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Trans-critical vapor compression cycle using butane (R600) as refrigerant for industrial waste heat recovery

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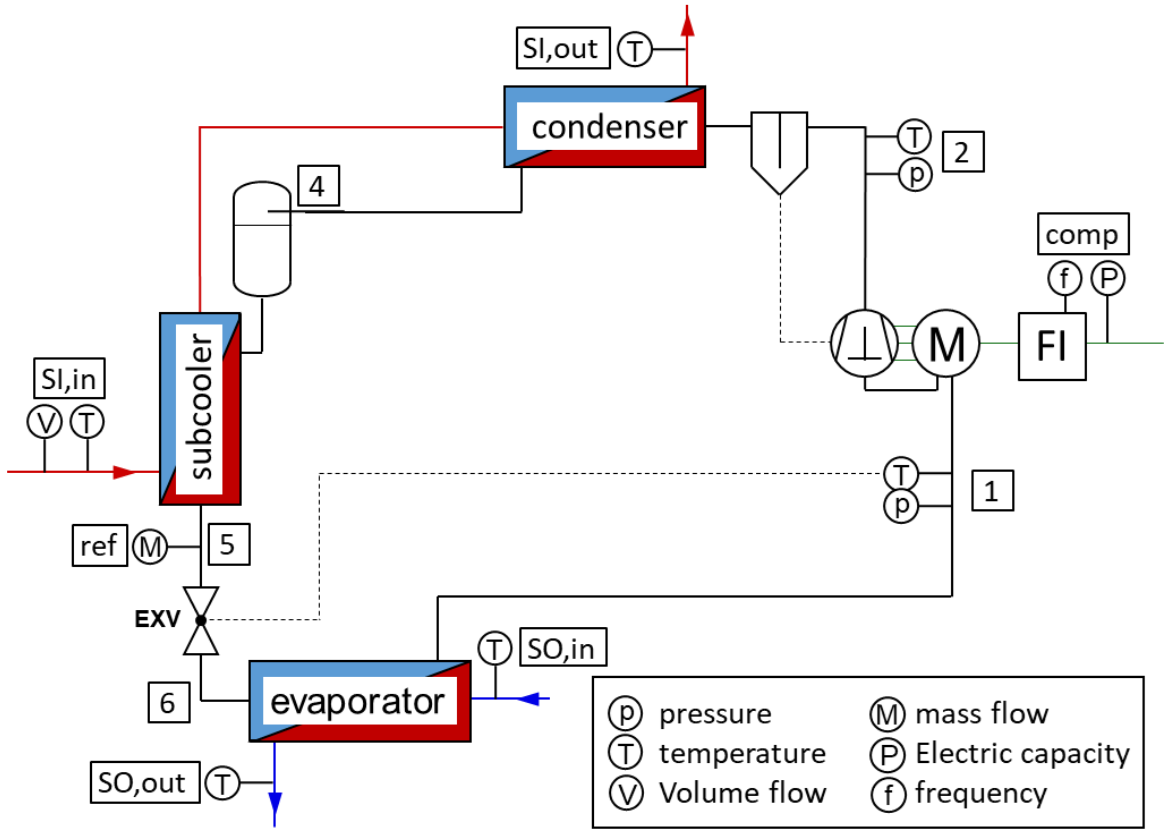
Content

- Introduction of the Project
- Sub-critical test rig
- Simulation model to investigate trans-critical operation
- Influence of operating parameters in trans-critical operation
- Conclusions and Outlook

Project TransCrit

- Development of a high temperature vapor compression heat pump (HTHP)
- Industrial waste heat recovery
- Heat sink outlet temperatures > 150 °C
- Trans-critical process
  - Compression into super-critical state
  - Heat rejection at gliding temperature
  - Control of high-side pressure necessary
- Natural working fluid → R600 (n-butane): p_{crit}=37,96 bar t_{crit}=152 °C
- Project Partner

Sub-critical test rig

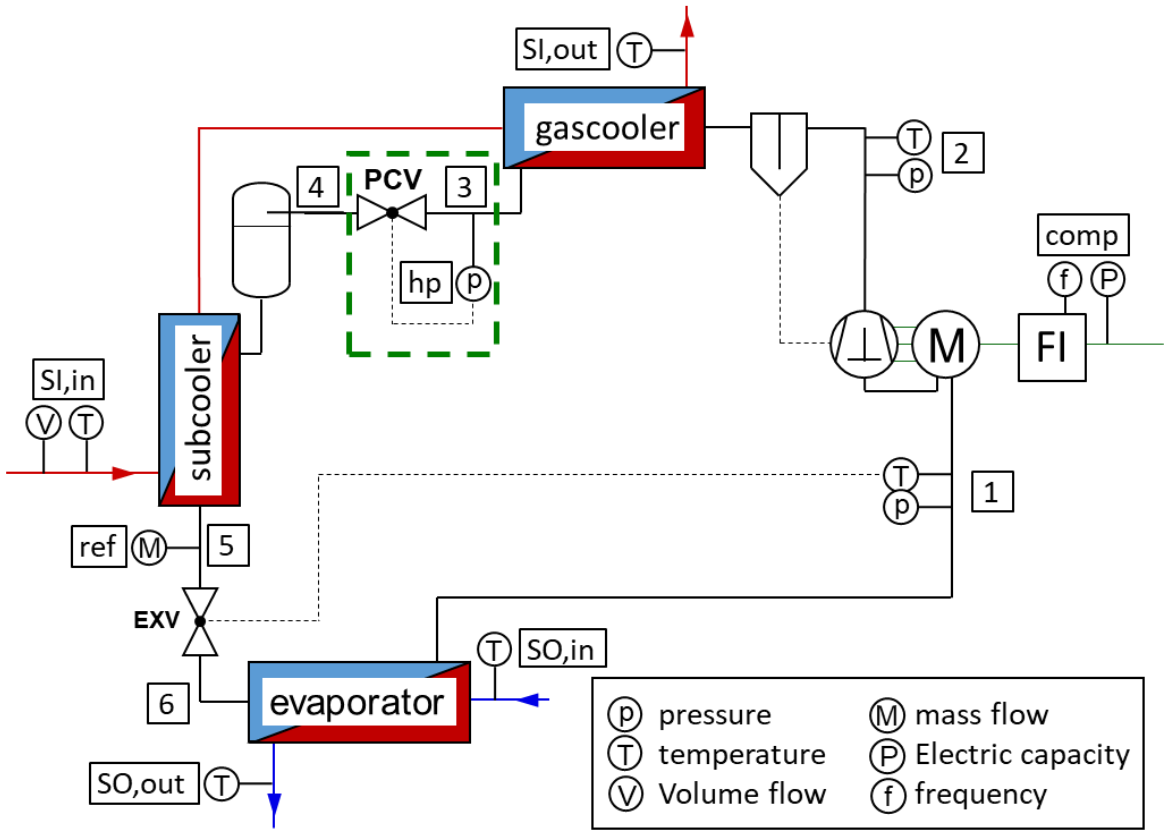


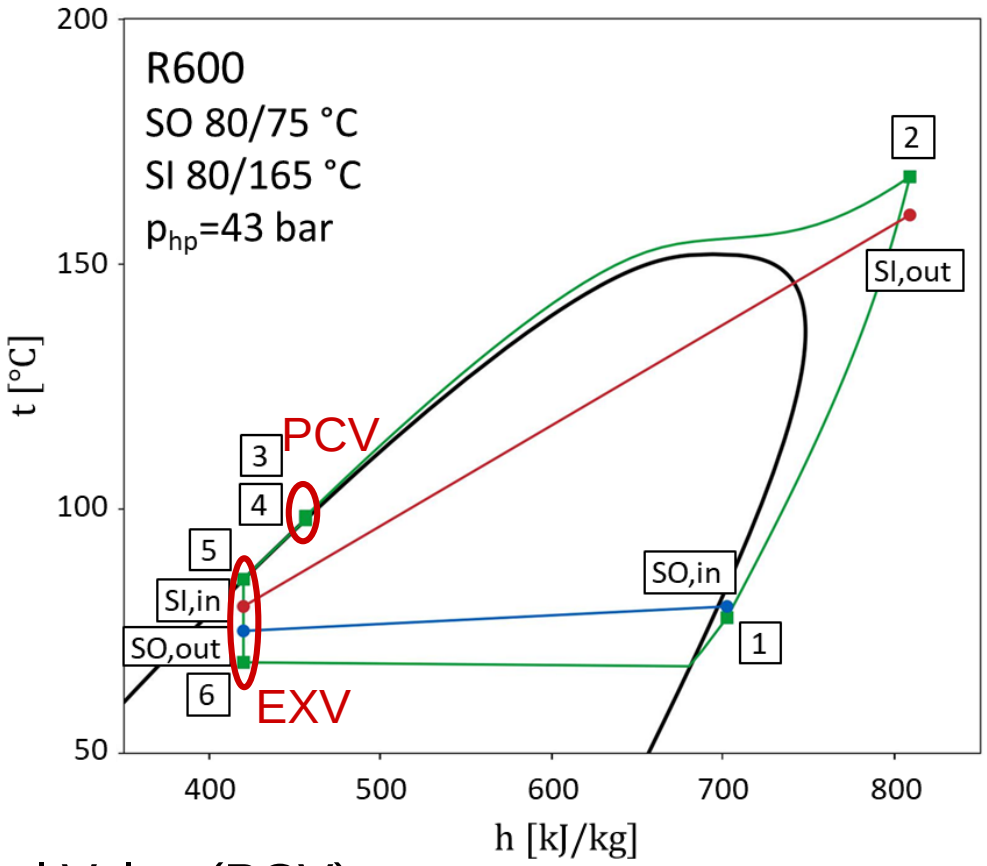
- R600 HTHP (Project HotCycle)
- Condensing temperatures up to 110°C
- 45 kW heating capacity @ heat source 70/65°C, heat sink 80/110°C
- Modified separating hood reciprocating compressor
- Brazed plate heat exchangers

➢ Evaluation of compressor and system efficiencies

$$\eta_{is,ov} = \frac{\dot{m}_{ref} \cdot (h_{ref,2s} - h_{ref,1})}{P_{el,comp}} \qquad \eta_{is,i} = \frac{h_{ref,2s} - h_{ref,1}}{h_{ref,2} - h_{ref,1}} \qquad \lambda_{vol} = \frac{\dot{m}_{ref}}{\dot{V}_{swept} \cdot \rho_{ref,1}} \qquad COP_h = \frac{\dot{Q}_{h,w}}{P_{el,comp}}$$

Simulated trans-critical cycle



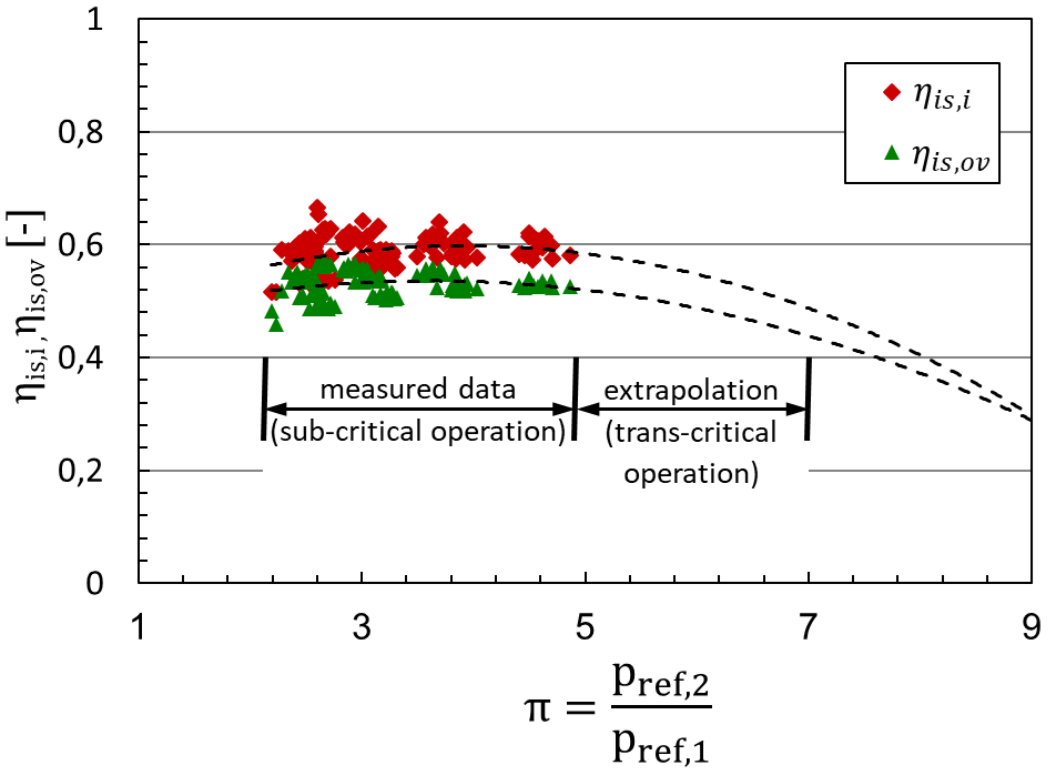


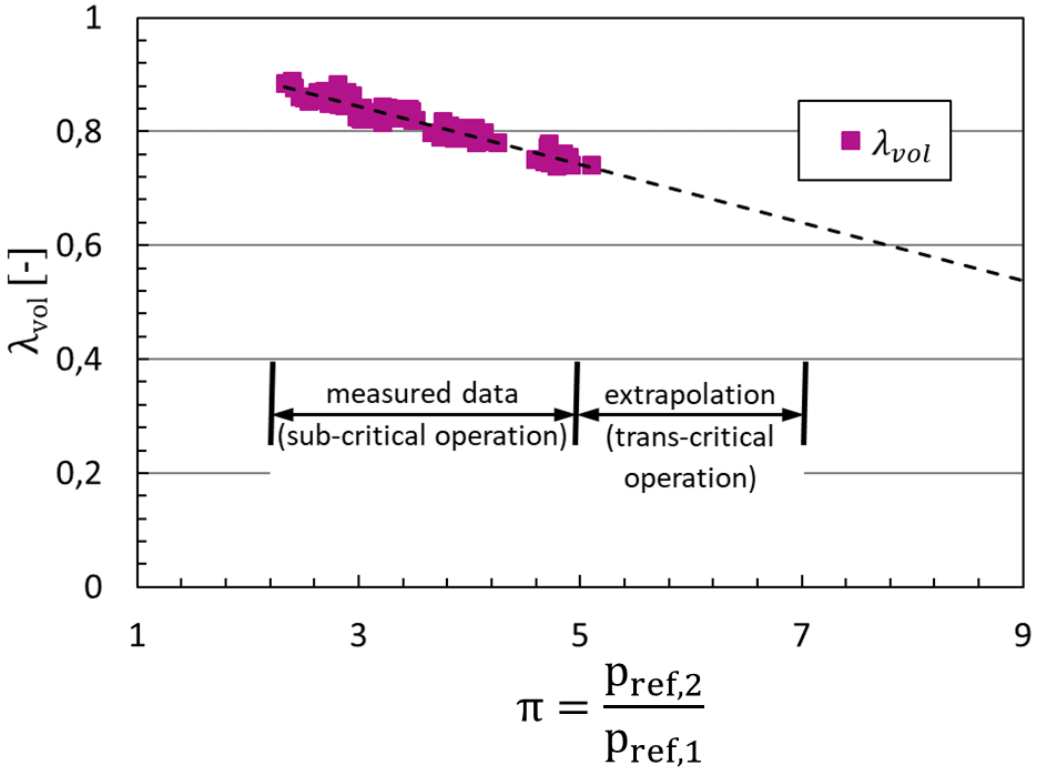
- Control of high-side pressure with Pressure Control Valve (PCV)
- Influence of operating parameters studied:

  high-side pressure, suction gas superheat, heat sink temperature

Simulation Model

- TIL-Suite (TLK Thermo), Modelica language in Dymola
- Compressor: efficiencies evaluated from measurement data

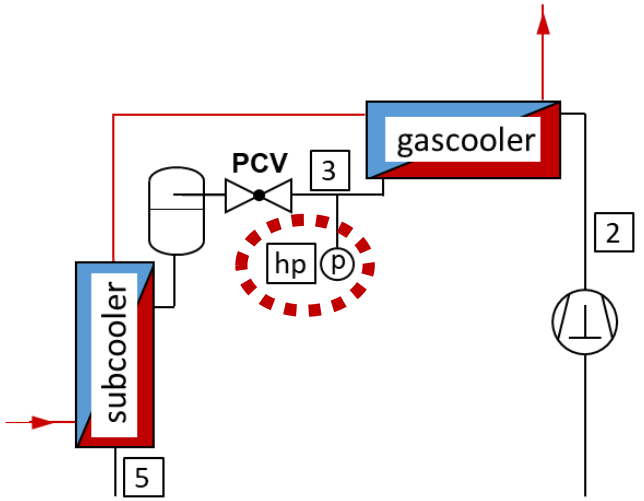


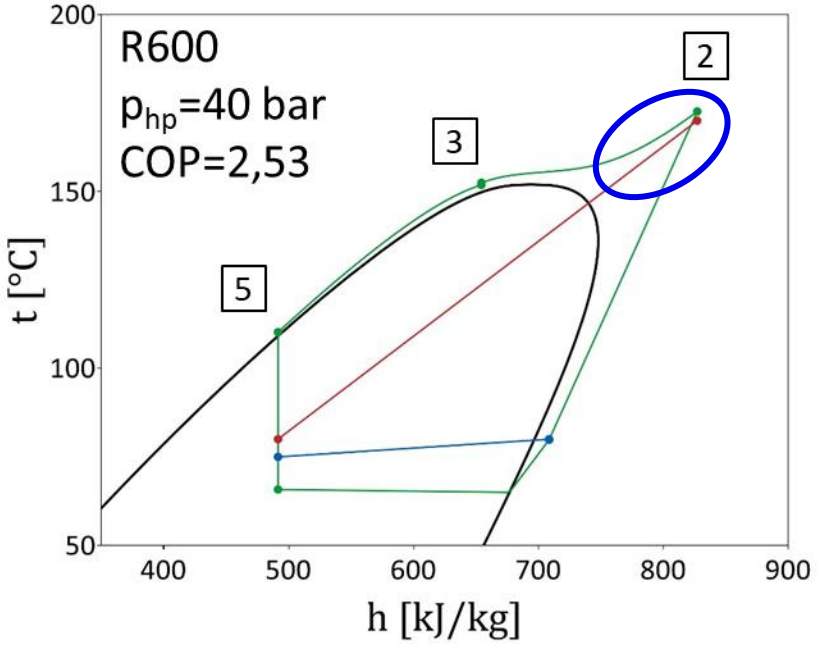


- Plate heat exchangers: finite volume approach
- Sub-critical simulation: COP_{mod} vs. COP_{meas} max. 7%

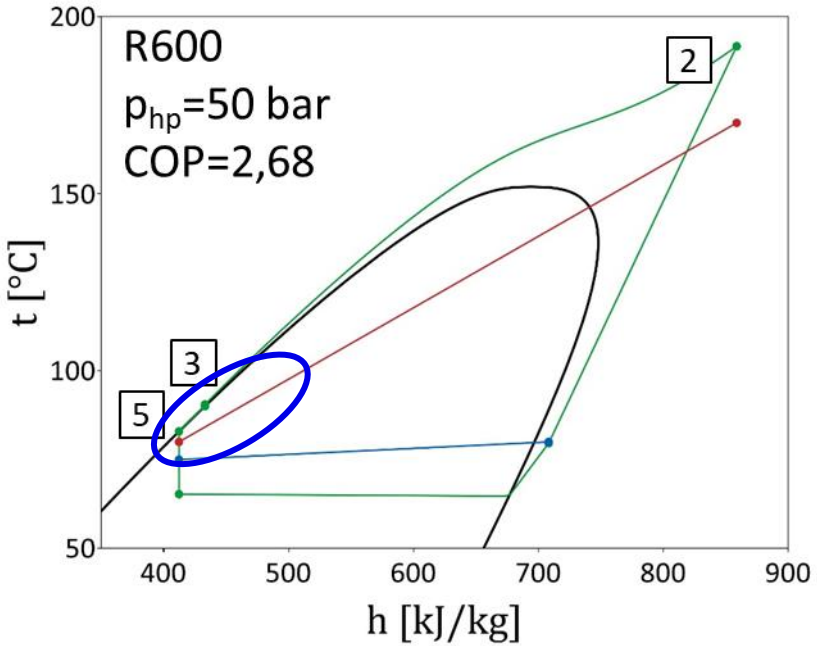
Influence of high-side pressure

- Variation of high-side pressure with constant heat sink temperatures and compressor inlet state
- Location of pinch point in gascooler changes
- Optimum high-side pressure exists

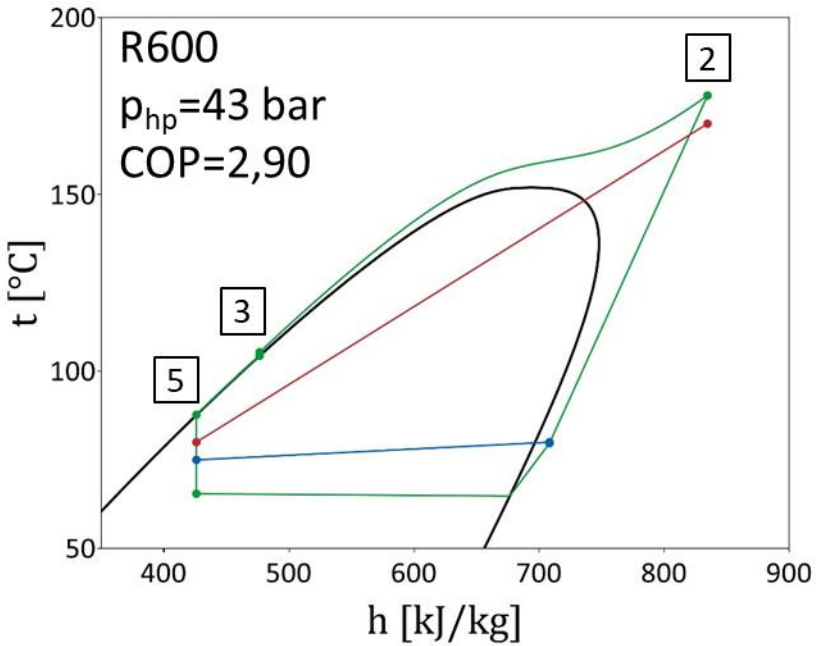




$p_{hp} < p_{opt}$

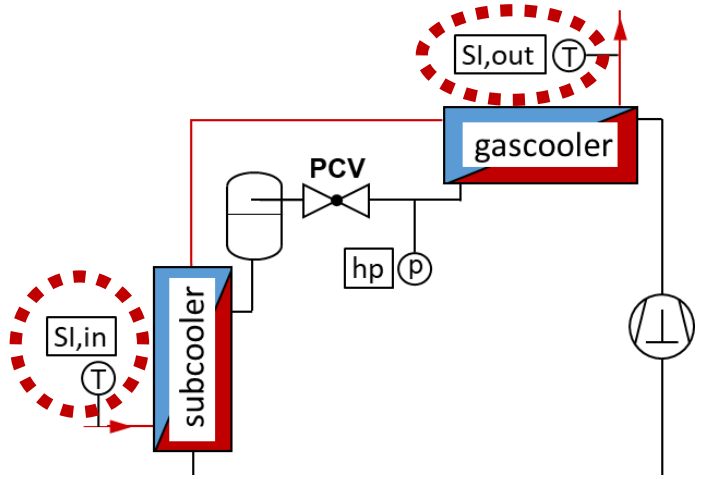


$p_{hp} > p_{opt}$

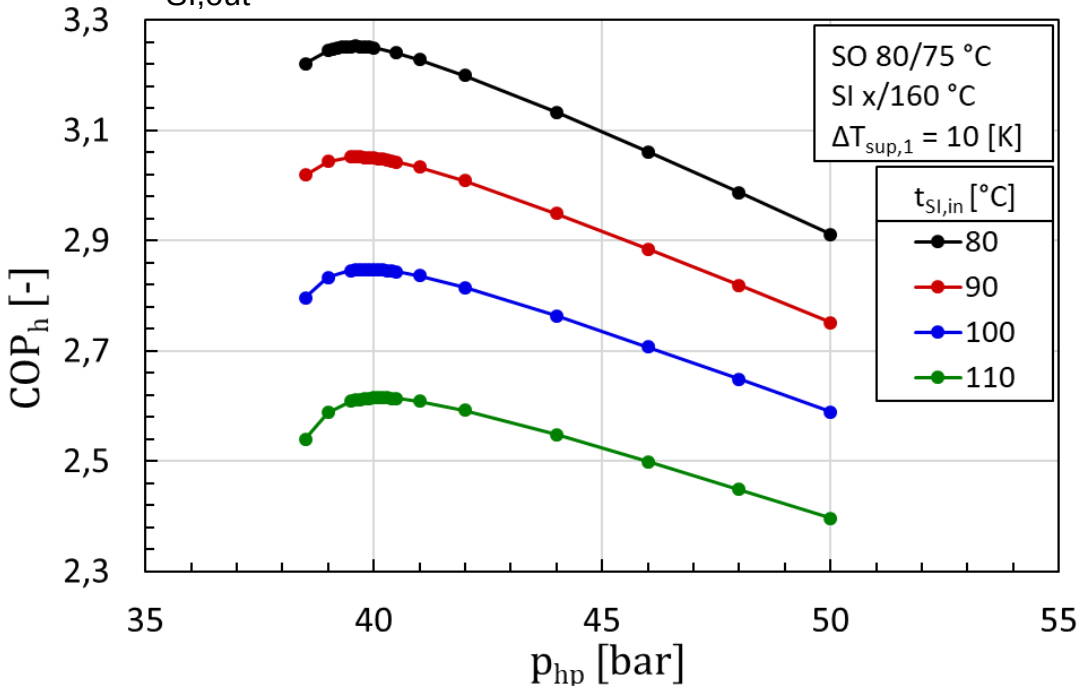


$p_{hp} = p_{opt}$

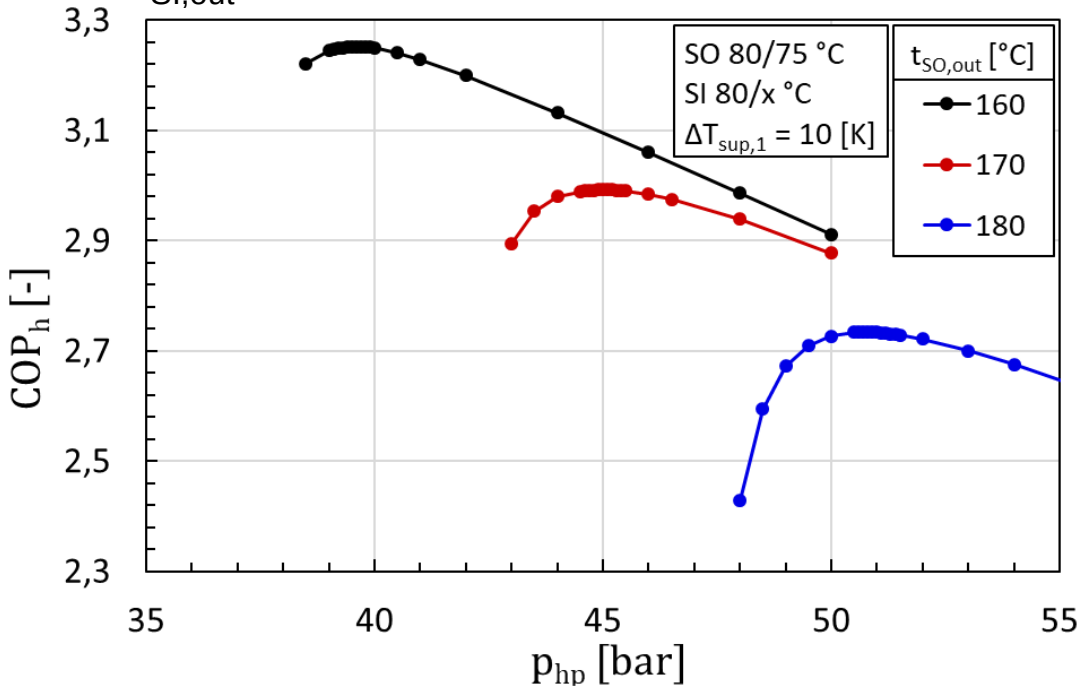
Influence of heat sink temperature



$t_{SI,in}$ ...80 ÷ 110 °C
$t_{SI,out}$ …160 °C

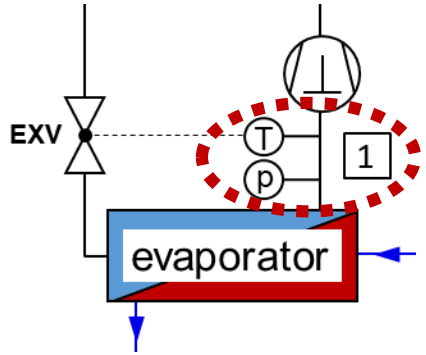


$t_{SI,in}$ ...80 °C
$t_{SI,out}$ …160 ÷ 180 °C

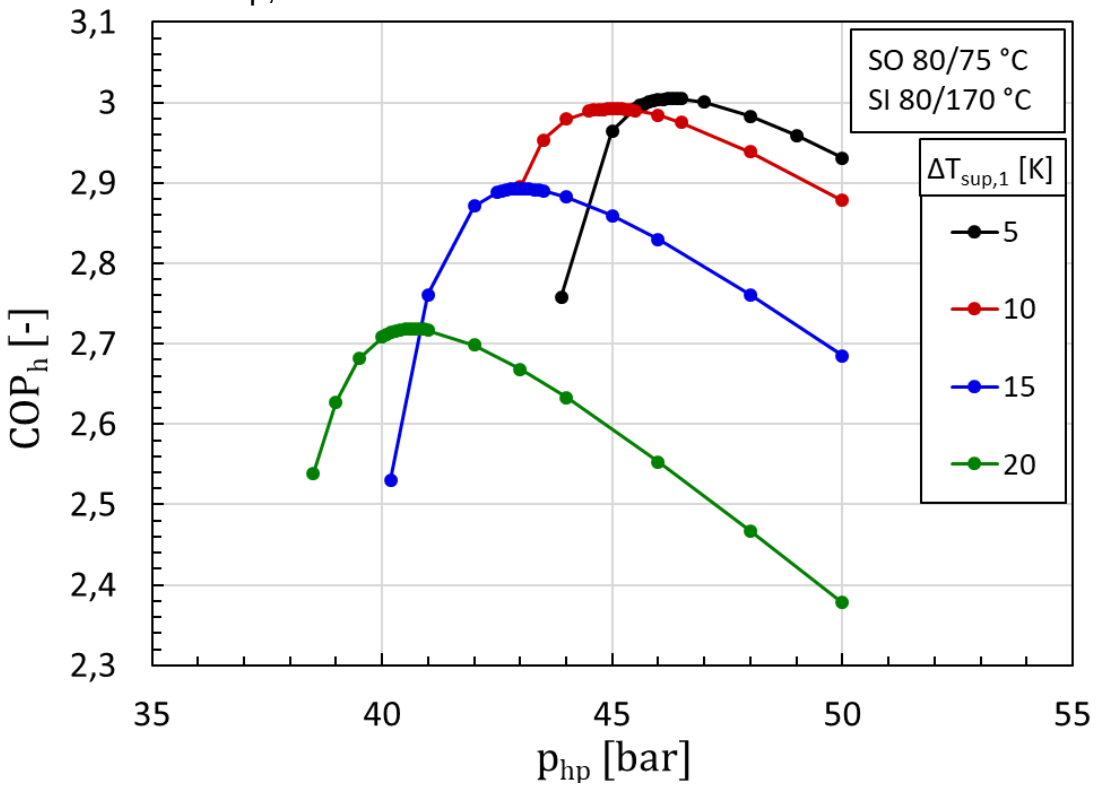


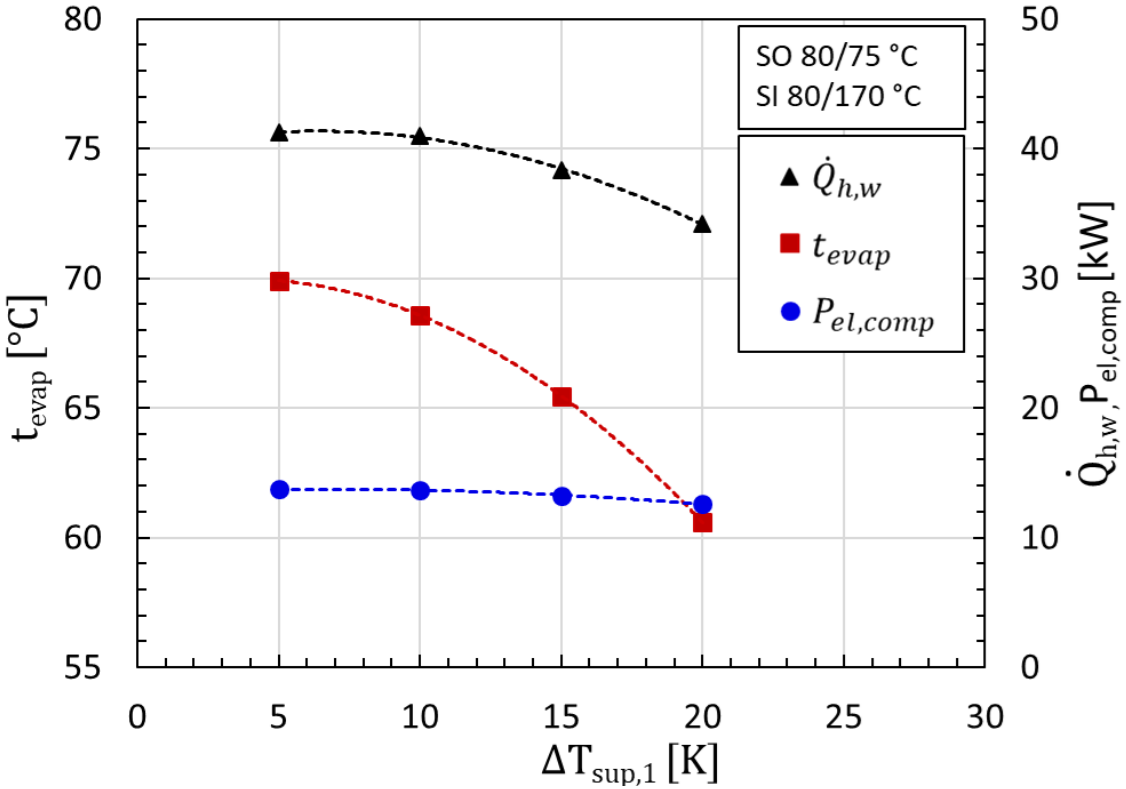
Influence of suction gas superheat

$$\Delta T_{sup,1} = t_{ref,1} - t_{sat}(p_{ref,1})$$



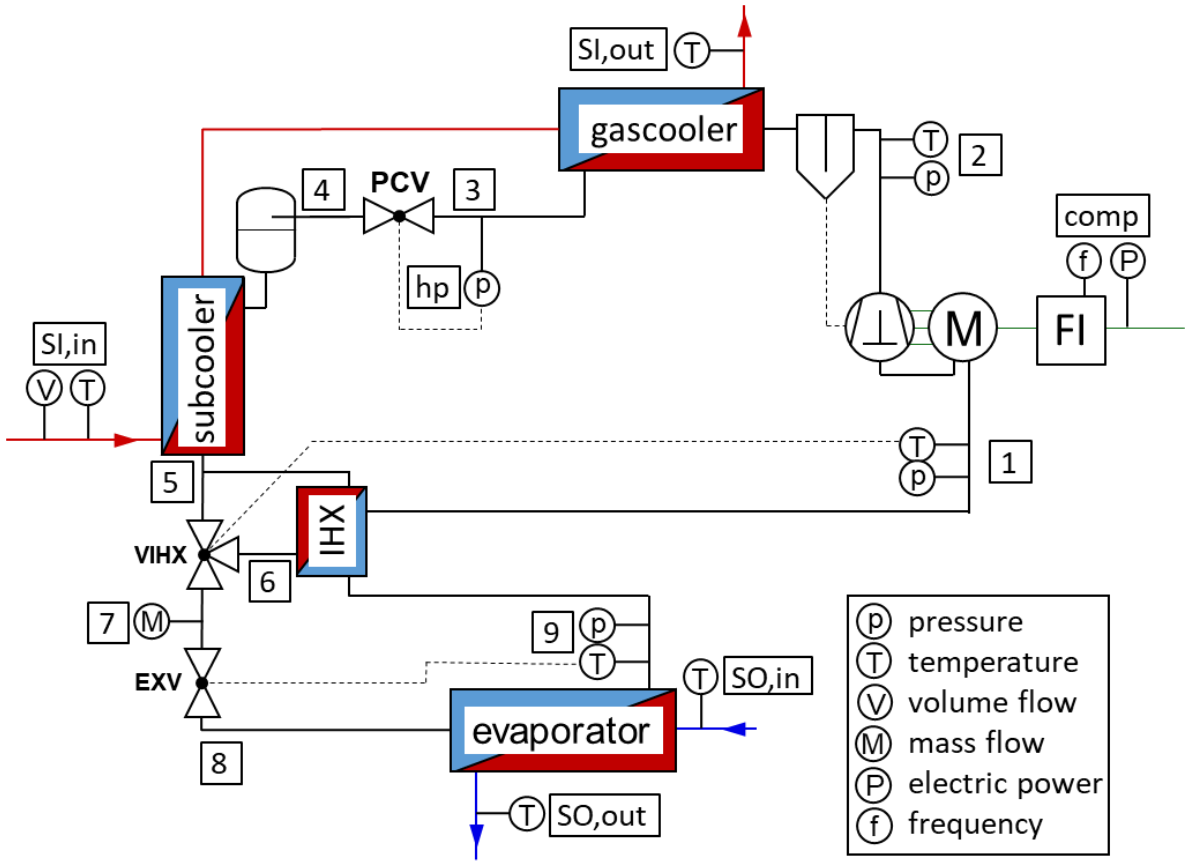
$\Delta T_{sup,1}$ …5 ÷ 20 K

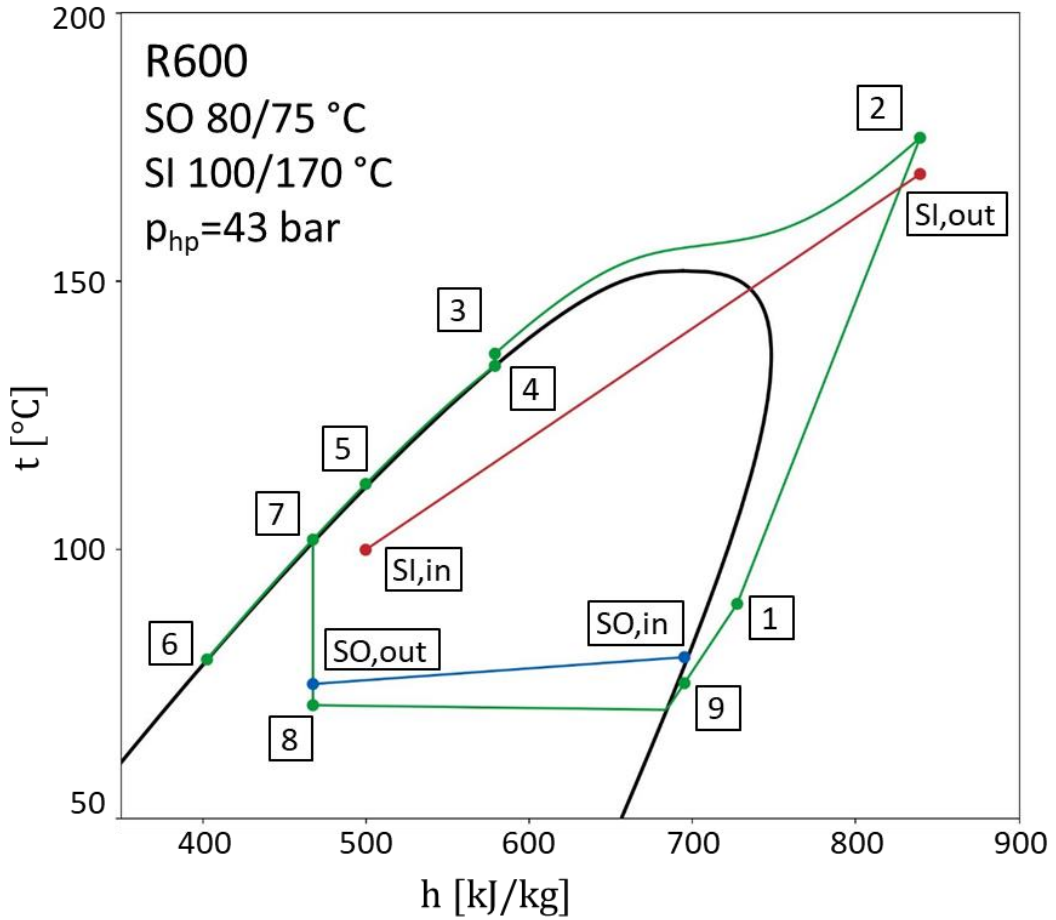




Suggested cylce improvements

- Internal heat exchanger (IHX)

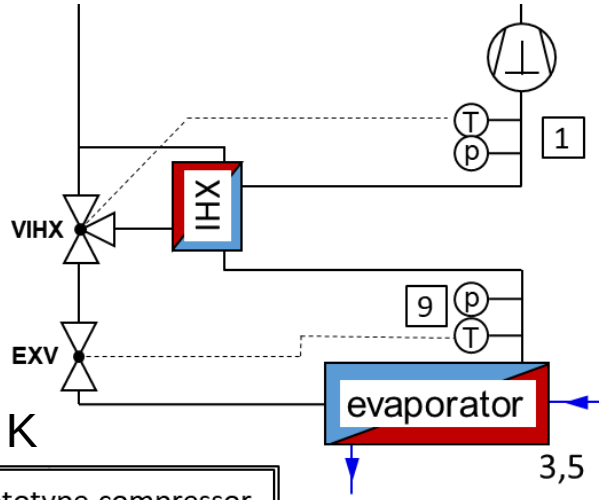




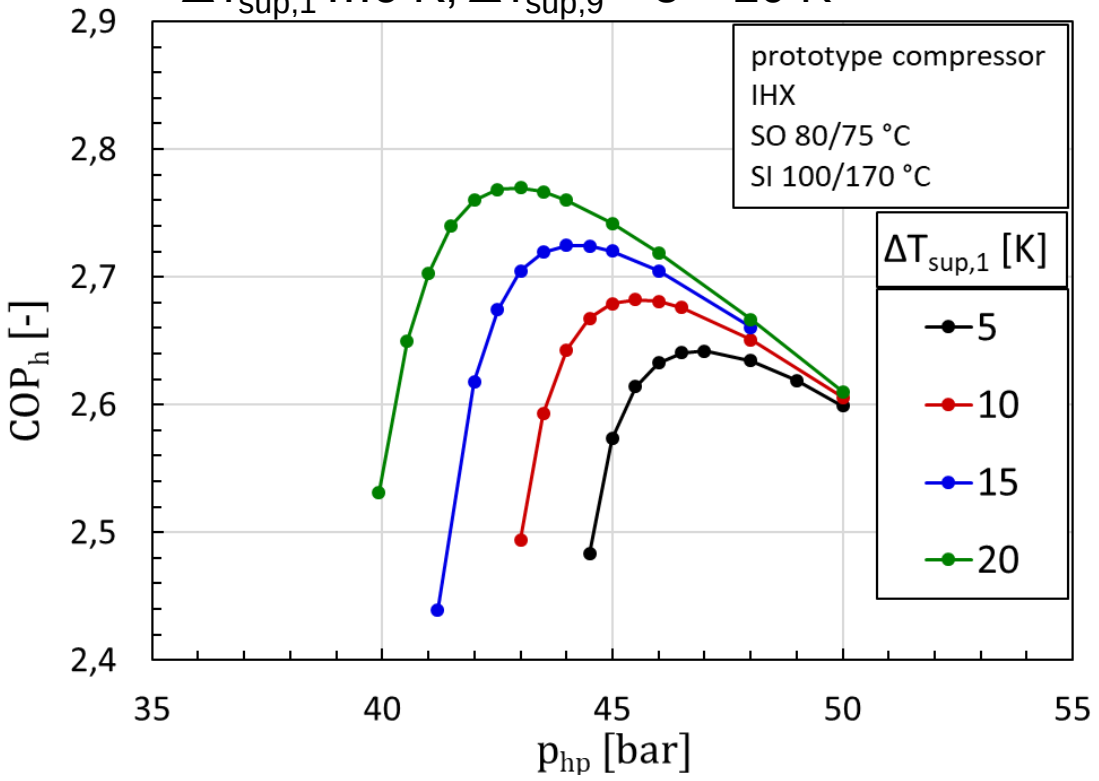
- Alternative compressor: Data from Bitzer 4VE-10P with R134a (Bitzer, 2018)

Bitzer, 2018. Bitzer Software v. 6.9.2074, BITZER Kühlmaschinenbau GmbH, Sindelfingen, Germany

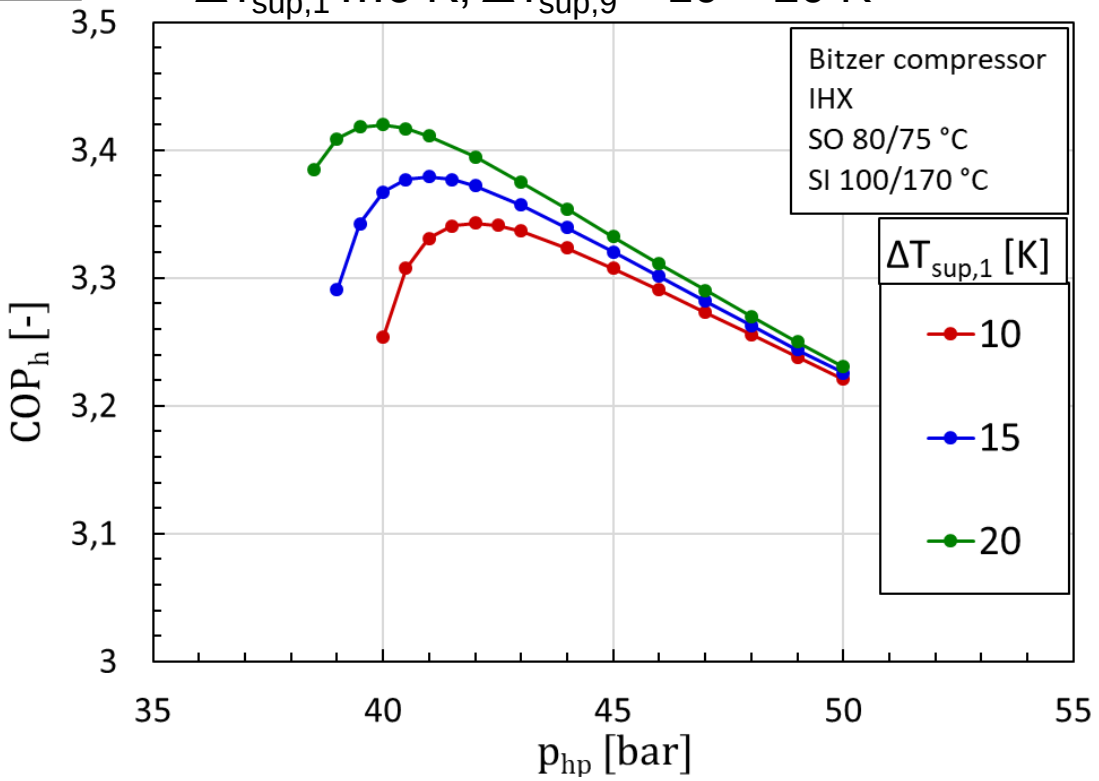
Trans-critical operation, improved cycle



$\Delta T_{sup,1}$ …5 K, $\Delta T_{sup,9}$ = 5 ÷ 20 K



$\Delta T_{sup,1}$ …5 K, $\Delta T_{sup,9}$ = 10 ÷ 20 K



Conclusions

- Sub-critical model: Deviation of COP_{model} vs. COP_{meas} < 7%
- Trans-critical operation was investigated by means of simulation
  - Optimum high-side pressure depending on operating conditions
    - ➢ Moves to lower pressures when increasing suction gas superheat
    - ➢ Application of IHX increases the COP
  - Trans-critical simulation
    - heat sink 100/170 °C,
    - heat source 80/75 °C,
    - 20 K suction gas superheat (5K at evaporator outlet, 20K at compressor inlet)
    - ➢ COP_h=3,4
  - Development of a trans-critical HTHP prototype based on simulation results
    - ➢ one-stage cycle, LP-accu, IHX

Outlook

- First tests of the prototype will deliver operational experiences
- Detailed experimental tests to investigate:
  - Operational behaviour and operating limits
  - Charaterization of compressor and system efficiencies
- Further tests to investigate oil durability and compressor performance at high temperature and pressure levels

Acknowledgement

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