Modeling Thermodynamic Systems

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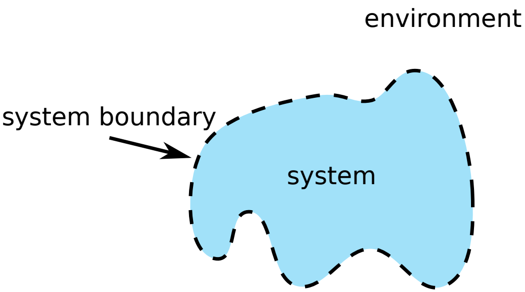
Introduction

Contents

Thermodynamic systems

Thermodynamic system

- Boundary separates system from environment
- Can be open or closed to mass and energy transfer
- homogenoeus/heterogeneous
- State of the system can be described through various properties



Thermodynamic state

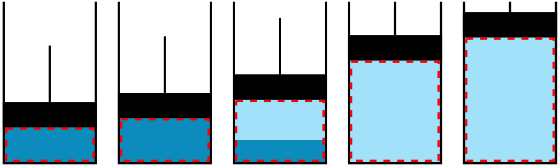
Thermodynamic state

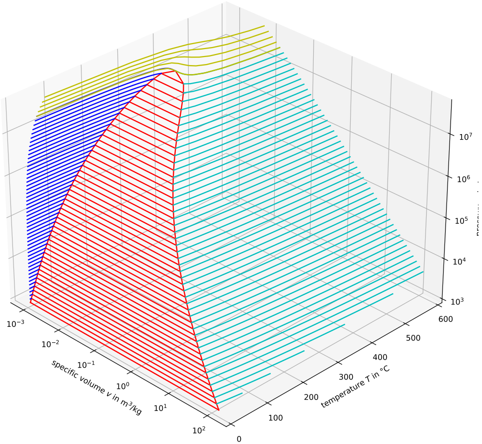
- intensive properties (independant of size of the system)
  - pressure p, unit: $\mathrm{Pa} = {}^{\mathrm{N}}/_{\mathrm{m}^2}$
  - temperature T, unit: K
- mass specific properties (per kg of mass of the system)
  - specific volume $v = \frac{1}{\rho}$, unit: ${}^{\mathrm{m}^3}/_{\mathrm{kg}}$
  - specific enthalpy h, unit: ${}^{\mathrm{J}}/_{\mathrm{kg}}$
  - specific entropy s, unit: ${}^{\mathrm{J}}/_{\mathrm{kg \cdot K}}$

Phases of fluids

Phases of fluids

- Liquid, two-phase or gaseous
- Isobaric heating leads to evaporation
- Temperature during evaporation is constant





Determining thermodynamic state

Determining thermodynamic state

- Two properties define the state, e.g.
  - pressure and volume
  - temperature and volume
  - pressure and enthalpy
  - pressure and entropy
- pressure and temperature NOT in two-phase region

Exercise

- Calculate the density of R290 at 5 bar and 50 °C.
- What is the enthalpy of saturated liquid ammonia at 75 °C?
- Calculate the vapor mass fraction for the same enthalpy as before but at 25 °C.
- At what pressure does Ammonia start to boil under a pressure of 4 bar?
- What pressure values correspond to saturation temperature of 20 °C, 65 °C and 110 °C for water?
- Calculate the entropy of R134a at saturated gaseous state and a temperature of 10 °C.
- What is the temperature of R134a at the same entropy as previously but twice as much pressure?

Exercise

- Plot saturation curve (pressure vs. temperature) fo r Ammonia, Water, R134a, Pentane, R290, R600 and R1233zd(E) in a log-p,T diagram for temperature ranging from -25 °C to 125 °C.
- Plot the pressure ratio of saturation pressure vs. saturation pressure at 10 °C over a range of temperature from 30 °C to 80 °C.
- Calculate the entropy for the saturated liquid and vapor lines for temperature values larger than -25 °C. Plot the lines in a T,s diagram.
- Compare the individual lines. What factors might restrict the usage of working fluids in heat pumps?

Thermodynamic processes

Thermodynamic processes

- simplification: open system in steady state operation
- energy balance equation connects
  - outlet o and inlet i states of the fluids with
  - process energy work $\dot{W}$ and heat $\dot{Q}$

$$\dot{Q} + \dot{W} = \sum_{o} \dot{m}_\mathsf{o} \cdot h_o \cdot - \sum_{i} m_i \cdot h_i$$

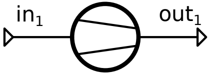
- simplification: single mass flow

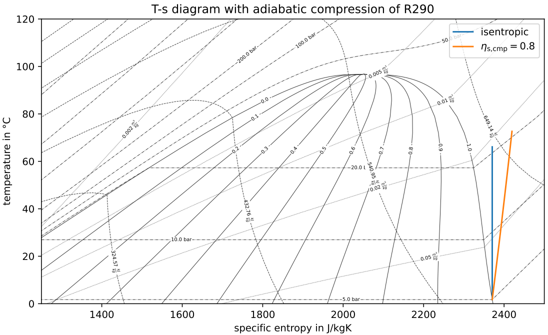
$$\dot{Q} + \dot{W} = \dot{m} \cdot (h_o - h_i)$$

Components: Compressor

Components: Compressor

- Adiabatic to the ambient: $\dot{Q} = 0$
- Energy balance: $\dot{W} = \dot{m} \cdot (h_{\text{out}} - h_{\text{in}})$
- Pressure ratio: $pr = \frac{p_{\text{out}}}{p_{\text{in}}} > 1$
- Isentropic efficiency:
  - $\eta_{\text{s,comp}} = \frac{h_{\text{out,s}} - h_{\text{in}}}{h_{\text{out}} - h_{\text{in}}}$
  - $h_{\text{out,s}} = h\left(p_{\text{out}}, s\left[p_{\text{in}}, h_{\text{in}}\right]\right)$

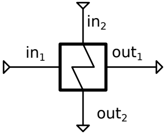


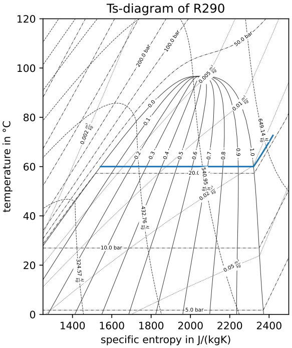


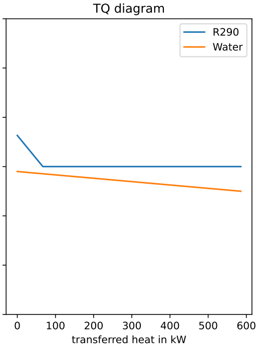
Components: Heat Exchanger

Components: Heat Exchanger

- no transfer of work: $\dot{W} = 0$
- energy balance: $\dot{Q} = \dot{m} \cdot (h_{\text{out}} - h_{\text{in}})$
- pressure losses neglected: $p_{\text{out}} = p_{\text{in}}$
- for example
  - evaporator: $h_{\text{out}} = h_{\text{sat,gas}}\,(p)$
  - condenser: $h_{\text{out}} = h_{\text{sat,liq}}\,(p)$
- two-sided
  - $\dot{Q}_{\text{h}} = \dot{m}_{\text{h}} \cdot (h_{\text{out,h}} - h_{\text{in,h}})$
  - $\dot{Q}_{\text{c}} = -\dot{Q}_{\text{h}} = \dot{m}_{\text{c}} \cdot (h_{\text{out,c}} - h_{\text{in,c}})$



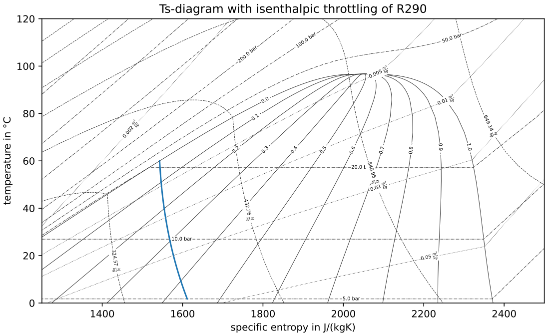




Components: Valve

Components: Valve

- adiabatic and no transfer of work
  - $\dot{W} = 0$
  - $\dot{Q} = 0$
- energy balance: $0 = \dot{m} \cdot (h_{\text{out}} - h_{\text{in}})$
- pressure ratio: $pr = \frac{p_{\text{out}}}{p_{\text{in}}} < 1$



Exercise

Implement a model, that allows you to model isentropic compression.

- What power does the compressor draw if 5 kg/s of R290 are compressed from saturated gaseous state at 15 °C to a pressure corresponding to a saturation temperature of 60 °C?
- What is the outlet temperature?
- How much mass can be compressed by the same machine, if 300 kW of power is available?

Now consider thermodynamic inefficiencies by incorporating isentropic efficiency in the model.

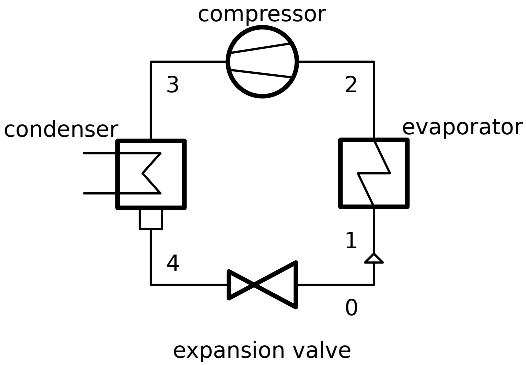
- Assume isentropic efficiency of 80 %. What power is drawn at 5 kg/s and what is the outlet temperature?
- The outlet temperature is measured to be 75 °C, what is the isentropic efficiency?
- How does the compressor power requirement change as function of the isentropic efficiency?

Exercise

- How much heat is required to completely evaporate 3 kg/s saturated liquid R134a at 10, 20 and 30 °C?
- Which volumetric flow of air is required to provide the heat in any of the three cases? Assume, that the minimal temperature difference between the air and the working fluid is 3 K and the air temperature changes by 5 K.
- Which volumetric flow of water is required under the same circumstances?
- What information can you transfer to the heat exchanger design?

Simple heat pump model

- Simple 4-component cycle
- No secondary side for heat exchangers



Model	parameters		
location	parameter	value	unit
2	temperature	10	°C
4	temperature	60	°C
compressor	efficiency	80	%
condenser	heat transfer	1	MW

Exercise

- Create a model of the heat pump using R290 as refrigerant in Python and calculate
  - the compressor power input
  - the COP of the heat pump
  - the mass flow of the refrigerant
  - the evaporation and the condensation pressure levels
- Create a log p-h diagram of the process
- Change the working fluid to ammonia. Why and how does it affect the COP?
- Create two plots, that indicate dependency of the COP towards evaporation and condensation temperature respectively?

Exercise

- With R290 as working fluid, assume the compressor power is limited to 0.2 MW:
  - How much heat can be provided by the condenser in this case?
  - What amount of heat can be delivered when the heat source temperature is reduced to 0 °C?
  - At what heat source temperature level does the heat pump 1 MW of heat again?

Let's code it!