EPFL

ETA-Lab
Energy Transport Advances

ME-251: Thermodynamics and energetics I
Open Systems III

Zhengmao Lu

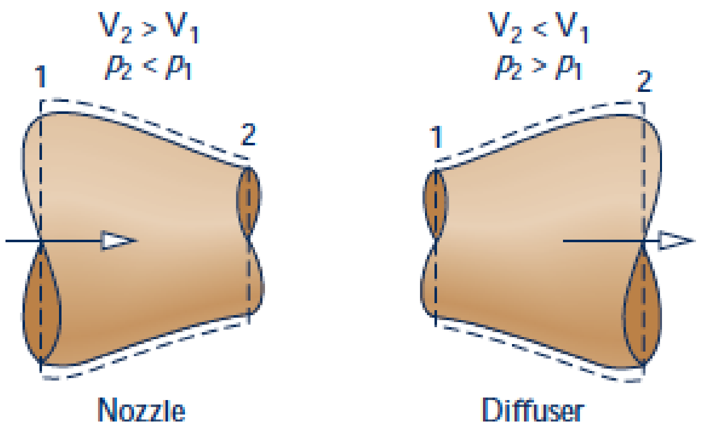
Energy Transport Advances Laboratory

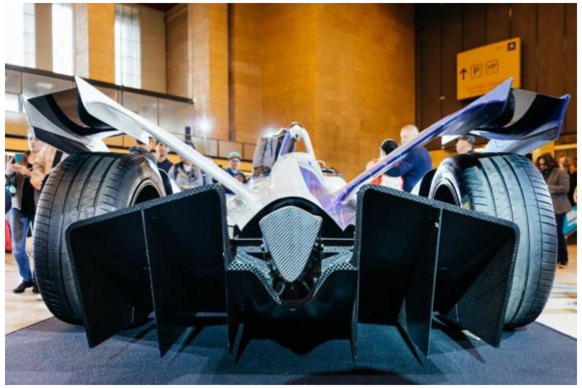
EPFL Mechanical Engineering

2025 Fall Semester

Photo Credit: Trougnouf

Last Time





Steady state, one inlet and one exit

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

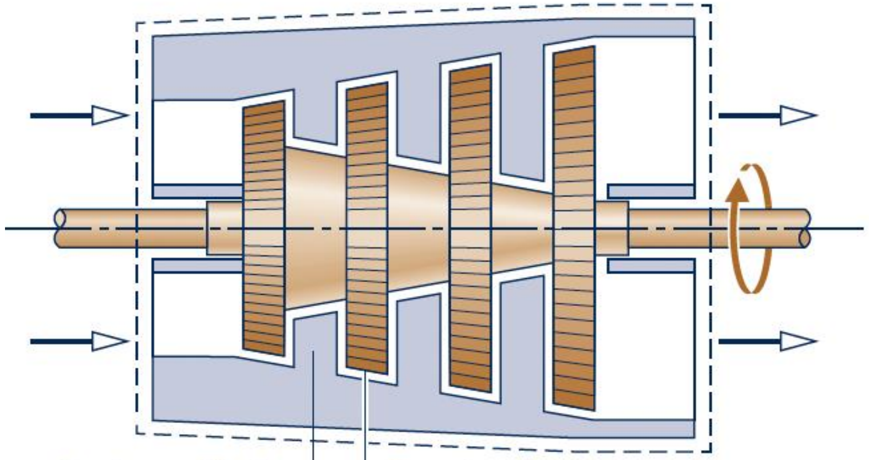
Neglecting changes in PE and heat transfer (assumption)

$$h_1 - h_2 + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2} = 0$$

No work other than flow work, $\dot{W}_{cv} = 0$

Last Time

Steady-state steam/gas turbine



One inlet and one exit

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

Neglecting changes in KE and PE (assumption)

$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2) = 0$$

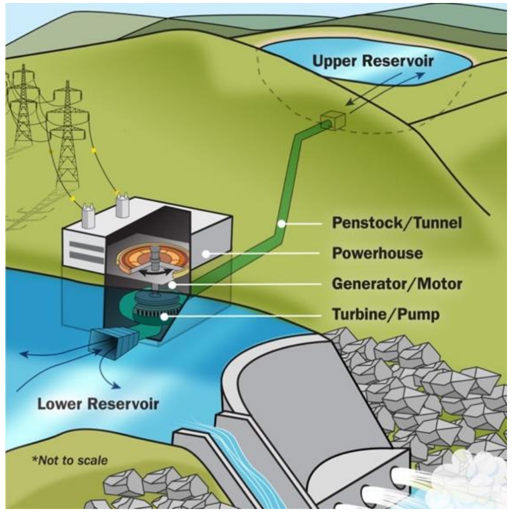
Further neglecting heat transfer (assumption)

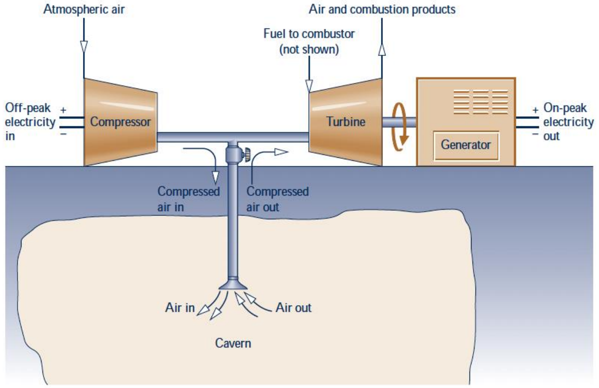
$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

$\dot{W}_{cv} > 0$ for turbines

Last Time

Pump and compressor





Steady state, one inlet one exit $\dot{m}_i = \dot{m}_e = \dot{m}$

Ignoring KE change and heat transfer (assumption)

$$-\dot{W}_{cv} + \dot{m}(h_1 - h_2 + g(z_1 - z_2)) = 0$$

For compressors (gas), often further neglecting PE change (assumption)

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

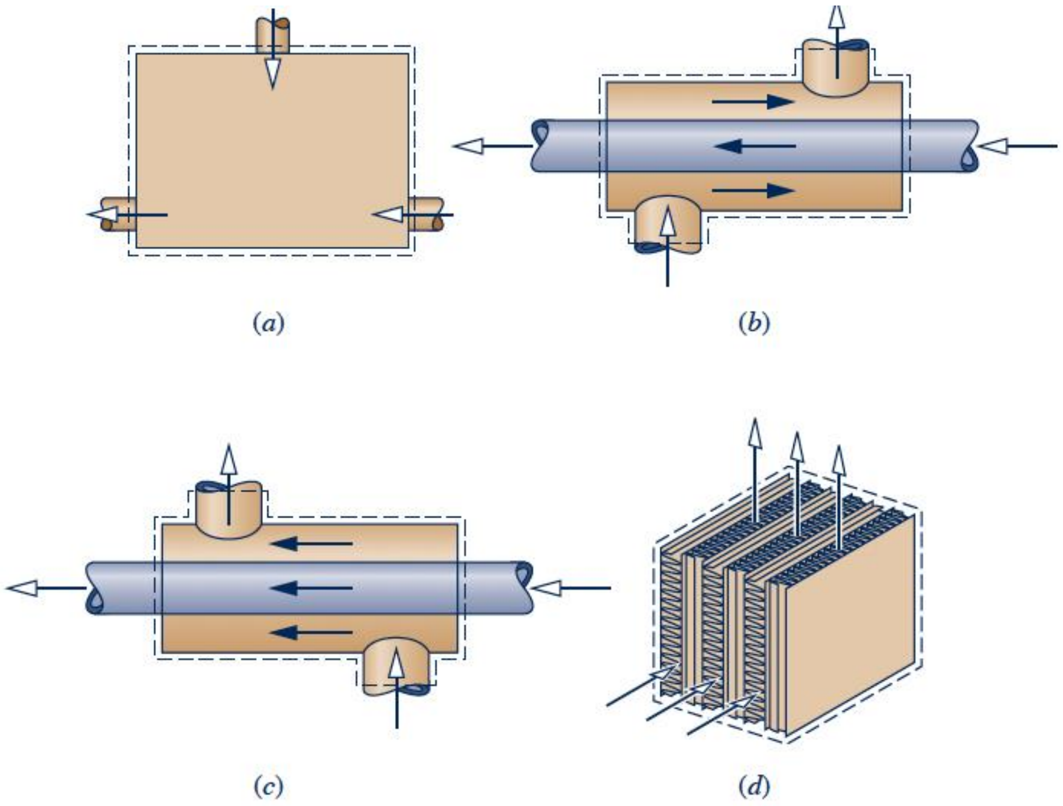
$\dot{W}_{cv} < 0$ for compressors and pumps

ILOs for Today

- Apply 1st law to heat exchangers and throttling valves
- Quick review of what we have learned so far
- Motivating the 2nd law of thermodynamics

Reading: 4.9-4.11, 5.1

Heat Exchangers



(a) Direct contact heat exchanger (mixing chamber)

(b) Tube-within-a-tube counterflow heat exchanger

(c) Tube-within-a-tube parallel flow heat exchanger

(d) Cross-flow heat exchanger

Modeling Heat Exchangers (Steady State)

Multi-inlets, multi-exits $\sum_i \dot{m}_i = \sum_o \dot{m}_o$

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

Flow work only $\dot{W}_{cv} = 0$

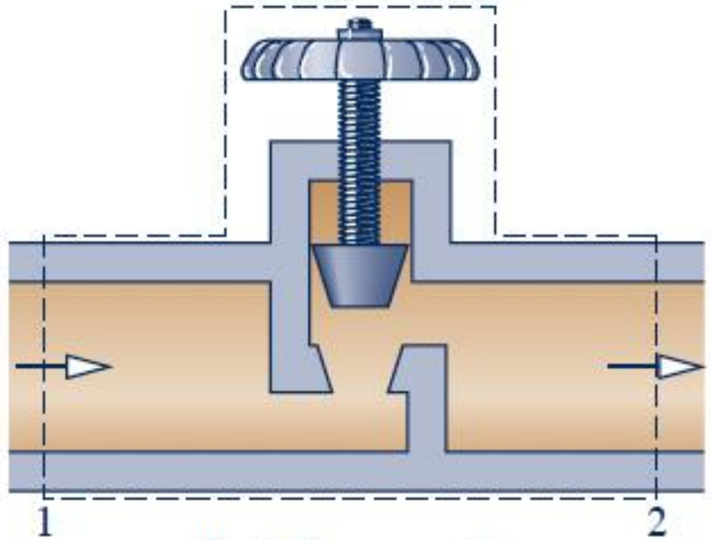
Neglecting KE and PE changes (assumption)

$$0 = \dot{Q}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e$$

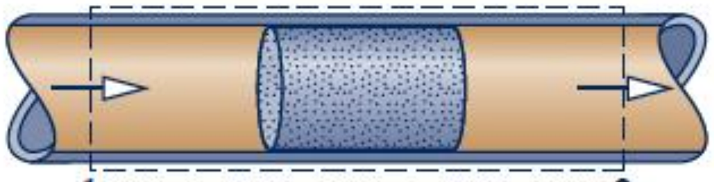
Further neglecting heat transfer with surroundings (assumption)

$$\sum_i \dot{m}_i h_i = \sum_e \dot{m}_e h_e$$

Throttling Devices (Steady State)



Adding a partially opened valve or a porous plug to reduce pressure



One inlet and one exit

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

Flow work only $\dot{W}_{cv} = 0$

$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 - h_2 + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2} + g(z_1 - z_2)\right) = 0$$

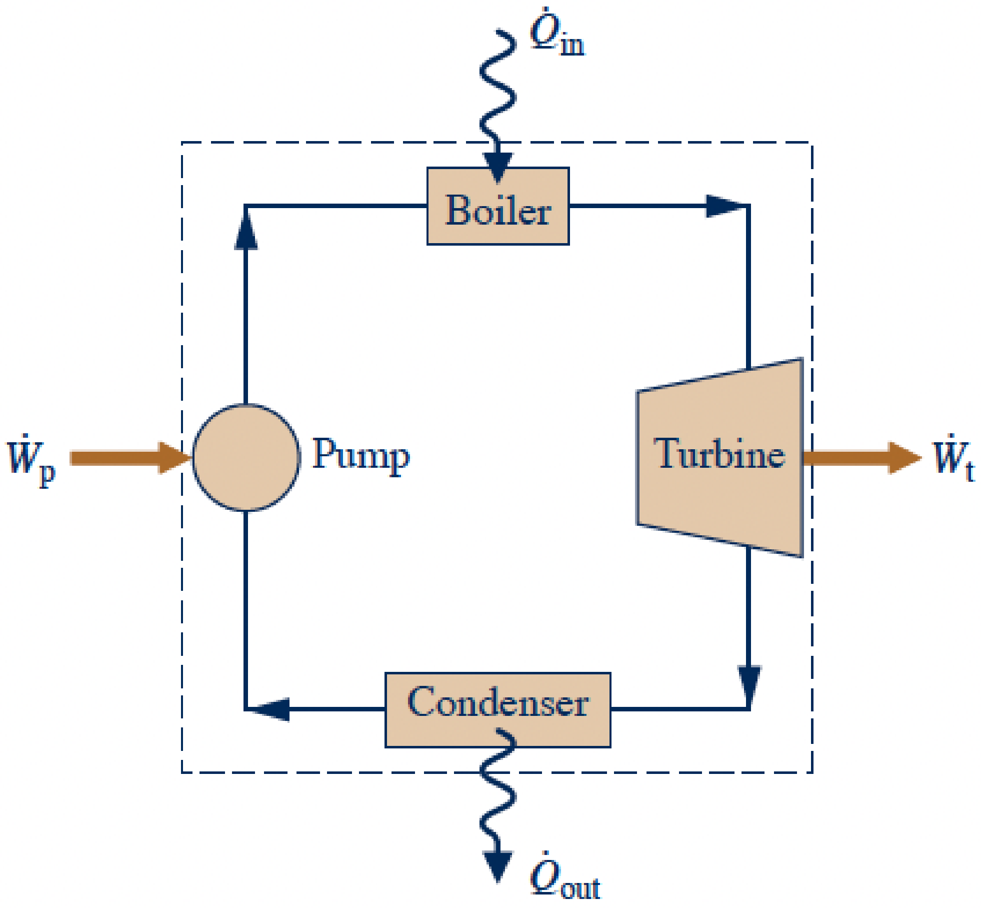
Neglecting heat transfer and PE change (assumption)

$$h_1 - h_2 + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2} = 0$$

Further neglecting KE difference between downstream and upstream (assumption)

$$h_1 = h_2$$

System Integration

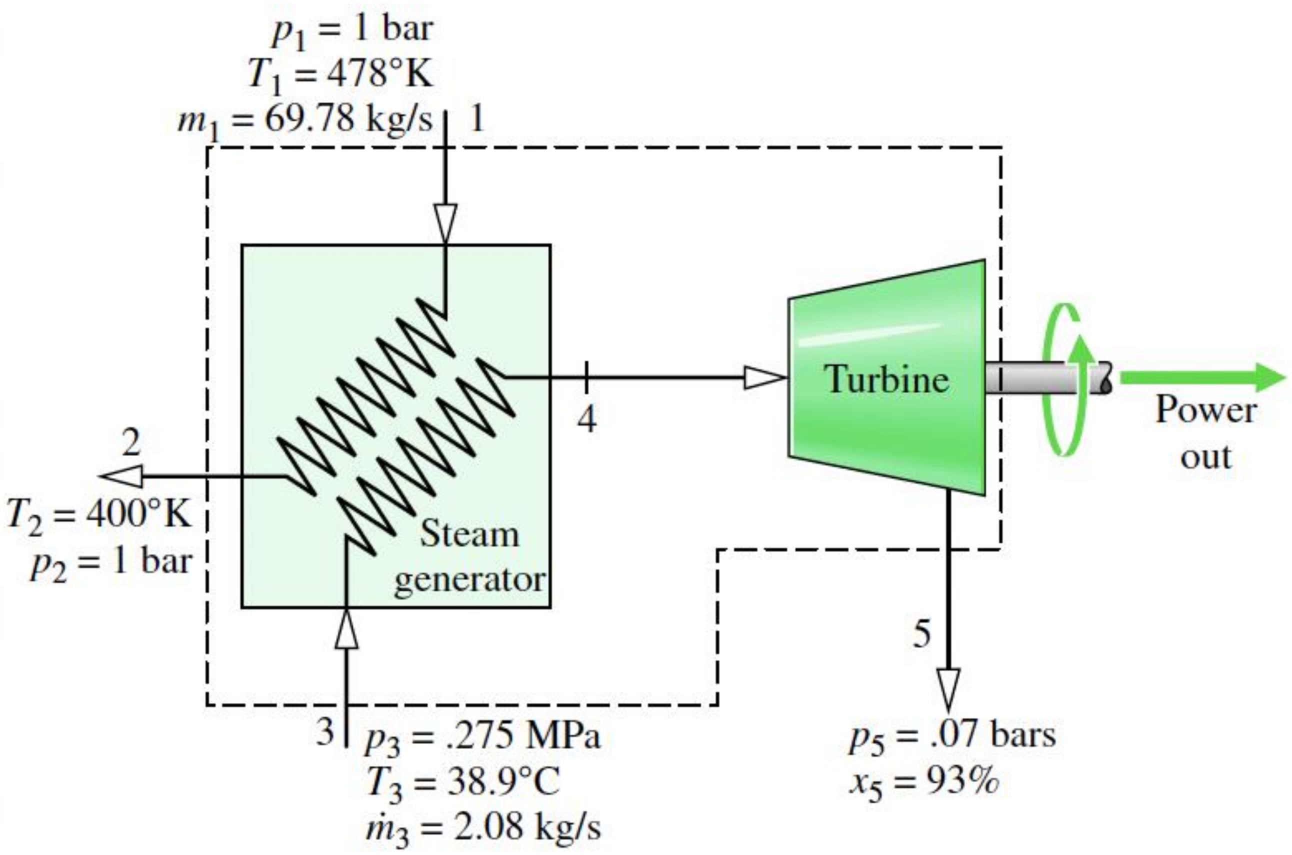


Applying 1st law to a simple vapor power cycle at steady state

$$0 = \left(\dot{Q}_{in} - \dot{Q}_{out}\right) - \left(\dot{W}_t - \dot{W}_p\right)$$

Moran Example 4.10

Combustion product



Steady-state waste heat recovery system

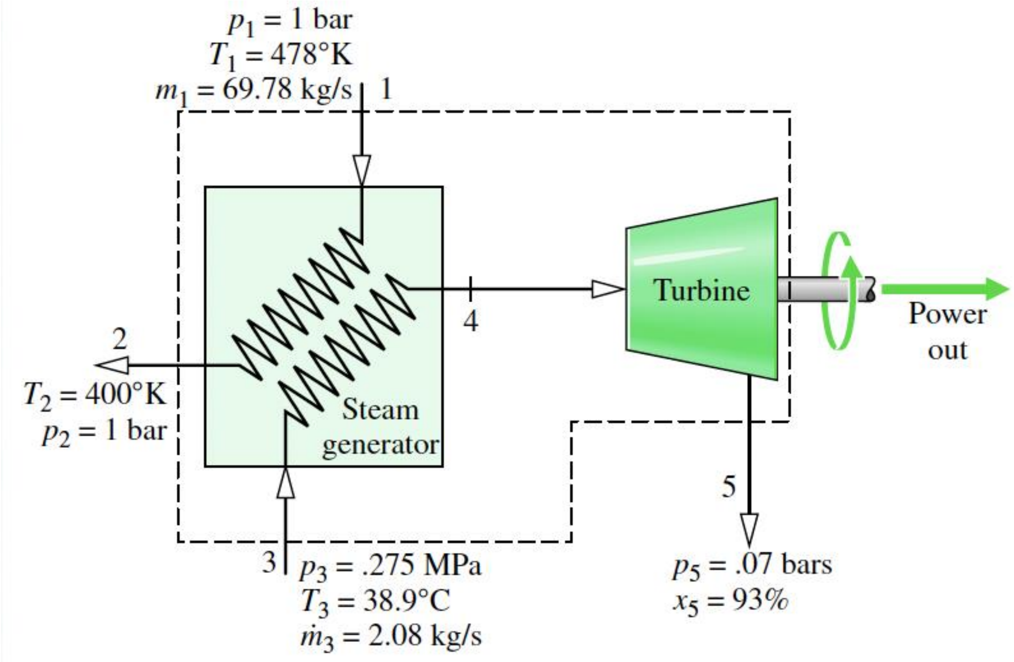
Heat exchange between the CV and the surrounding negligible

Neglect pressure drop for water flowing through the steam generator

Combustion product modeled as air with perfect gas behavior $c_p = 1005$ J/kg/K

Determine the power output of the turbine and the turbine inlet temperature

Moran Example 4.10



Mass conservation

$$\dot{m}_1 = \dot{m}_2 \qquad \dot{m}_3 = \dot{m}_5$$

Steady-state energy balance

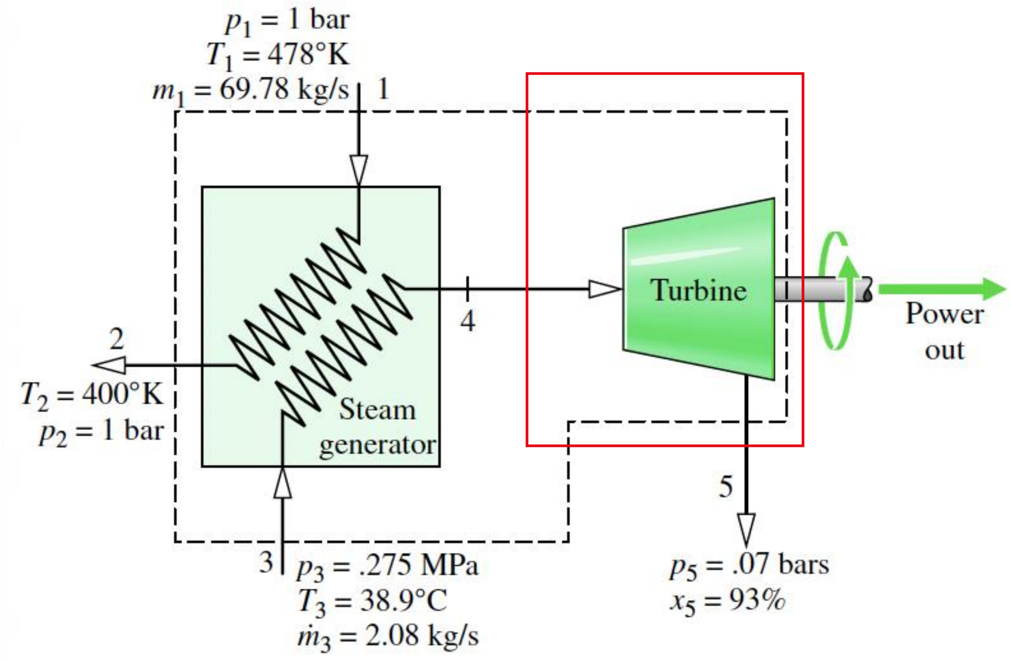
$$0 - \dot{W}_{cv} + \dot{m}_1 h_1 + \dot{m}_3 h_3 - \dot{m}_2 h_2 - \dot{m}_5 h_5 = 0$$

$$\dot{W}_{cv} = \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_5)$$
$$= \dot{m}_1 c_p(T_1 - T_2) + \dot{m}_3(h_3 - h_5)$$

With a property database, one can get $h_3(p_3, T_3)$ and

$$h_5 = h_f(p_5) + 0.93(h_g(p_5) - h_f(p_5))$$

Moran Example 4.10



No pressure drop along steam generator

$$p_4 = p_3$$

Mass conservation $\dot{m}_4 = \dot{m}_5 = \dot{m}_3$

Steady-state energy balance

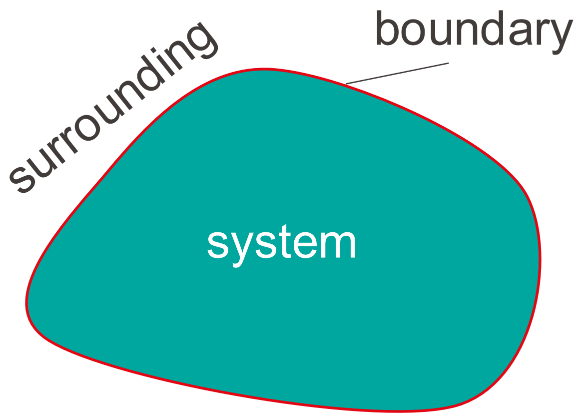
$$0 - \dot{W}_{cv} + \dot{m}_4 h_4 - \dot{m}_5 h_5 = 0$$

$$h_4 = h_5 + W_{cv}/\dot{m}_3$$

General Concepts

WIKIPEDIA
The Free Encyclopedia

Thermodynamics is a branch of physics that deals with heat, work, and temperature, and their relation to energy, entropy, and the physical properties of matter and radiation.

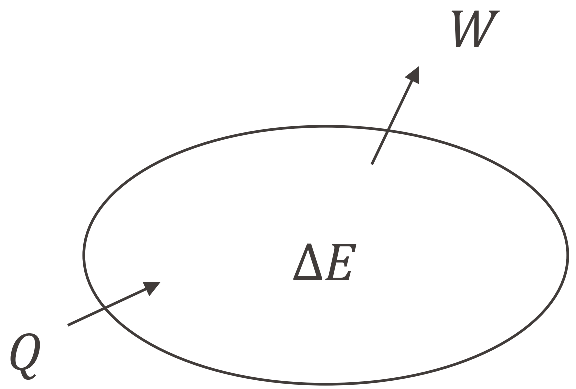


To perform thermodynamics analysis, we need to define the **system**, the **surrounding** and the **boundary** that separate the two

We consider **work transfer, mass transfer, heat transfer** across the boundary

1^{st} Law for Closed Systems

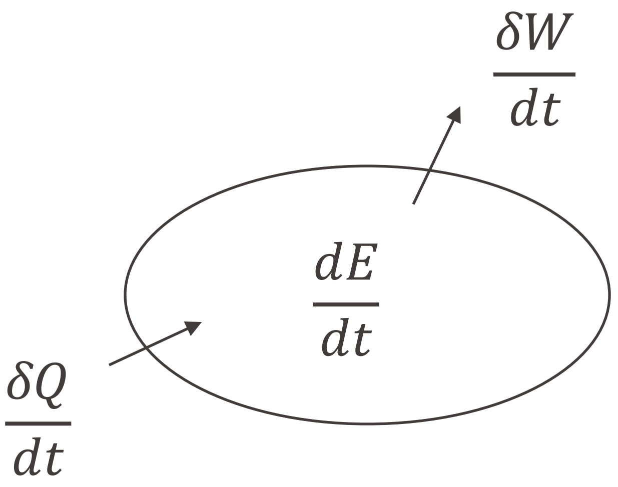
Change in the amount of energy contained within a system during some time interval	=	Net amount of energy transferred into the system by heat transfer during the time interval	−	Net amount of energy transferred out of the system by work during the time interval



$$\Delta E = E_2 - E_1 = Q - W \quad \text{in [J]}$$

Time Rate Form of 1st Law for Closed Systems

Time rate of change in the amount of energy contained within a system at time *t*	=	Net rate at which energy is transferred **into** the system by heat transfer at time *t*	−	Net rate at which energy is transferred **out of** the system by work at time *t*



$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

Heat flow rate - Power

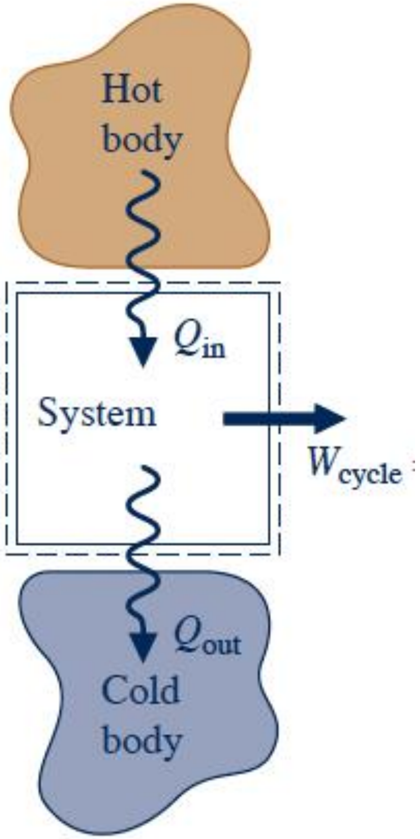
Everything is in [W]

1st Law for Closed Systems

Energy change in kinetic energy, potential energy, and internal energy

Energy transfer: **work** (expansion/compression, shaft, electric,…)
heat (conduction, convection, radition)

Thermodynamic Cycles

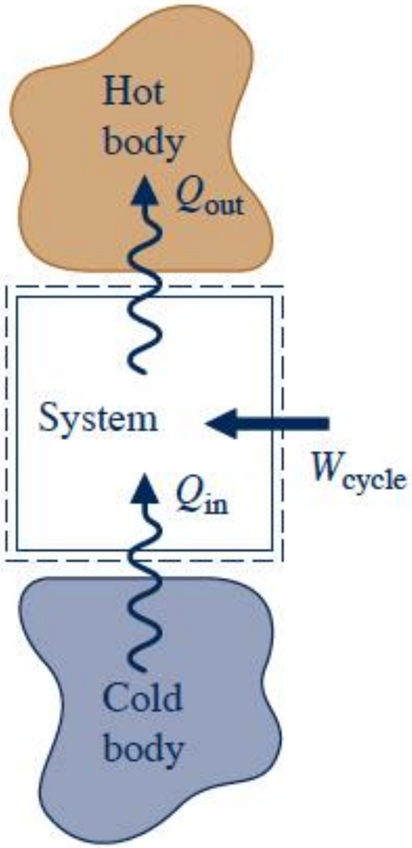


Power cycle

$$W_{cycle} = Q_{in} - Q_{out}$$

Output

$$\eta = \frac{W_{cycle}}{Q_{in}}$$



Refrigeration and heat pump cycle

$$W_{cycle} = Q_{out} - Q_{in}$$

Input

$$\beta_{ACR} = \frac{Q_{in}}{W_{cycle}}$$

$$\gamma_{HP} = \frac{Q_{out}}{W_{cycle}}$$

How to Describe a System's Intensive State

- **State principle**: for closed systems

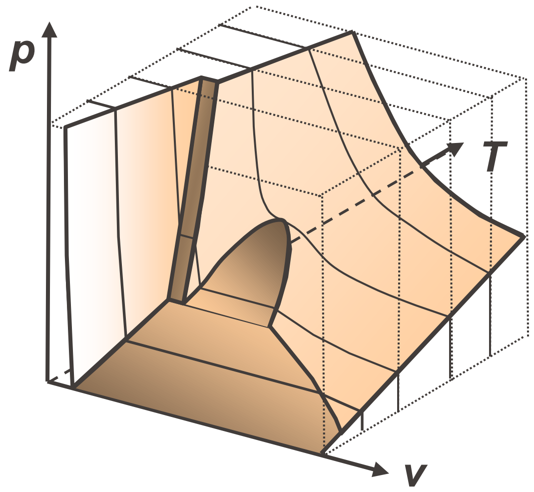
# of independent properties = # of relevant work exchange modes + 1 (associated with heat)

  - E.g., for gas in a piston-cylinder assembly, number of independent properties 2 (**temperature** associated with heat transfer and pressure associated with **compression/expansion work**)

- **Simple system**: only one work exchange mode as the system undergoes quasiequilibrium processes (**two independent properties**).

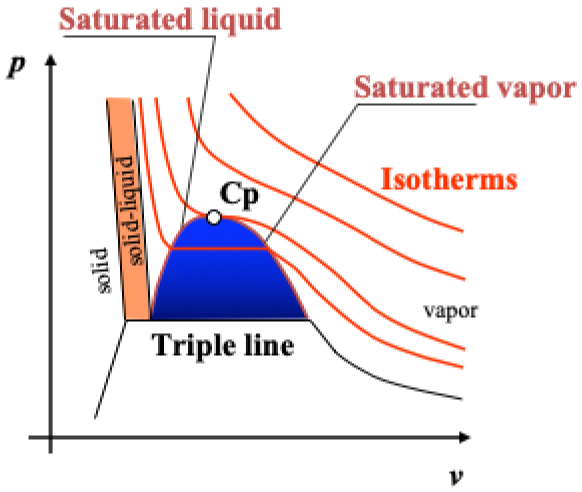
Equation of State

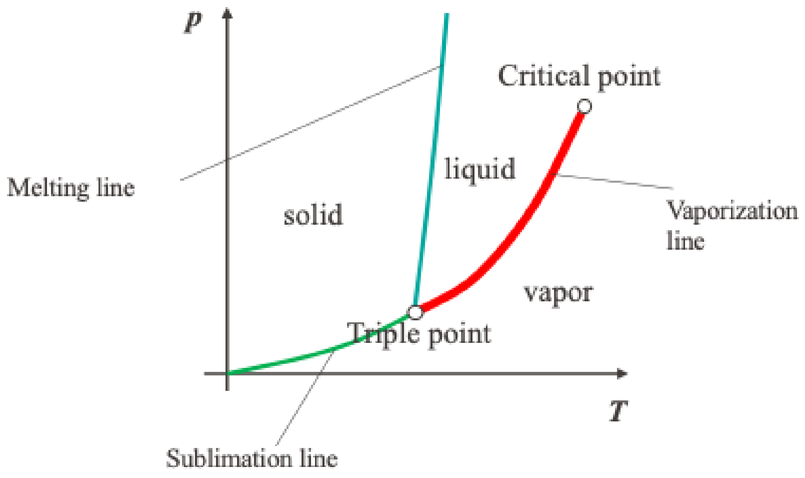
- Single phase region
- Two phase region
- Saturation states
- Critical point
- Triple line

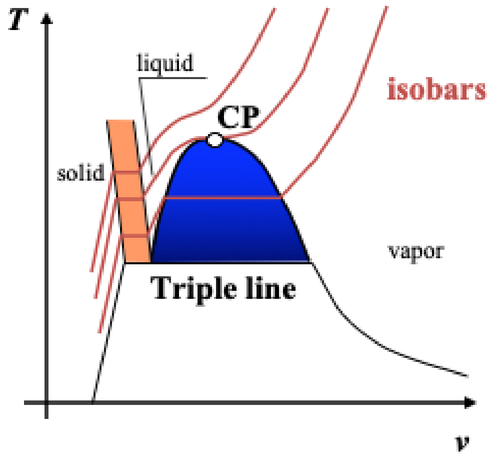


Equation of State

- p-v diagram
- T-v diagram
- p-T phase diagram
- Steam quality



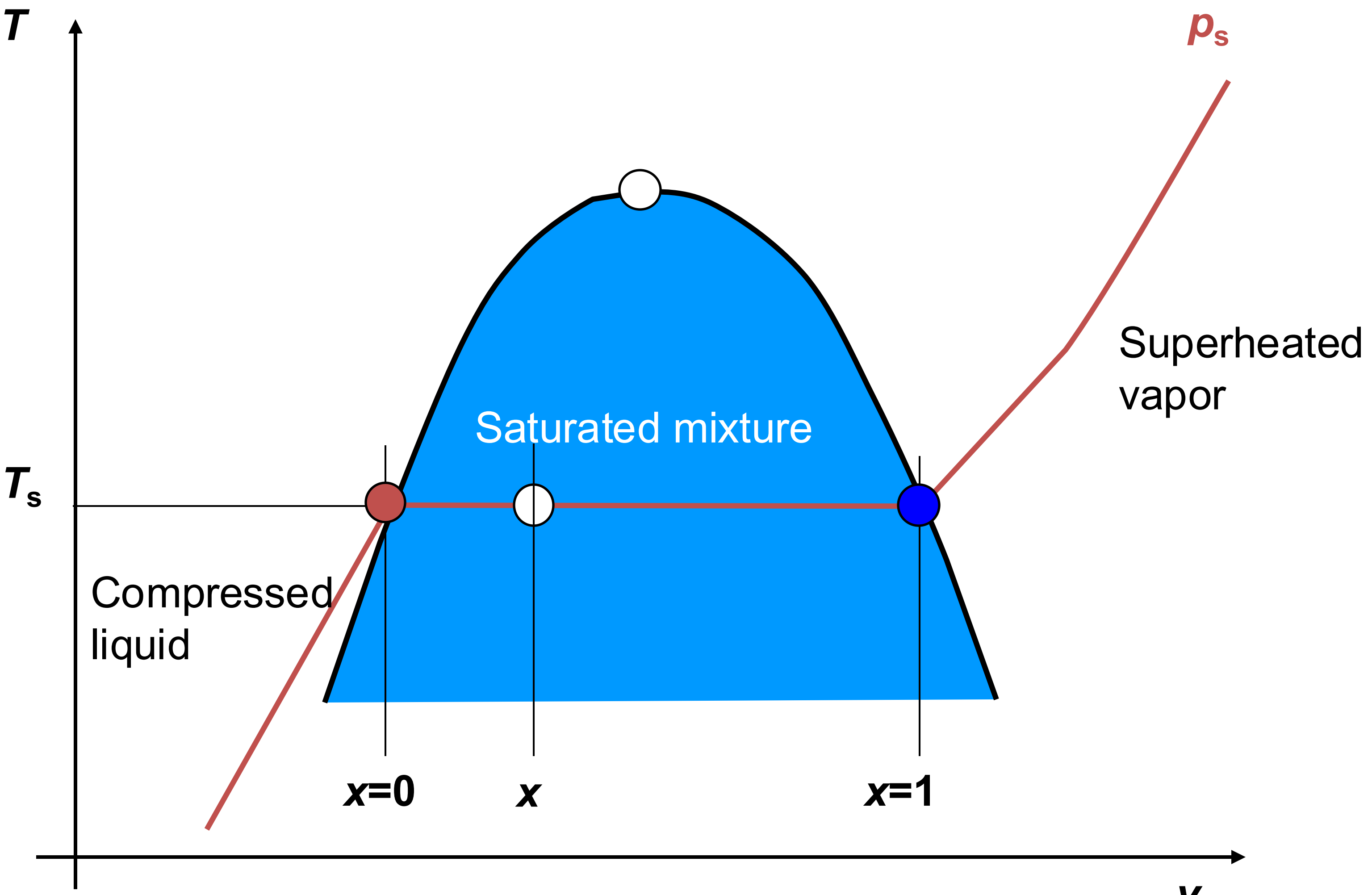




Compressed Liquid and Superheated Vapor

For per mass properties *y* (e.g., *v, h, u*)

$$y(x) = xy_g + (1-x)y_f$$



Thermodynamic Properties

- Specific enthalpy $h = u + pv$ [J/kg]
- Specific heat at a constant volume $c_v = \left(\frac{\partial u}{\partial T}\right)|_v$
- Specific heat at a constant pressure $c_p = \left(\frac{\partial h}{\partial T}\right)|_p$

Incompressible Substance

- Liquids and solids are often modeled as incompressible v = const

$$u = u(T) \qquad c_v = \frac{du}{dT} = c(T) = c_p \qquad \text{At constant } T, dh = v dp$$

Ideal Gas

- $\frac{pv}{RT} = \frac{p\tilde{v}}{\tilde{R}T} = Z \equiv 1$, the dilute limit of real gases

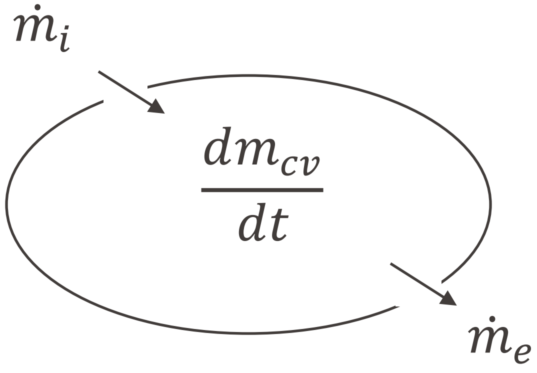
  T: temperature [K]
  $\tilde{R}$: universal gas constant [J/K/mol]
  R: specific gas constant [J/K/kg]
  $\tilde{v}$: molar volume [m^3/mol]

$u = u(T)$ $\quad$ $h = u + pv = u(T) + RT$ $\quad$ $c_v = \frac{du}{dT} = c(T)$ $\quad$ $c_p = c_v(T) + R$

Specific heat ratio $k = \frac{c_p}{c_v} = 1 + \frac{R}{c_v}$

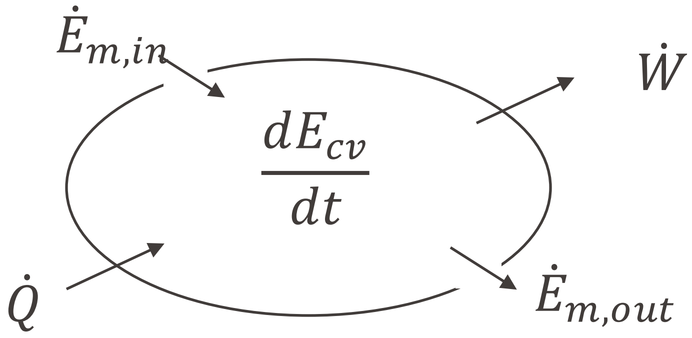
Perfect gas c_v is constant, or equivalently c_p is constant or k is constant

1st Law for Open Systems



Mass balance

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$



Energy balance

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right) - \sum_o \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + g z_e \right)$$

1st Law for Open Systems

- Nozzle/diffuser $$h_i + \frac{V_i^2}{2} = h_e + \frac{V_e^2}{2}$$ Ignoring heat transfer, potential energy change

- Turbine, compressor, pump $$W_{cv} = \dot{m}\left(h_i - h_e + +g(z_i - z_e)\right)$$ Ignoring heat transfer and KE change

- Heat exchanger $$0 = \dot{Q}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e$$ Ignoring mechanical energy change

- Throttling device $$h_i = h_e$$ Ignoring heat transfer and mechanical energy change