Heat Pump Systems

Summary W12

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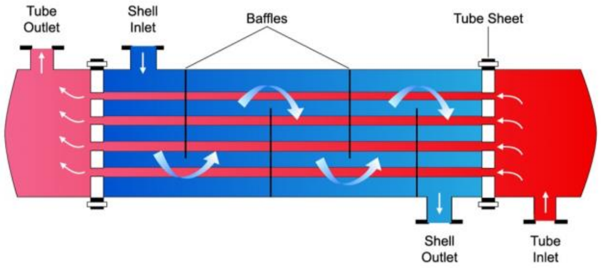
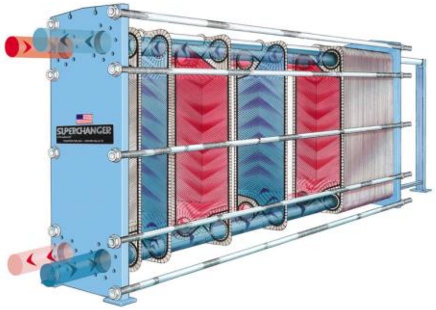
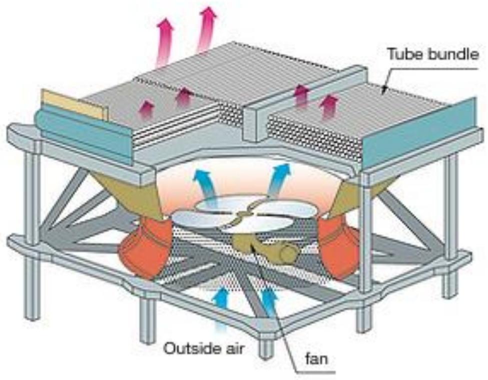
Heat Exchanger Function

- Heat exchangers transfer heat from hot fluid to cold fluid
  - Temperature difference between hot and cold composite should be as low as possible
  - Pressure drops should be as low as possible
  - Heat exchanger area should be as small as possible to reduce cost
- Different types depending on fluids and capacity

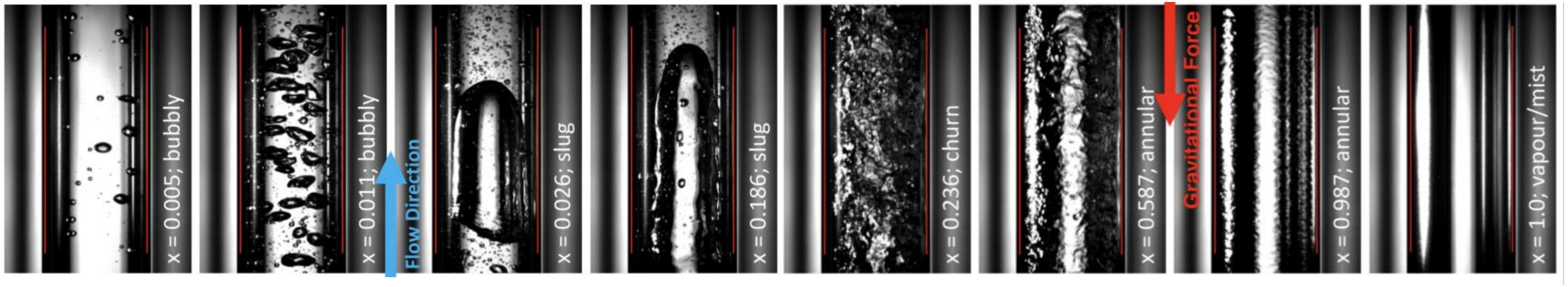






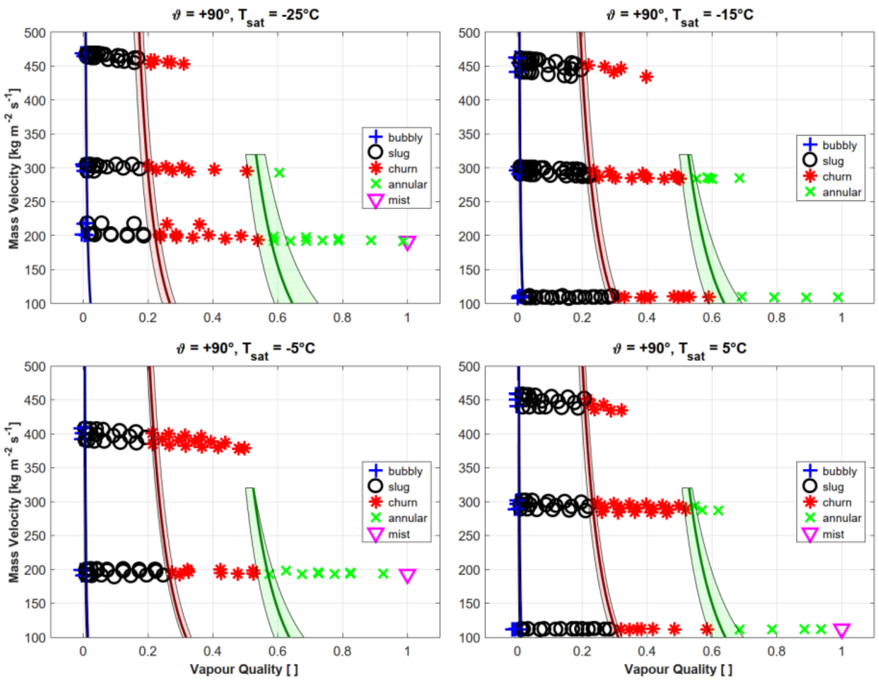
Heat Exchanger Function

- Heat transfer occurs primarily through convection from fluid to wall and through conduction across wall
- Convection is usually limiting factor → challenging to model, particularly for two-phase flows
- Convective heat transfer strongly dependent on flow patterns



D. Schmid, B. Verlaart, P. Petagna, R. Revellin, J. Schiffmann. **Flow Pattern Observations and flow pattern map for adiabatic two-phase flow of carbon-dioxide in vertical upward and downward direction**. Experimental Thermal and Fluid Sciences, vol. 131, 110526, 2022.

Flow Pattern Maps

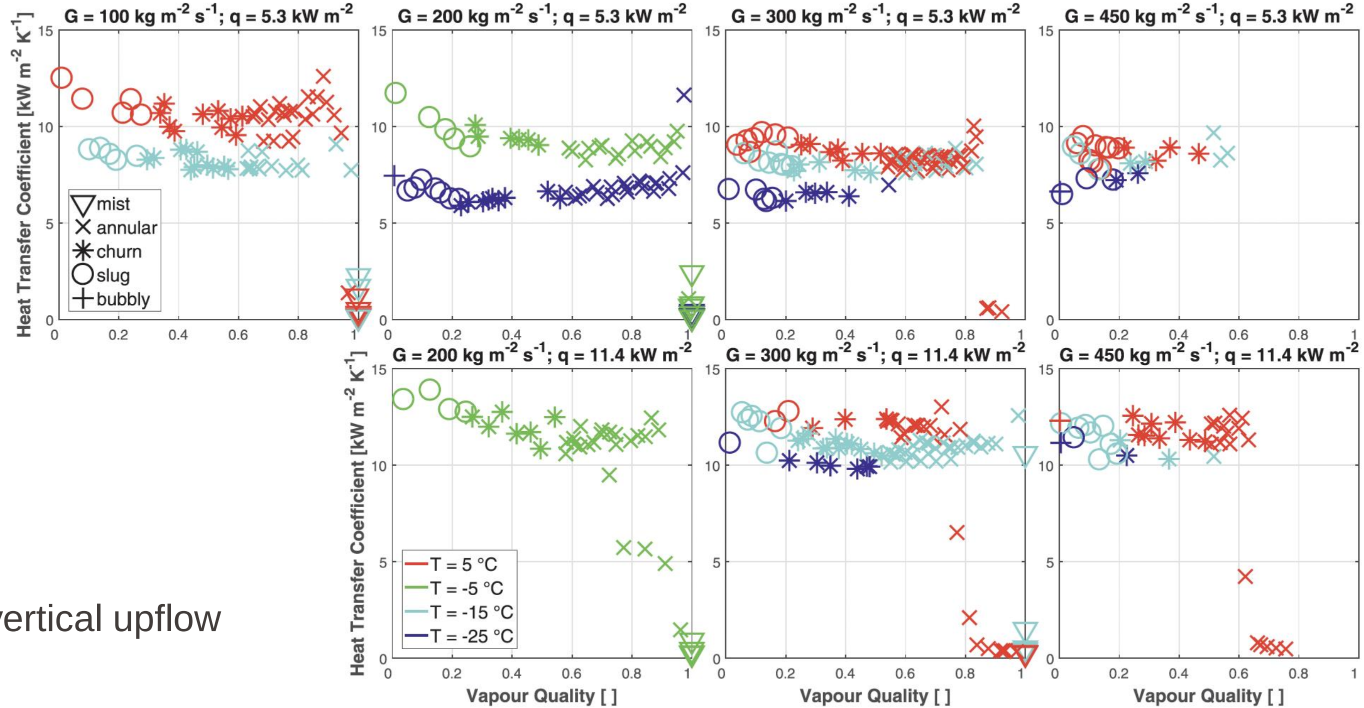


CO_2, vertical upflow

- Flow patterns as a function of vapor quality, saturation temperature, and mass velocity

D. Schmid, B. Verlaart, P. Petagna, R. Revellin, J. Schiffmann. **Flow Pattern Observations and flow pattern map for adiabatic two-phase flow of carbon-dioxide in vertical upward and downward direction**. Experimental Thermal and Fluid Sciences, vol. 131, 110526, 2022.

Convection Coefficient Maps



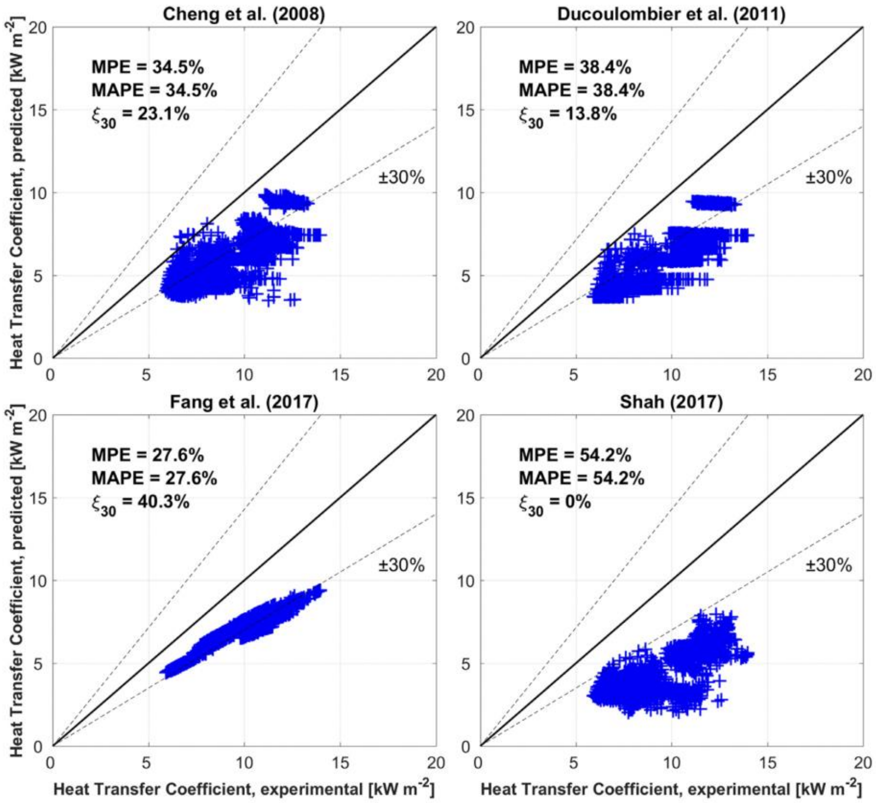
CO_2, vertical upflow

- Heat transfer coefficient as a function of vapor quality, saturation temperature, and mass velocity

D. Schmid, B. Verlaat, P. Petagna, R. Revellin, J. Schiffmann. **Heat transfer of flow boiling carbon dioxide in vertical upward direction.** International Journal of Heat and Mass Transfer, vol. 196, 123246, 2022.

Performance of Typical Correlations

- Available correlations usually not very accurate
- Heat transfer coefficient highly dependent on fluid, mass-flux, geometry



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Heat Pump Systems

Transcritical Heat Pumps & Ejectors

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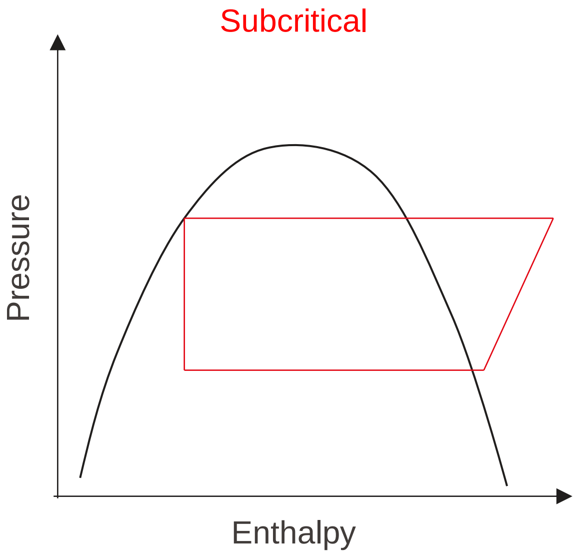
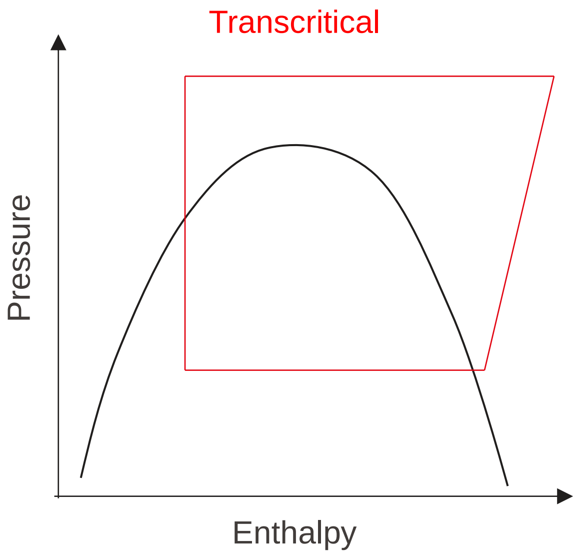
Transcritical Heat Pumps

- Transcritical operation means hot source is above and cold source below critical point
- Typical applications are heat pumps with CO_2 as working fluid





Transcritical CO_2 Heat Pumps

- CO_2 is interesting working fluid for heat pumps
  - Natural refrigerant, non-toxic, non-flammable, excellent thermal properties
  - High volumetric heat capacity → compact machines
  - High pressures (critical pressure 73.8 bar)

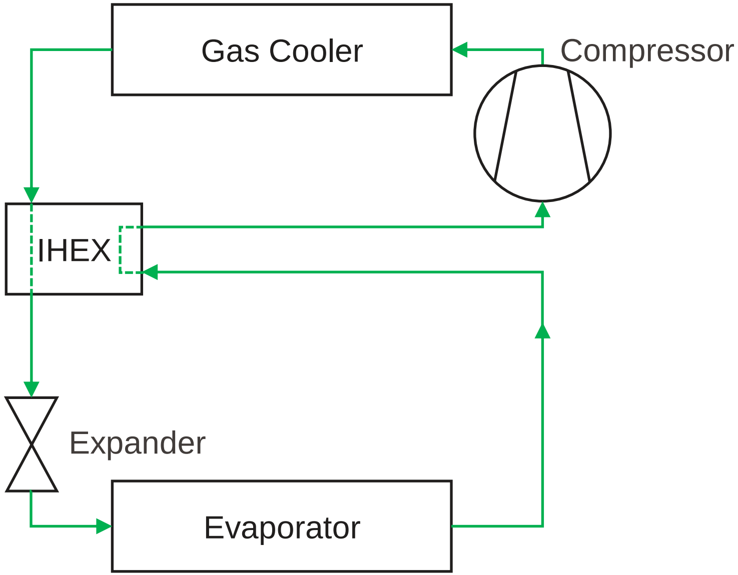
- Typical hot source temperatures lead to transcritical operation for CO_2
  - Heat rejection with large temperature glide
  - Suffer from high expansion losses

Transcritical CO_2 Heat Pumps

- Possible mitigation of high expansion losses
  - Internal heat exchanger → suction superheater cycle
  - Supercritical turbine expander
  - Ejector cycles

Transcritical CO_2 Heat Pumps

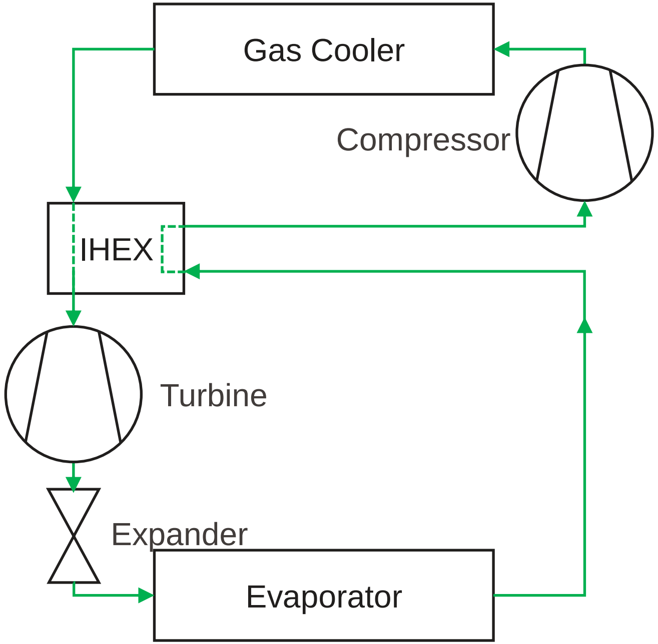
- Internal heat exchanger configuration (suction superheater cycle)
  - Improves COP and capacity by ~5-15%
  - Leads to higher compressor discharge temperatures (~10K)



E. Torrella, D. Sánchez, R. Llopis, R. Cabello, Energetic evaluation of an internal heat exchanger in a CO_2 transcritical refrigeration plant using experimental data, International Journal of Refrigeration, Volume 34, Issue 1, 2011, Pages 40-49.

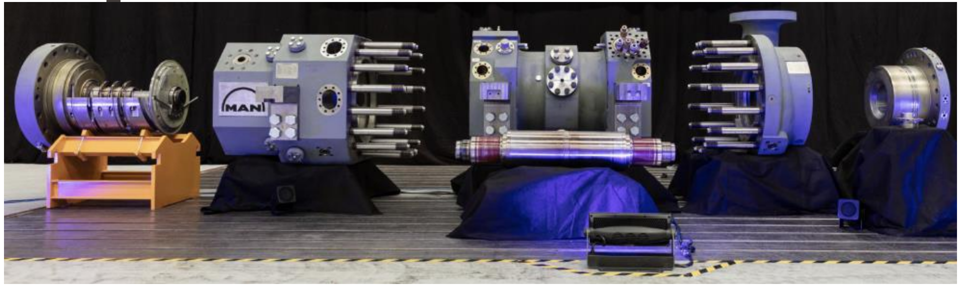
Transcritical CO_2 Heat Pumps

- Supercritical turbine expander
  - Turbine expander recovers work up to saturation line
  - Two-phase expansion continued in valve
  - Internal heat exchanger improves COP
  - Supercritical turboexpander improves COP by 20-30%

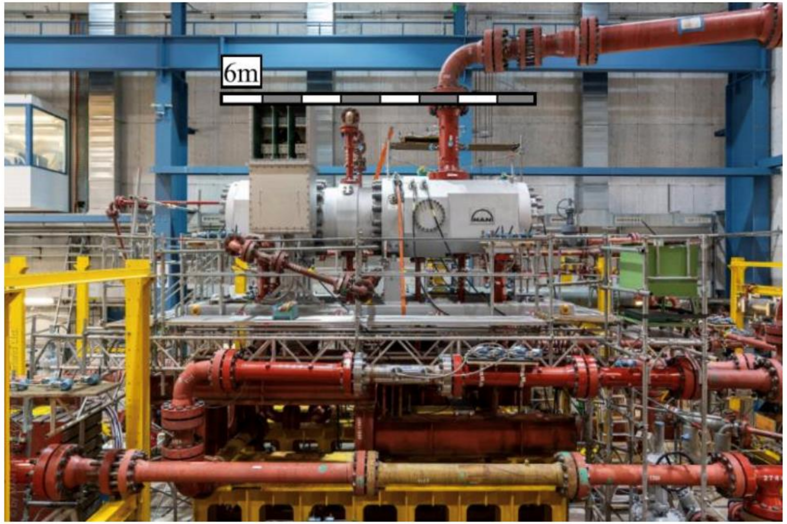


Gabrielli, P., Sansavini, G., Singh, S., Garcia, L. S., Jacquemoud, E., and Jenny, P.. "Off-Design Modeling and Operational Optimization of Trans-Critical Carbon Dioxide Heat Pumps." *J. Eng. Gas Turbines Power*. October 2022; 144(10): 101004

Transcritical CO_2 Heat Pumps



- Supercritical turbine expander
  - For a district heating heat pump with a heating power of 35MW
  - Turbine on same rotor as compressor
  - Hermetic design → no leakage
  - Supported on magnetic bearings
  - Oilfree solution

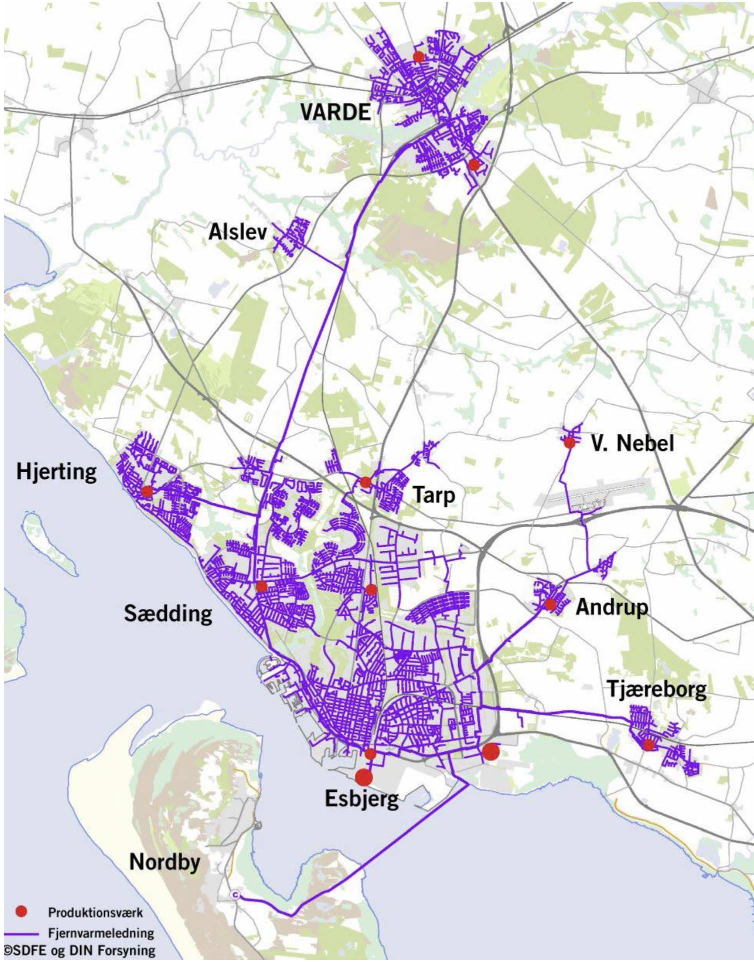


Parameter	Unit	Max. Value
Motor Active Power	MW_{el}	10.5
Heating Duty	MW_{th}	35
Cooling Duty	MW_{th}	25
CO_2 Pressure	bar	140
CO_2 Temperature	°C	130
Min. CO_2 Evaporation Temperature	°C	-2

Wolscht, L., Knobloch, K., Jacquemoud, E., & Jenny, P. (2023). Dynamic Simulation and Experimental Validation of a 35 MW Heat Pump Based on a Transcritical CO2 Cycle. In Proceedings of the 5th European sCO2 Conference (pp. 93-105). EWL, University Duisburg-Essen.

Transcritical CO_2 Heat Pumps

- Climate-neutral district heating for 100‘000 inhabitants in Esbjerg (DK)
  - 280‘000 MWh/y CO2-neutral district heating → sufficient for 25.000 households
  - 100‘000 t CO2 savings per year → emission of approx. 55.000 cars
  - 60 MWth power → 50m swimming pool to boil in <4h
  - 4000 Liter/s sea water demand → 15 bathtubs per second



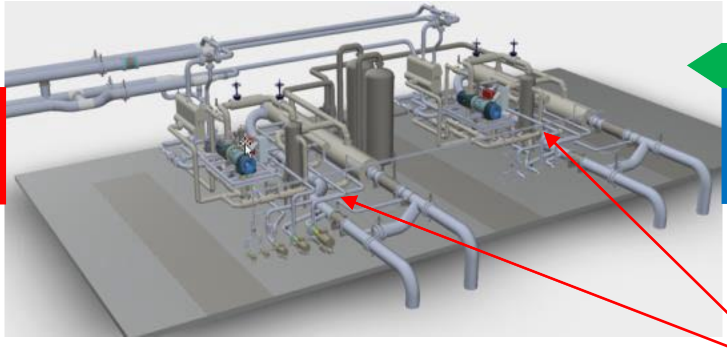
Transcritical CO_2 Heat Pumps

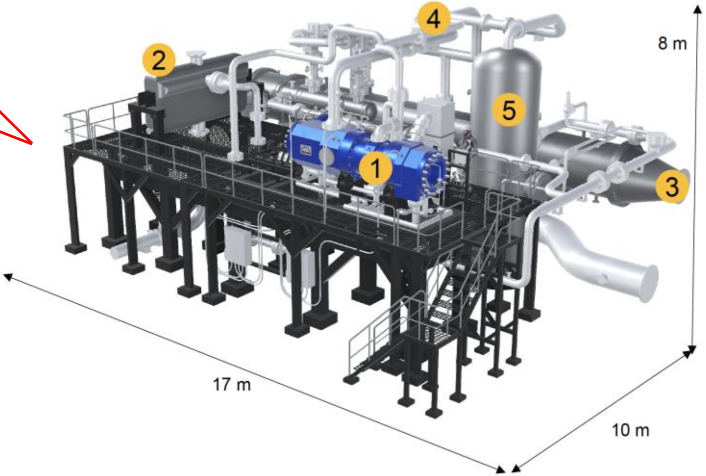
- Two units provide CO_2 free $60MW_{th}$

Green energy

Seawater source 1-20°C

District heat $60MW_{th}$ 60-90°C



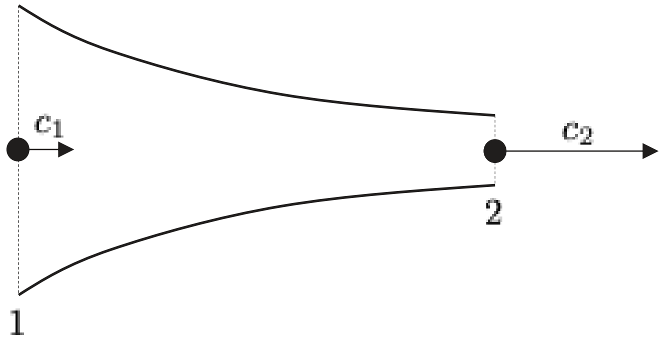


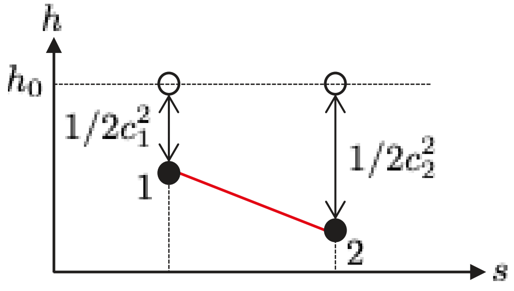
Transcritical CO_2 Heat Pumps

- Mitigation of high expansion losses
  - Internal heat exchanger
  - Supercritical turbine expander
  - Ejector

What is an Ejector?

- Static pressure in channel drops with flow velocity

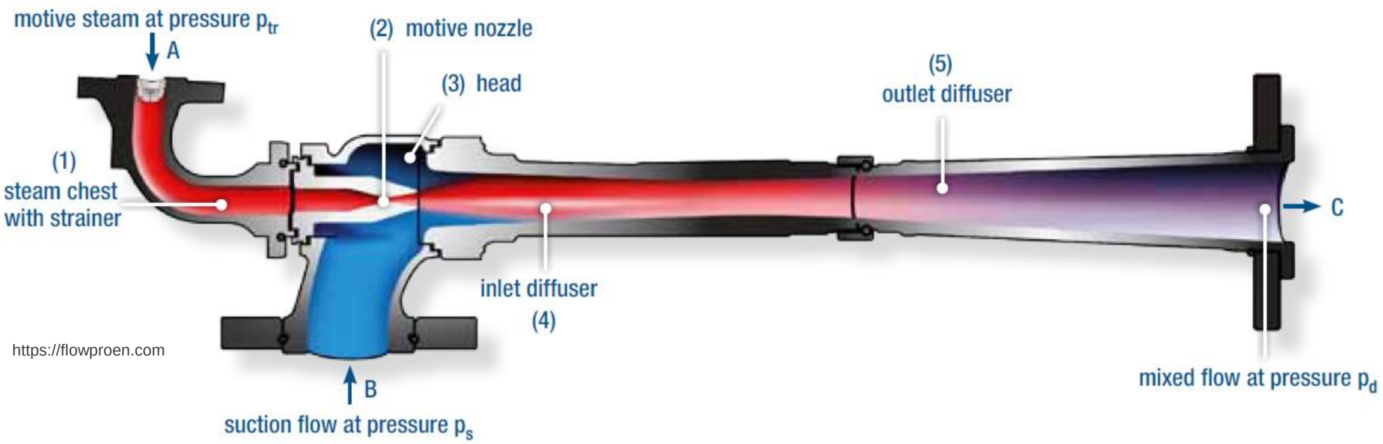




- Effect can be used to reduce pressure and/or accelerate gas
- High momentum flow at nozzle discharge can be used to accelerate other fluid at rest

What is an Ejector?

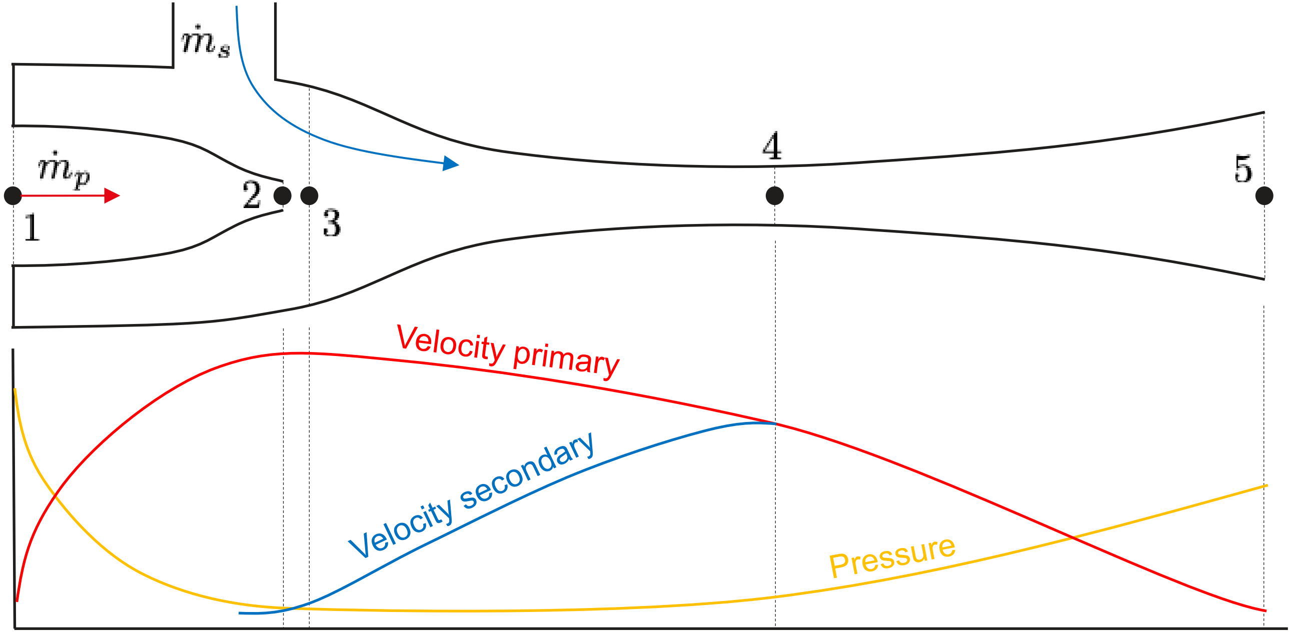
- Primary flow (motive fluid) accelerated in nozzle
- Reduced pressure used as suction for secondary gas
- High momentum of primary flow accelerates secondary flow
- Pressure recovered in diffuser



https://flowproen.com

Working Principle

- Ejectors can be used to increase pressure of secondary flow

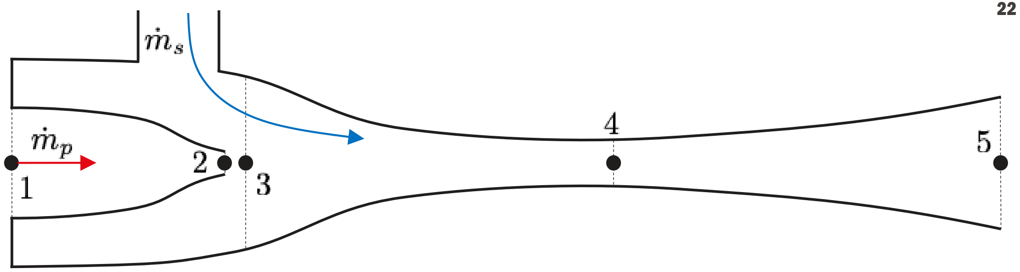


Ejector in Heat Pumps

- Ejectors offer interesting features for heat pumps
  - Simple device → cheap
  - No moving parts
  - May be noisy

- Applications
  - Thermally driven heat pumps for cooling duty
  - Pre-compression in vapor compression cycles

Working Principle



- Mass balance

$$\dot{m}_p + \dot{m}_s = \dot{m}_3 = \dot{m}_4 = \dot{m}_5$$

- Energy balance

$$\dot{m}_p h_{0p} + \dot{m}_s h_{0s} = (\dot{m}_p + \dot{m}_s)\, h_{05}$$

$$h_0 = h + c^2/2$$

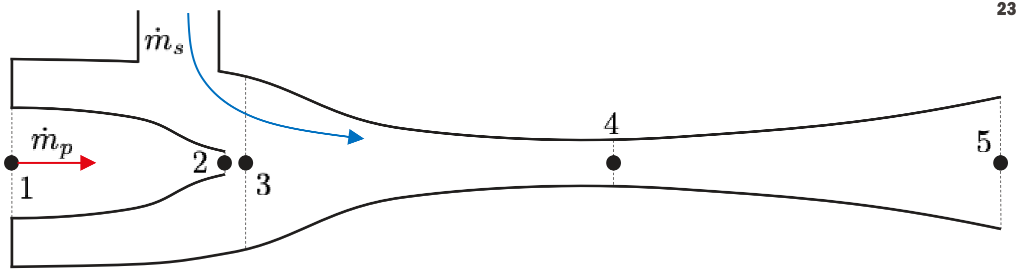
- Conservation of momentum

$$\dot{m}_p c_2 + \dot{m}_s c_3 = (\dot{m}_p + \dot{m}_s)\, c_4$$

$$\dot{m}_p c_2 = (\dot{m}_p + \dot{m}_s)\, c_4$$

$$\Rightarrow \quad \frac{\dot{m}_s}{\dot{m}_p} = \frac{c_2}{c_4} - 1$$

Working Principle



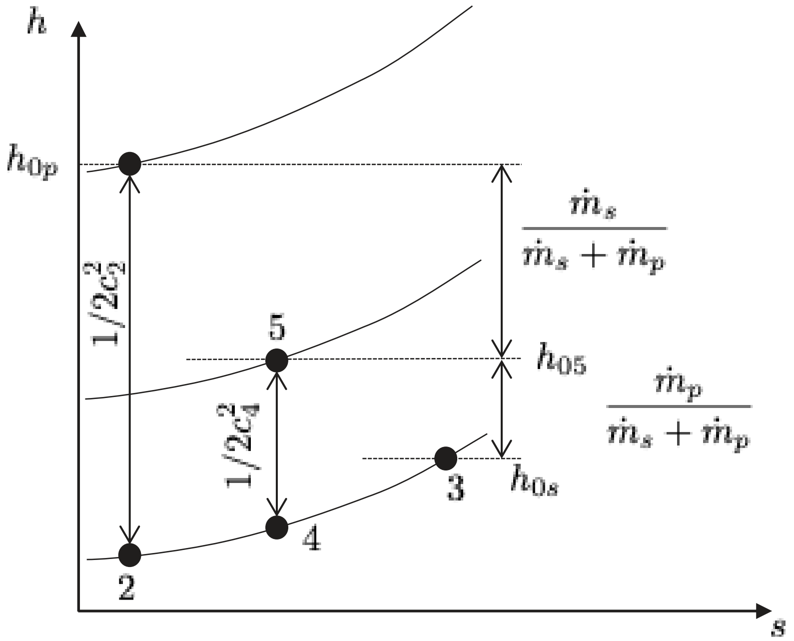
- In hs-diagram
  - Energy balance defines outlet enthalpy

$$\frac{\dot{m}_p h_{0p} + \dot{m}_s h_{0s}}{\dot{m}_p + \dot{m}_s} = h_{05}$$

  - Momentum equation defines outlet pressure

$$\frac{\dot{m}_s}{\dot{m}_p} = \alpha_e \frac{c_2}{c_4} - 1$$

  - Assumes acceleration and diffusion occur isentropically ($\alpha_e = 1$)

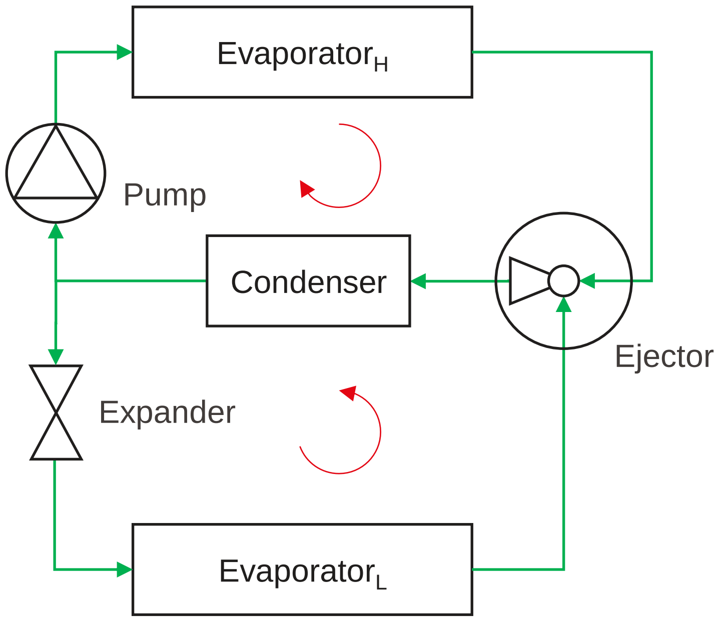


Aplications of Ejectors

- Thermally Driven Refrigeration Heat Pump
- Driven by compressor discharge to pre-compress
- Pre-compression through expansion (booster)

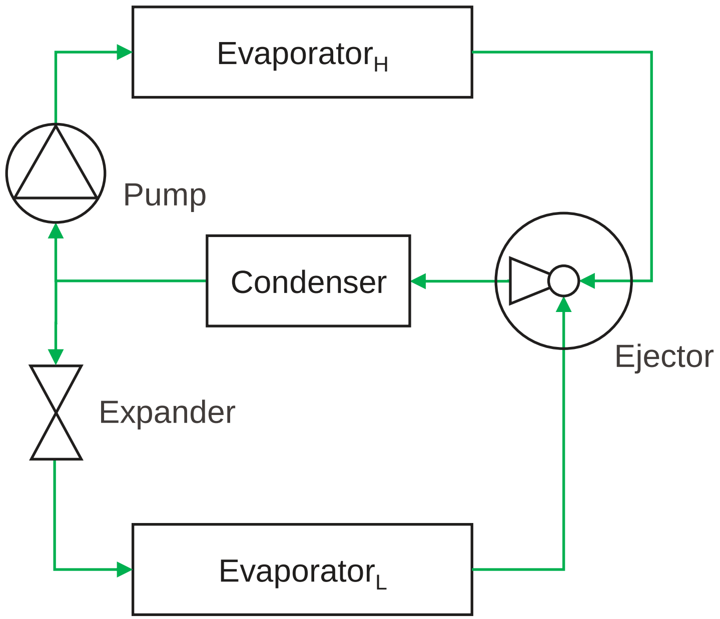
Thermally Driven Refrigeration Heat Pump

- Requires a “driving cycle” to provide pressurized primary flow
- Cycle absorbs heat at high temperature
- Primary fluid used to compress secondary fluid in ejector



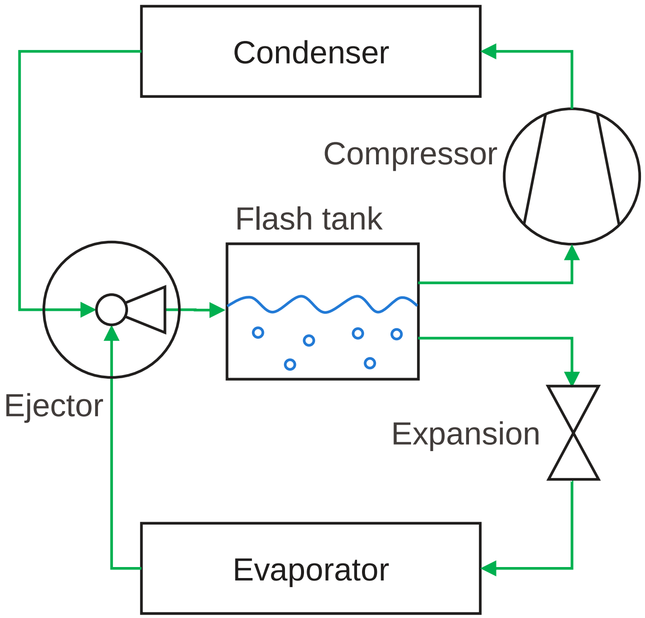
Thermally Driven Refrigeration Heat Pump

- Typical temperatures: T_H = 80°C, T_L = 5°C, T_{Cond} = 30°C
- COP_C = 0.13 – 0.5



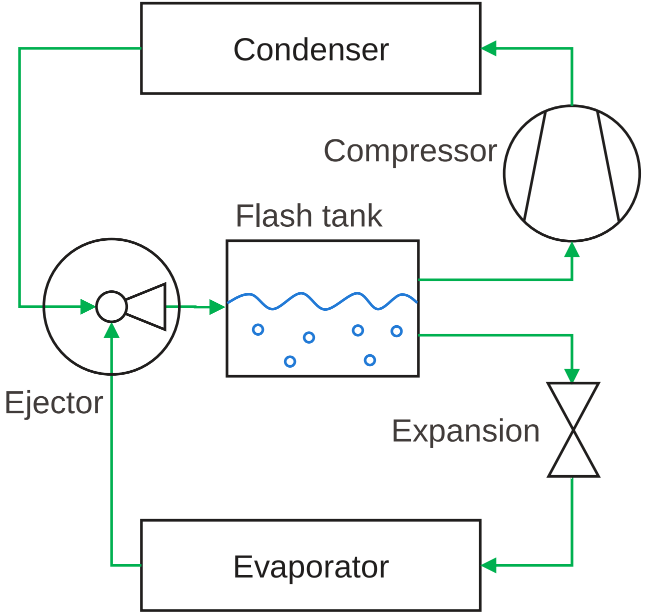
Pre-Compression Through Expansion

- Ejector driven by expansion process to pre-compress fluid
- Pre-compression reduces compressor work
- Interesting for cycles operated close or above critical point to reduce expansion losses
- Improvement of COP up to 10-20%
- Poor off-design performance



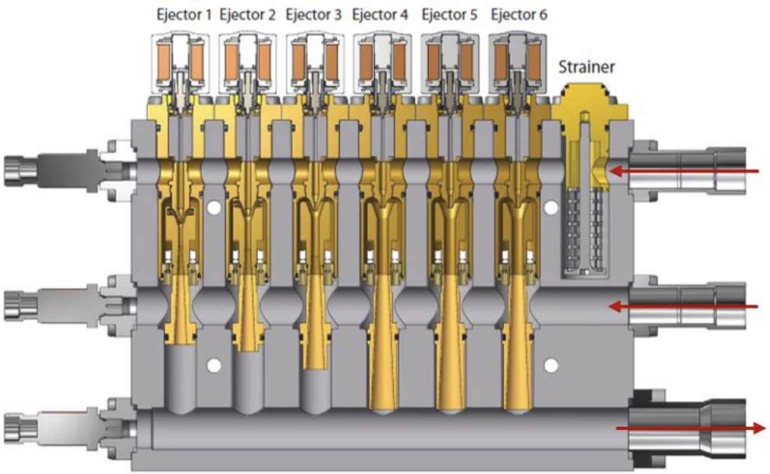
Pre-Compression Through Expansion

- In Ph-diagram



Pre-Compression Through Expander

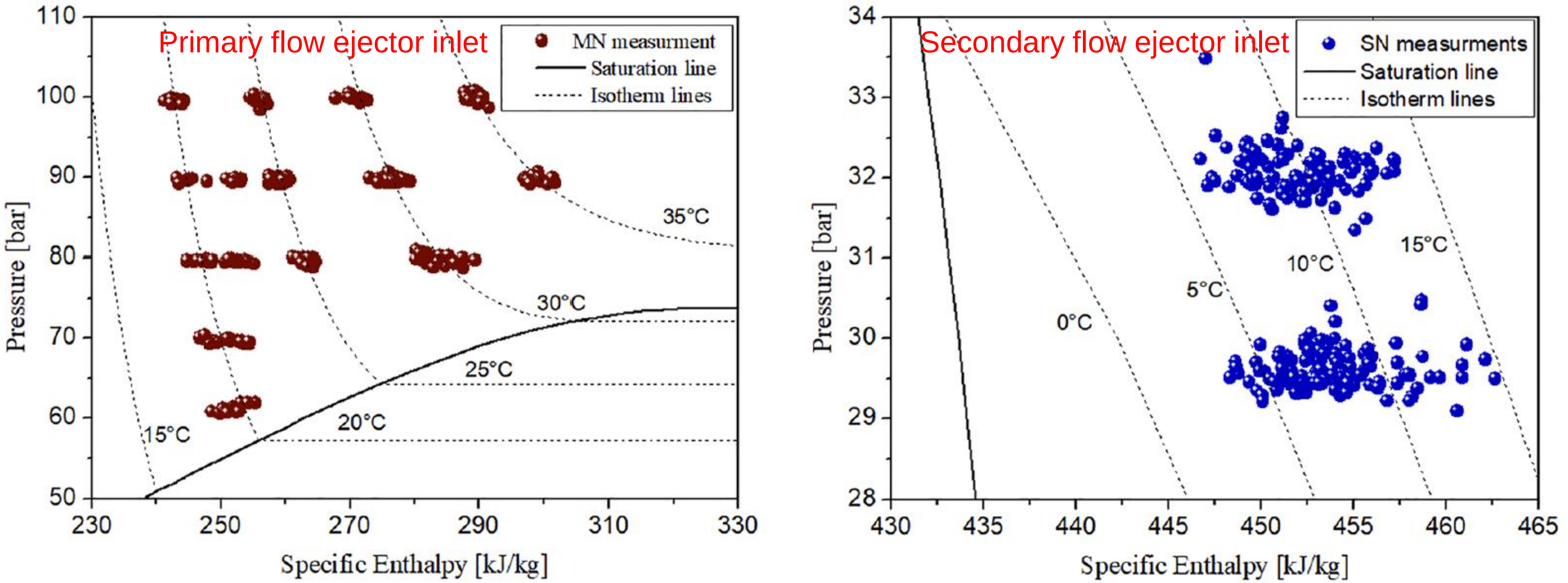
- Poor off-design performance → multi-ejector-packs
- Each ejector turned on/off depending on required mass flows



https://assets.danfoss.com/documents/latest/397042/AI311723869490en-000202.pdf

Experimental Data on Multi-Ejector-Pack in Transcritical CO_2 Heat Pump

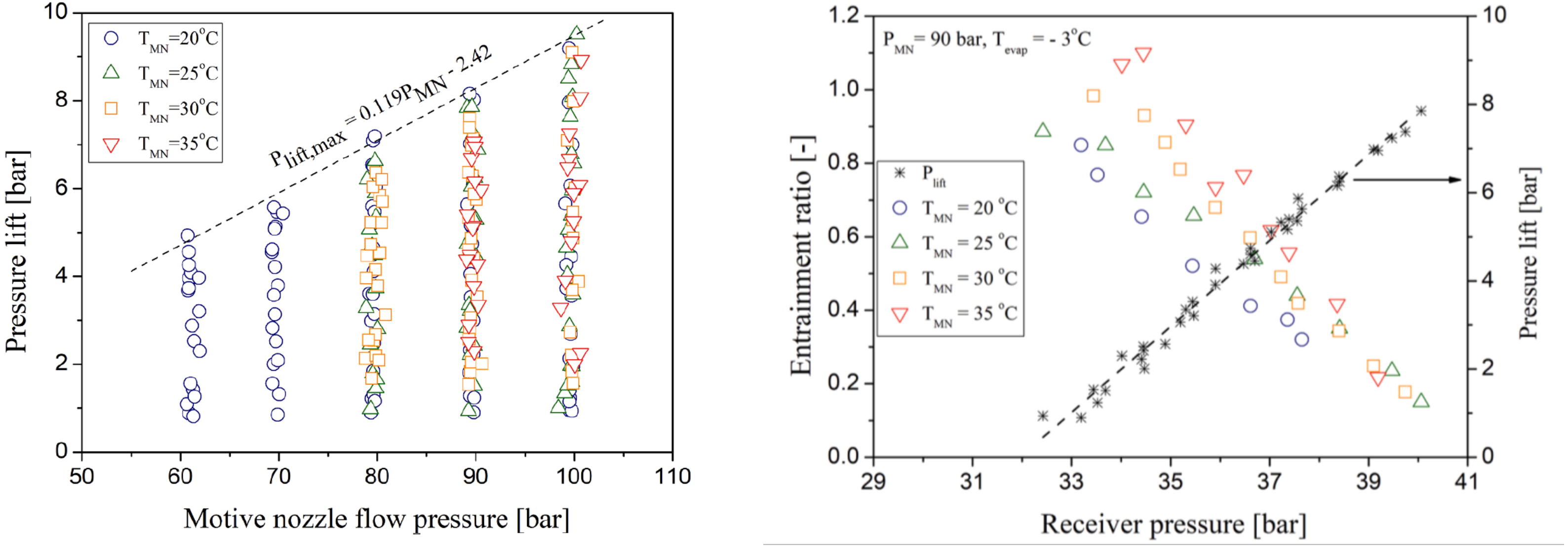
- Ejector data points



A. Elbarghthi, A. Hafner, K. Banasiak, V. Dvorak, An experimental study of an ejector-boosted transcritical R744 refrigeration system including an exergy analysis, Energy Conversion and Management, Volume 238, 2021, 114102.

Experimental Data on Multi-Ejector-Pack in Transcritical CO_2 Heat Pump

- Measured ejector performance
  - Maximum pressure rise 9.51 bar → low entrainment ratio
  - Ejector recovers up to 37% of expansion losses



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Transcritical CO_2 Heat Pump Cycles

- Transcritical heat pump cycles interesting if hot source requires large temperature rise
- CO_2 is interesting fluid (natural) but leads to high pressures
- Transcritical cycles suffer from high expansion losses → mitigation
  - Internal heat exchanger
  - Supercritical turbine expander
  - Ejector cycles

Exercices

- Theory questions
- Ejector cycle heat pump

EPFL

Heat Pump Systems

Exam

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Organization

- Date: 23.06.2023, 15.15 – 18.15h
- Place: BS 260, BS270, attributed seats

- Allowed support
  - Non-annotated cheat sheet provided on Moodle
  - Calculator

- Not allowed
  - Slides, exercises, corrections, books
  - Computer, pads, cell phone
  - Any other communication system

Exam

- Exam covers all topics seen in course
- Composed of theoretical (MCQ) and numerical problems to solve
- Preparation
  - Study course and summaries
  - Understand exercises and corrections