,j})$

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 $\longrightarrow$ $M_{ORC} = \max(M_{FL,j})$
4. Minimum LR volume $\rightarrow$ $V_{LR} = \dfrac{M_{ORC} - M_{min}}{\rho_{l,min}}$

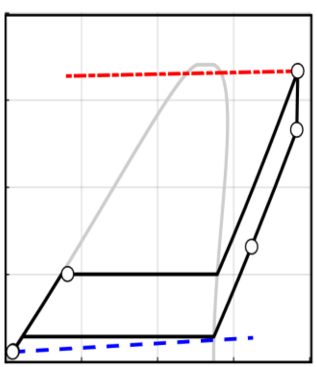
M_{min} $\xrightarrow{\text{Full-load only}}$



$\min(M_{FL,j})$

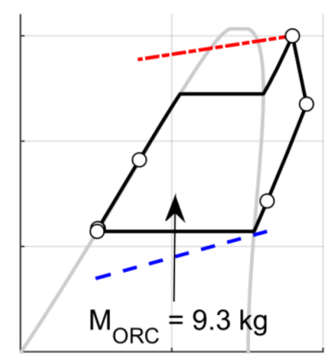
Example #2: Optimal charge and LR size

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 $\rightarrow V_{LR} = \dfrac{M_{ORC} - M_{min}}{\rho_{l,min}}$



$\min(M_{PL,j})$
$\approx \min(M_{FL,j} - M_{ev,j})$

Part-load $\longleftarrow$ M_{min} $\longrightarrow$ Full-load only



$\min(M_{FL,j})$

V.

CONCLUSIONS AND PERSPECTIVES

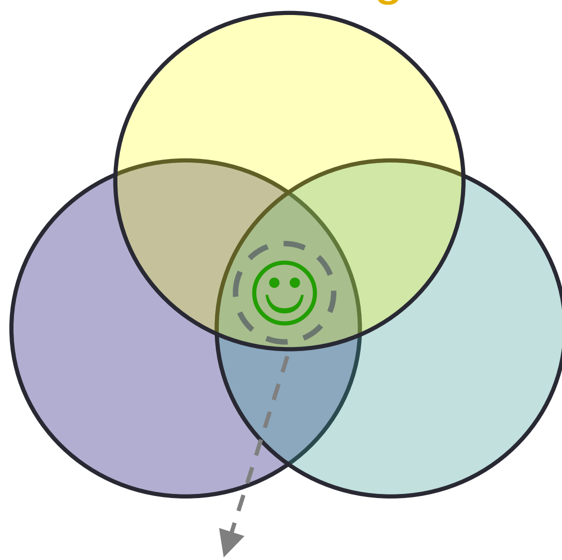
Overall summary

- 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

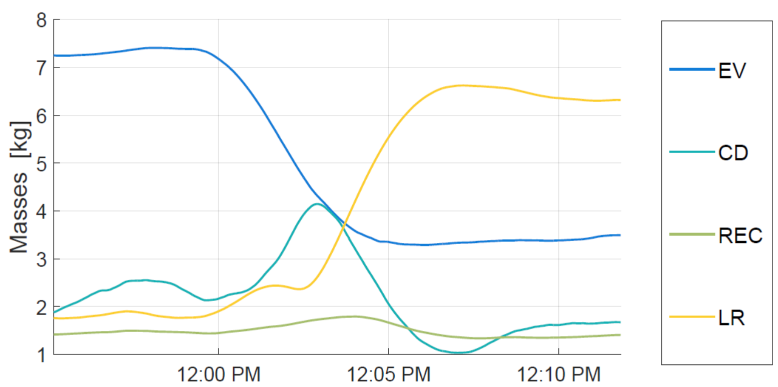
1. True off-design models MUST be charge-sensitive.
2. The charge distribution is related to spatial occupation of the liquid/vapour phases.
3. The master is the evaporator. The low-pressure components are slaves.
4. Any knowledge on the charge inventory (or the zones distribution) can help to characterize 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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Thermodynamics Laboratory

University of Liège

Belgium