Thermodynamics and energetics 1

Profs. Zhengmao Lu and Sophia Haussener

Laboratory of Renewable Energy Sciences and Engineering

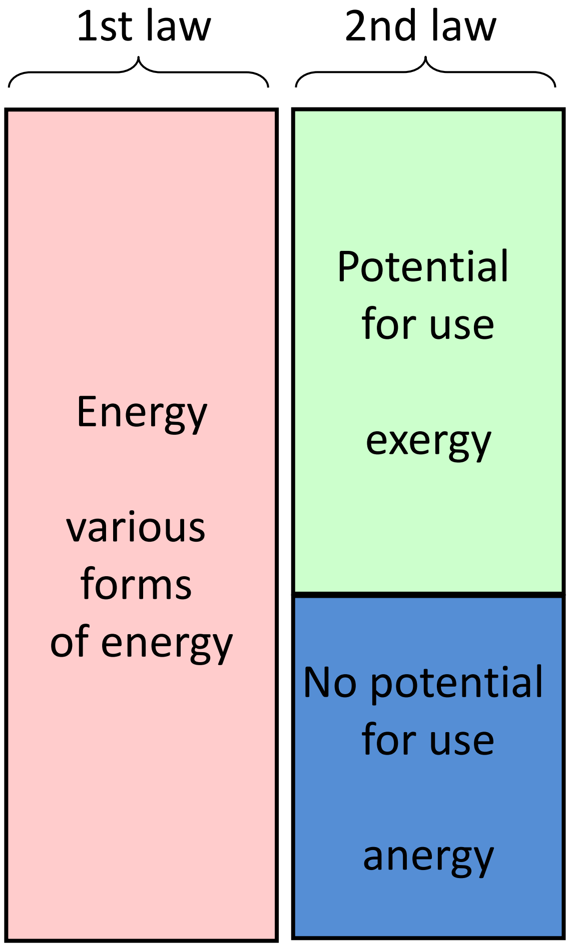
Summary lecture

- Outline

1. Generalities
2. Energy and 1st law for closed systems
3. Energy transfer by heat
4. Thermodynamic properties
5. 1st law for closed and open systems
6. 2nd law and entropy
7. Exergy
8. Applications
9. Mixtures and psychrometry

Exergy

- What is the potential for use?



1st law

2nd law

Energy

various forms of energy

Potential for use

exergy

No potential for use

anergy

Exergy

- Exergy – definition:

$$Ex = U - U_0 + KE + PE - T_0\left(S - S_0\right) + p_0\left(V - V_0\right)$$

- Specific exergy:

$$ex = u - u_0 + ke + pe - T_0\left(s - s_0\right) + p_0\left(v - v_0\right)$$

- Exergy difference between two states:

$$Ex_2 - Ex_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0\left(S_2 - S_1\right) + p_0\left(V_2 - V_1\right)$$

- Specific exergy difference between two states:

$$ex_2 - ex_1 = (u_2 - u_1) + (ke_2 - ke_1) + (pe_2 - pe_1) - T_0\left(s_2 - s_1\right) + p_0\left(v_2 - v_1\right)$$

Exergy balance - closed systems

- Closed systems:

$$Ex_2 - Ex_1 = \underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right)\delta Q}_{\textbf{Exergy transfer by heat transfer}} - \underbrace{\left(W_{12} - p_0\left(V_2 - V_1\right)\right)}_{\textbf{Exergy transfer by work}} - \underbrace{T_0\sigma}_{\textbf{Exergy destruction}\text{ by irreversibilities}}$$

- Rate:

$$\frac{dEx}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{12} - p_0\frac{dV}{dt}\right) - T_0\dot{\sigma}$$

- Expressed alternatively:

$$Ex_2 - Ex_1 = Ex_q - Ex_w - Ex_d$$

Exergy balance - open systems

- Open systems – Exergy:

$$\frac{dEx}{dt}=\sum_j\left(1-\frac{T_0}{T_j}\right)\dot{Q}_j-\left(\dot{W}-p_0\frac{dV}{dt}\right)+\underbrace{\sum_i\dot{m}_i ex_{f,i}-\sum_e\dot{m}_e ex_{f,e}}-T_0\dot{\sigma}$$

Change in exergy within the volume = **Exergy transfer via heat transfer** - **Exergy transfer** via work + **Convective exergy transfer at the inlets and outlest** - **Exergy destruction due to irreversibilities**

- With flow exergy:

$$ex_f=u-u_0+ke+pe-T_0\left(s-s_0\right)+p_0\left(v-v_0\right)+(p-p_0)v$$

$$ex_f=ex+(p-p_0)v$$

Exergetic efficiency

- Exergy efficiency describes the effectiveness of energy resource utilization

$$\varepsilon_{ex} = \frac{\text{used exergy}}{\text{provided exergy}} \qquad \eta = \frac{\text{used energy}}{\text{provided energy}}$$

energy efficiency

- Components:
  - Turbine:

$$\varepsilon_{ex} = \frac{\left(\dot{W} / \dot{m}\right)}{ex_{f,i} - ex_{f,e}}$$

  - Compressor/pump:

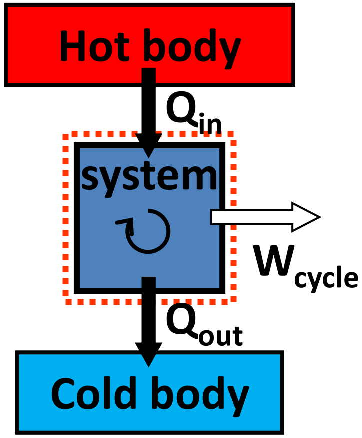
$$\varepsilon_{ex} = \frac{ex_{f,e} - ex_{f,\mathrm{i}}}{\left(-\dot{W}_{\mathrm{cv}} / \dot{m}\right)}$$

  - Heat exchanger: (non/mixing)

$$\varepsilon_{ex} = \frac{m_c\left(ex_{f,e,c} - ex_{f,i,c}\right)}{m_h\left(ex_{f,i,h} - ex_{f,e,h}\right)} \qquad \varepsilon_{ex} = \frac{m_2\left(ex_{f,3} - ex_{f,2}\right)}{m_1\left(ex_{f,1} - ex_{f,3}\right)}$$

Power systems

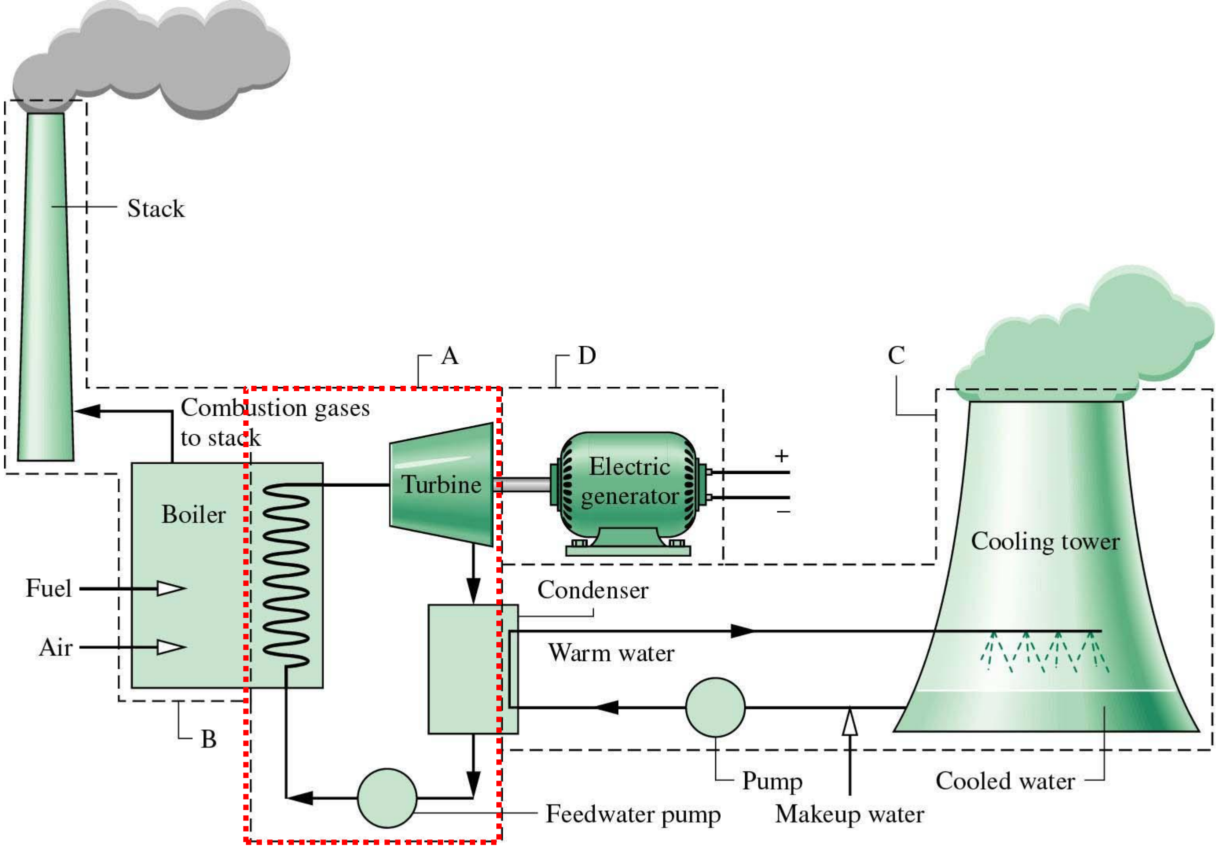
- Produce net power output from a energy source, such as fossil fuel, nuclear, or solar power



- Three major types of systems:
  - Vapor power plants (working fluid alternately vaporizes and condenses)
  - Gas turbine power plants (working fluid gas, series of components)
  - Internal combustion engines (working fluid gas, reciprocating)

Vapor power systems

- Vapor power systems:
  - Water is the working fluid, which alternately vaporizes and condenses
  - Majority of electrical power generation done by these systems
  - Basic components in a simplified systems are:
    - Boiler
    - Turbine
    - Condenser
    - Pump



Vapor power systems

- Idealized *Rankine* cycle:
  - Turbine: *isentropic* expansion

$$\dot{W}_{\mathrm{t}} / \dot{m} = (h_1 - h_2)$$

  - Condenser: *isobaric* heat transfer

$$\dot{Q}_{\mathrm{out}} / \dot{m} = (h_3 - h_2)$$

  - Pump: *isentropic* compression

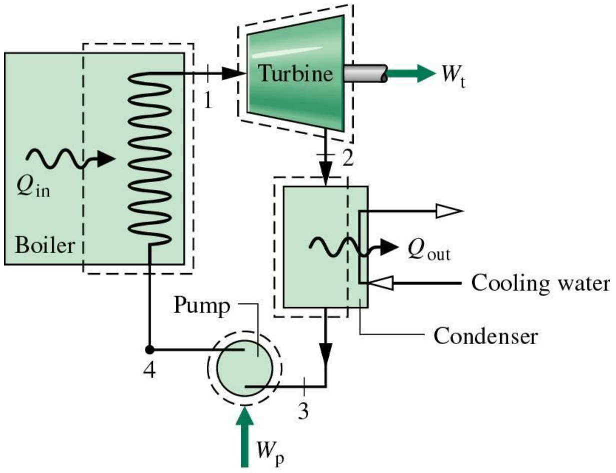
$$\dot{W}_{\mathrm{p}} / \dot{m} = (h_3 - h_4)$$

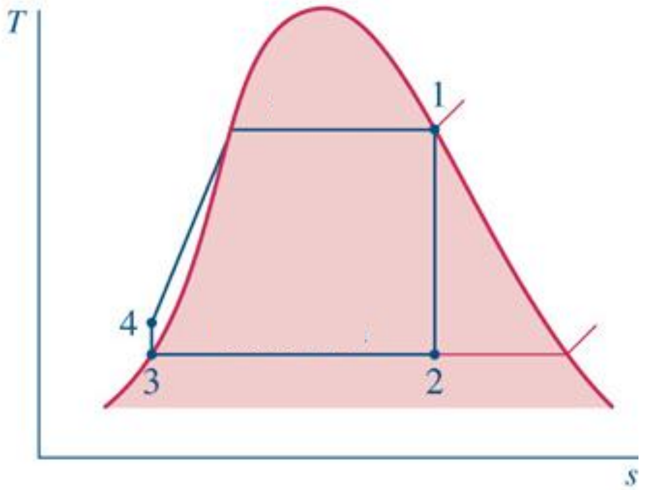
  - Boiler: *isobaric* heat transfer

$$\dot{Q}_{\mathrm{in}} / \dot{m} = (h_1 - h_4)$$

  - Efficiency:

$$\eta = \frac{\dot{W}_{\mathrm{t}} / \dot{m} + \dot{W}_{\mathrm{p}} / \dot{m}}{\dot{Q}_{\mathrm{in}} / \dot{m}} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_4)}$$



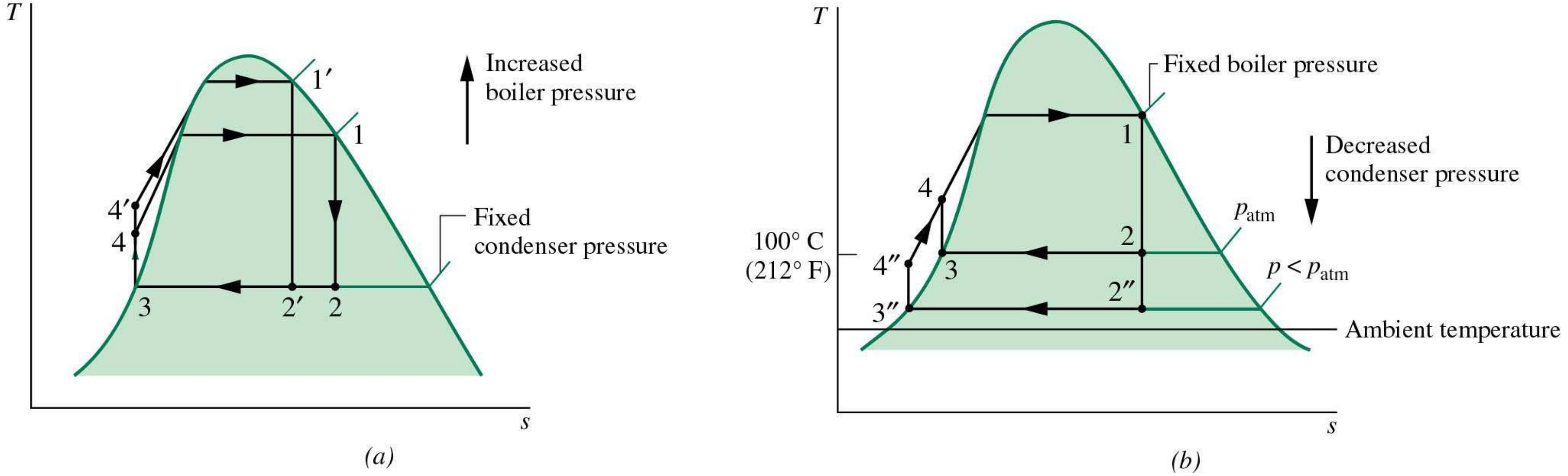


Vapor power systems

- Idealized Rankine cycle: effects of components on performance:
  - Increase of average temperature at which energy is added and decrease of average temperature at which energy is rejected leads to increased efficiency (Carnot):

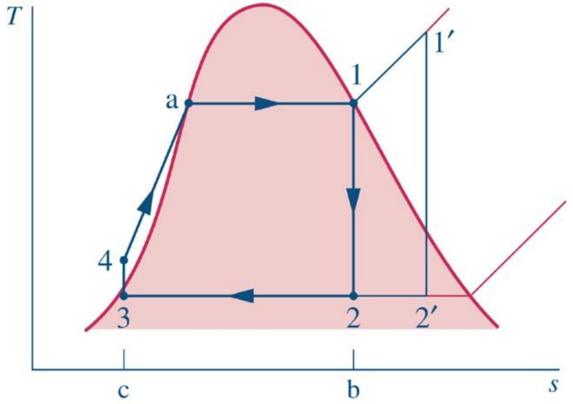
$$\eta_{\text{ideal}} = \frac{(\dot{Q}_{\text{in}}/\dot{m})_{\text{int,rev}} - (\dot{Q}_{\text{out}}/\dot{m})_{\text{int,rev}}}{(\dot{Q}_{\text{in}}/\dot{m})_{\text{int,rev}}} = 1 - \frac{T_{\text{out}}}{\overline{T}_{\text{in}}}$$

  - Increase in boiler pressure and decrease in condenser pressures:

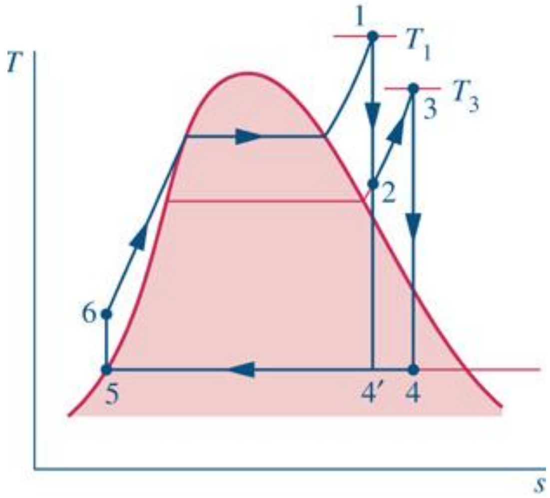


Vapor power systems

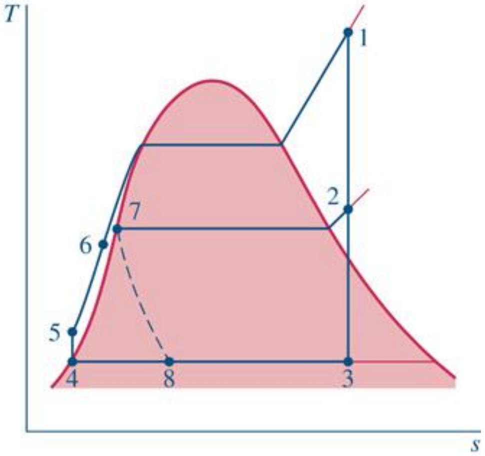
- Rankine cycle: improving performance:
  - Superheating (using additional heat exchanger, combination of boiler and heat exchanger is called steam generator)



  - Reheating



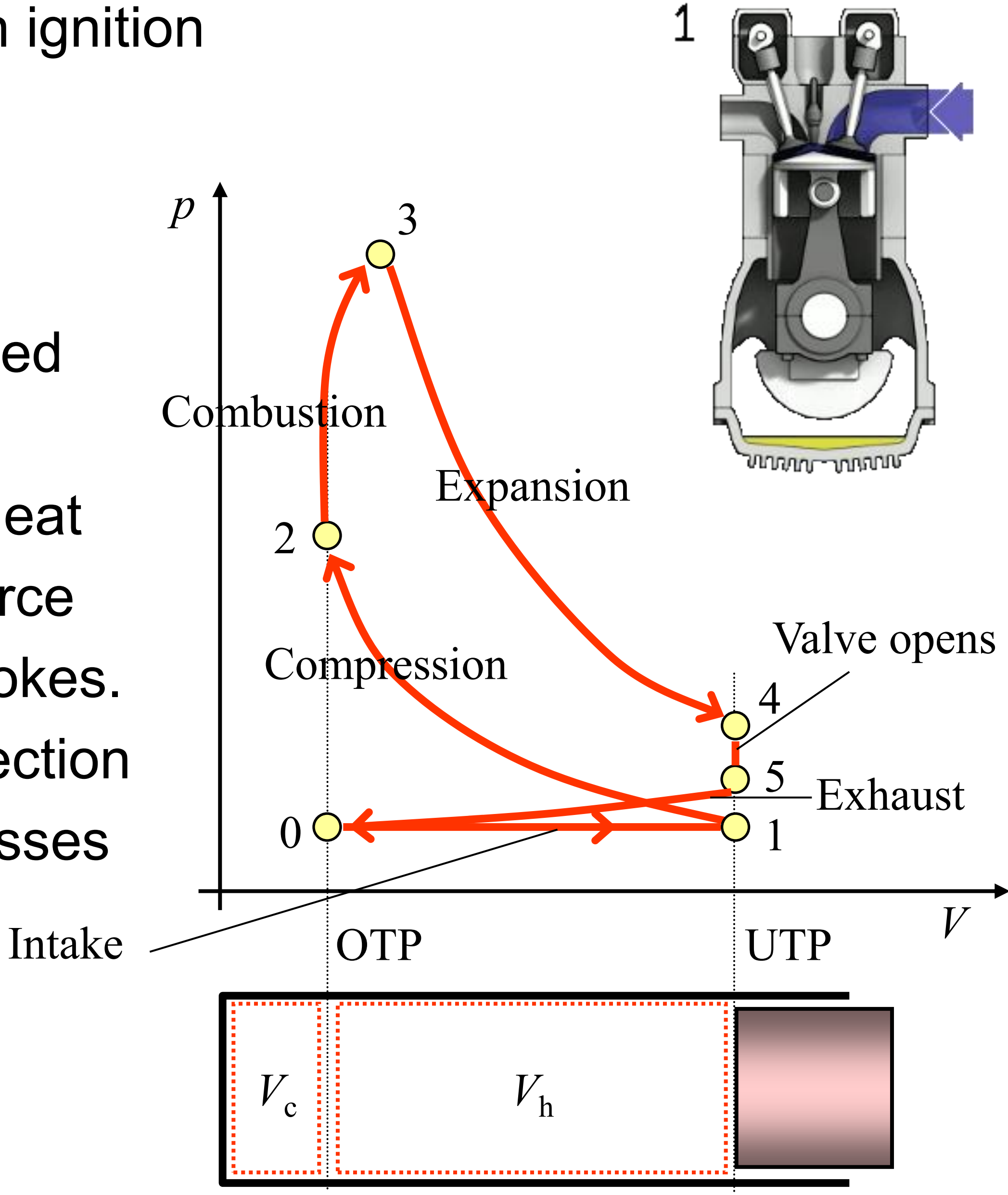
  - Regeneration via open/closed feedwater heater



Internal combustion engines

- Spark ignition or compression ignition

- *Air-standard analysis:*
  - Fixed amount of air modeled as ideal gas
  - Combustion modeled by heat transfer from external source
  - No exhaust and intake strokes. Constant volume heat rejection
  - Internally reversible processes



Internal combustion engines

- Air-standard Otto cycle:
  - 1-2: Isentropic compression

$$\frac{W_{12}}{m} = u_1 - u_2$$

  - 2-3: Constant-volume heat transfer

$$\frac{Q_{23}}{m} = u_3 - u_2$$

  - 3-4: Isentropic expansion

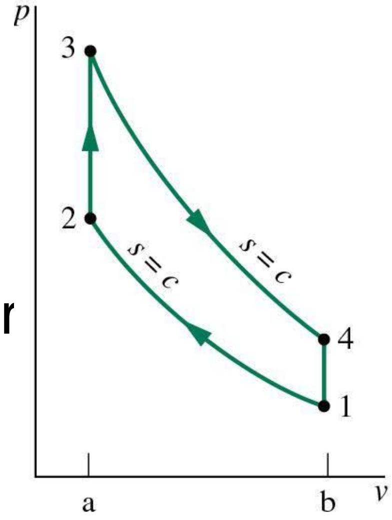
$$\frac{W_{34}}{m} = u_3 - u_4$$

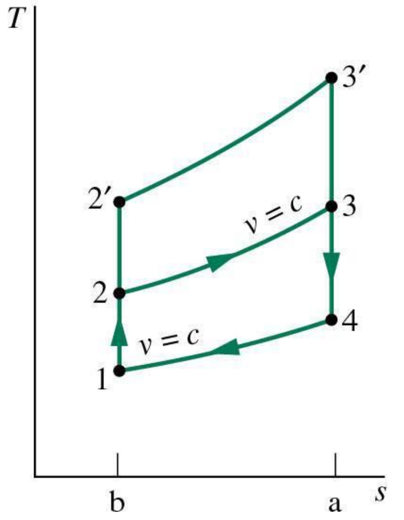
  - 4-1: Constant-volume heat

$$\frac{Q_{41}}{m} = u_1 - u_4$$

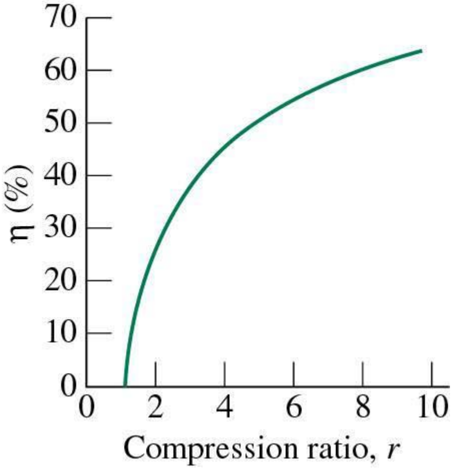
  - Cycle efficiency:

$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{u_3 - u_4 + u_1 - u_2}{u_3 - u_2}$$





Compression ratio: $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$



Internal combustion engines

- Air-standard Diesel cycle:
  - 1-2: Isentropic compression

$$\frac{W_{12}}{m} = u_1 - u_2$$

  - 2-3: Constant-pressure heat transfer

$$\frac{W_{23}}{m} = p_2(v_3 - v_2) \qquad \frac{Q_{23}}{m} = u_3 - u_2 + \frac{W_{23}}{m}$$

  - 3-4: Isentropic expansion

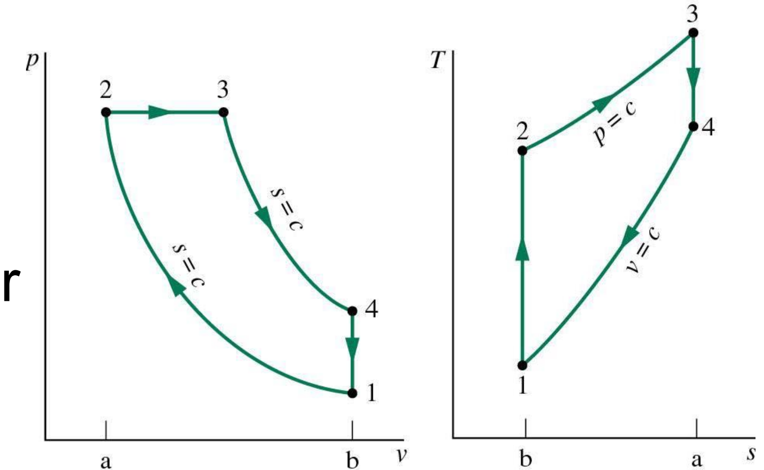
$$\frac{W_{34}}{m} = u_3 - u_4$$

  - 4-1: Constant-volume heat rejection

$$\frac{Q_{41}}{m} = u_1 - u_4$$

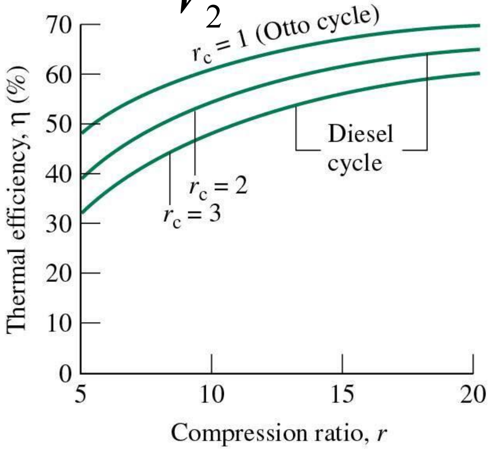
  - Cycle efficiency:

$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_2 - u_4 + u_1}{h_3 - h_2}$$



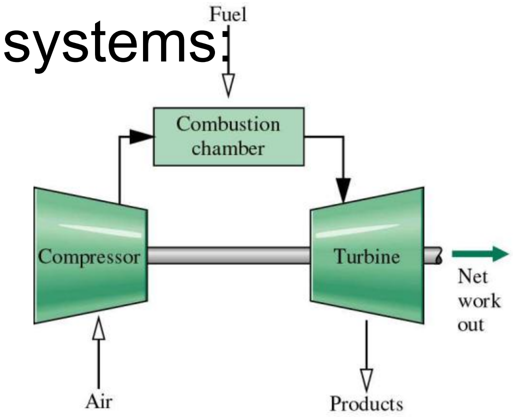
Compression ratio: $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$

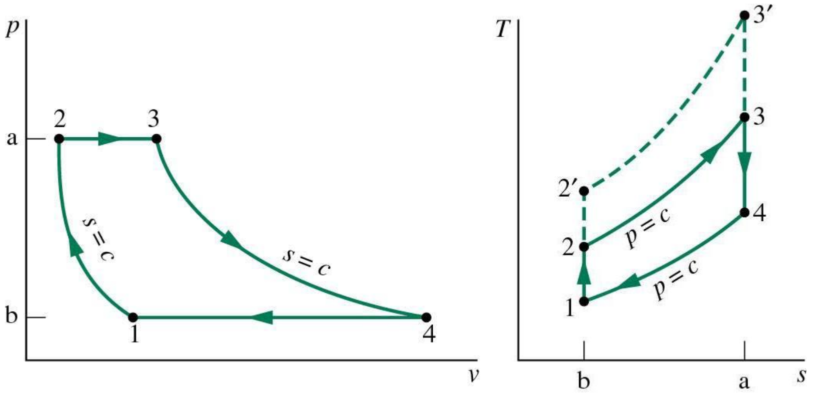
Cut-off ratio: $r_c = \frac{V_3}{V_2}$



Gas turbine power plants

- Gas turbine systems:





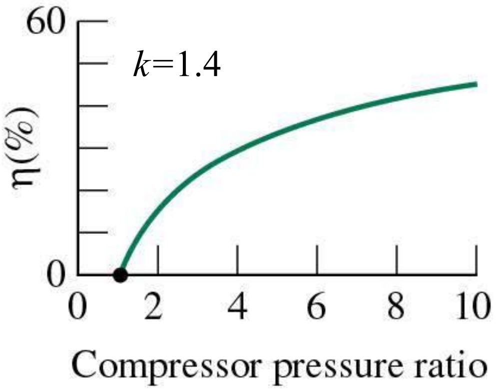
- Air-standard Brayton cycle (ideal):
  - 1-2: Isentropic compression $\frac{\dot{W}_{12}}{\dot{m}} = h_1 - h_2$
  - 2-3: Isobaric heat transfer $\frac{Q_{23}}{m} = h_3 - h_2$
  - 3-4: Isentropic expansion $\frac{\dot{W}_{34}}{\dot{m}} = h_3 - h_4$
  - 4-1: Isobaric heat transfer $\frac{Q_{41}}{m} = h_1 - h_4$

Cycle efficiency:

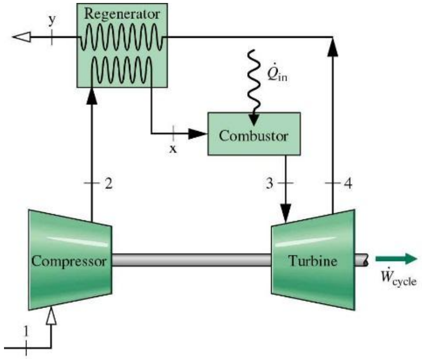
$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2}$$

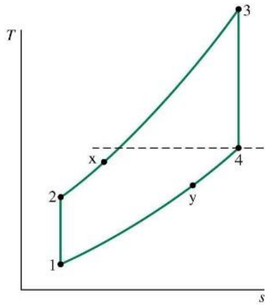
Gas turbine power plants

- Air-standard Brayton cycle: pressure ratio effect on performance
  - Efficiency increases with increasing pressure ratio

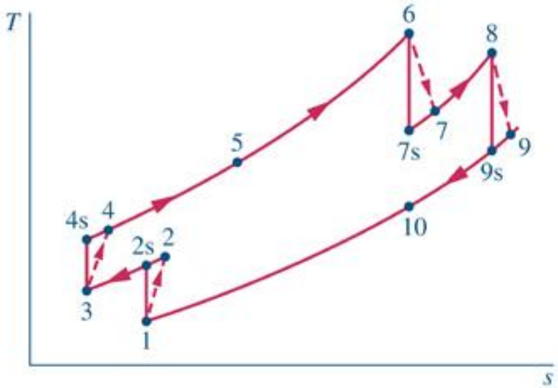


  - Regeneration:



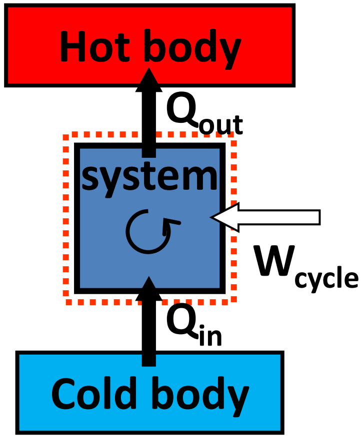


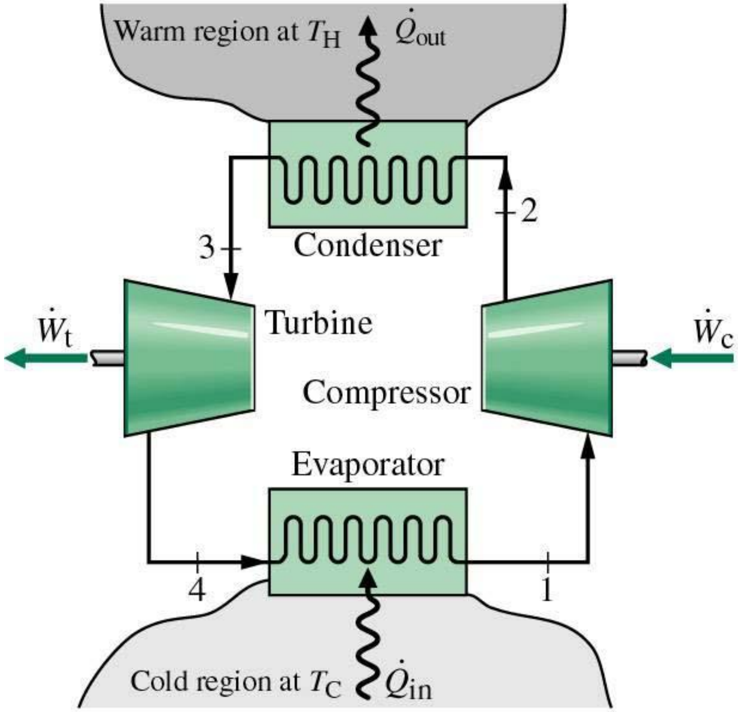
  - Reheating and intercooling:



Refrigeration and heat pump systems

- Refrigeration and heat pump
  - Maintain cold temperature below temperature of surrounding
  - Maintain high temperature above temperature of surrounding





Vapor-compression refrigeration system

- Practical refrigeration/heat pump cycle, ideal:
  - 1-2: Isentropic compression

$$\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$$

  - 2-3: Isobaric heat rejection

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$

  - 3-4: throttling process

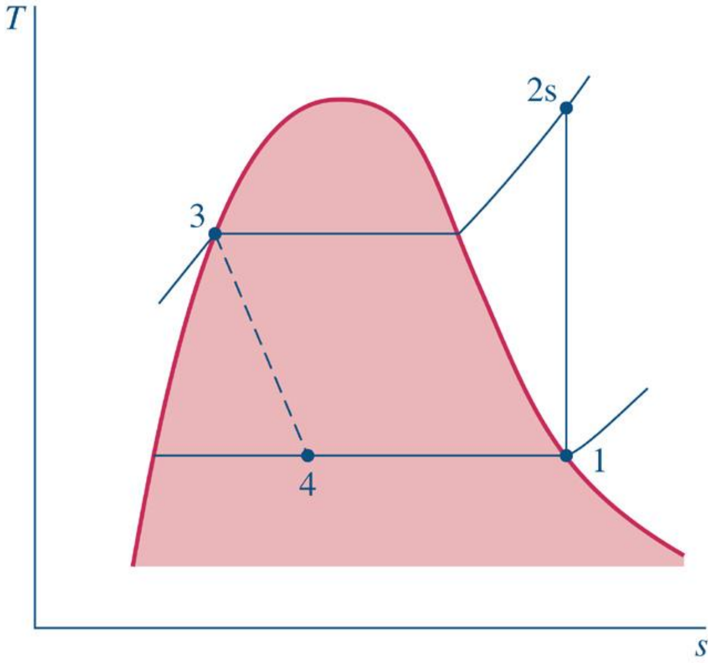
$$h_3 = h_4$$

  - 4-1: Isobaric heat addition

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

  - Coefficient of performance: $\mathrm{COP}_{\mathrm{cm}} = \frac{h_1 - h_4}{h_2 - h_1} < \mathrm{COP}_{\mathrm{cm,max}}$

$$\mathrm{COP}_{\mathrm{hm}} = \frac{h_2 - h_3}{h_2 - h_1} < \mathrm{COP}_{\mathrm{hm,max}}$$



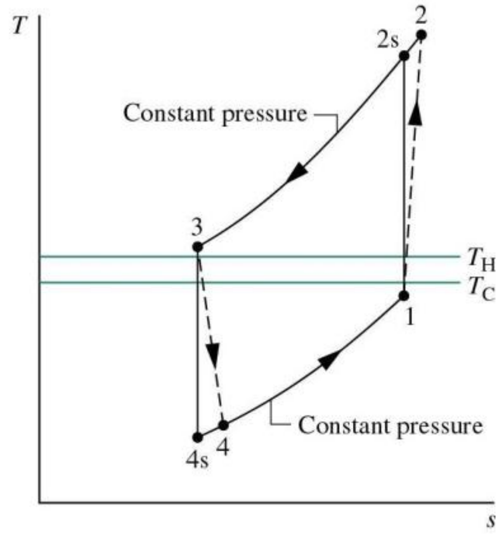
Gas refrigeration systems

- Gas refrigeration systems, Brayton refrigeration cycle
  - 1-2: (Isentropic) compression

$$\frac{\dot{W}_{\mathrm{c}}}{\dot{m}} = h_1 - h_2$$

  - 2-3: Isobaric cooling

$$\frac{\dot{Q}_{\mathrm{out}}}{\dot{m}} = h_3 - h_2$$



  - 3-4: (Isentropic) expansion

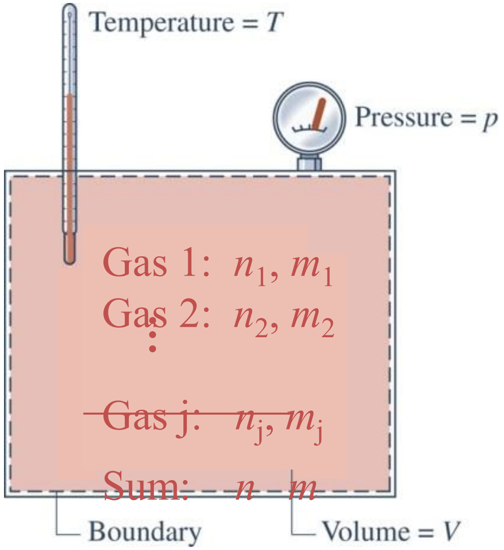
$$\frac{\dot{W}_{\mathrm{t}}}{\dot{m}} = h_3 - h_4$$

  - 4-1: Isobaric evaporation

$$\frac{\dot{Q}_{\mathrm{in}}}{\dot{m}} = h_1 - h_4$$

  - Coefficient of performance: $\mathrm{COP}_{\mathrm{cm}} = \dfrac{h_1 - h_4}{\left|h_1 - h_2 - (h_3 - h_4)\right|}$

Mixtures



- The mass, number of moles, and molecular weight M_i of component are related by:

$$n_i = \frac{m_i}{M_i}$$

- The ***mass fraction*** is the relative amount of each component in the mixture. The mass fraction mf_i of component i is:

$$mf_i = \frac{m_i}{m}$$

- Dalton model: assumes ***each component behaves as an ideal gas*** as if it were alone at T and V. *But* individual components do not exert the mixture pressure p but a ***partial pressure*** denoted by p_i:

$$p_i = \frac{n_i \overline{R} T}{V}$$

- p_i can be determined alternatively from:

$$p_i = y_i p$$

Mixtures

Evaluating *U*, *H*, and *S* for Ideal Gas Mixtures

- when working on a molar basis expressions for ***U***, ***H***, and ***S*** of a mixture consisting of several components are

$$U = n_1\tilde{u}_1 + n_2\tilde{u}_2 + \cdots + n_j\tilde{u}_j = \sum_{i=1}^{j} n_i\tilde{u}_i(T)$$

$$H = n_1\tilde{h}_1 + n_2\tilde{h}_2 + \cdots + n_j\tilde{h}_j = \sum_{i=1}^{j} n_i\tilde{h}_i(T)$$

$$S = n_1\tilde{s}_1 + n_2\tilde{s}_2 + \cdots + n_j\tilde{s}_j = \sum_{i=1}^{j} n_i\tilde{s}_i(T, p_i)$$

- Then for perform thermodynamic analyses of systems involving nonreacting ideal gas mixtures no new fundamental principles are required.

Definitions

- Humidity ratio

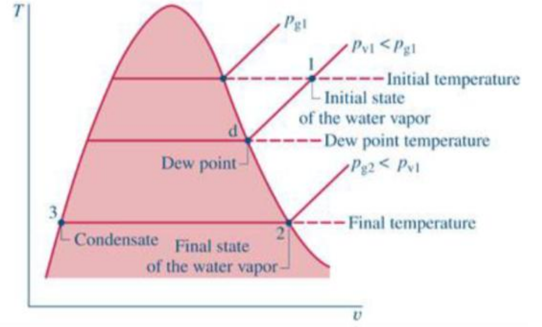
$$\omega = \frac{m_v}{m_a}$$

$$\omega = \frac{m_v}{m_a} = \frac{\dfrac{M_v p_v V}{\bar{R}T}}{\dfrac{M_a p_a V}{\bar{R}T}} = \frac{M_v p_v}{M_a p_a} = 0.622\frac{p_v}{p_a} = 0.622\frac{p_v}{p - p_v}$$

- Relative humidity

$$\phi = \left.\frac{y_v}{y_{v,sat}}\right)_{T,p}$$

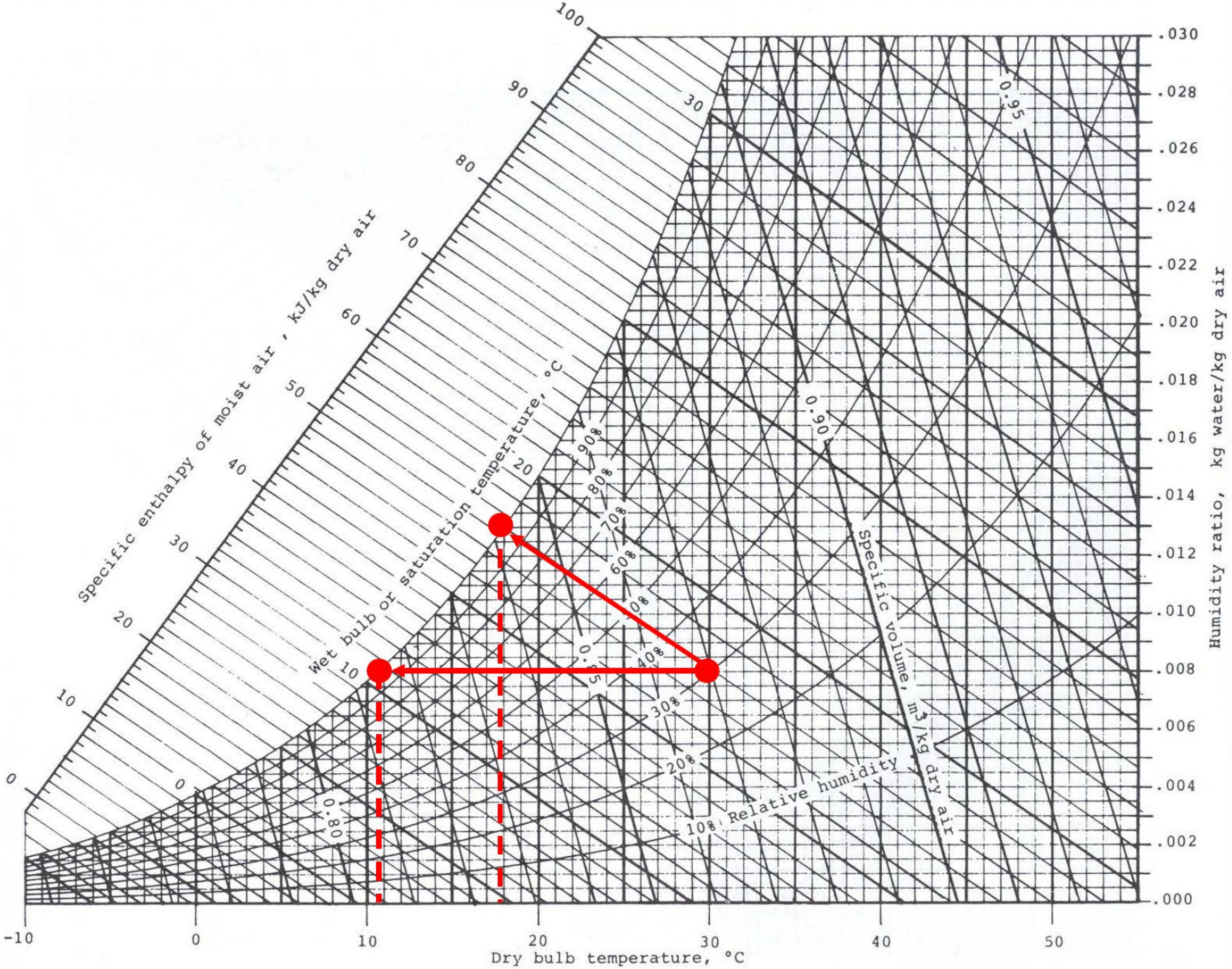
$$\left.\begin{aligned} p_v &= y_v p \\ p_g &= y_{v,sat} p \end{aligned}\right\} \rightarrow \phi = \left.\frac{p_v}{p_g}\right)_{T,p}$$



- Dew point temperature, wet bulp temperature, dry bulp temperature, and adiabatic saturation temperature:

$$\omega = \frac{h_a(T_{as}) - h_a(T) + \omega'\left[h_g(T_{as}) - h_f(T_{as})\right]}{h_g(T) - h_f(T_{as})}$$

Psychrometric chart



Source: ASHRAE Transactions, 1988.

Final Exam Format

- 3 hours one-session written exam: Thursday 22.01.2026 from 15h15 to 18h15 (in STCC, detailed seat assignment TBD)

- 16 multiple choice questions, testing your understanding on key concepts and simple calculation + 2 calculation/analysis questions

- You are allowed to bring a cheat sheet (one A4 paper; you can write things on both sides) and a **calculator** with you to the exam.

- **A favor to ask**: fill in the course evaluation form after finishing your test

- Q&A to prepare for exam: **January 16, 10:00**
  - Option 1: in-person (room TBD)
  - Option 2: zoom (link TBD)