Transcritical CO_2 heat pump for tap water heating: experimental validation of an auto adaptive algorithm for high pressure optimization

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Introduction

- European energy market destabilized by conflict in Ukraine

REPowerEU Actions

- REPowerEU --> Aggressive transition plan
  Key role of heat pump technology generates a rapid market growth

- F-Gas Regulation --> Further restrictions on use of HFC and HFO, GWP lower than 150

F-GAS

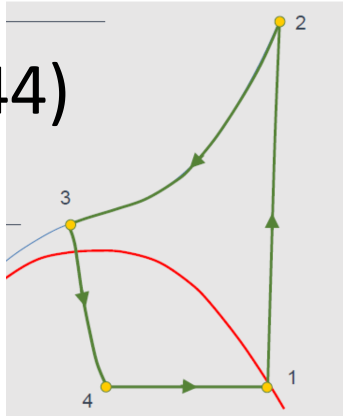
- PFAS topic --> Proposal to ban the use of compounds containing PFAS

Introduction

- Majority of manufactures will use hydrocarbons --> R-290 seems a “new standard”
  - Benefits in terms of operating range, efficiency and design of units VS R-410A
  - High flammability means low usability in some HP applications

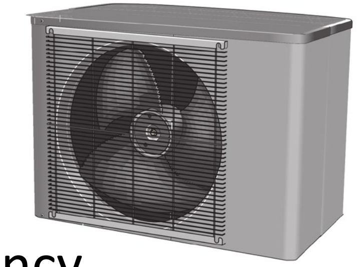
- In this scenario it’s extremely important to evaluate all possible natural refrigerants alternatives in residential HVAC --> CO_2 (R-744)

- Mainly used in refrigeration market, need to maximize the transcritical unit efficiency



Introduction

- Liao correlation --> COP is maximized with high pressure mng
- In hydronic HP, COP depends also from secondary fluid capacity
- How to optimize it?
  - Model based optimization, “ad hoc” correlations, derived from experimental data
  - Real time optimization approach without a priori model, but relying on system measurement:



- Proposal
  - This work characterizes an algorithm to generate a suitable index for efficiency, defined as simple as possible to be calculated, but accurate enough to guarantee the unit performance

Test Rig Description

Test unit used in our lab in CAREL HQ (Italy)

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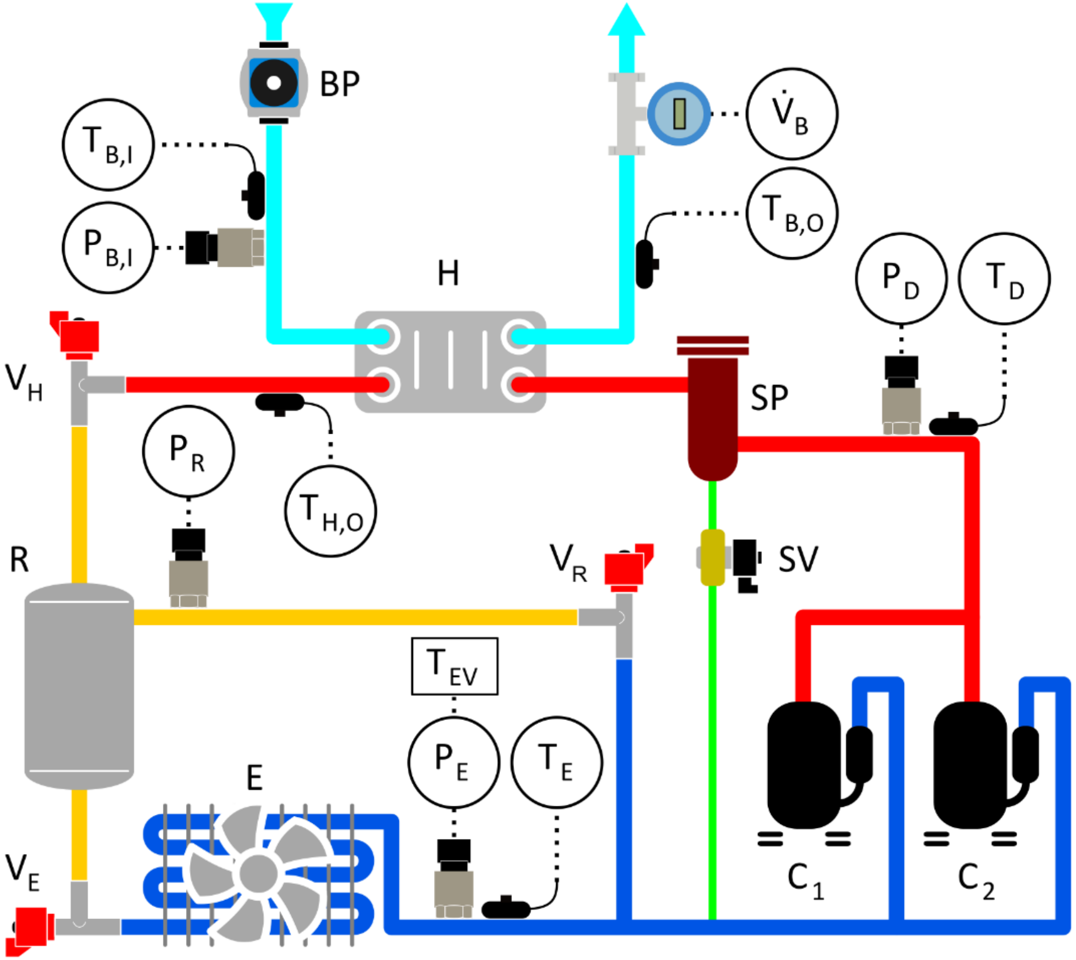
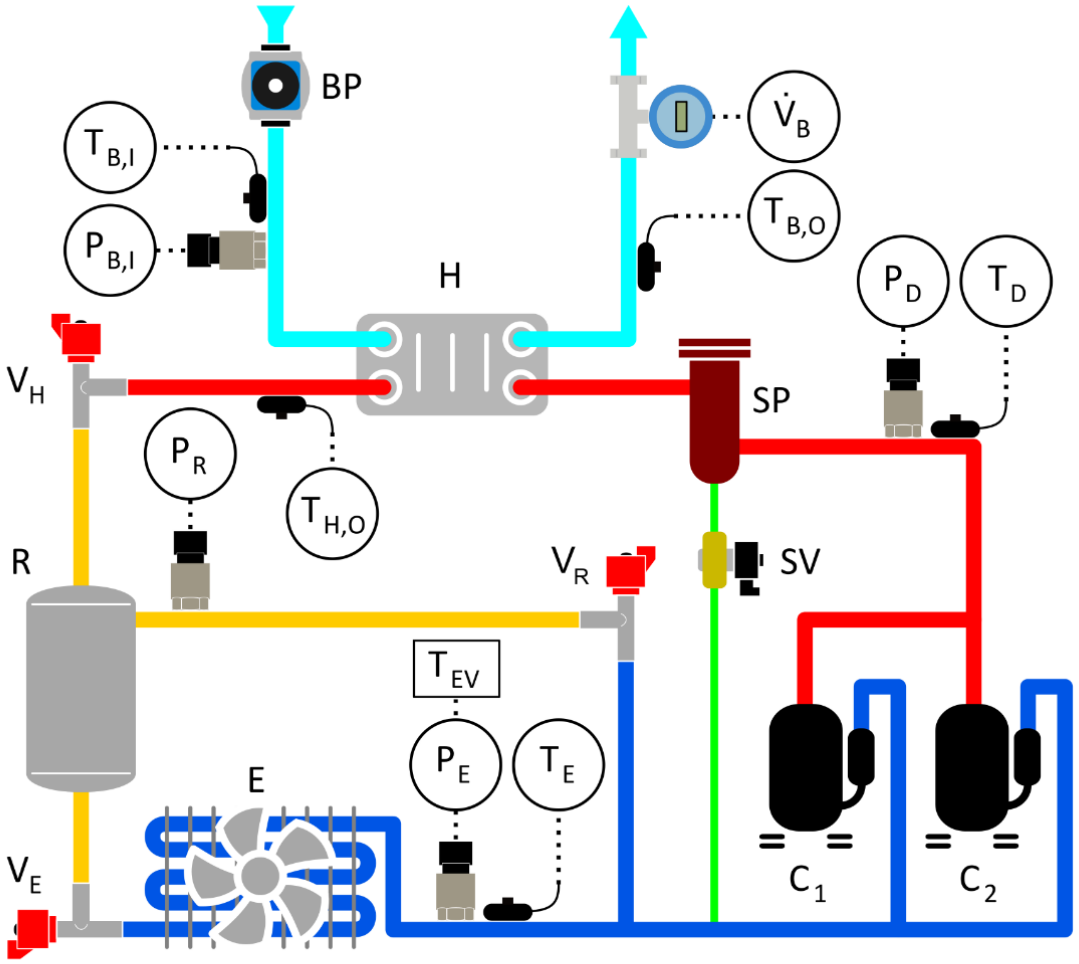


Test Rig Description

Transcritical CO_2 heat pump schematic.

B: brine, **BP**: variable-speed brine pump,
C: rotary compressor, **D**: discharge, **E**: finned-coil evaporator, **EV**: evaporation, **H**: heat rejection heat exchanger, **I**: inlet, **O**: outlet, **P**: pressure,
R: receiver, **SP**: oil separator, **SV**: solenoid valve,
T: temperature, **V**: modulating valve,
$\dot{V}$: volumetric flow rate.



Experimental Tests

The developed algorithm aims to match the two fluid streams through online thermodynamic calculation and simplified modeling of the heat rejection phenomena. To do so, the measurements on both the heat rejection side (P_D, T_D and $T_{H,O}$) and brine side ($T_{B,I}$ and $T_{B,O}$) are used as inputs of an Artificial Neural Network (ANN) architecture.

Focus of the present work is dedicated to CO_2 side in terms of heat rejection pressure regulation.
The target of the proposed algorithm is then to search for the optimal P_D that maximizes the unit COP, adapting to the imposed brine side conditions.

Experimental Tests

$$\text{COP calculation} = \frac{Q_B}{PWR_C} = \frac{\dot{V}_B \, \rho_B \, c_{P,B} \, (T_{B,O} - T_{B,I})}{PWR_{C_1} + PWR_{C_2}}$$

Test Condition

Condition	$T_{B,I}$ [°C]	$T_{B,O}$ [°C]	T_{EV} [°C]
a	15	55 / 65 / 70	-5
b	10	55 / 65 / 70	-5
c	15	55 / 65 / *	-8

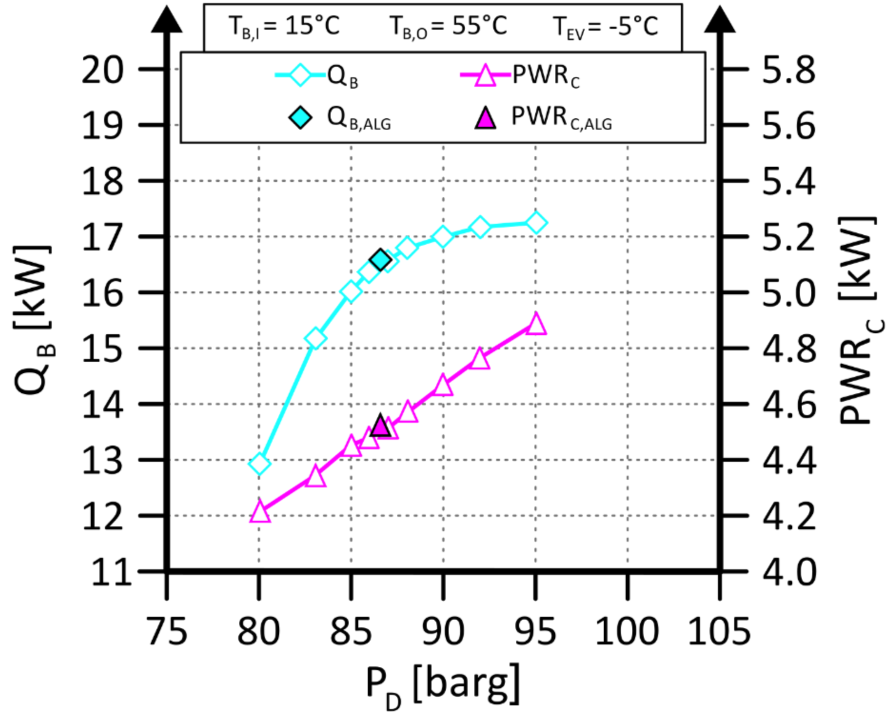
* $T_{B,O}$ =70°C not investigated due to system technical limitations.

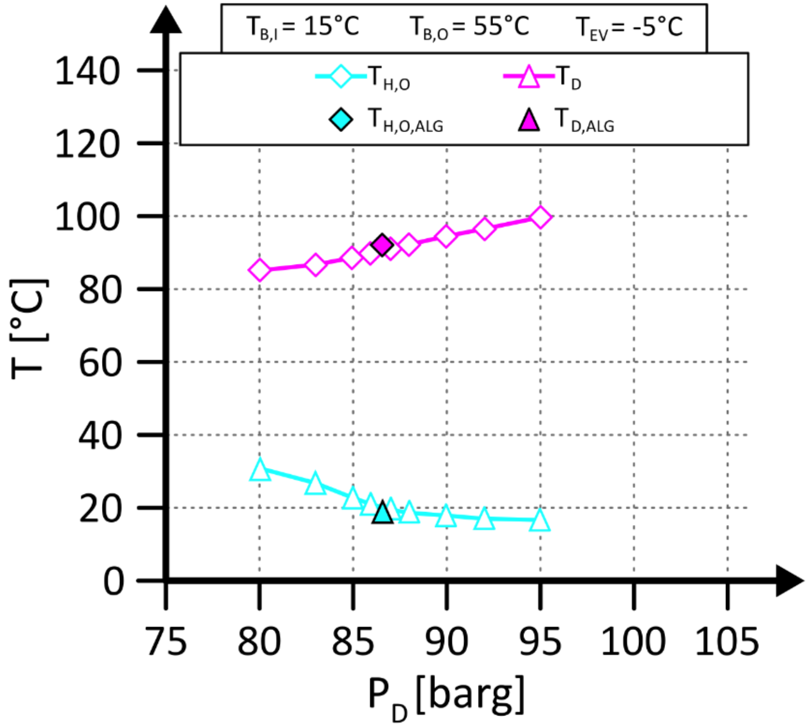
Indexes for evaluation

$$dev_P = P_{D,OPT} - P_{D,ALG} \quad [\text{bar}]$$

$$dev_{COP} = \frac{COP_{OPT} - COP_{ALG}}{COP_{OPT}} \cdot 100 \quad [\%]$$

Results



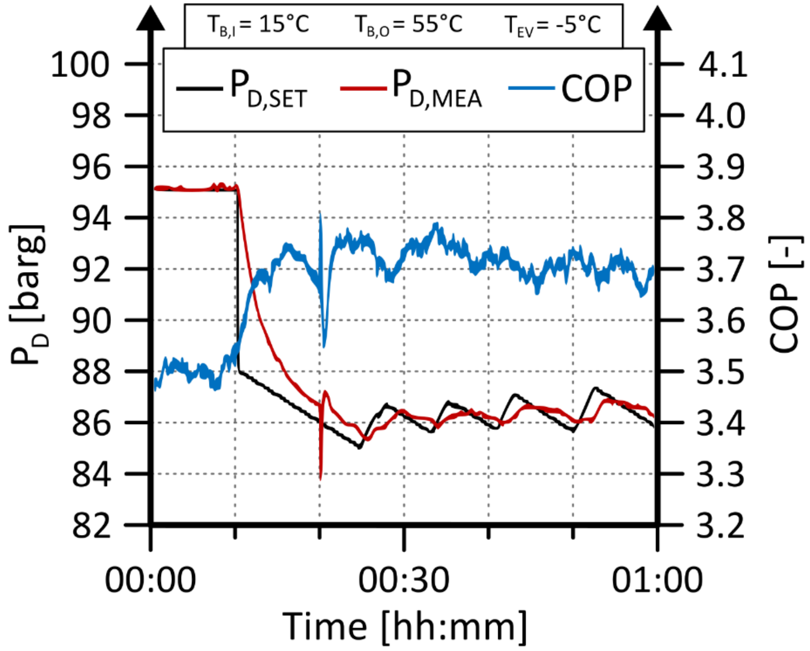


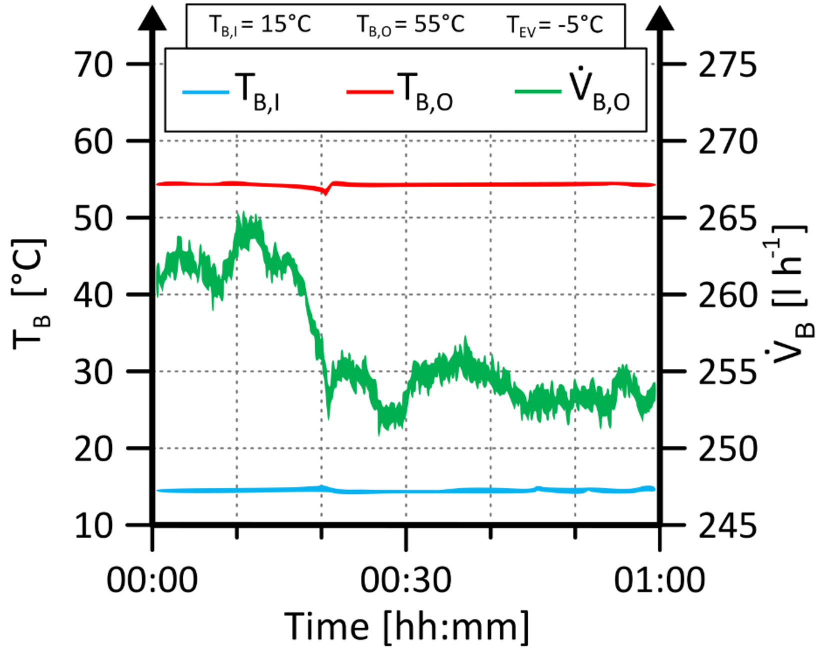
Experimental curves

Algorithm is capable to identifying a point for slope changing

Optimal point for heat rejection phenomenon

Results



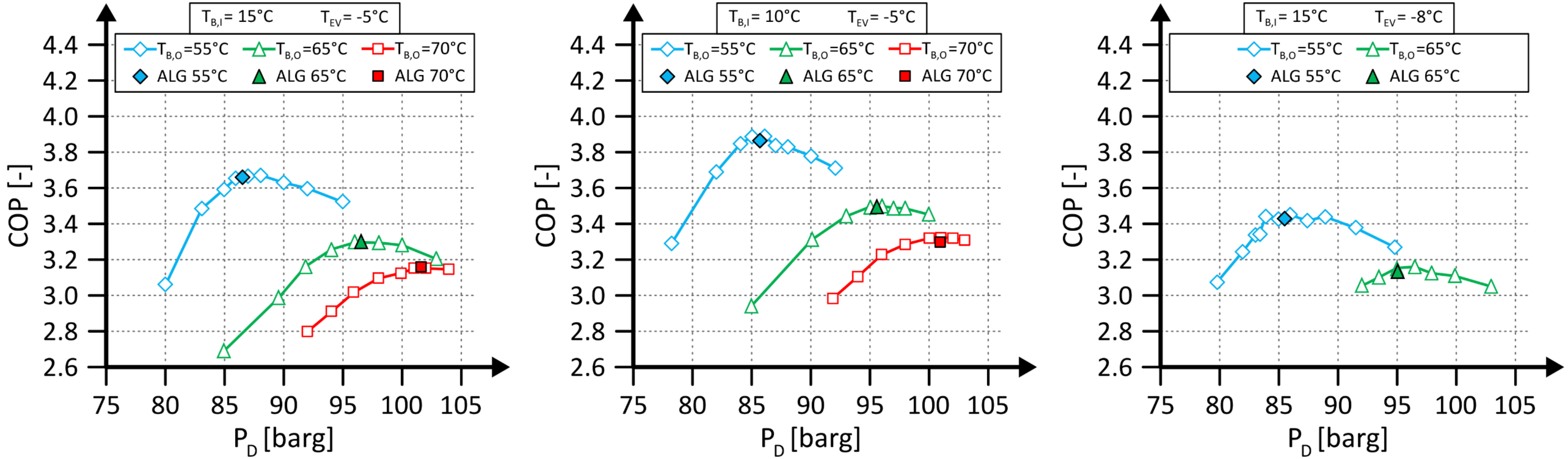


Experimental curves

Behavior of algorithm during a convergence test. Also destabilizations due to internal unit functions (oil refill) don't influence results

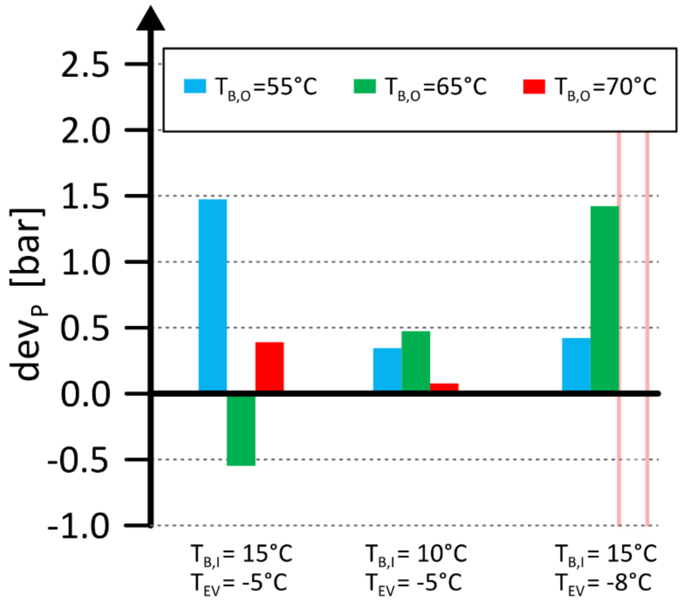
Bypass harsh disturbances and instabilities

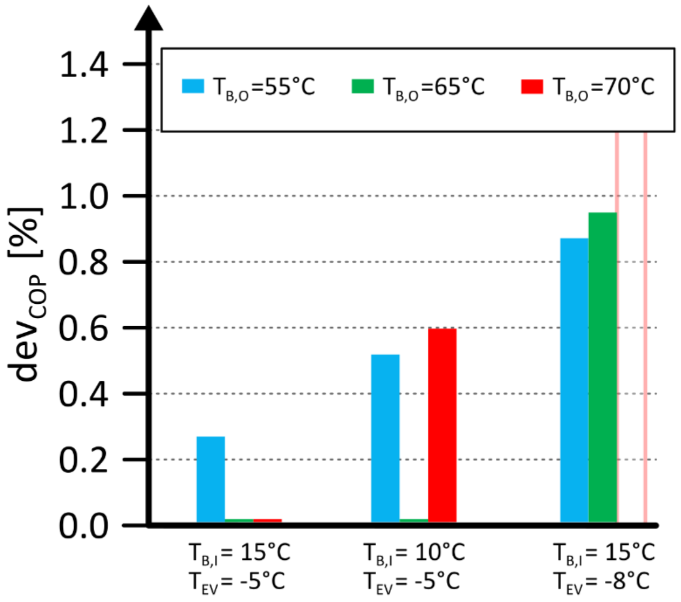
Results



T_B,I = 15°C T_EV = -5°C
T_B,O=55°C T_B,O=65°C T_B,O=70°C
ALG 55°C ALG 65°C ALG 70°C
COP [-]
4.4 4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6
75 80 85 90 95 100 105
P_D [barg]
T_B,I = 10°C T_EV = -5°C
T_B,O=55°C T_B,O=65°C T_B,O=70°C
ALG 55°C ALG 65°C ALG 70°C
COP [-]
P_D [barg]
T_B,I = 15°C T_EV = -8°C
T_B,O=55°C T_B,O=65°C
ALG 55°C ALG 65°C
COP [-]
P_D [barg]

Results





Experimental results

Evaluation of convergences results.

Values of $T_{B,O}$ and $T_{B,I}$ improve significantly COP and influence the optimal sets value.

Optimal sets are not significantly influenced by COP or T_{EV} .

Results

- The values of dev_P are influenced by the arbitrary choice of the pressure values P_D selected to build up the experimental curves

- The condition that mostly influences the optimal pressure $P_{D,OPT}$ is the $T_{B,O}$

- The variations of $T_{B,I}$ and T_{EV}, have a significant effect in the values of the COP but not a great influence on the optimal pressure determination.

Conclusions

- An auto adaptive algorithm for optimal transcritical heat rejection pressure determination has been developed and experimentally investigated on a CO_2 air/water heat pump unit for a DHW application.

- The Artificial Neural Network (ANN) architecture used by the algorithm allows local thermodynamic calculations in order to match the refrigerant and secondary fluid streams so to reach the highest unit Coefficient Of Performance (COP).

- The optimal pressure depends on the coupling of CO_2 and water streams capacities.

- The algorithm showed uniform convergence behavior and robustness against noises and disturbances.

Next steps

- Response timings of tests are related to PIDs calibration, which will be considered in future developments for further optimizations.

- A great advantage of such algorithm is the possibility of its inclusion inside an industrial controller with standard computational performances.

- Future works are focused on testing the ability of the algorithm to adapt on different system features such as (but not limited to): fixed-speed water pump with modulating compressors, extended temperature range on water and evaporation sides, heat recovery integrated design, secondary circuit layout coupling.

Thanks for your attention