Lecture 8

Topic 2

First Law of Thermodynamics

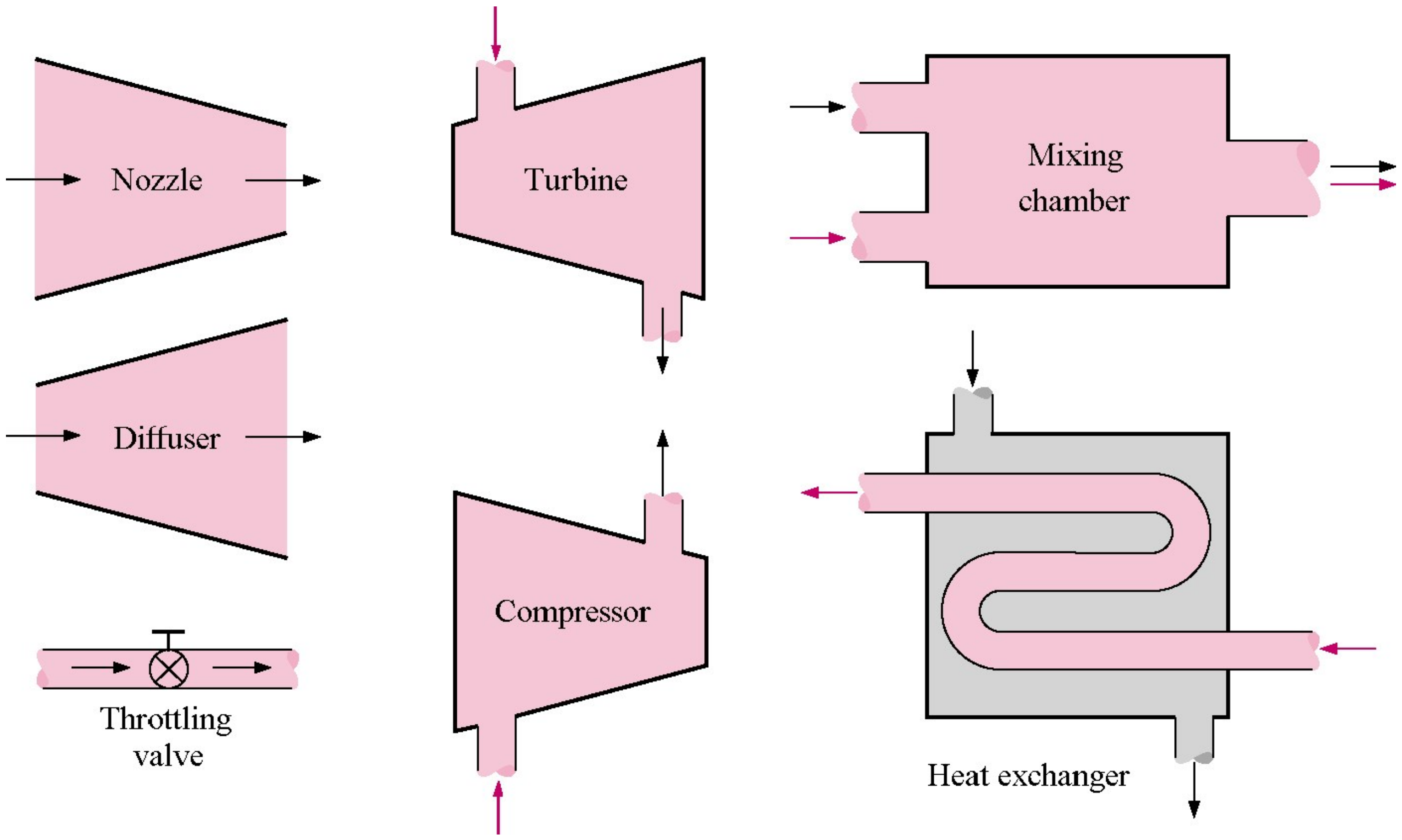
Topics

– **2.6 Steady flow Engineering Devices**

Reading:
Ch 4: 4.4 – 4.6 Borgnakke & Sonntag Ed. 8
Ch 5: 5-4 & 5-5 Cengel & Boles Ed. 5

2.6 Steady-Flow Engineering Devices

- In this lecture we will focus on mass and energy analysis for steady-flow engineering devices
- Below are example devices that we will cover



2.6 Key Equations

- Conservation of mass

$$\Delta \dot{m}_{system} = \sum \dot{m}_i - \sum \dot{m}_e$$

0
Steady state

$$\dot{m}_i = \dot{m}_e = \dot{m} \qquad \& \qquad \rho_i \vec{V}_i A_i = \rho_e \vec{V}_e A_e$$

- Conservation of energy

$$\Delta \dot{E}_{system} = \dot{Q}_{IN} - \dot{W}_{OUT} + \sum \dot{m}_i \left(h_i + \frac{\vec{V_i}^2}{2} + g z_i \right) - \sum \dot{m}_e \left(h_e + \frac{\vec{V_e}^2}{2} + g z_e \right)$$

0
Steady state

$$\dot{Q}_{IN} + \sum \dot{m}_i \left(h_i + \frac{\vec{V_i}^2}{2} + g z_i \right) = \dot{W}_{OUT} + \sum \dot{m}_e \left(h_e + \frac{\vec{V_e}^2}{2} + g z_e \right)$$

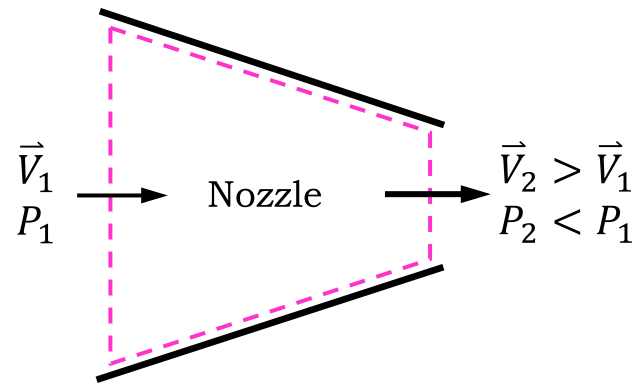
2.6.1 Nozzles and Diffusers

Nozzle

- Device used to increase fluid velocity at the expense of drop in pressure
- Contour designed to reduce exit area, reducing fluid pressure & increasing fluid velocity

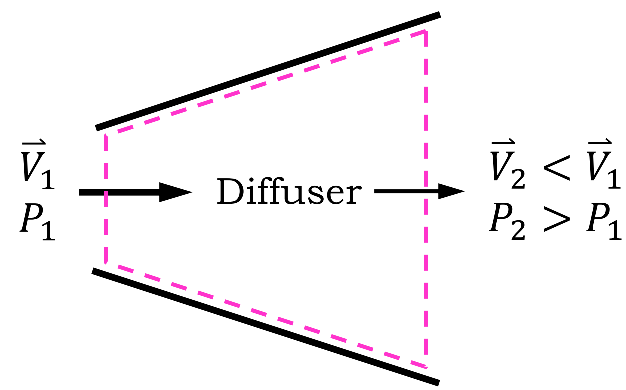
Diffuser

- Device used to decelerate fluid velocity, resulting in an increase of pressure
- Opposite of nozzle (direction of flow is reversed)



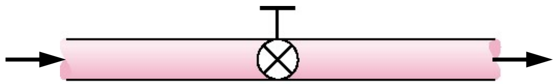
Equations

- Conservation of Mass: $\Delta \dot{m}_{system} = \dot{m}_1 - \dot{m}_2 = 0$
  - $\dot{m}_1 = \dot{m}_2 = \dot{m}$ & $\rho_1 \vec{V}_1 A_1 = \rho_2 \vec{V}_2 A_2$
- Conservation of Energy: $\Delta \dot{E}_{system} = 0\ (steady\ state)$
  - Adiabatic, no work, Δz = 0
  - $\cancelto{0}{\dot{Q}_{IN}} + \dot{m}_1\left(h_1 + \frac{\vec{V}_1{}^2}{2} + \cancelto{0}{gz_1}\right) = \cancelto{0}{\dot{W}_{OUT}} + \dot{m}_2\left(h_2 + \frac{\vec{V}_2{}^2}{2} + \cancelto{0}{gz_2}\right)$
  - $h_1 + \frac{\vec{V}_1{}^2}{2} = h_2 + \frac{\vec{V}_2{}^2}{2}$
  - $\vec{V}_2 = \sqrt{2(h_1 - h_2) + \vec{V}_1{}^2};\ \ h_2 = h_1 - \frac{1}{2}(V_2^2 - V_1^2)$



2.6.2 Throttling devices

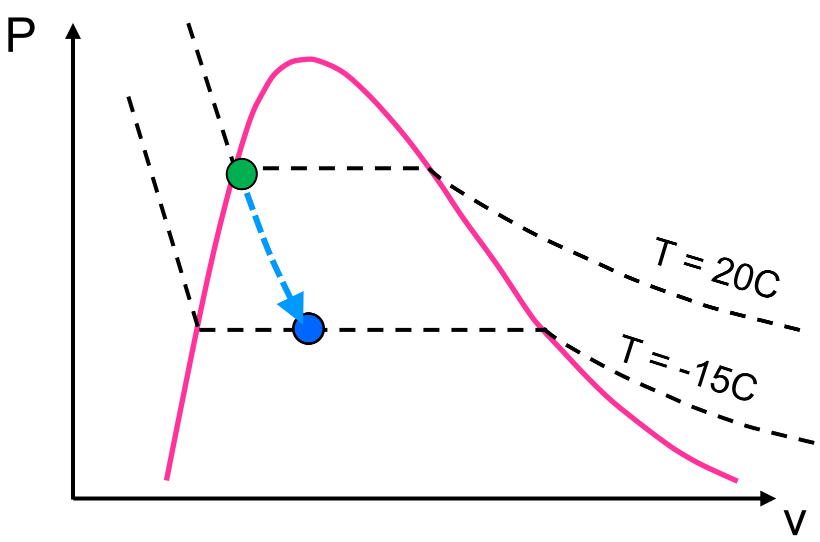
- Flow-restricting device that causes a <u>pressure drop</u> in the fluid
  - Examples: throttle valve, orifice plate, plug, capillary tube
- Similar to nozzle, but velocities are less significant
- Uses of a throttle
  - Control fluid flow rate
  - Phase change
    - Refrigeration: pressure drop from hot liquid to cold liquid + vapor mixture

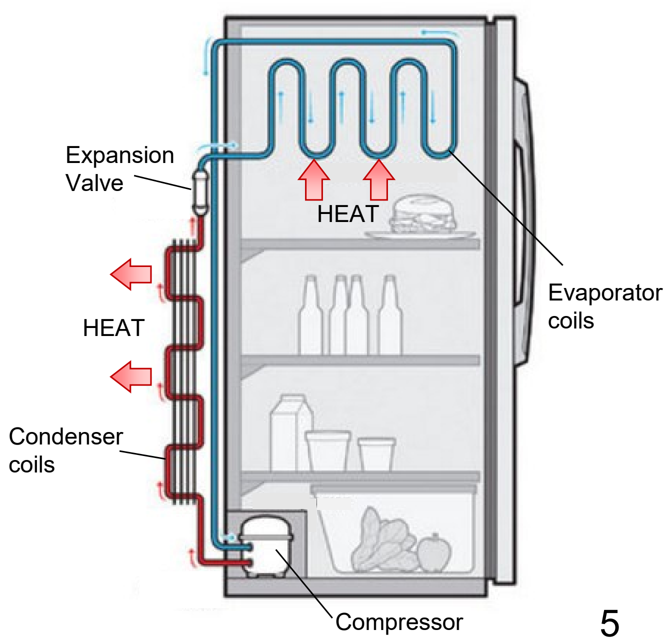


(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube





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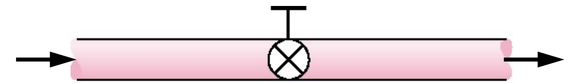

(a) An adjustable valve

(b) A porous plug

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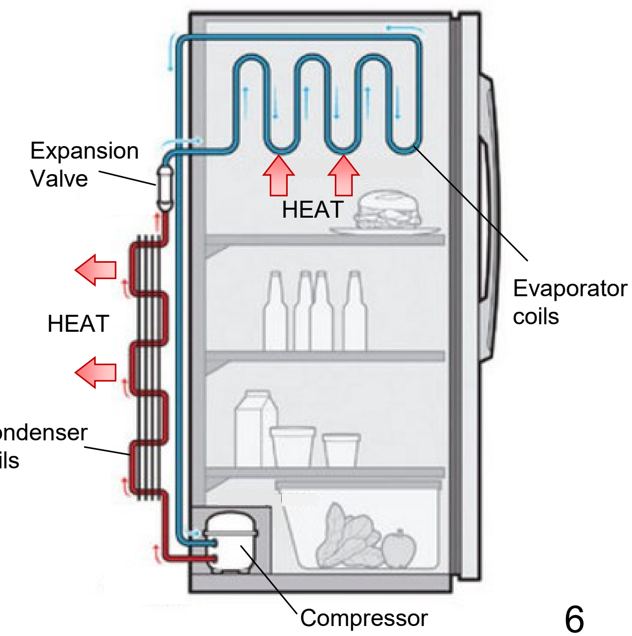

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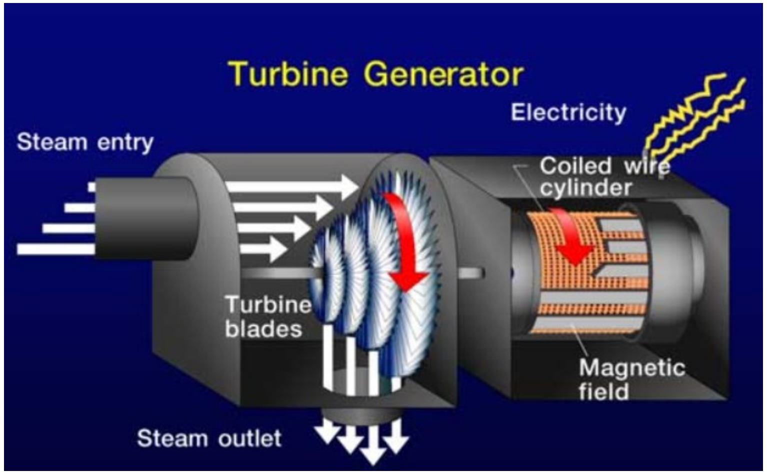
- Conservation of Energy: $\Delta\dot{E}_{system} = 0\ (steady\ state)$
  - Adiabatic, no work, $\Delta z = 0$, $\Delta\vec{V} \sim 0$
    - $\cancelto{0}{\dot{Q}_{IN}} + \dot{m}_1\left(h_1 + \cancelto{0}{\frac{\vec{V}_1^2}{2}} + \cancelto{0}{gz_1}\right) = \cancelto{0}{\dot{W}_{OUT}} + \dot{m}_2\left(h_2 + \cancelto{0}{\frac{\vec{V}_2^2}{2}} + \cancelto{0}{gz_2}\right)$
    - $h_1 = h_2$; constant enthalpy process to lower P.

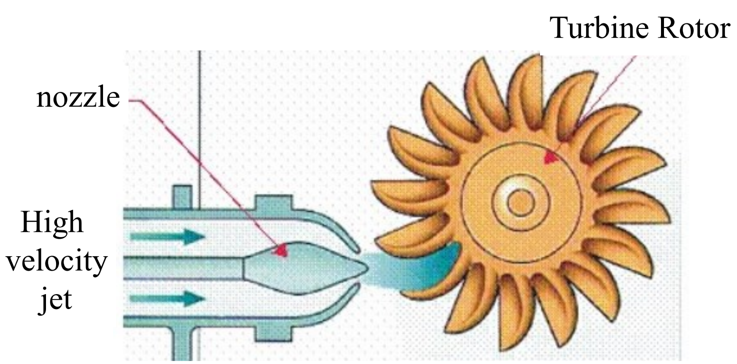
2.6.3 Turbines

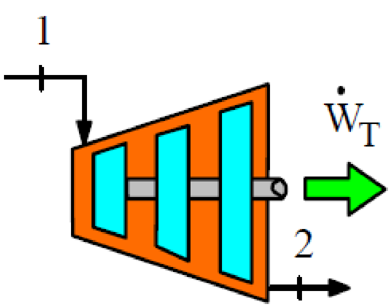
- Rotary steady-state machine that produces shaft work at the expense of a pressure drop.
- Two general classes of turbines are steam and gas

Working Principle

- Fluid enters turbine at high T,P
- Fluid goes through a series of nozzles (fixed blade passages). Fluid expands to lower pressure, increasing velocity
- High velocity fluid impinges onto turbine blades, rotating the blades & the rotor shaft
- Shaft work is produced, generating power
- Velocity of fluid is reduced from turning blades
- $P_2 < P_1$, $\underbrace{\vec{V}_2 > \vec{V}_1}_{often\ negligible\ compared\ to\ \Delta h}$, $T_2 < T_1$







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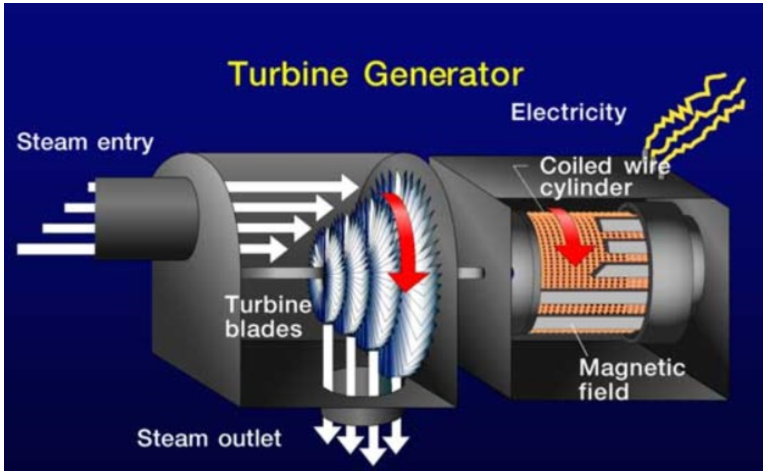

<u>Equations</u>

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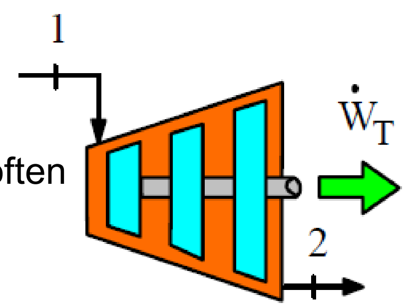
- Conservation of Energy: $\Delta\dot{E}_{system} = 0\ (steady\ state)$
  - $\Delta z = 0$, $\Delta\vec{V}\sim 0$, Usually heat is lost to surrounding. For simplified analysis, often given as adiabatic.



  - $\cancelto{?}{\dot{Q}_{IN}} + \dot{m}_1\left(h_1 + \cancelto{0}{\frac{\vec{V}_1^{\,2}}{2}} + \cancelto{0}{gz_1}\right) = \dot{W}_{OUT} + \dot{m}_2\left(h_2 + \cancelto{0}{\frac{\vec{V}_2^{\,2}}{2}} + \cancelto{0}{gz_2}\right)$
  - $\dot{W}_{OUT} = \dot{m}(h_1 - h_2) + \dot{Q}_{IN}$; usually heat transfer is OUT (heat lost) $\rightarrow -\dot{Q}_{OUT}$
  - Work is OUT of the system $\rightarrow\ h_1 > h_2$
  - $\dot{W}_{OUT} = \dot{m}(h_1 - h_2)$ (if adiabatic)

2.6.4 Compressors

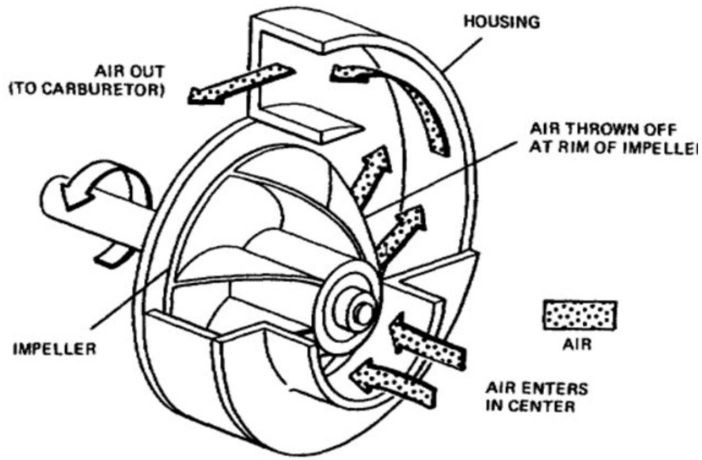
- Device used to increase pressure of a *gaseous* fluid by inputting shaft work
- Types of compressors
  - Rotary (axial or centrifugal flow)
  - Piston/cylinder

Working Principle (rotary)

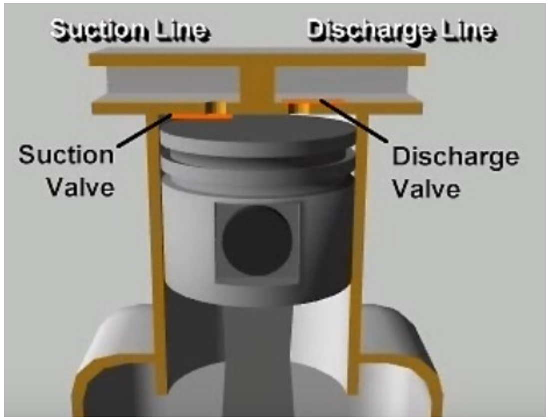
- Fluid enters at low pressure via rotating blades
- Fluid exits blades at high velocity
- Fluid passes through diffuser → fluid decelerates and pressure increases
- https://www.youtube.com/watch?v=s-bbAoxZmBg

Working Principle (piston)

- Piston moves downwards, lowering cylinder pressure and draws in fluid via suction valve
- Piston moves upwards, reducing volume and compressing the fluid to higher pressure
- Fluid exits via discharge valve
- https://m.youtube.com/watch?v=kFQu9uoZWKg



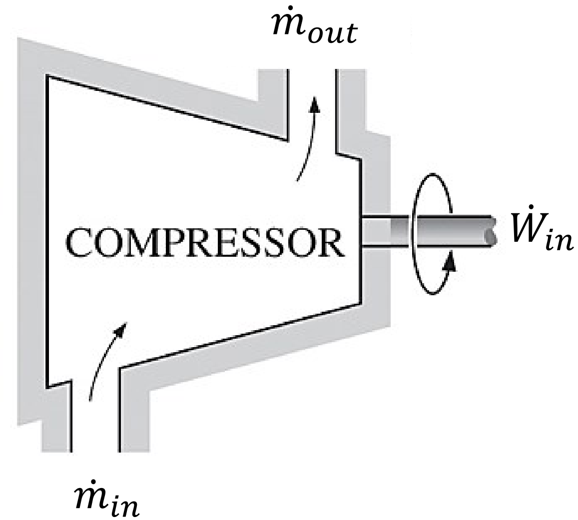
Rotary



Piston/Cylinder

2.6.4 Compressors

- Device used to increase pressure of a ***gaseous*** fluid by inputting shaft work



- $P_2 > P_1$, $\underbrace{\vec{V}_2 < \vec{V}_1}_{often\ negligible\ compared\ to\ \Delta h}$, $T_2 > T_1$

Equations

- Conservation of Mass: $\Delta\dot{m}_{system} = \dot{m}_1 - \dot{m}_2 = 0$
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- Conservation of Energy: $\Delta\dot{E}_{system} = 0\ (steady\ state)$
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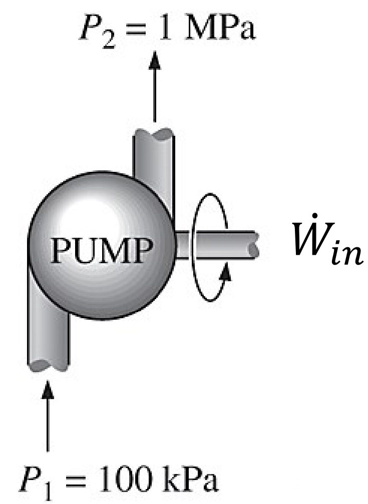
  - $\underset{?}{\cancel{\dot{Q}_{IN}}} + \dot{m}_1\left(h_1 + \underset{0}{\cancel{\frac{\vec{V}_1^{\,2}}{2}}} + \underset{0}{\cancel{gz_1}}\right) = \dot{W}_{OUT} + \dot{m}_2\left(h_2 + \underset{0}{\cancel{\frac{\vec{V}_2^{\,2}}{2}}} + \underset{0}{\cancel{gz_2}}\right)$
  - $\dot{W}_{OUT} = \dot{m}(h_1 - h_2) + \dot{Q}_{IN}$; usually heat transfer is OUT (heat lost) $\rightarrow -\dot{Q}_{OUT}$
  - Work is INTO the system $\rightarrow\ h_2 > h_1$
  - $\dot{W}_{IN} = \dot{m}(h_2 - h_1)$ (if adiabatic)

2.6.5 Liquid pumps

- Device used to increase pressure of a *__liquid__* fluid by inputting shaft work
- Similar function as a compressor, but fluid is now incompressible



(*a*) Compressing a liquid

__Equations__

- Conservation of Mass: $\Delta \dot{m}_{system} = \dot{m}_1 - \dot{m}_2 = 0$
  - $\dot{m}_1 = \dot{m}_2 = \dot{m}$
- Conservation of Energy: $\Delta \dot{E}_{system} = 0\ (steady\ state)$
  - $\Delta z = 0\ (not\ always)$, $\Delta \vec{V} \sim 0$, heat lost often negligible (adiabatic).
  - $\cancelto{0}{\dot{Q}_{IN}} + \dot{m}_1 \left(h_1 + \cancelto{0}{\frac{\vec{V}_1^{\,2}}{2}} + \cancelto{0}{g z_1} \right) = \dot{W}_{OUT} + \dot{m}_2 \left(h_2 + \cancelto{0}{\frac{\vec{V}_2^{\,2}}{2}} + \cancelto{0}{g z_2} \right)$
  - $\dot{W}_{OUT} = \dot{m}(h_1 - h_2)$
  - Work is INTO the system → $h_2 > h_1$
  - $\dot{W}_{IN} = \dot{m}(h_2 - h_1)$

https://www.youtube.com/watch?v=BaEHVpKc-1Q

2.6.5 Liquid pumps

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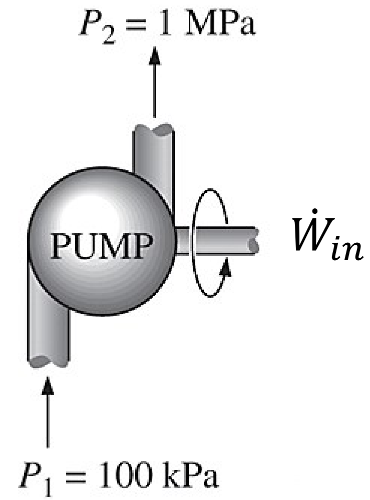
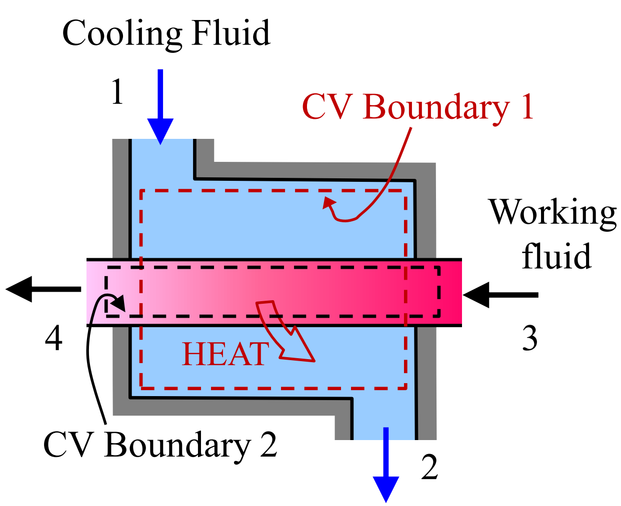


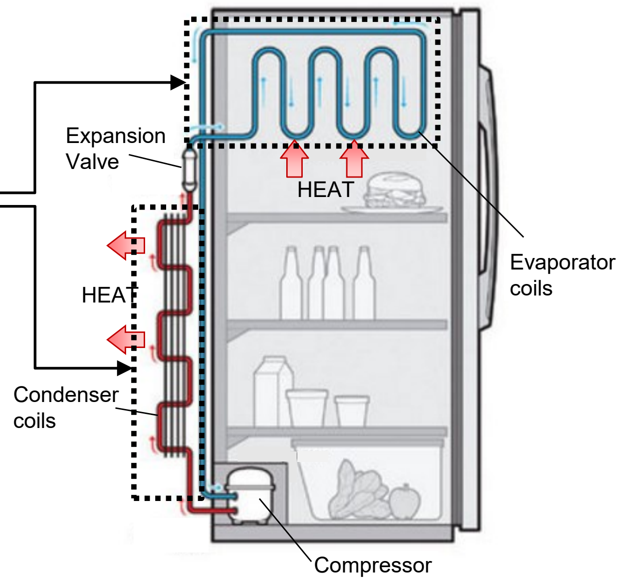
- Recall enthalpy difference can be written as:
  - $h_2 - h_1 = u_2 - u_1 + [(Pv)_2 - (Pv)_2]$
- For incompressible liquids specific volume is constant
- The pumping process for an incompressible liquid is essentially isothermal
  - Isothermal gives: $\Delta T = 0 \rightarrow (u_2 - u_1) = 0$
  - Thus: $(h_2 - h_1) = v(P_2 - P_1)$
- Since $v_2 = v_1 = v$, the work *input* to the pump becomes
  - $\dot{W}_{IN,Compressor} = \dot{m}(h_2 - h_1) = \dot{m}v(P_2 - P_1)$

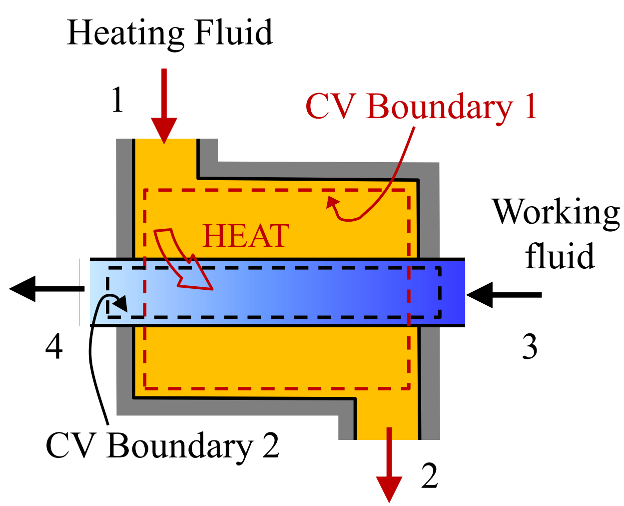
2.6.6 Heat Exchangers

- Device allowing energy exchange between hot and cold fluids without mixing the fluids
  - Little / NO heat transfer with surroundings
- <u>Working fluid</u>
  - Fluid of interest needing heat added/removed to produce a given exit condition
  - Phase change can occur for the working fluid
- <u>Cooling/heating fluid</u>
  - Fluid used to remove/add heat to working fluid
  - Air and water are common cooling/heating fluids



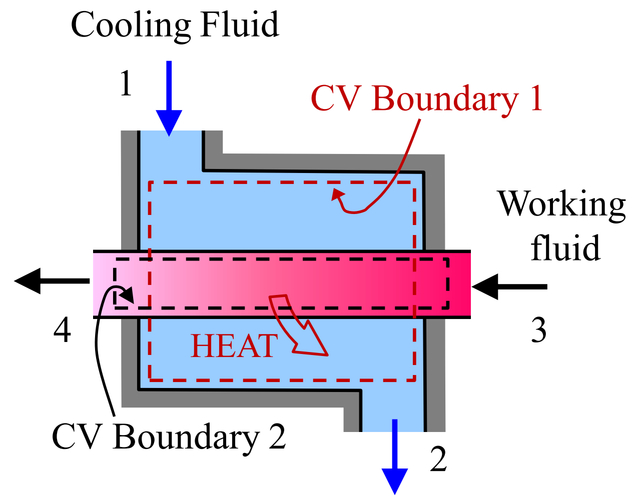
<u>Evaporators</u> & <u>Condensers</u> in Refrigeration systems are examples of heat exchangers where refrigerant exchanges heat with air



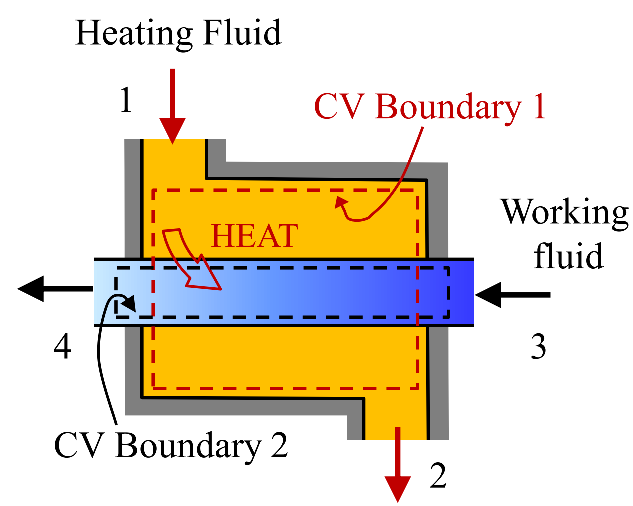


2.6.6 Heat Exchangers

- Derivation of mass and energy equations will depend on control volume chosen
- <u>Control Volume 1 – Entire Heat exchanger</u>
  - Conservation of Mass: $\Delta \dot{m}_{system} = 0$
    - $\dot{m}_1 + \dot{m}_3 = \dot{m}_2 + \dot{m}_4$
  - Conservation of Energy: $\Delta \dot{E}_{system} = 0\ (steady\ state)$
    - $\Delta z = 0,\ \Delta \vec{V} = 0, \dot{Q} = 0, \dot{W} = 0.$
    - $\dot{m}_{cool/heat}(h_1 - h_2\ ) = \dot{m}_{working\ fluid}(h_4 - h_3\ )$
    - Heat received/rejected to cooling/heating fluid is heat rejected/received to working fluid

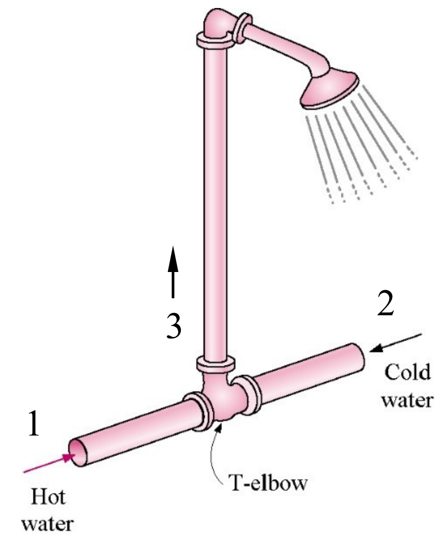


- <u>Control Volume 2 – Working fluid</u>
  - Conservation of Mass: $\Delta \dot{m}_{system} = 0$
    - $\dot{m}_3 = \dot{m}_4 = \dot{m}_{working\ fluid}$
  - Conservation of Energy: $\Delta \dot{E}_{system} = 0\ (steady\ state)$
    - $\Delta z = 0,\ \Delta \vec{V} = 0, \dot{Q} \neq 0, \dot{W} = 0.$
    - $\dot{Q}_{34} = \dot{m}_{working\ fluid}(h_4 - h_3\ )$
    - Heat rejected/received to working fluid is heat received/rejected to cooling/heating fluid



2.6.7 Mixing chambers

- The mixing of two (or more) fluids in a chamber
- The ordinary shower is an example of a mixing chamber
- Processes usually occur at constant pressure



Equations

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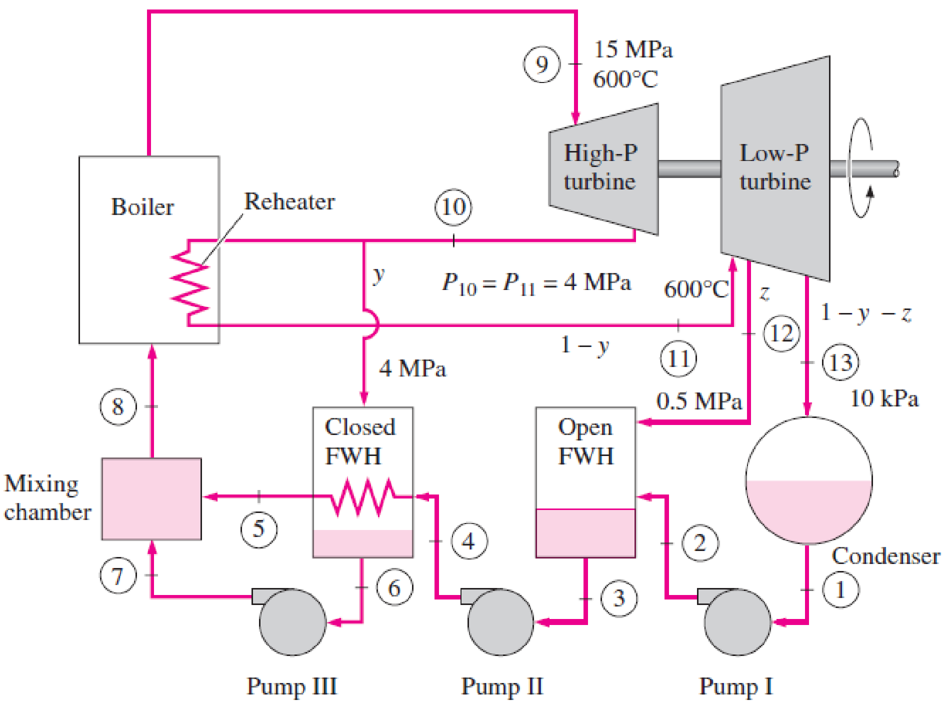
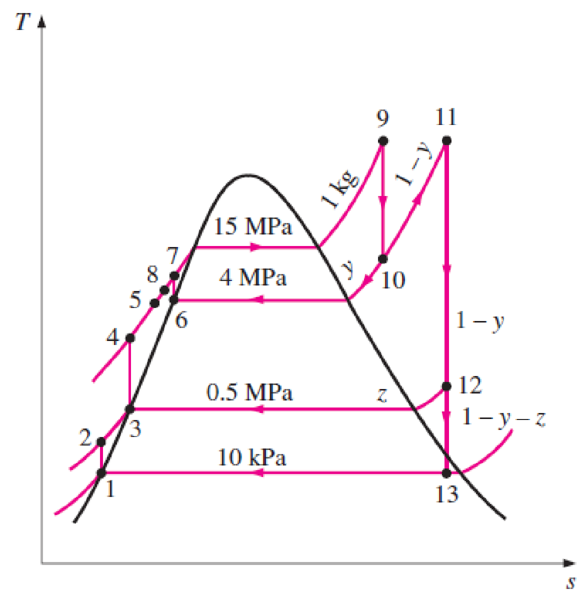
  - $\cancelto{0}{\dot{Q}_{IN}} + \dot{m}_i \left(h_i + \cancelto{0}{\frac{\vec{V}_i^{\,2}}{2}} + \cancelto{0}{g z_i} \right) = \cancelto{0}{\dot{W}_{OUT}} + \dot{m}_e \left(h_e + \cancelto{0}{\frac{\vec{V}_e^{\,2}}{2}} + \cancelto{0}{g z_e} \right)$
  - $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

Why study so many devices?

- Power plants, steam engines, and most thermodynamic cycles encompass many thermodynamic devices
- Property of the working fluids at each state give rise to the net power output, heat input required, and how much heat needs to be dumped to the surroundings.
- Properties of the working fluid also determines efficiency of the power plant / engine / system (i.e. how well are we converting heat into work?).



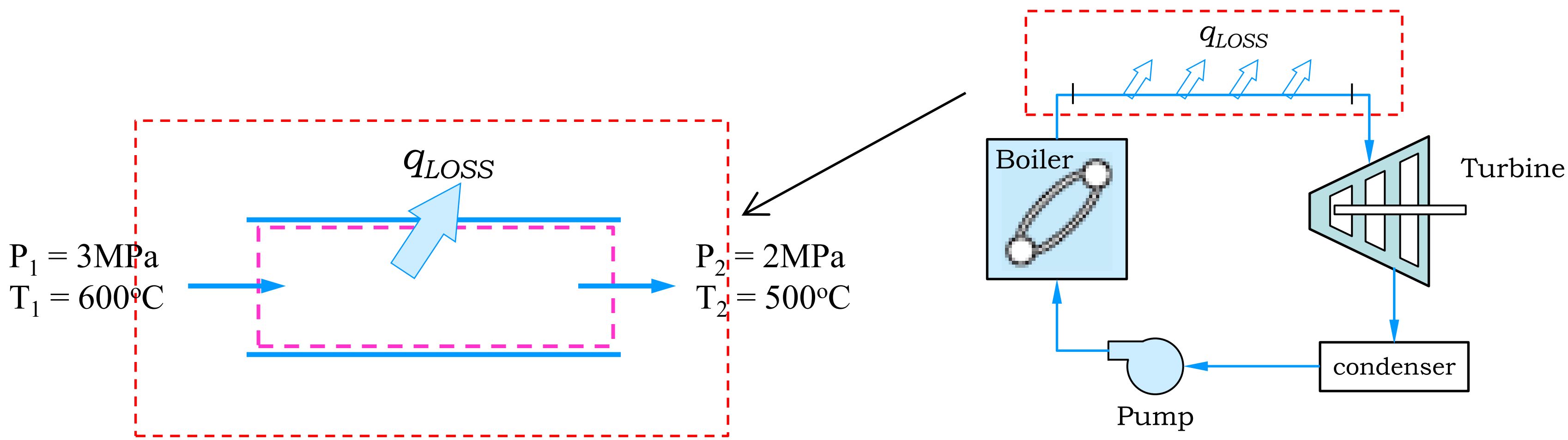


Accompanying Exercises

Pipe and Duct flow – i.e. straight nozzle/diffuser. No increase in velocity, but pressure drop or heat transfer can be significant if the pipe length is long.

Exercise 2-4

In a simple steam power plant, steam leaves a boiler at 3 MPa, 600°C, and enters a turbine at 2 MPa, 500°C. Determine the in-line heat loss from the steam per kilogram of mass flowing in the pipe between the boiler and the turbine.

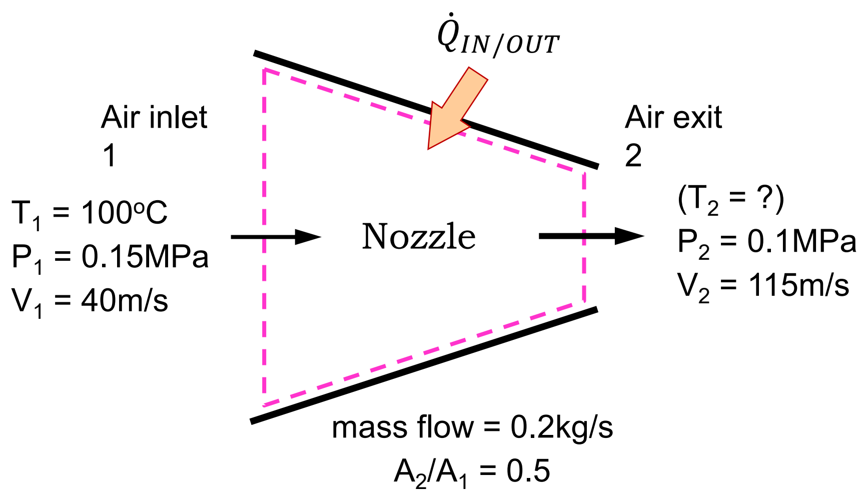


[ans: 214.79 kJ/kg]

Nozzle

Exercise 2-5

Air at 100°C, 150 kPa, 40 m/s, flows through a converging duct with a mass flow rate of 0.2 kg/s. The air leaves the duct at 100 kPa, 115 m/s. The exit-to-inlet duct area ratio is 0.5. Find air exit temperature and the required rate of heat transfer to the air when no work is done by the air. Is the exit temperature warmer or colder than the inlet? Assume ideal gas with constant specific heats C_P = 1.004 kJ/kgK and R = 0.287 kJ/kgK.

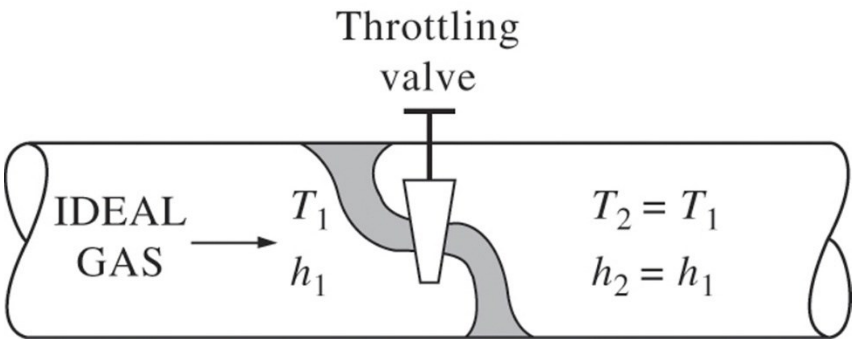


[ans: Q = -1.96 kW, T_2 = 357.6 K colder]

Throttle

Exercise 2-6

Apply the energy balance for throttling process. Does the gas temperature change during the throttling process when the working fluid is an ideal gas?

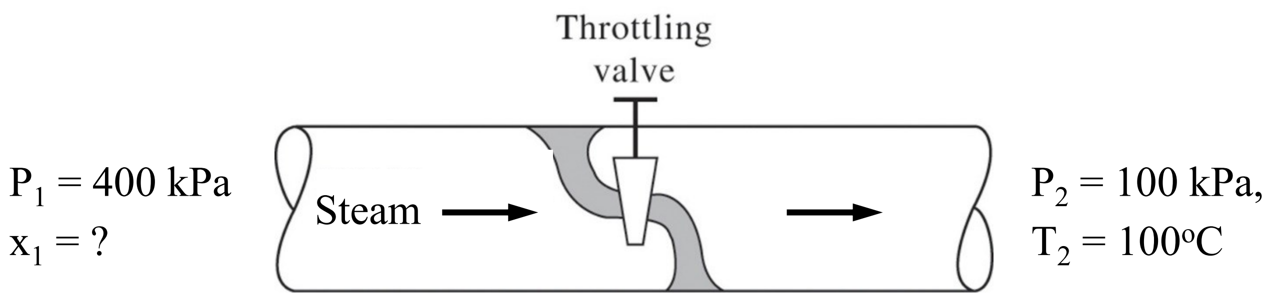


[ans: no]

Throttle

<u>Exercise 2-7</u>

One way to determine the quality of saturated steam is to throttle the steam to a low enough pressure that it exists as a superheated vapor. Saturated steam at 400 kPa and quality x_1 is throttled to 100 kPa, 150°C. Determine the initial quality of the steam at 400 kPa. Does the water temperature increase or decrease in this process?



[ans: 0.971, temperature decreases]

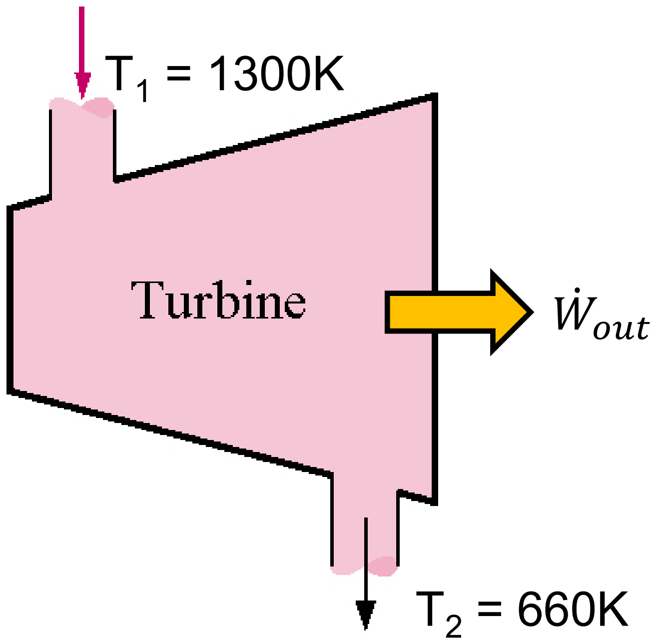
Turbine

Exercise 2-8

High pressure air at 1300K flows into an aircraft gas turbine and undergoes a steady-state, steady-flow, adiabatic process to the turbine exit at 660K.

a) Calculate the work done per unit mass of air flowing through the turbine using $C_{p,ave}$ = 1.138 kJ/kg·K.

b) Calculate the work done per unit mass when using the ideal gas air tables in the back of the book (i.e. Table A7.1 (Borgnakke & Sonntag).

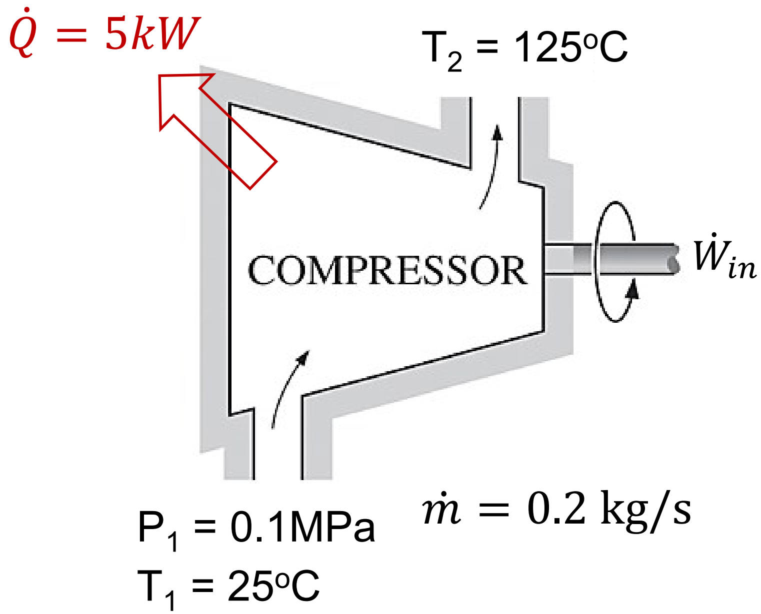


[ans: (a) 728.3 kJ/kg, (b) 725.1 kJ/kg]

Compressor

Exercise 2-9

Nitrogen gas is compressed in a steady-state, steady-flow, adiabatic process from 0.1MPa, 25°C. During the compression process the temperature becomes 125°C. The mass flow rate of nitrogen is 0.2 kg/s. If heat is lost to the surroundings at 5 kW, determine the work done on the nitrogen, in kW. Assume ideal gas with constant specific heat C_p = 1.039 kJ/kg·K.



[ans: 25.8 kW]

Pump

Exercise 2-10

Apply the conservation of energy equation to a pump and include the change in kinetic and potential energy of the fluid streams entering and leaving the system.

$$\dot{Q}_{net} + \dot{m}_i\left(h_1 + \frac{\vec{V_1}^2}{2} + gz_1\right) = \dot{W}_{net} + \dot{m}_2\left(h_2 + \frac{\vec{V_2}^2}{2} + gz_2\right)$$

Show that if we remove the pumping work, we will arrive at the Bernoulli's equation for frictionless, incompressible fluid flow through a pipe.

Bernoulli's Equation: $$\frac{P_2}{\rho} + \frac{\vec{V}_2^2}{2g} + z_2 = \frac{P_1}{\rho} + \frac{\vec{V}_1^2}{2g} + z_1$$