Heat Pump Systems

Summary W3

Prof. J. Schiffmann

École
polytechnique
fédérale
de Lausanne

Entropy Definition

- New state variable entropy (S) defined through Clausius

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\bigg|_{rev} \Rightarrow dS = \frac{\delta Q}{T}\bigg|_{rev} \Rightarrow TdS = \delta Q|_{rev}$$

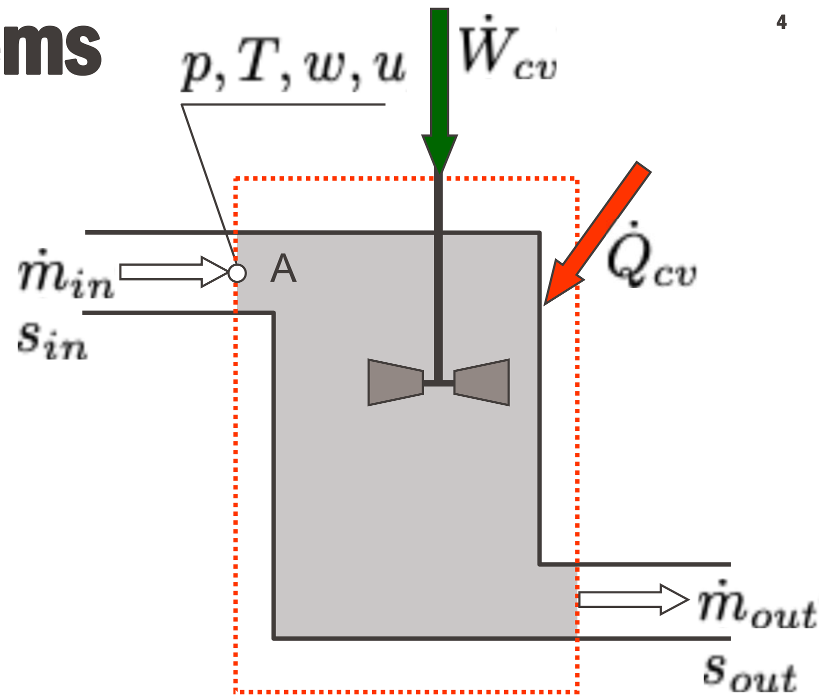
- Entropy is a state property → Knowledge of two other state properties defines also entropy of state

Entropy Change

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + \sigma$$

- Entropy change between two states results from
  - Entropy transfer due to heat transfer → dependent on process and independent from work
  - Entropy production through irreversibility → dependent on process, always > 0 due to 2nd law!

Entropy Balance in Open Systems



- Entropy can also be convected across system through mass fluxes

- Entropy balance for open system

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_{in} \dot{m}s|_{in} - \sum_{out} \dot{m}s|_{out} + \dot{\sigma}_{cv}$$

Comments

- 1st law
  - No energy produced only transformed
  - Equivalence of work and heat

- 2nd law
  - No conservation of entropy, entropy can be produced
  - Entropy transfer associated with heat transfer → can be positive or negative
  - In open systems entropy is convected across system boundary through mass fluxes
  - Irreversibility produces entropy
  - Entropy production (irreversibility) corresponds to lost work
  - Change of entropy in closed system is result of heat transfer and dissipation

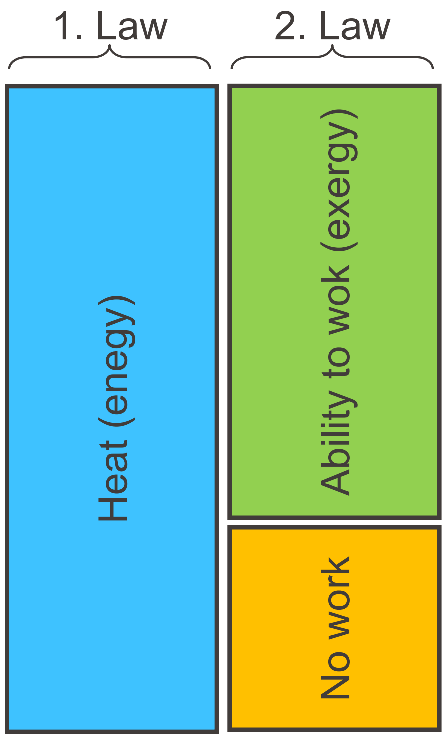
Quality of Energy

- Second law gives indication regarding quality of energy

- Heat delivered at certain temperature can only partially be transformed into work

$$\eta_c = 1 - \frac{Q^-_{cold}}{Q^+_{hot}} = 1 - \frac{T_{cold}}{T_{hot}}$$

- Work has higher quality than heat, but 1st law does not differentiate



Concept of Exergy

- Idea is to indicate maximum work of a system relative to ambient conditions (pressure P_0 & temperature T_0)
- All system that has a thermodynamic “tension” relative to ambient has ability to transform it into work via reversible process → exergy
- Exergy is a thermodynamic state variable
- Such approach ensures simultaneous satisfaction of 1st & 2nd law

Exergy Balance in Open Systems

- Transfer of exergy through convection across system boundary
- Definition of co-enthalpy in analogous way as for closed system and with definition of enthalpy

$$\frac{dEx_{cv}}{dt} = \underbrace{\sum_j \int \left(1 - \frac{T_0}{T_j}\right) \delta \dot{Q}}_{\text{Balance of heat exergy}} + \underbrace{\dot{W}_{cv} + p_0 \frac{dV_{cv}}{dt}}_{\text{Balance of work}} + \underbrace{\sum_i \dot{m}_i k_i - + \sum_o \dot{m}_o k_o}_{\text{Balance of co-ethalpy}} - \underbrace{T_0 \dot{\sigma}_{cv}}_{\text{Exergy losses } \dot{L}}$$

Conclusion

- Opposed to energy balance, exergy analysis combines 1st and 2nd law into a new thermodynamic state
- Exergy analysis automatically merges energy balance with feasibility limits imposed by 2nd law
- Energy efficiency does not consider quality of energy → may lead to spurious values
- Exergy efficiency suggested to be more sound approach to assess quality of thermodynamic system

?

Power Cycles and Heat Pumps

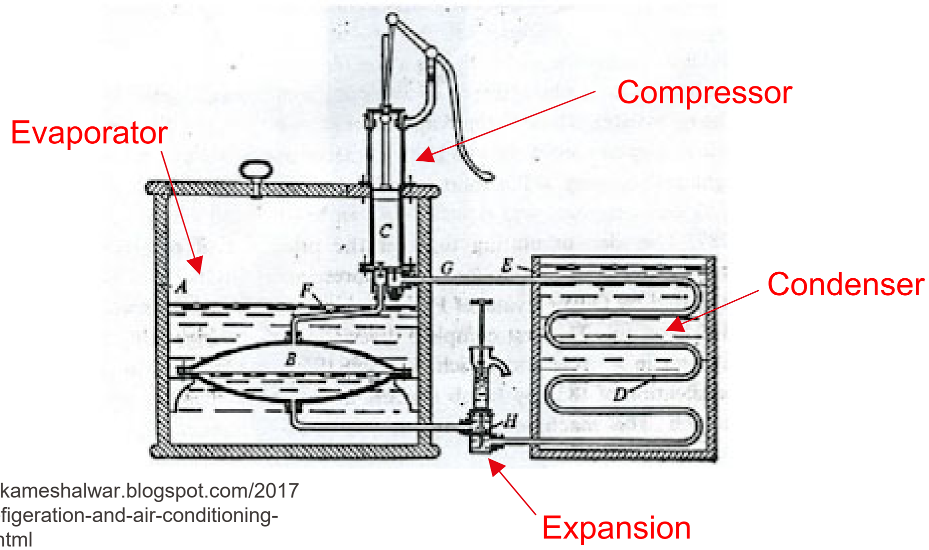
Introduction to Heat Pumps

Prof. J. Schiffmann

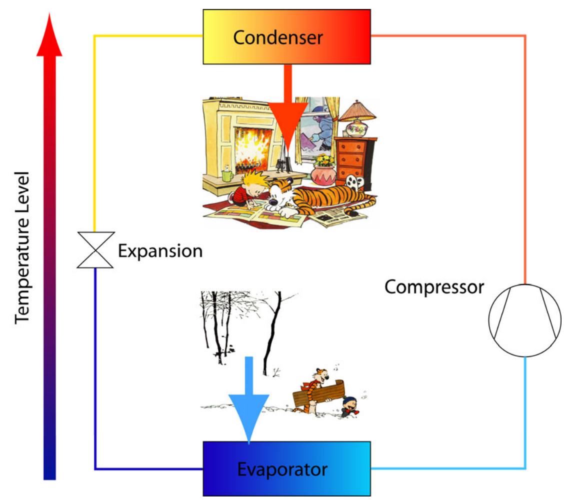
École polytechnique fédérale de Lausanne

What is a Heat Pump?

- Heat pump allows to gather heat at low temperature (cooling) and to reject it at higher temperature (heating)
- Can be used to provide cooling and/or heating
- Composed of compressor, condenser, expansion valve & evaporator



http://kameshalwar.blogspot.com/2017/03/refigeration-and-air-conditioning-brief.html



What is a Heat Pump Thermodynamically?

- Bithermal thermodynamic cycle working in anti-clockwise direction
- Work is invested to drive the cycle, which absorbs and supplies heat at different temperatures

Heating heat pump cycle

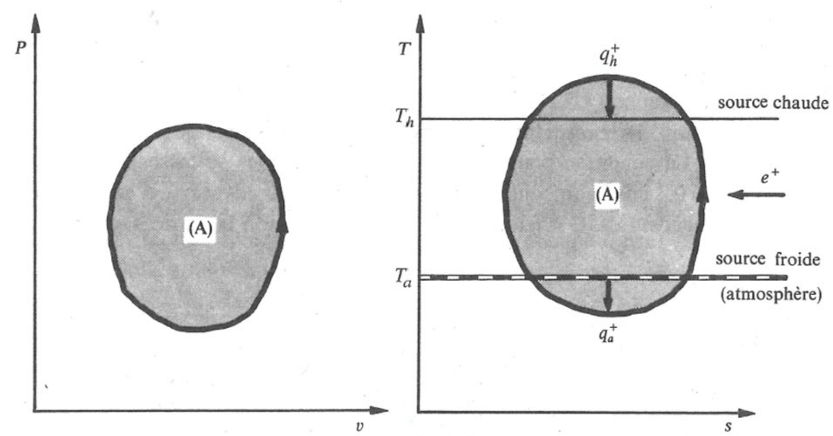


Fig 13.18 Favrat

Cooling heat pump cycle

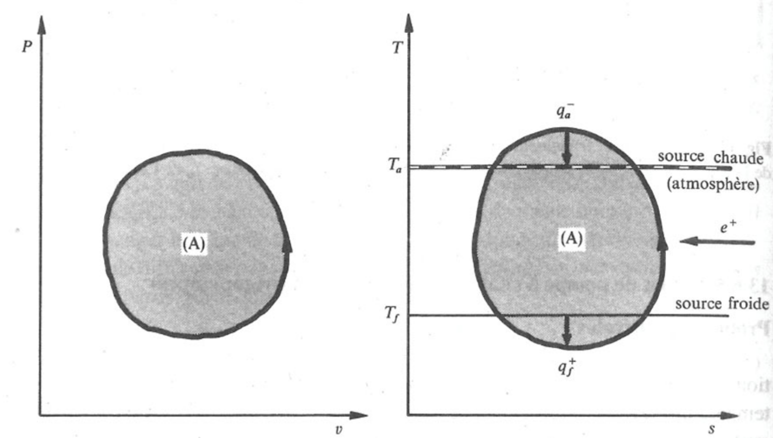


Fig 13.22 Favrat

Heating Heat Pump Energy Balance

- Heat q_h delivered at T_h is the main objective
- Circular integral in P-v or T-s increased by irreversibility corresponds to invested work or to heat balance
- Invested work corresponds to heat balance → 1st law

$$e^+ = q_h^- - q_a^+ = -\oint Pdv + r = -\oint Tds + r$$

$$q_h^- = e^+ + q_a^+$$

- Entropy balance on the heating cycle

$$\oint dS = \oint \frac{\delta Q_a^+}{T_a} + \oint \frac{\delta Q_h^+}{T_h} + \oint \delta S^i = 0$$

≥ 0 according to 2nd law

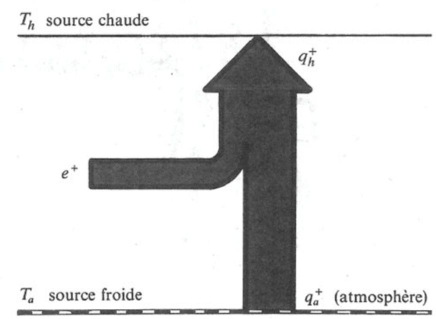


Fig. 13.19 Favrat

Ideal Heating Heat Pump Effectiveness

- With heat delivered at constant temperatures (T_a & T_h) for perfect cycle ($r = 0$) energy and entropy balance become:

$$e^+ = q_h^- - q_a^+$$

$$\underbrace{-\frac{q_a^+}{T_a}}_{\Delta s} + \underbrace{\frac{q_h^-}{T_h}}_{-\Delta s} = 0$$

- Using entropy balance and combining with energy balance, ideal performance metric can be expressed

$$\frac{q_h^-}{e^+} = \frac{1}{\underbrace{1 - \frac{T_a}{T_h}}_{1/\Theta_h}}$$

Exergy Approach

- Exergy balance over stationary system

$$\sum_k \left[\dot{E}_k^+\right] + \sum_i \left[\dot{E}_{qi}^+\right] + \sum_n \left[\dot{E}_{yn}^+\right] = \dot{L} \geq 0$$

- For heating heat pump cycles becomes

$$e^+ - q_h^- \underbrace{\left(1 - \frac{T_a}{T_h}\right)}_{\Theta_h} = l \qquad\qquad \eta = \frac{q_h^-}{e^+}\Theta_h$$

Exergy efficiency ≤ 1

Heating Heat Pump Effectiveness

- Heating effectiveness definition

$$\epsilon_h = \frac{q_h^-}{e^+} = 1 + \frac{q_a^+}{e^+} = \frac{1}{\Theta_h}\underbrace{\left(1 - \frac{l}{e^+}\right)}_{\eta} = COP_h$$

Specific exergy losses: l

Coefficient of performance: COP_h

Exergy efficiency: η

Carnot factor $\Theta_h = 1 - \frac{T_a}{T_h}$

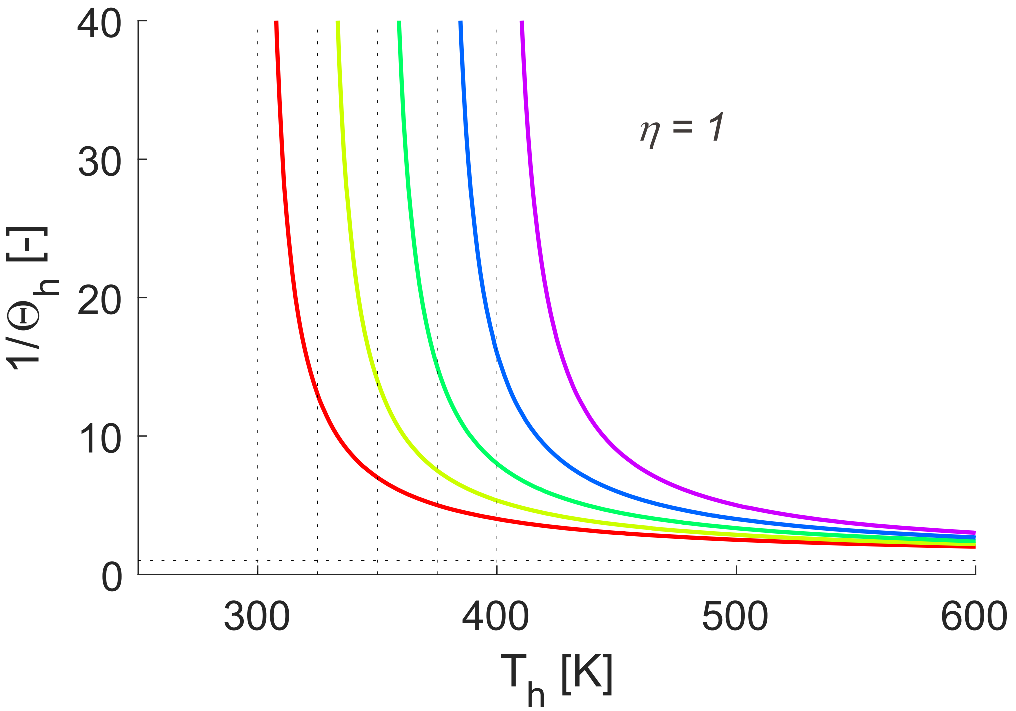
- Link between Carnot factor and exergy efficiency in heating mode

Heating Heat Pump Effectiveness

- Heating effectiveness
  - Towards infinity for $T_h \rightarrow T_a$
  - Towards 1 for $T_h \rightarrow \infty$
  - Increases with T_a
  - Is > 1

- Since heating effectiveness can take values on large range metric can be disconcerting

- Heating effectiveness worthless without indication of T levels



Refrigeration Heat Pump Energy Balance

- Circular integral in P-v or T-s increased by irreversibility corresponds to invested work or to heat balance
- Invested work corresponds to heat balance → 1st law

$$e^{+} = q_a^{-} - q_f^{+} = -\oint Pdv + r = -\oint Tds + r$$

$$q_f^{+} = q_a^{-} - e^{+}$$

- Entropy balance on the refrogeration cycle

$$\oint dS = \oint \frac{\delta Q_a^{+}}{T_a} + \oint \frac{\delta Q_f^{+}}{T_f} + \oint \delta S^{i} = 0$$

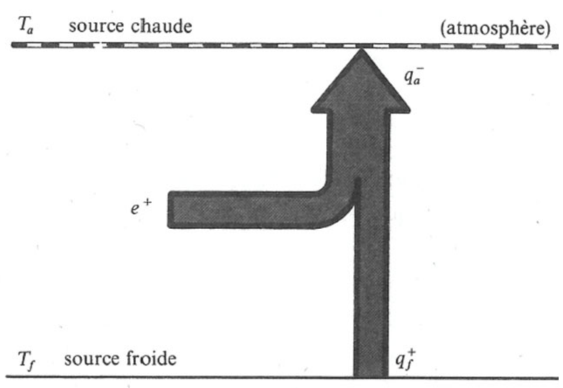


Fig. 13.23 Favrat

Refrigeration Heat Pump Effectiveness

- Cooling effectiveness definition

$$\epsilon_f = \frac{q_f^+}{e^+} = \frac{q_a^-}{e^+} - 1 = -\frac{1}{\Theta_f} \underbrace{\left(1 - \frac{l}{e^+}\right)}_{\eta} = COP_f$$

Specific exergy losses: l

Coefficient of performance: COP_f

Exergy efficiency: η

Carnot factor $\Theta_f = 1 - \frac{T_a}{T_f}$

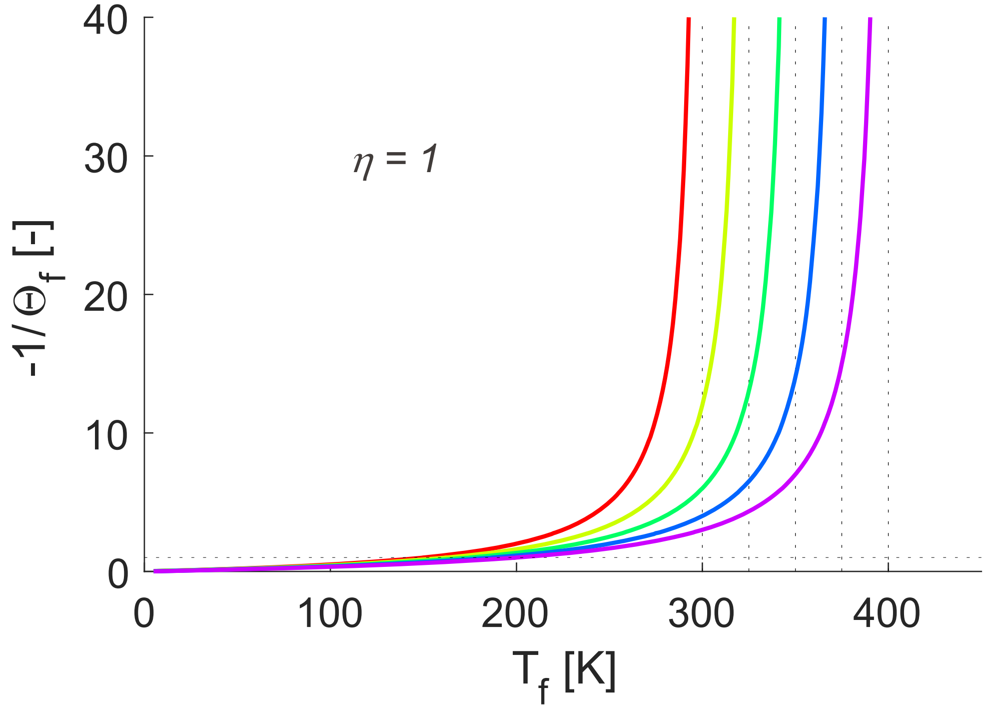
- Link between Carnot factor and exergy efficiency in cooling mode

Refrigeration Heat Pump Effectiveness

- Cooling effectiveness
  - Towards infinity for $T_f \rightarrow T_a$
  - Towards 0 for $T_f \rightarrow 0$
  - Decreases with T_a

- Since heating effectiveness can take values on large range metric can be disconcerting

- Cooling effectiveness worthless without indication of T levels



Power Cycles and Heat Pumps

Technical Implementation of Heat Pumps

Prof. J. Schiffmann

École polytechnique fédérale de Lausanne

Typical Heat Pump Settings

- Typical cases of bi-thermal heat pump cycles
- Bi-thermal → transfer occurs with two different thermal sources → involves pressure change within cycle

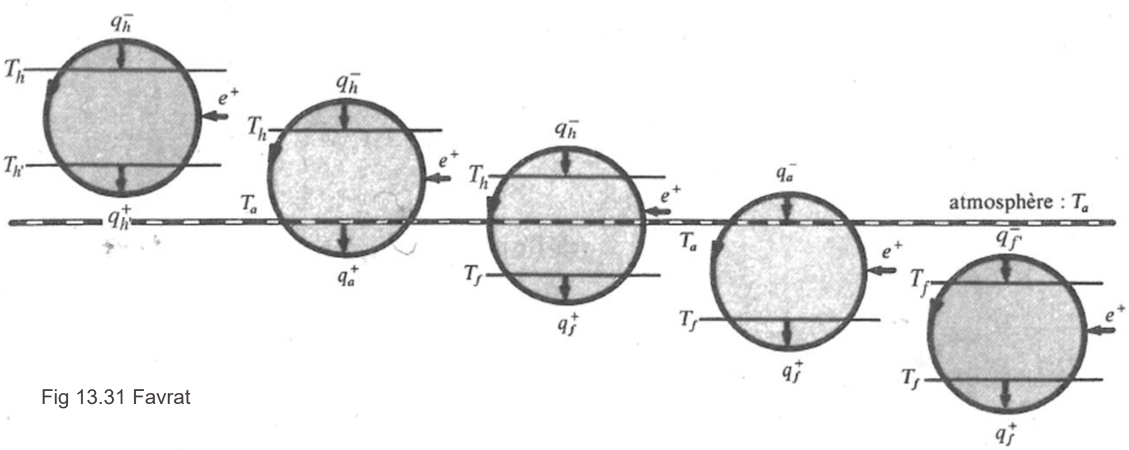


Fig 13.31 Favrat

- Most common are cases b and d → one if thermal source is atmosphere

EPFL

How Can Heat Pump Cycle Be Realized Thermodynamically?

- Reversed Stirling cycle
  - Composed of two isothermal and two isochoric processes, with internal heat transfer
  - Possible to realize as closed system with displacement

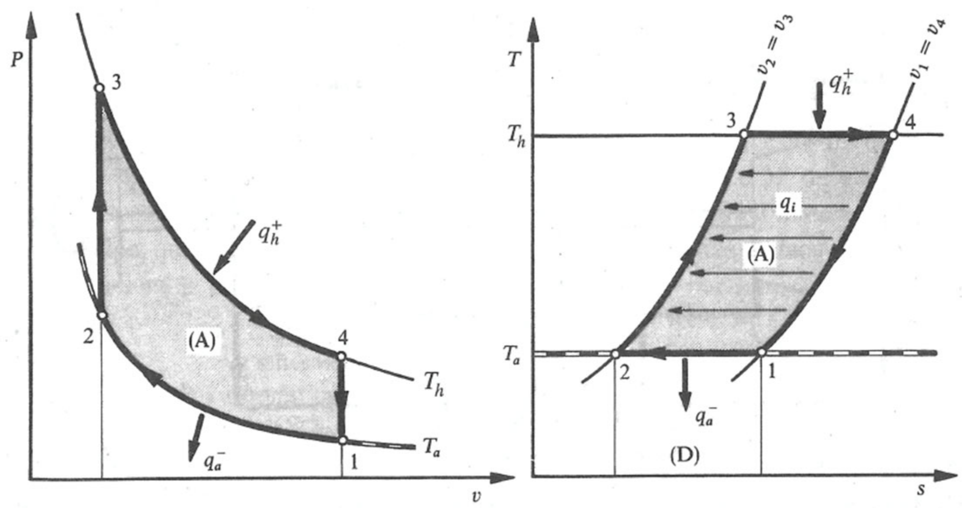


Fig 13.13 Favrat

How Can Heat Pump Cycle Be Realized Thermodynamically?

- Reversed Ericsson cycle
  - Composed of two isothermal and two isobaric processes, with internal heat transfer
  - Possible to realize as closed system

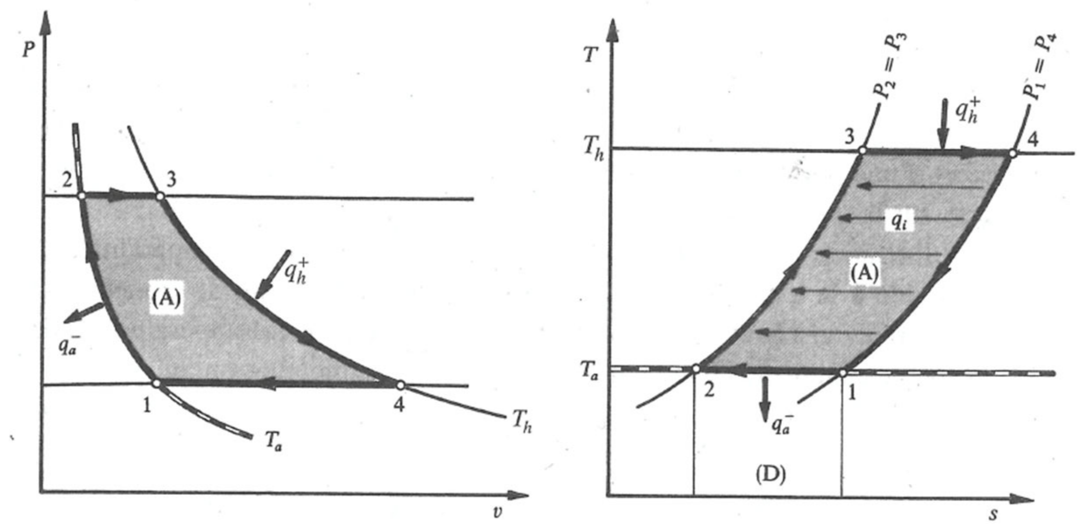
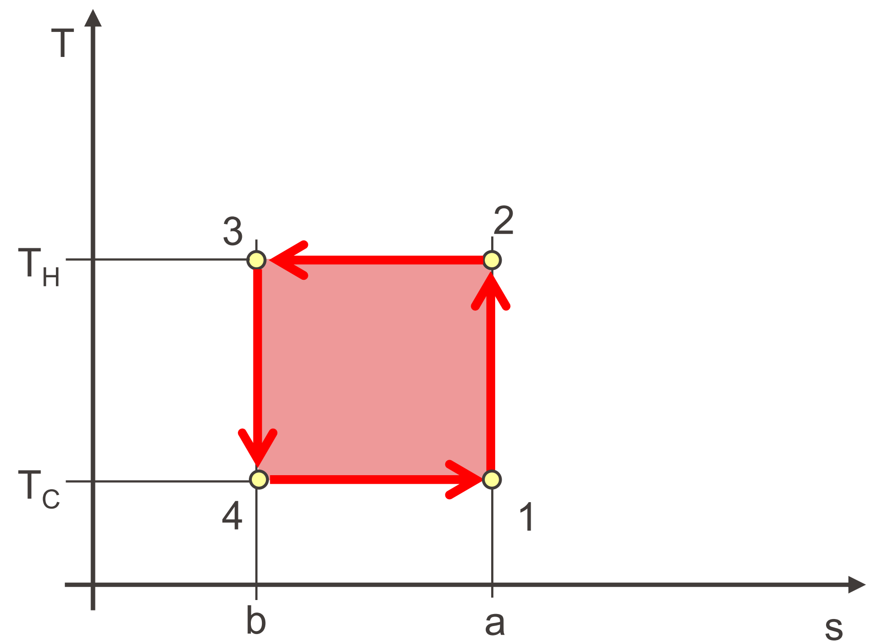


Fig 13.15 Favrat

How Can Heat Pump Cycle Be Realized Thermodynamically?

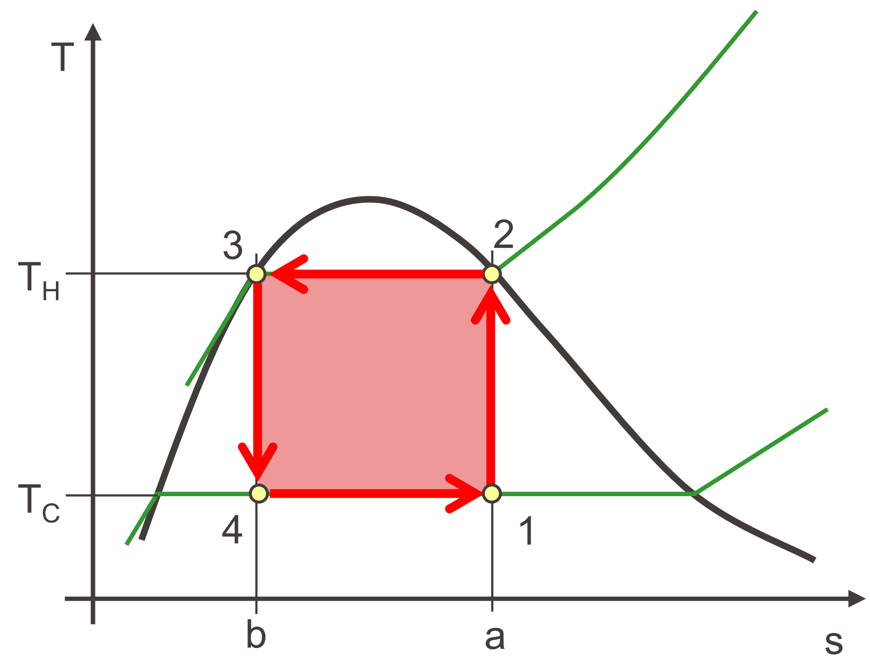
- Reversed Carnot cycle
  - Composed of two isothermal and two isentropic processes, without internal heat transfer
  - Possible to realize with a closed system without fluid transfer



Technical Challenges of Reversed Carnot Cycle

- Isothermal compression and expansion are challenging to achieve technically → make use of working fluid evaporation and condensation

- Requires isentropic compression and expansion in two phase zone



EPFL

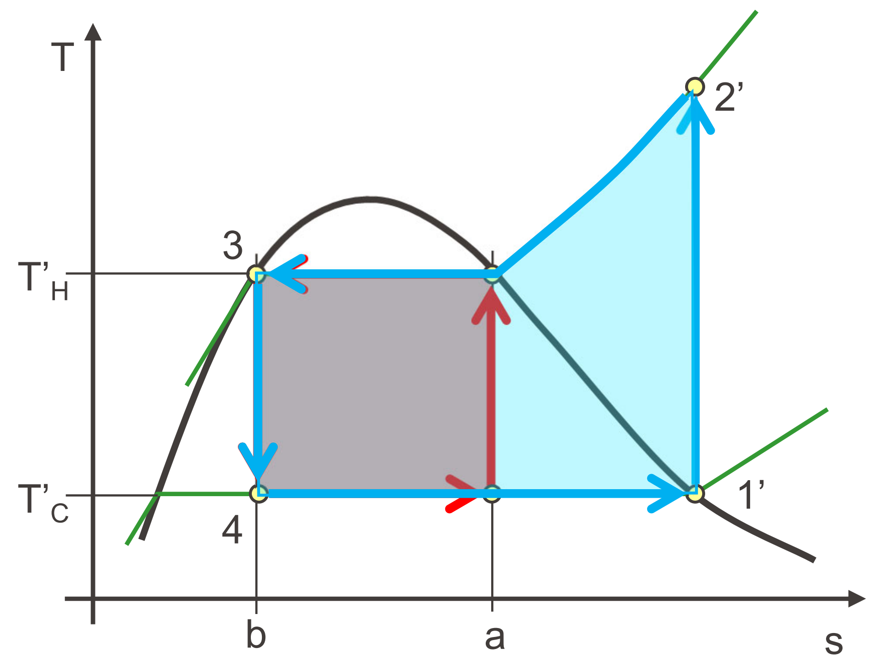
Technical Challenges of Reversed Carnot Cycle

- Humid compression challenging due to presence of liquid phase in working chambers

- Liquid in working chamber decreases lubricant effect

- Liquid in working chamber yields very high pressures → failure

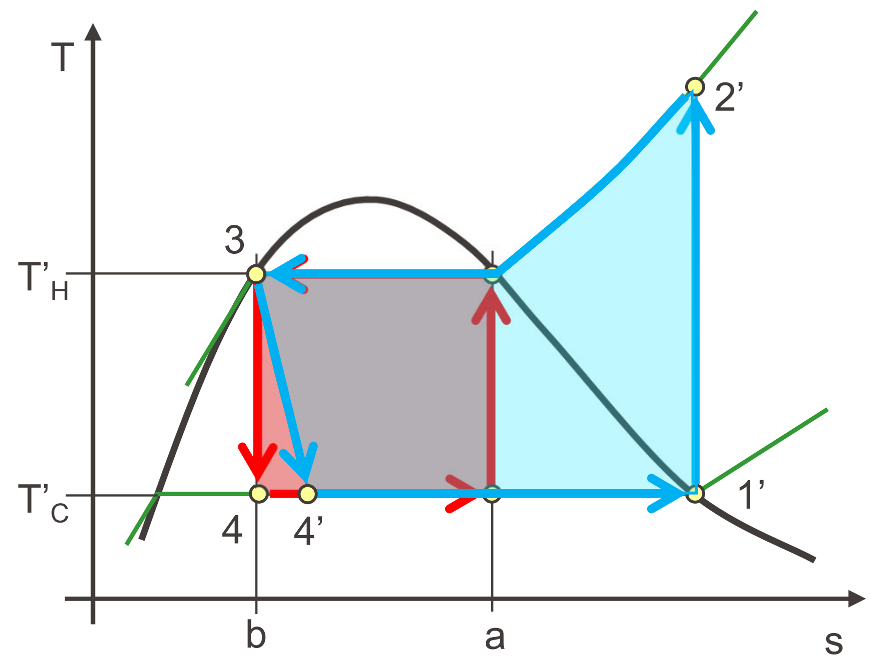
- Dry compression is preferred to protect compression machine from destruction



EPFL

Technical Challenges of Reversed Carnot Cycle

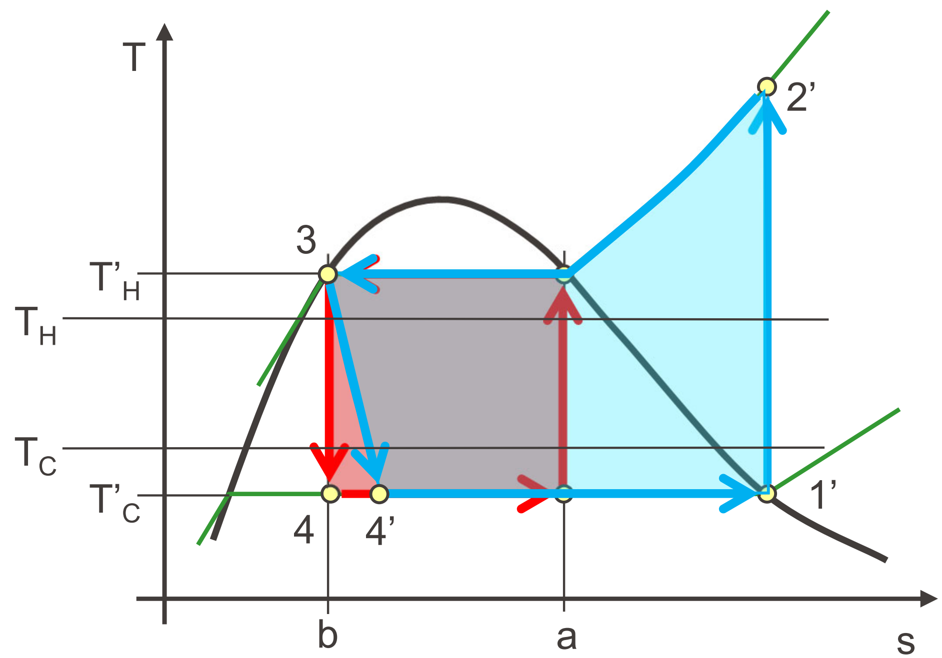
- Wet expansion through turbine or expander difficult and yields low power due to low share of vapor
- Expensive equipment for little return
- Energy transfer from expander to compressor challenging
  → regulation of expansion flow
- Use of two phase expansion valve preferred solution
  → isenthalpic expansion



Technical Challenges of Reversed Carnot Cycle

- Heat transfer in condenser and evaporator requires finite temperature difference

- Leads to a de-evaluation of heat



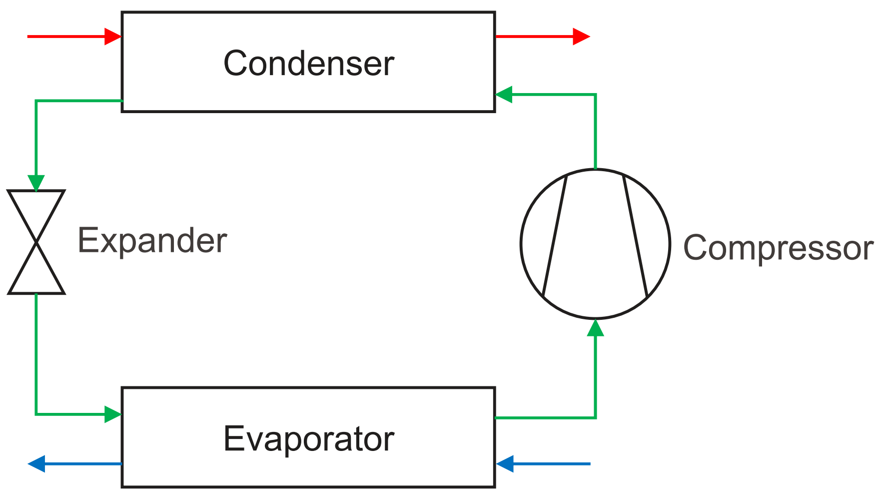
Technical Challenges

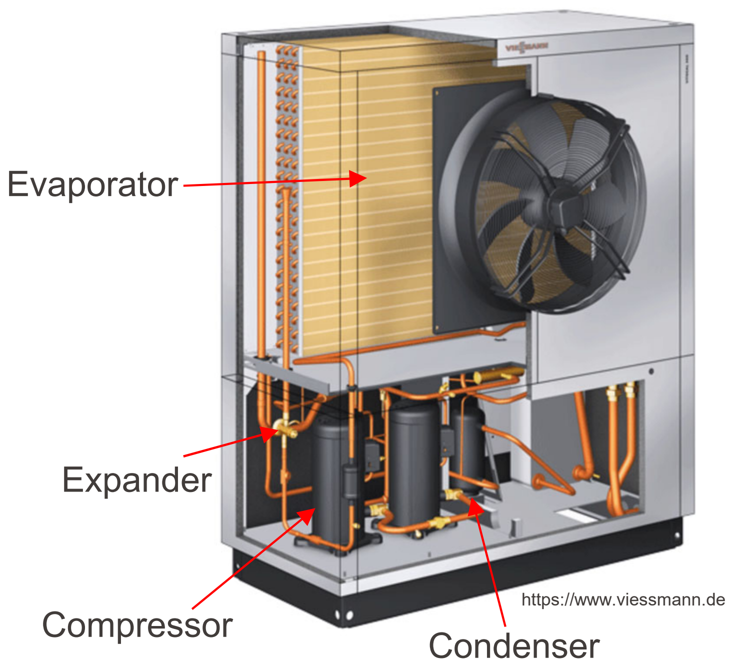
- Ideal thermodynamic cycles require
  - Isothermal compression / expansion
  - Wet compression / expansion
  - Ideal heat transfer with thermal sources
  - Perfect insulation

- Realization of ideal thermodynamic cycles challenging from technological point of view

Typical Components in Heat Pumps

- Typical layout of domestic-scale air-water heat pump

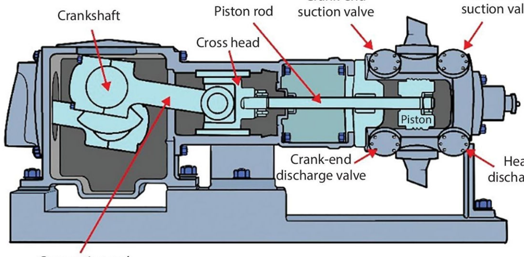




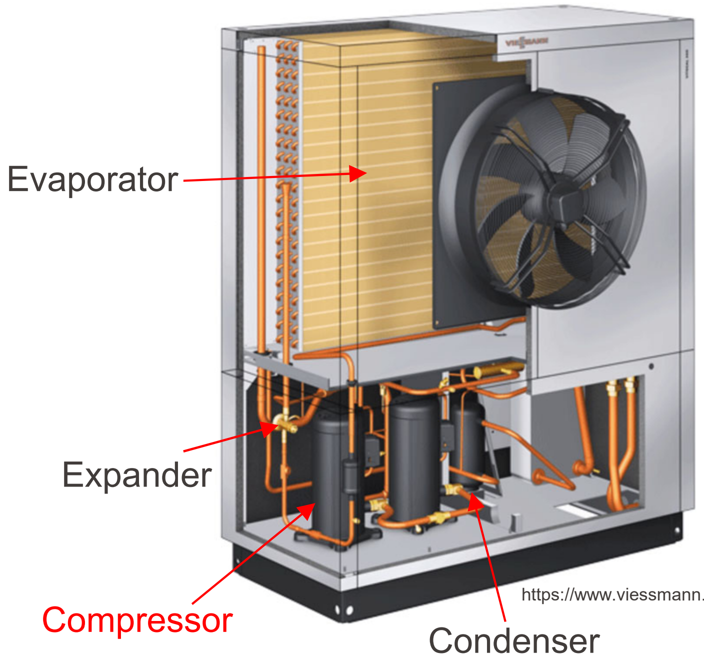
Compressor

- Compressor increases pressure from evaporation to condensation
- Various working principles
- Large capacity range

Compressor types
- Positive displacement
- Dynamic



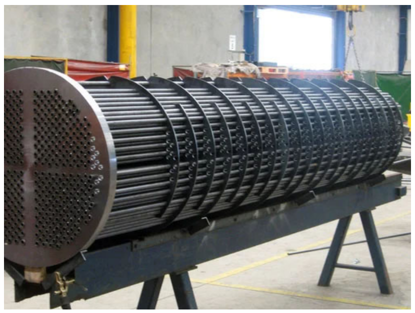
https://www.oreilly.com/

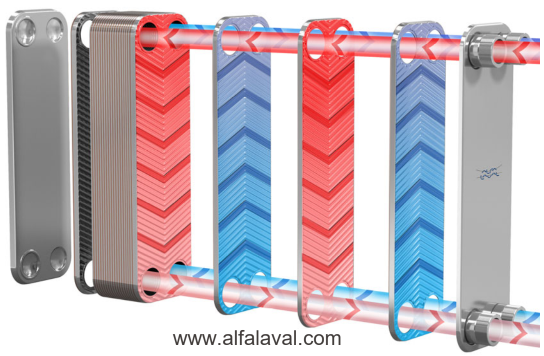


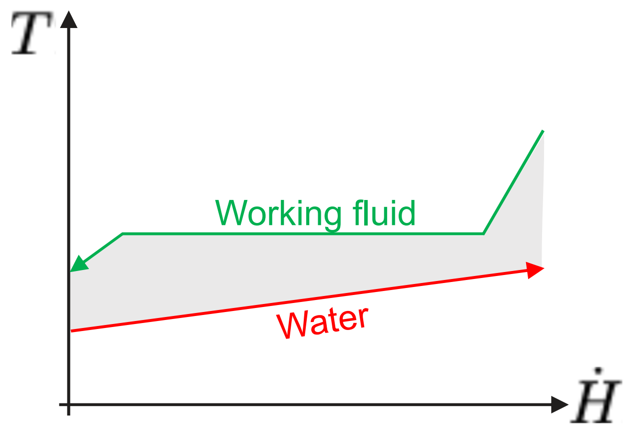
https://www.viessmann.de

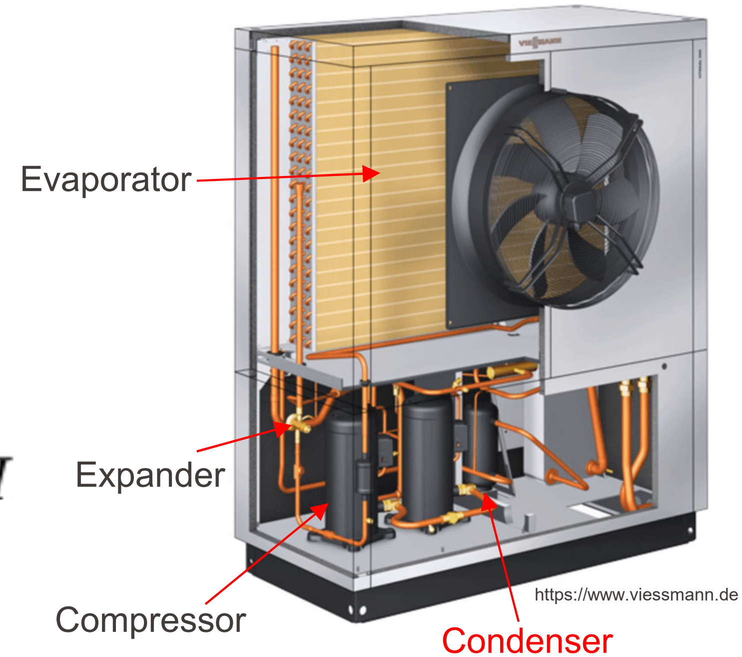
Condenser

- Condenser rejects heat and condenses working fluid
- Various types depending on power and fluids



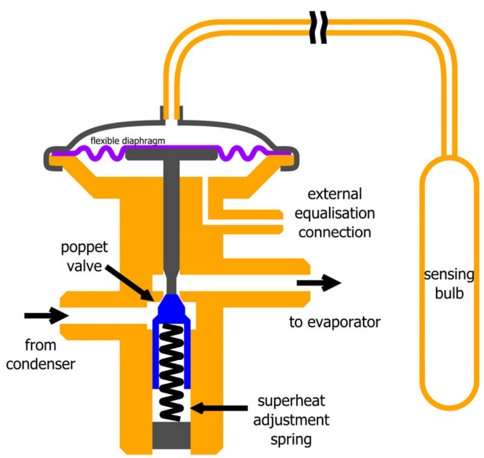




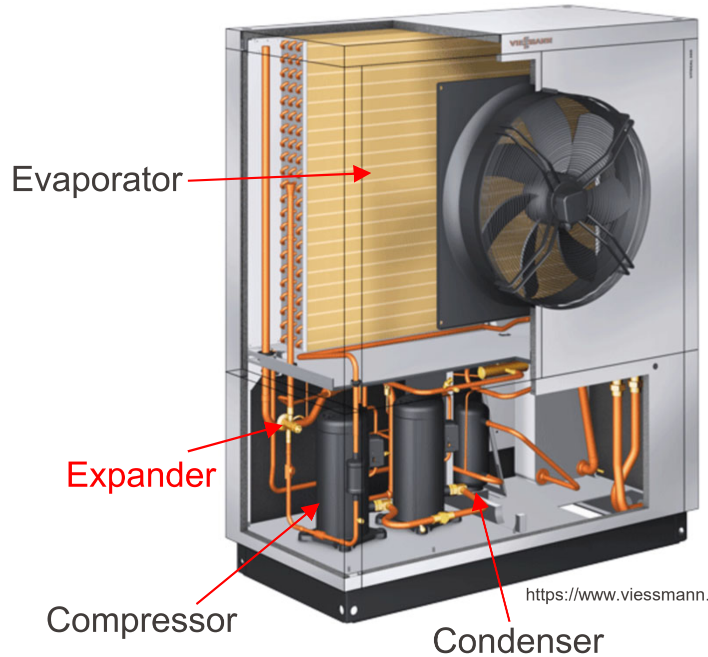


Expander

- Expander reduces pressure from condensation to evaporation level
- Expander is throttle valve with variable orifice
- Controlled by working fluid temperature at evaporator discharge



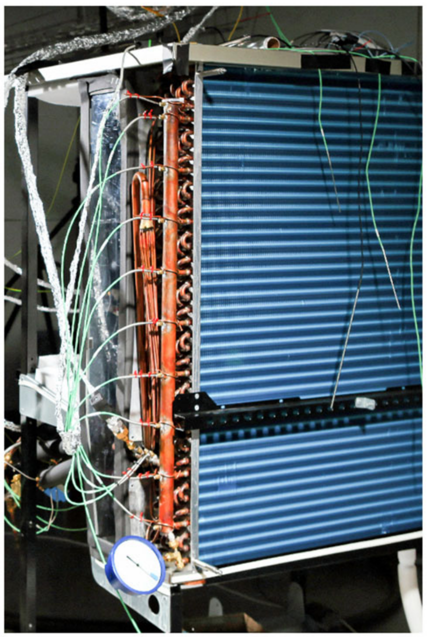
https- en.wikipedia.org wiki Thermal_expansion_valve# media File-Thermostatic_expansion_valve.png



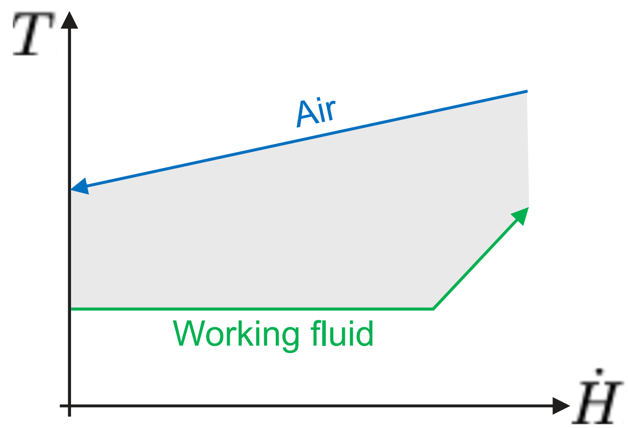
https://www.viessmann.de

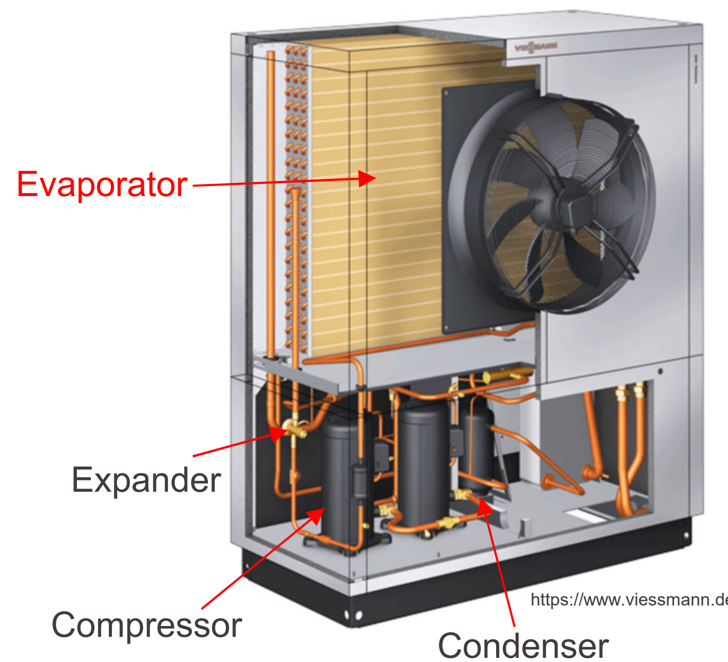
Evaporator

- Evaporator absorbs heat and evaporates working fluid



EPFL-Thesis 6764, Jean-Baptiste Carré, Experimental investigation of domestic heat pumps equipped with a twin-stage oil-free radial compressor





Outlook for W5

- Detailed performance analysis of heat pump based on vapor compression cycle
- Analysis of real heat pump based on single stage cycle
- Means to improve heat pump performance
- Analysis of two stage cycle with open flash tank economizer

Exercises W4

- Comprehension questions
- Thermodynamic analysis of an ideal vapor compression refrigeration cycle
- Thermodynamic analysis of an inverse Brayton cycle