ME 200 – Thermodynamics 1
Chapter 4 In-Class Notes
for Spring 2023

Energy Analysis for Open Systems

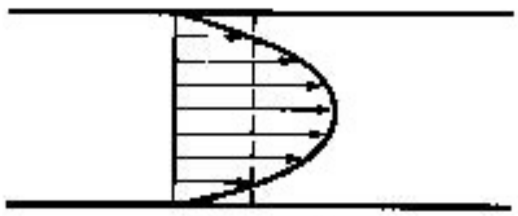
- Open System Mass Balances
- Open Energy Balances
- Lots of Applications

Lecture 13
Mass and Energy Balances

- Mass and Volume Flow Rates
- Mass Conservation for Open Systems
- Energy of a Flowing Fluid
- Energy Conservation for Open Systems

Mass and Volume Flow Rates

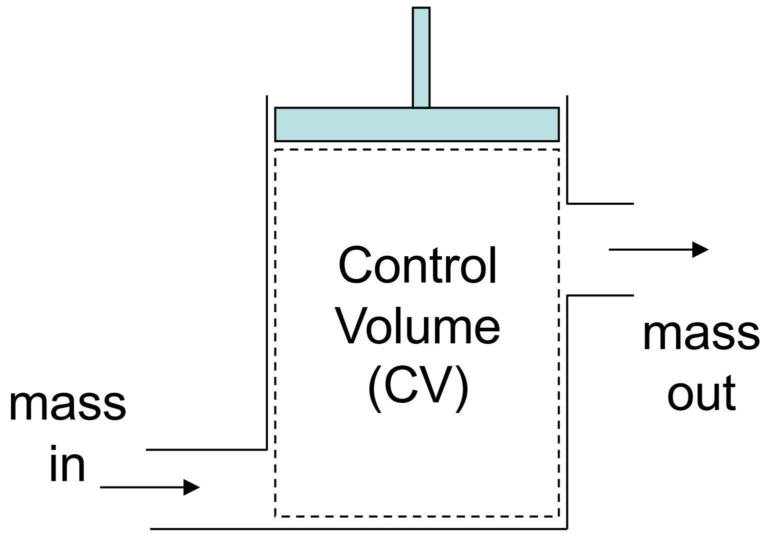
Velocity Profiles For Flow in a Duct



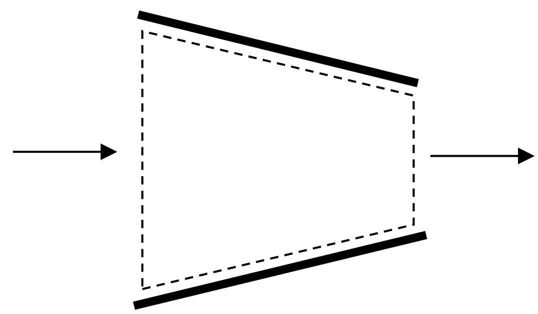
(*a*) Actual

(*b*) Average

Mass Conservation for Open Systems



piston cylinder



nozzle

For a process (over a finite time)

$$\begin{pmatrix} \text{total mass} \\ \text{entering CV} \end{pmatrix} - \begin{pmatrix} \text{total mass} \\ \text{leaving CV} \end{pmatrix} = \begin{pmatrix} \text{change in} \\ \text{CV mass} \end{pmatrix}$$

or

$$\sum m_i - \sum m_e = \Delta m_{CV}$$

On a rate basis, at any time

$$\sum \dot{m}_i - \sum \dot{m}_e = \frac{dm_{CV}}{dt}$$

Steady-Flow Assumption

- Total mass within control volume does not change with time
- Appropriate assumption for many open systems considered in ME 200 (e.g., compressors, turbines, heat exchangers, nozzles)

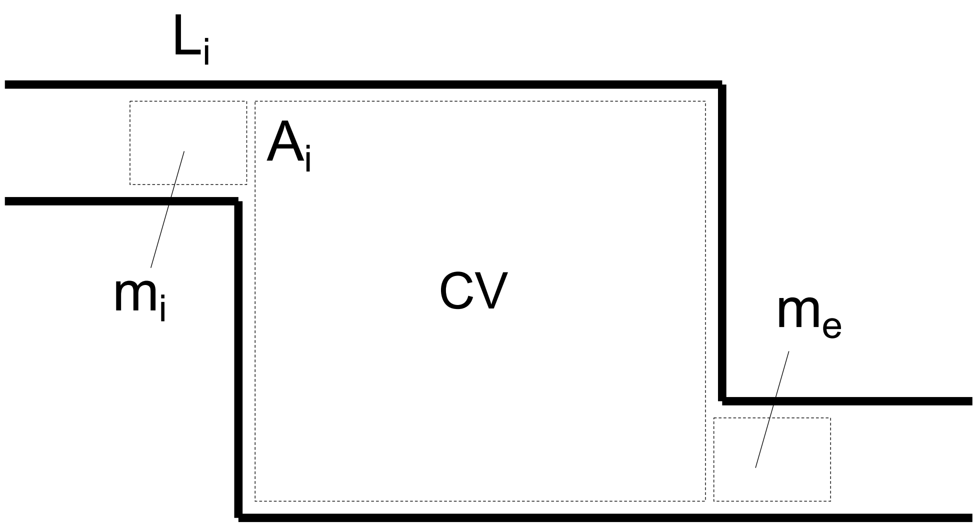
$$\frac{dm_{CV}}{dt} = 0 \Rightarrow \sum \dot{m}_e = \sum \dot{m}_i$$

or

$$\sum \frac{A_i V_i}{v_i} = \sum \frac{A_e V_e}{v_e}$$

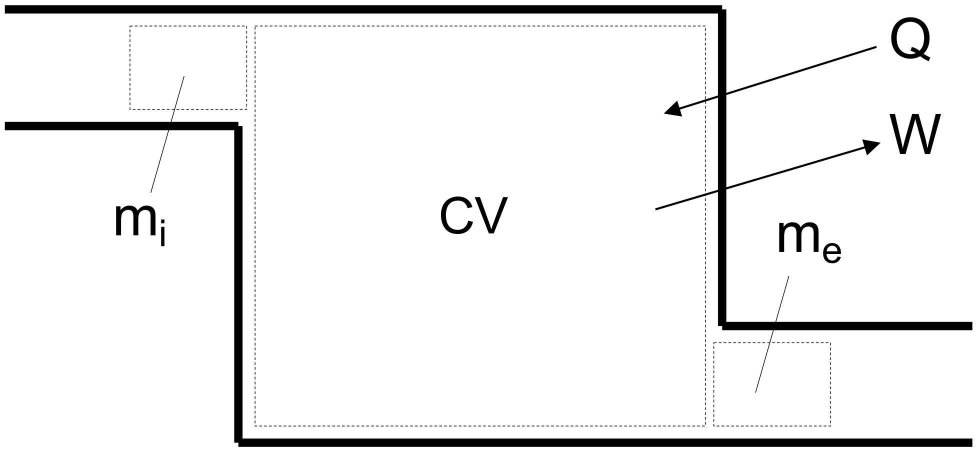
Energy of a Flowing Fluid

Consider mass entering and leaving a control volume during a short time, Δt



Energy Conservation for Open Systems

Consider mass, work, and heat entering and/or leaving a control volume during a short time, Δt

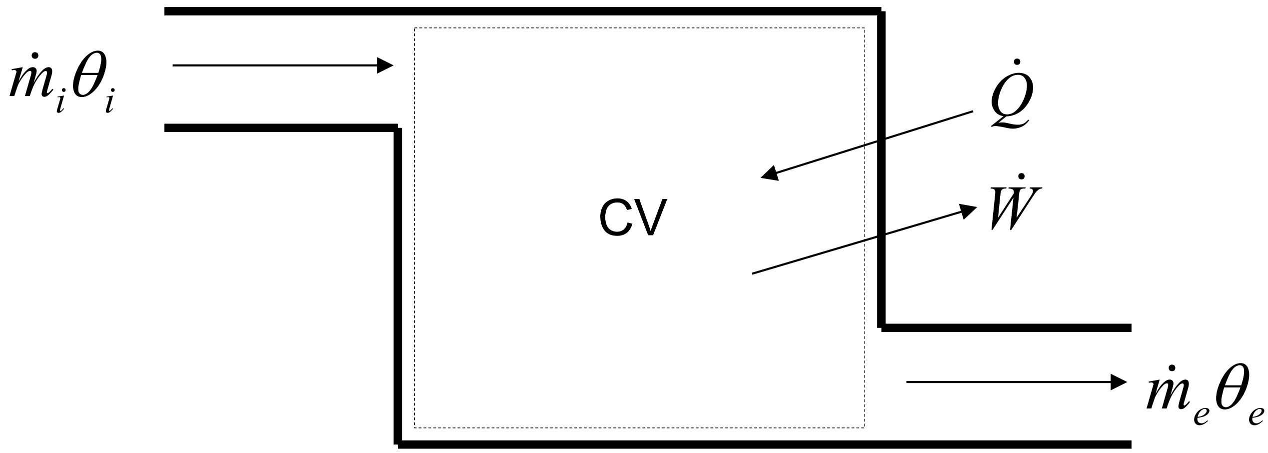


Then, for this process (over a finite time)

$$\begin{pmatrix}\text{change in}\\ \text{CV energy}\end{pmatrix} = \begin{pmatrix}\text{energy transferred to CV}\\ \text{by mass, heat, and work}\end{pmatrix} - \begin{pmatrix}\text{energy transferred from CV}\\ \text{by mass, heat, and work}\end{pmatrix}$$

$$\Delta E_{CV} = \sum^{inlets} m_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum^{exits} m_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) + Q - W$$

Rate Form of 1st Law for Open Systems



$$\frac{dE_{CV}}{dt} = \sum^{inlets} \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum^{exits} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) + \dot{Q} - \dot{W}$$

Steady-Flow, Steady-State (SSSF)

- the mass of the CV is constant over time (SF)
- the state of the CV is constant over time (SS)

$$\frac{dm_{CV}}{dt} = 0 \quad \text{and} \quad \frac{de_{CV}}{dt} = 0$$

Therefore

$$\frac{dE_{CV}}{dt} = \frac{d(me)_{CV}}{dt} = e_{CV}\overbrace{\frac{dm_{CV}}{dt}}^{0} + m_{CV}\overbrace{\frac{de_{CV}}{dt}}^{0} = 0$$

1^{st} Law for SSSF Systems

$$\dot{Q} - \dot{W} = \sum^{exits} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right) - \sum^{inlets} \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i \right)$$

Notes

- For open systems' analysis, ME 200 will mostly deal with SSSF
- For SSSF systems, there will be no **boundary** work since volume must be constant

Single-Inlet, Single-Outlet SSSF Systems

$$\dot{Q} - \dot{W} = \dot{m} \left(h_e - h_i + \frac{V_e^2 - V_i^2}{2} + g(z_e - z_i) \right)$$

$$= \dot{m}(\Delta h + \Delta ke + \Delta pe)$$

Also

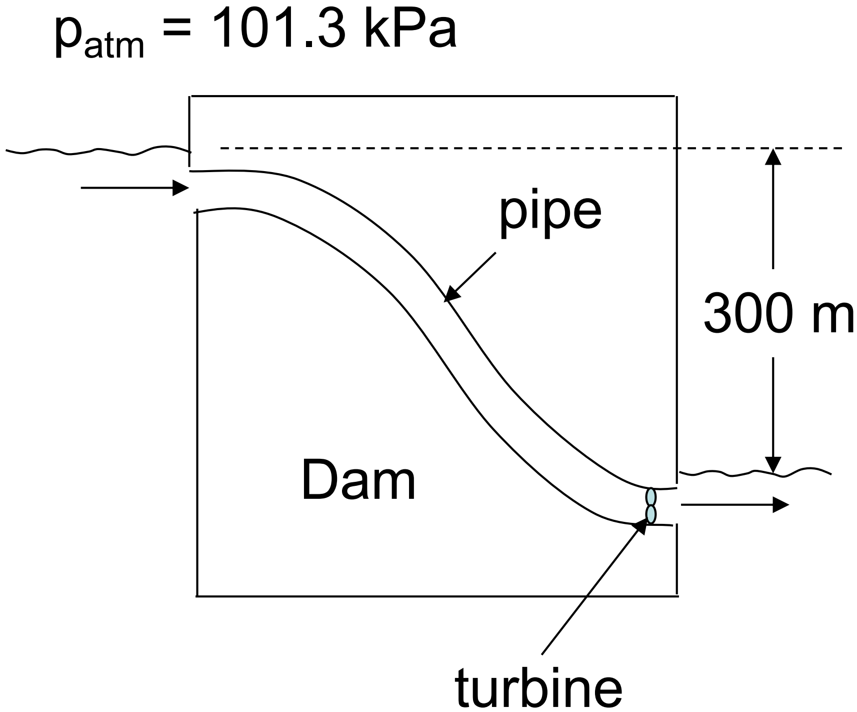
$$q - w = \Delta h + \Delta ke + \Delta pe$$

Notes

- There's only a single mass flow rate for this case
- For SSSF systems with single inlet and outlet, the symbol Δ denotes differences between exit and inlet properties (i.e., $\Delta h = h_e - h_i$)
- q, w, h, ke, pe are per unit of mass of fluid flowing

Lecture 14, 15, and 16
Open System 1st Law Examples

<u>Example – Hydroelectric Power Generation</u>



<u>Given</u>:
- volume flow of 10,000 l/s
- constant diameter pipe

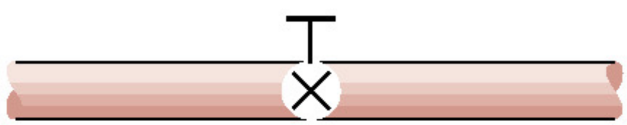
<u>Find</u>:
a) water mass flow
b) turbine power
c) turbine inlet pressure

<u>Assumptions</u>: 1) SSSF, 2) incompressible liquid, 3) adiabatic pipe and turbine, 4) atmospheric pressure at dam inlet and exit, 5) isothermal flow

Throttling Devices

- Flow restricting devices that cause a pressure drop without a work output
- Used to
  - control flow (e.g. faucet)
  - provide temperature drop (refrigeration, air conditioning)
  - measure flow rates

Examples:



(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube

An orifice is also a common throttling device

Energy and Mass Balances

$$\frac{dE_{CV}}{dt} = \dot{m}_1\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \dot{m}_2\left(h_2 + \frac{V_2^2}{2} + gz_2\right) + \dot{Q} - \dot{W}$$

$$\frac{dm_{CV}}{dt} = \dot{m}_1 - \dot{m}_2$$

Common assumptions for throttling devices

- SSSF: no changes with time
- adiabatic: small surface area and high flow rates
- Δpe = 0: small elevation change
- neglect kinetic energy terms

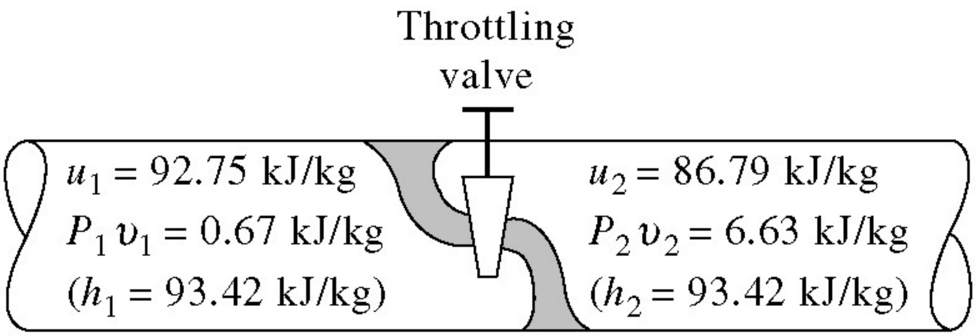
$$\frac{V_1^2}{2} << h_1 \text{ and } \frac{V_2^2}{2} << h_2$$

$\Rightarrow$ **Conservation of mass:**

$\Rightarrow$ **Conservation of energy:**

Isenthalpic Expansion

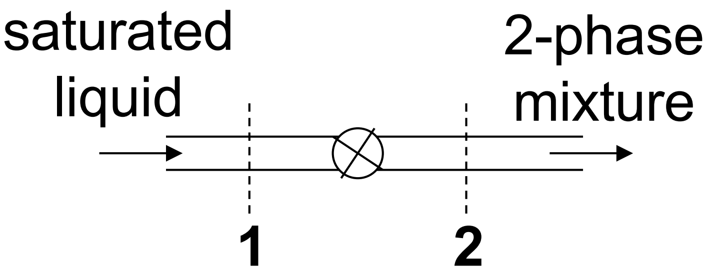
$$h_1 = h_2$$
$$or$$
$$u_1 + p_1 v_1 = u_2 + p_2 v_2$$



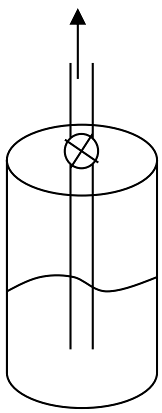
- Internal Energy + Flow Energy = Constant
- Can have a decrease in temperature due to two effects:
  - Change of phase that occurs with throttling of a saturated liquid to a lower pressure
  - Reduction in internal energy due to an increase in flow energy (CV does net flow work)

- Does the temperature of an ideal gas increase, decrease or remain the same when it is throttled to a lower pressure?

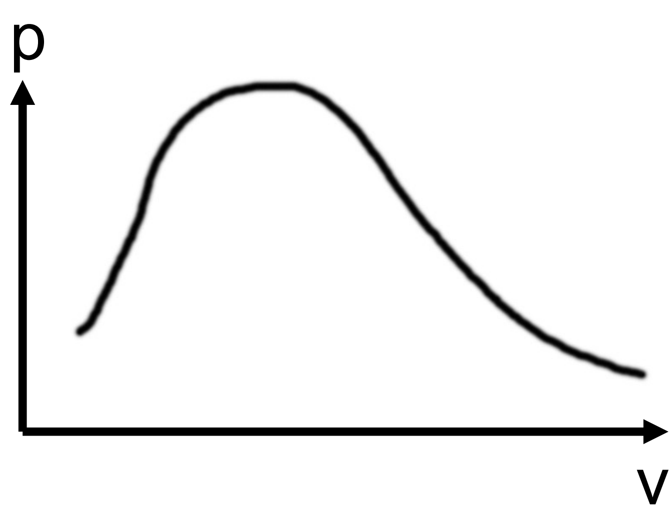
Two-Phase Expansion

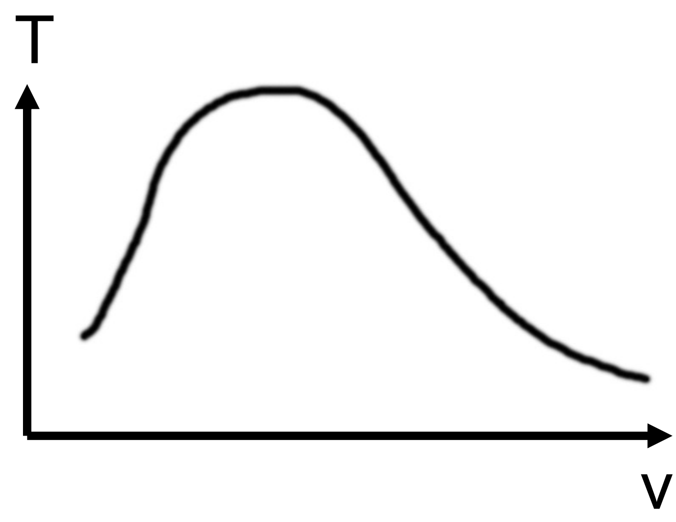


Expansion process in a refrigerator or air conditioner



What happens when you discharge liquid from a two-phase container?

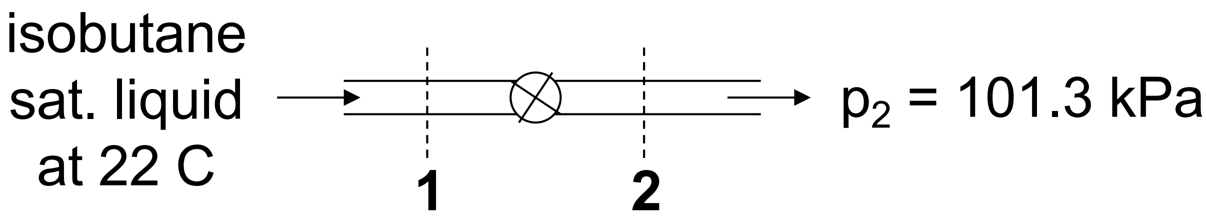




Example

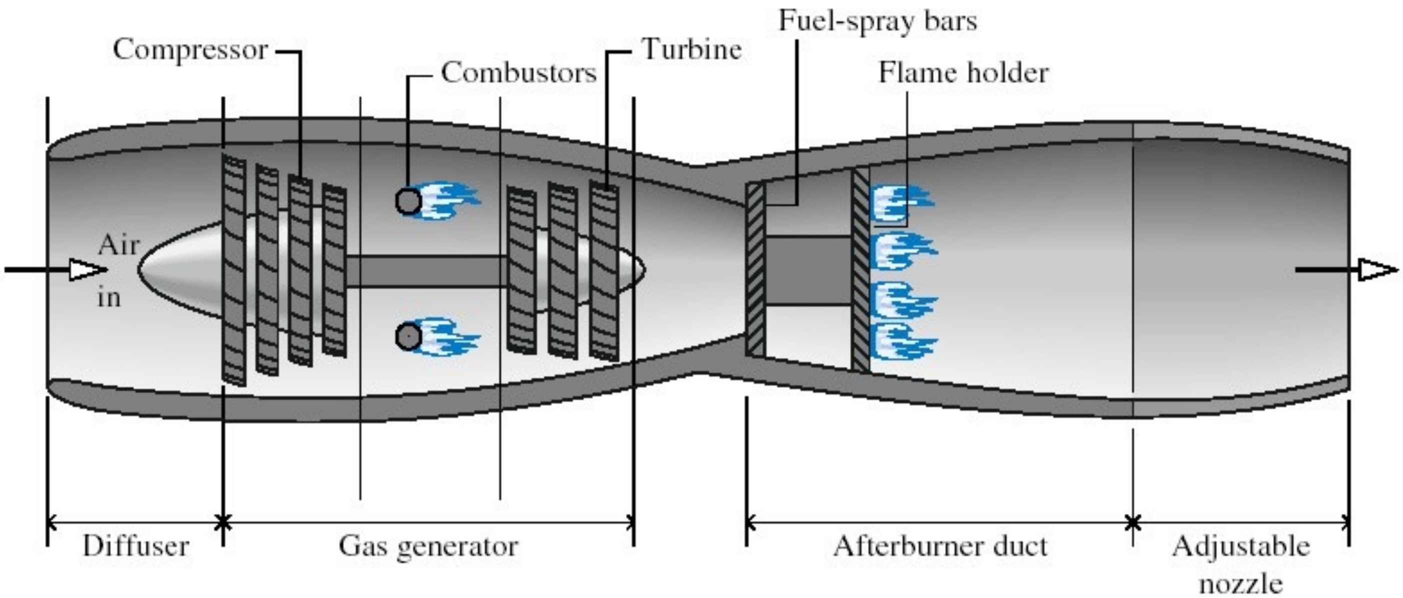
Given: Throttling liquid isobutane from a chamber at 22 C to the atmosphere

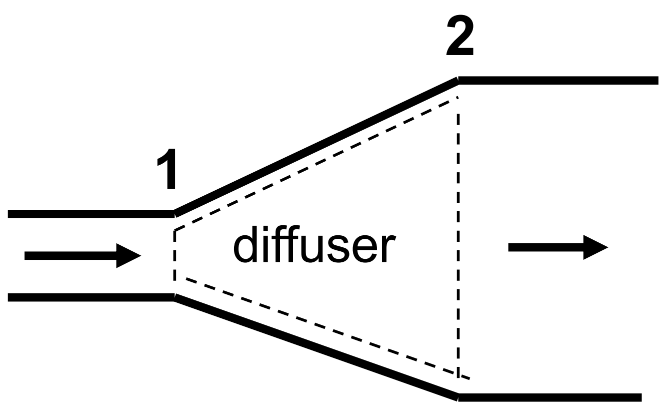
Find: exit temperature and quality

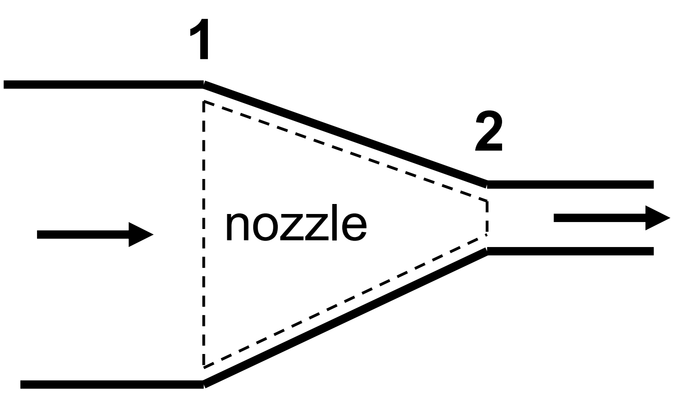


Nozzles and Diffusers

Jet Engine Example







Energy and Mass Balances

$$\frac{dE_{CV}}{dt} = \dot{m}_1\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \dot{m}_2\left(h_2 + \frac{V_2^2}{2} + gz_2\right) + \dot{Q} - \dot{W}$$

$$\frac{dm_{CV}}{dt} = \dot{m}_1 - \dot{m}_2$$

Common assumptions for nozzles and diffusers

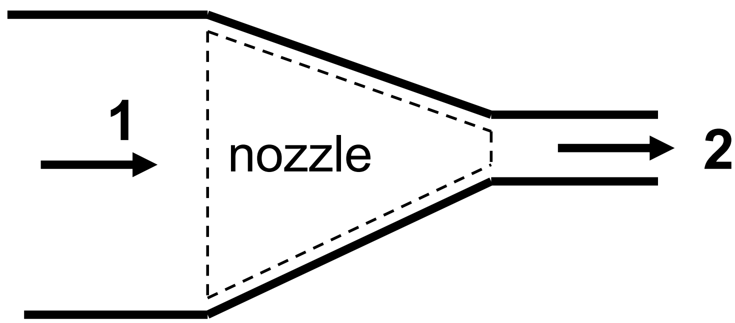
- SSSF: no changes with time
- adiabatic: insulated or "high" flow rates
- Δpe = 0: small elevation change
- $\dot{W}$ = 0: no work producing devices

Where does the energy come from to accelerate the fluid in a nozzle?

Example - Nozzle

Given: Nitrogen gas flows through a nozzle,
Inlet: p_1 = 2 bar, $V_1 \approx 0\ m/s,\quad \dot{m} = 0.5\ \text{kg/s}$
Outlet: p_2 = 1.25 bar, T_2 = 5°C, A_2 = 13 cm^2

System:



Find: Exit velocity, V_2
ΔT across the nozzle

Assumptions: (1) SSSF, (2) adiabatic, (3) $\Delta pe=0$
(4) no work, (5) N_2 is ideal gas, (6) constant specific heat

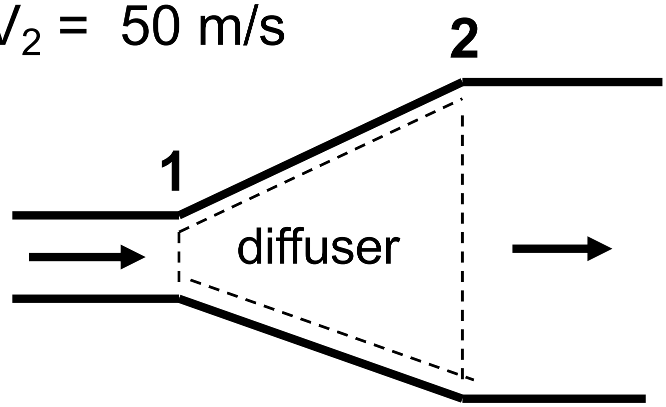
Example - Diffuser

Given: R-134a flows through an adiabatic diffuser

Inlet: p_1 = 12 bar, T_1 = 50^oC, V_1=130 m/s, A_1=25 cm^2

Outlet: p_2 = 14 bar, V_2 = 50 m/s

System:

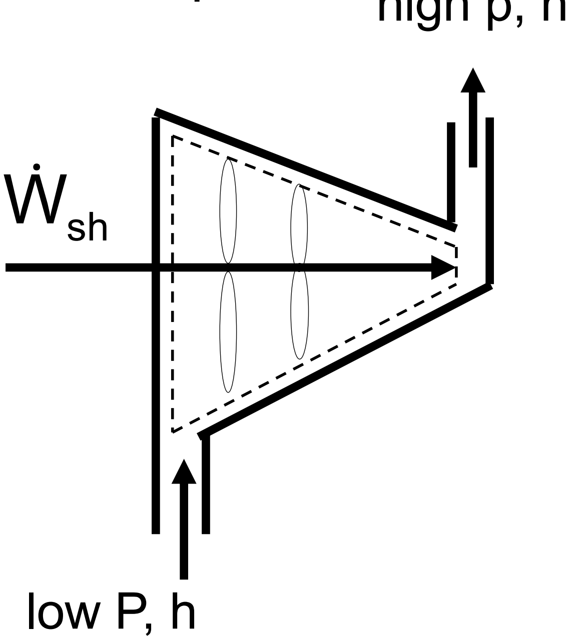


Find: (1) mass flow rate, , (2) exit enthalpy, h_2,
(3) exit temperature, T_2, and (4) exit area, A_2

Assumptions: (1) SSSF, (2) adiabatic, (3) Δpe=0
(4) no work

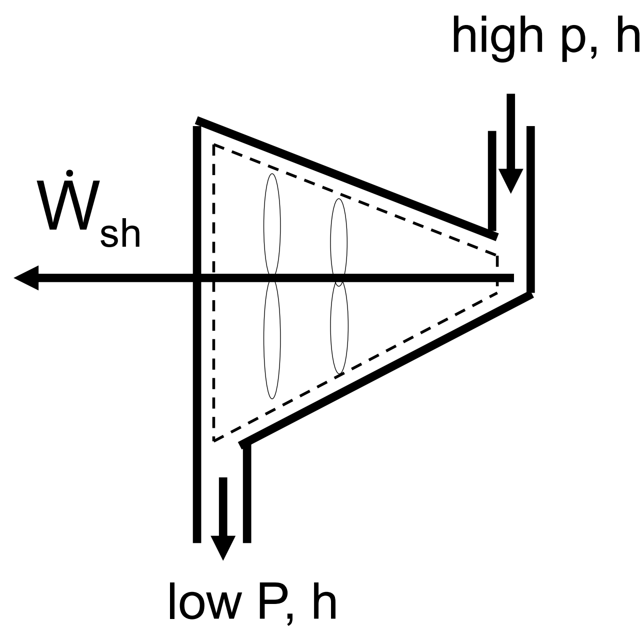
Compressors and Turbines

Compressor: increase pressure, density, and enthalpy of a gas through a work input



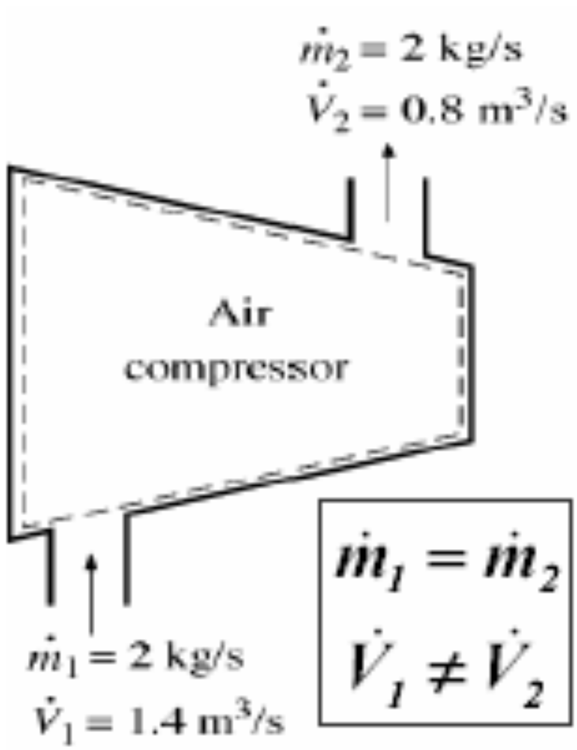
- A variety of types: bladed (radial or axial), piston cylinder, …
- Work input from a shaft connected to a motor, turbine, etc.
- Pumps for liquids, fans for small pressure rises

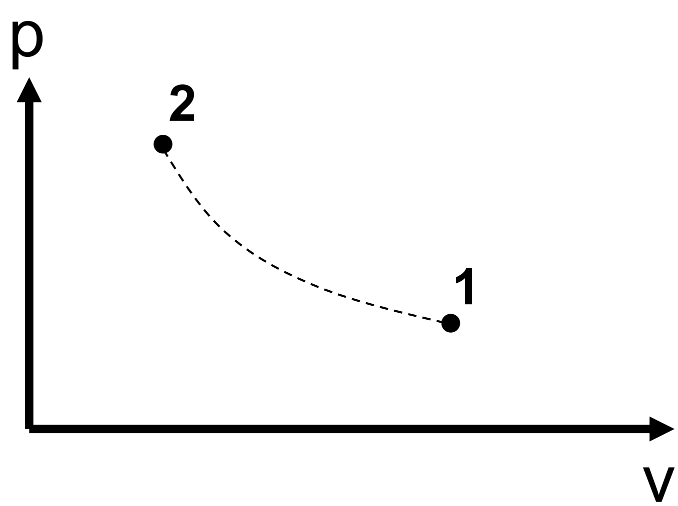
Turbine: produce work by expanding a gas to a lower pressure, density, and enthalpy



- Fluid does work on blades which are attached to a shaft
- Shaft often attached to a generator or compressor
- Steam, gas, hydroelectric, …

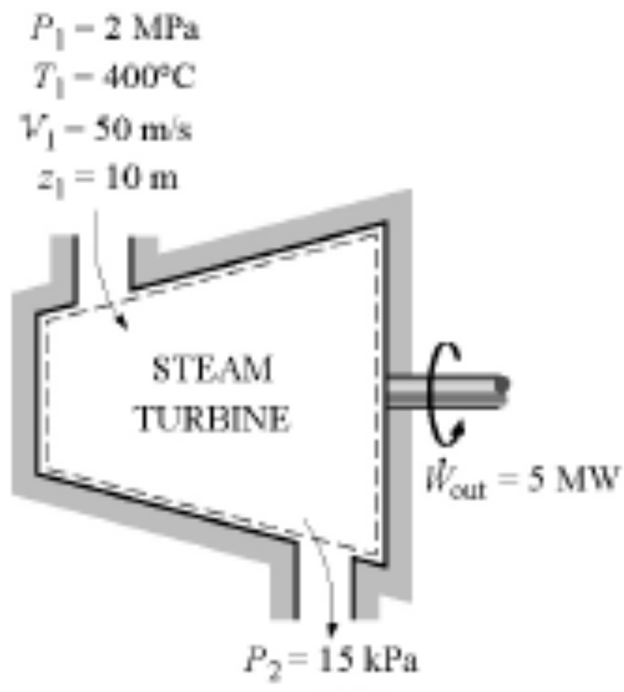
Air Compressor

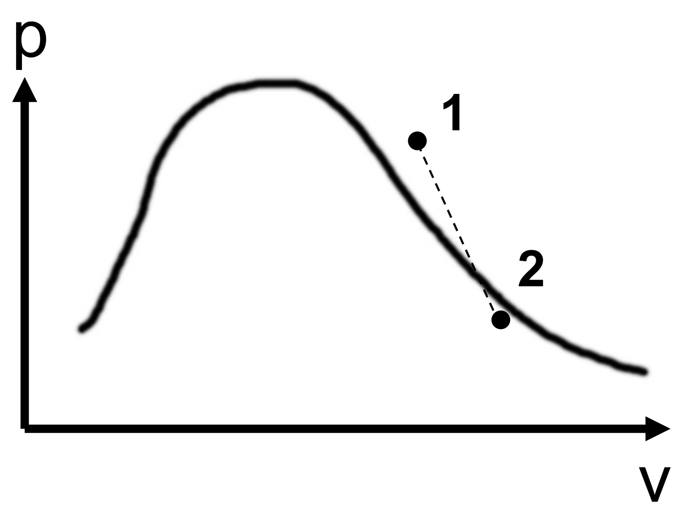




- Sometimes cool compressors to reduce discharge temperatures

Steam Turbine





- Can usually neglect heat transfer from turbines

- Kinetic energy changes are usually small compared to enthalpy changes

Energy and Mass Balances

$$\frac{dE_{CV}}{dt} = \dot{m}_1\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \dot{m}_2\left(h_2 + \frac{V_2^2}{2} + gz_2\right) + \dot{Q} - \dot{W}$$

$$\frac{dm_{CV}}{dt} = \dot{m}_1 - \dot{m}_2$$

Common assumptions for compressors and turbines

- SSSF: no changes with time
- adiabatic: heat transfer rate is often small compared to power (not always true)
- Δpe = 0: small elevation change
- Δke = 0 : most often a good assumption

Compressor Example

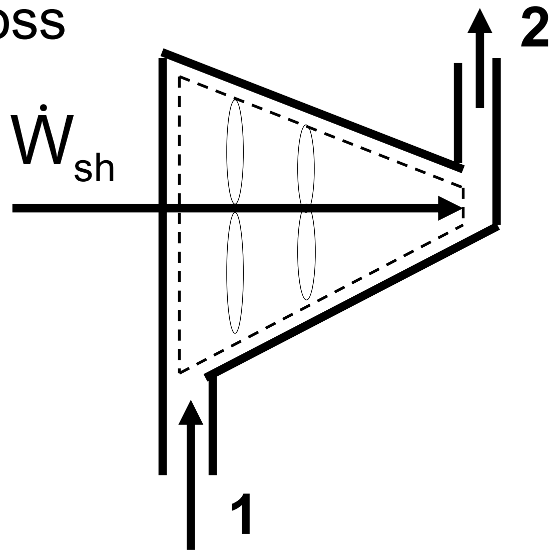
Given: Air compressor,

Inlet: T_1 = 320 K, p_1 =0.2 MPa, V_1=100 m/s, D_1 = 0.1 m

Outlet: T_2 = 650 K, p_2 =1.2 MPa, D_2 = 0.1 m

Negligible heat loss

System:



Find: (1) mass flow rate in kg/min, (2) shaft power

Assumptions: (1) SSSF, (2) Δpe =0, (3) adiabatic,
(4) air is ideal gas

Turbine Example

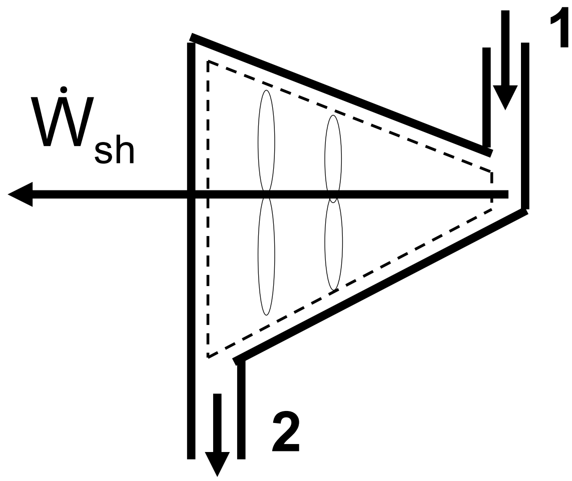
Given: Steam turbine

Inlet: p_1 = 80 bar, T_1 = 400°C, V_1 = 100 m/s, A_1=130 cm^2

Exit: T_2 = 240°C, p_2 = 15 bar, V_2 = 40 m/s

Heat Loss Rate: 300 kW

System:

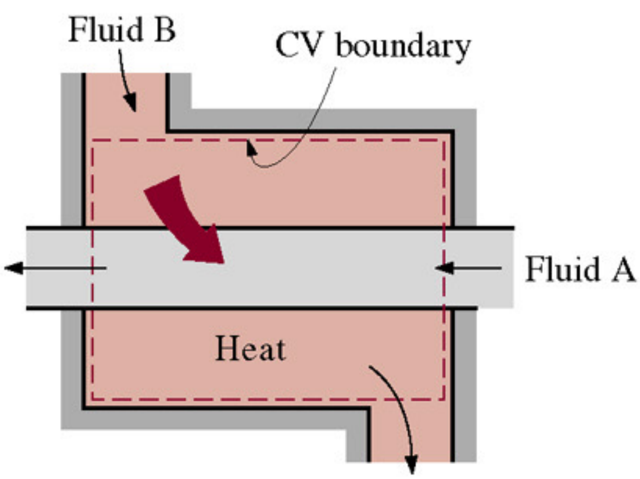


Find: (1) mass flow rate, (2) power output, and (3) exit area

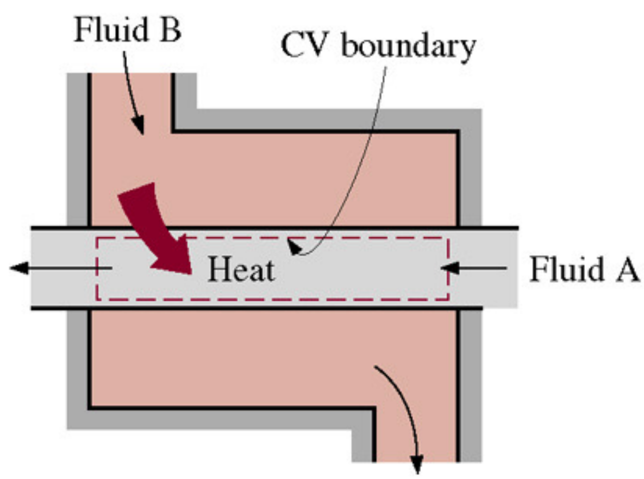
Assumptions: (1) SSSF and (2) Δpe=0

Heat Exchangers

- Two fluids exchange heat without mixing
- Energy balance depends on the system that is chosen
  - one of the flow streams (heat transfer occurs with surroundings)
  - both flow streams (negligible heat transfer with surroundings



(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)



(*b*) System: Fluid A ($Q_{CV} \neq 0$)

Energy and Mass Balances

$$\frac{dE_{CV}}{dt} = \sum^{inlets} \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum^{exits} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) + \dot{Q} - \dot{W}$$

$$\frac{dm_{CV}}{dt} = \sum^{inlets} \dot{m}_i - \sum^{exits} \dot{m}_e$$

Common assumptions for heat exchangers

- SSSF: no changes with time
- Δpe = 0: small elevation change
- negligible kinetic energy terms
- Negligible heat transfer between external enclosure of heat exchanger shell and surroundings (external surface area is small compared to surface area that exchanges heat between the two fluids)
- The pressure of each fluid does not change as it flows through the heat exchanger

Simplified Mass and Energy Balances

Fluid A

$$\dot{m}_{A,inlet} = \dot{m}_{A,exit} = \dot{m}_A$$

$$\dot{Q}_A = \dot{m}_A (h_{A,exit} - h_{A,inlet})$$

Fluid B

$$\dot{m}_{B,inlet} = \dot{m}_{B,exit} = \dot{m}_B$$

$$\dot{Q}_B = \dot{m}_B (h_{B,exit} - h_{B,inlet})$$

Entire Heat Exchanger (both fluids)

$$\dot{m}_A h_{A,exit} + \dot{m}_B h_{B,exit} = \dot{m}_A h_{A,inlet} + \dot{m}_B h_{B,inlet}$$

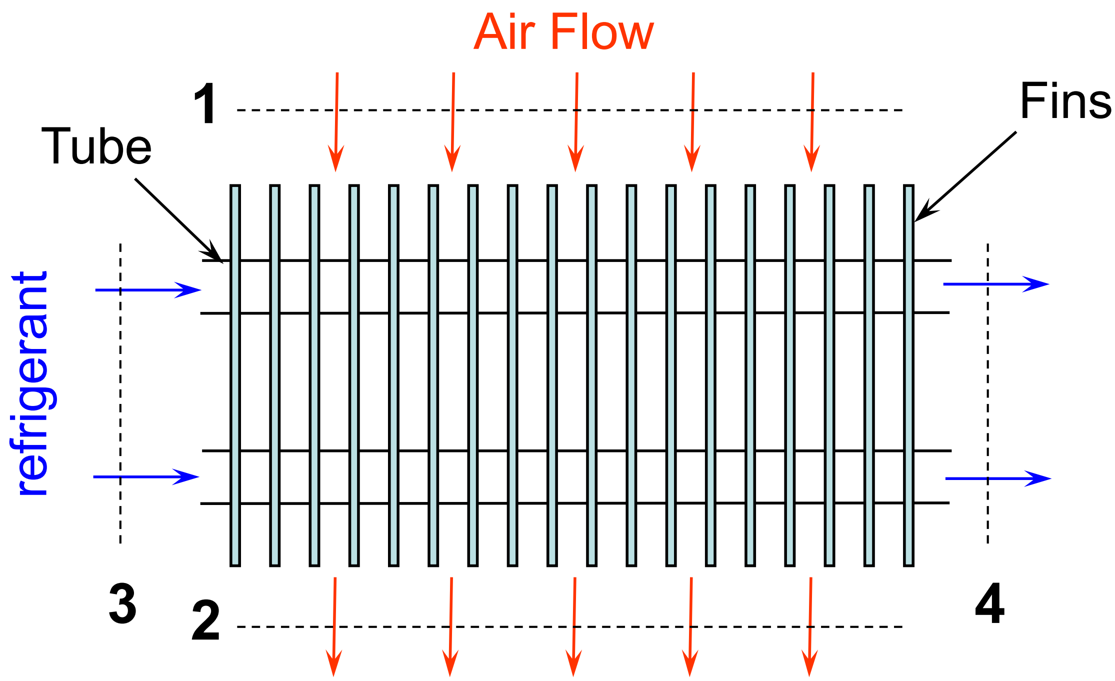
or

$$\dot{m}_A (h_{A,exit} - h_{A,inlet}) = \dot{m}_B (h_{B,inlet} - h_{B,exit})$$

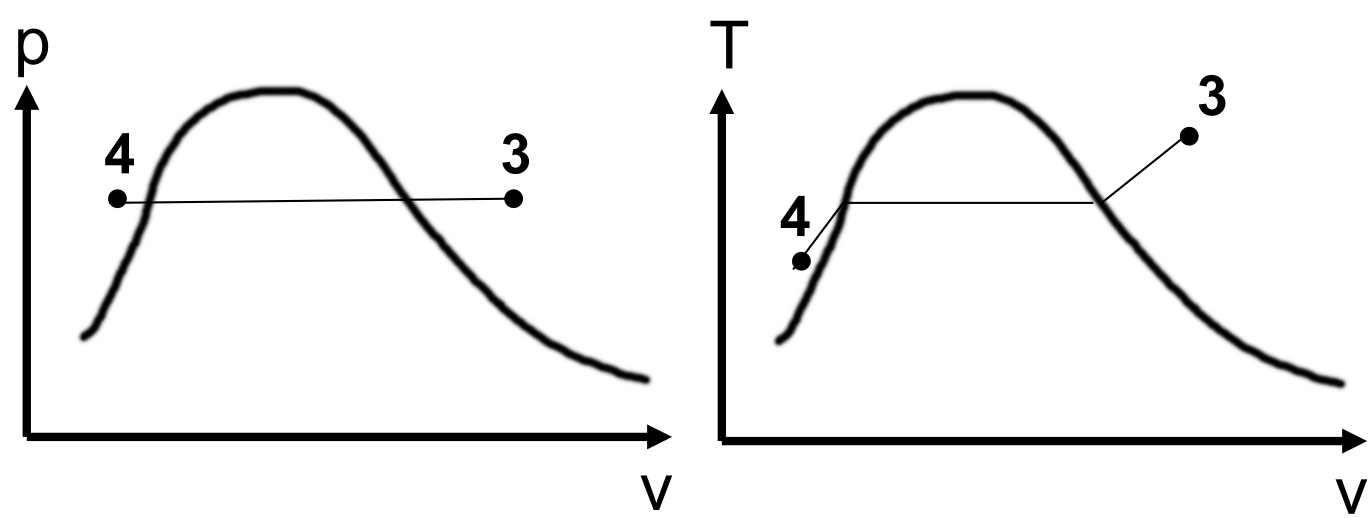
Relationship Between Fluid Heat Transfer Rates

$$\dot{Q}_A = -\dot{Q}_B$$

Air-Cooled Condenser for AC

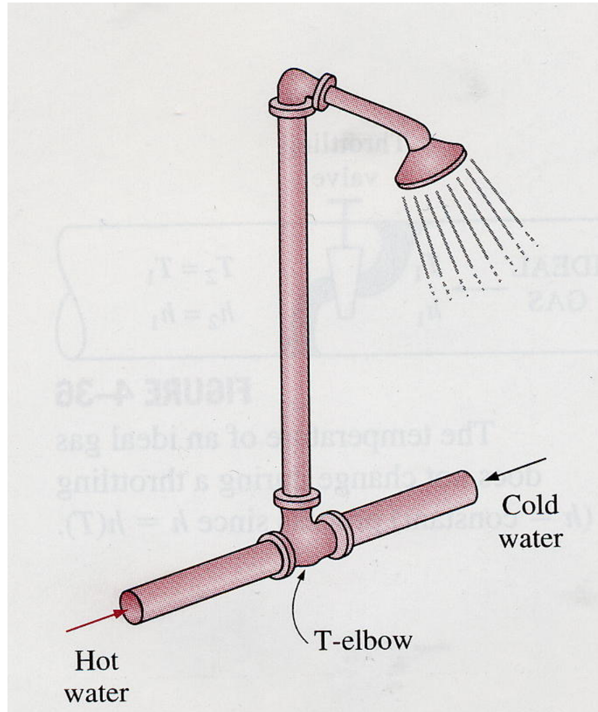


Refrigerant Changes



Adiabatic Mixing

- two streams are mixed in many practical applications
- the streams exchange heat internally, but heat transfer to/from the surroundings is usually negligible (the surface area is small)
- the mixing process is often assumed to occur at constant pressure
- potential and kinetic energy changes are small



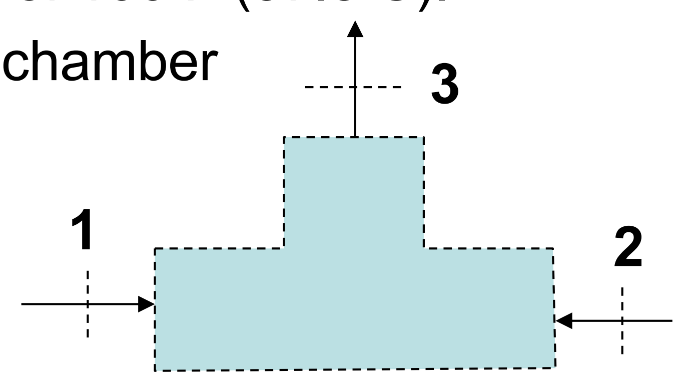
Shower Example

Given: Hot water at 140 F (60 C) is mixed with cold water at 60 F (15.6 C) in a shower at a pressure of 20 psia (1.4 bar)

Find: Fraction of hot water that is necessary for a mixed outlet temperature of 100 F (37.8 C).

System: water in mixing chamber

$p_3 = p_2 = p_1 = 1.4$ bar
$T_1 = 60$ C
$T_2 = 15.6$ C
$T_3 = 37.8$ C



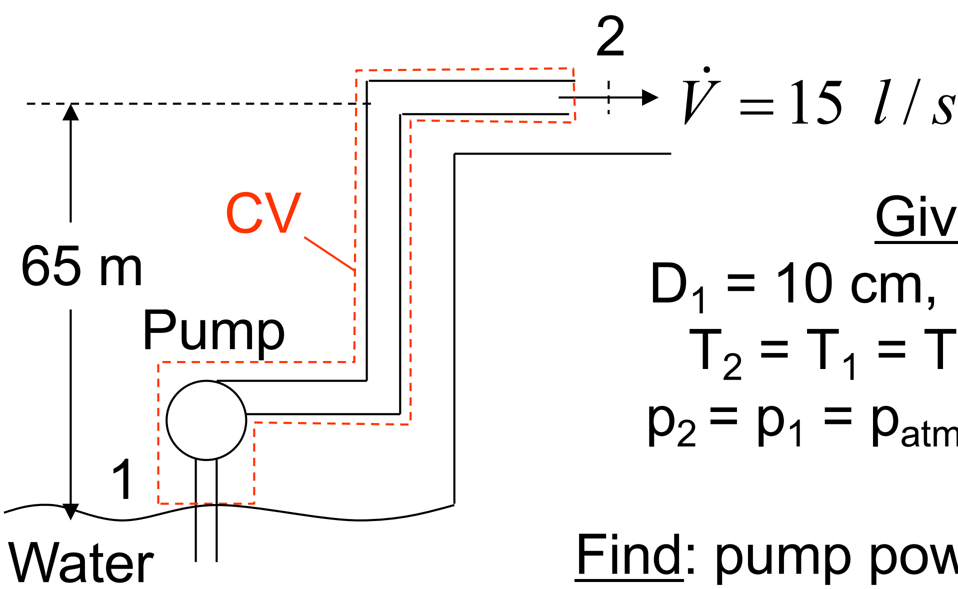
Assumptions: 1) SSSF, 2) negligible heat transfer to surroundings, 3) negligible changes in kinetic and potential energy, 4) no work producing devices, 5) incompressible liquid, 6) constant specific heat

Lecture 17
System Integration

Integrated Systems

- Combination of multiple devices that serve a given purpose
- Includes complete cycles or other systems / subsystems
- Often select a control volume that spans the entire system or subsystem

Water Pumping Example



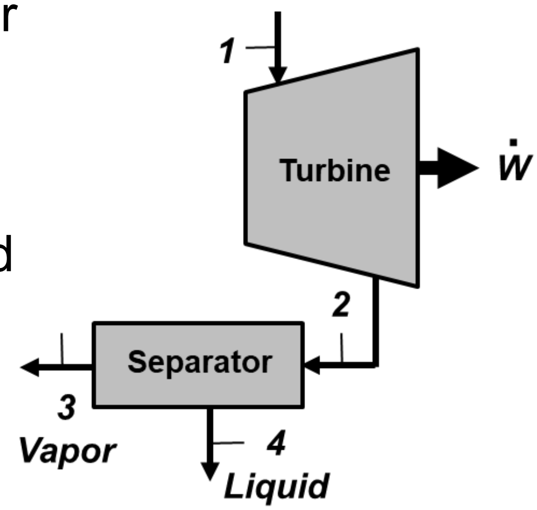
Given
D_1 = 10 cm, D_2 = 15 cm;
$T_2 = T_1 = T_{atm}$ = 20°C
$p_2 = p_1 = p_{atm}$ = 101.3 Pa

Find: pump power required

Assumptions: 1) SSSF, 2) adiabatic, 3) water is incompressible

Liquid Separator and Work Recovery

Given: System separates liquid water & water vapor while recovering work from the steam according to the operating states below. Neglect heat transfer and changes in potential and kinetic energy.



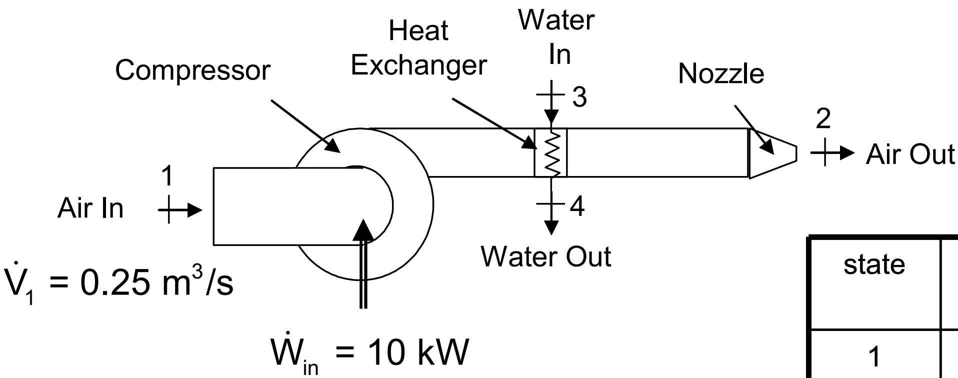
1) Find percentage of inlet mass flow rate converted to liquid, $\dot{m}_4/\dot{m}_1$
2) Show processes on *P*-*v* & *T*-*v* diagrams

State	*T* (°*C*)	*P* (kPa)	*x*	*h* (kJ/kg)
1	200	500	-	
2		100		2364
3		100	1.0	
4		100	0.0	

Part Cleaning Apparatus

Given: System draws air at low velocity and produces a high velocity jet of air for cleaning of manufactured parts. System includes a compressor for raising the air pressure, a heat exchanger for cooling the air, and a nozzle for producing the high velocity. The heat exchanger uses liquid water to cool the air. For the conditions shown below:

Find: a) mass flow rate of air (kg/s), b) required water flow rate (kg/s).



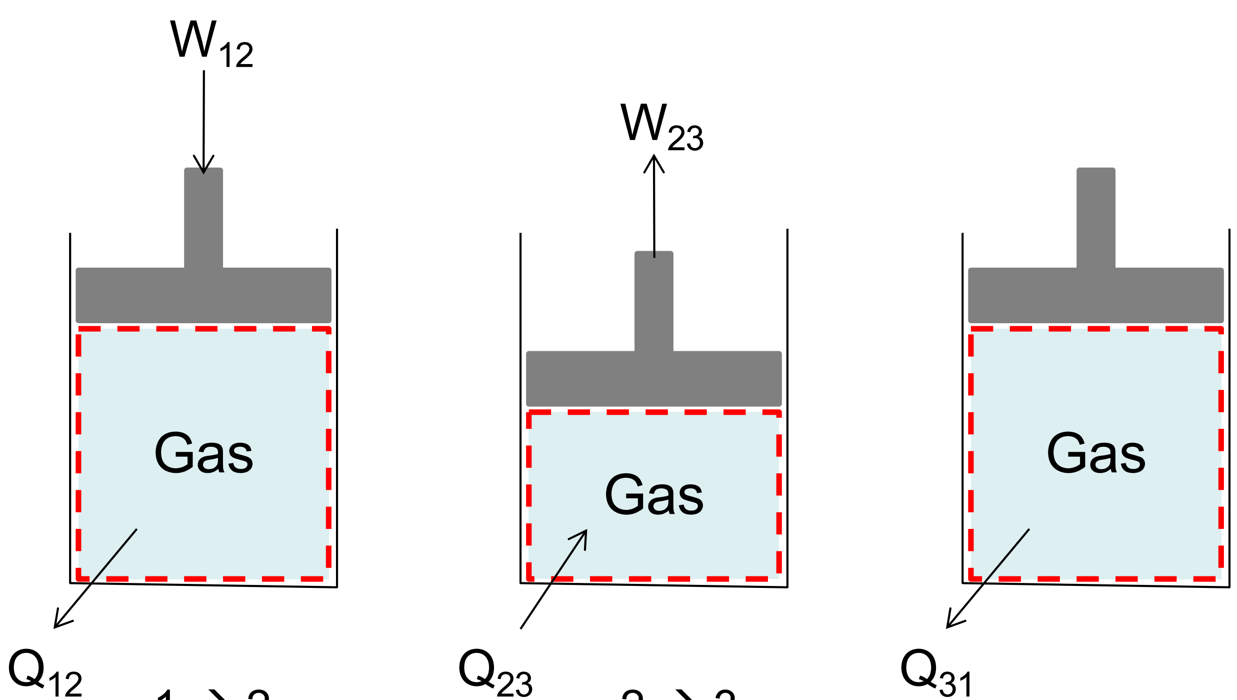
state	T (C)	P (kPa)	V (m/s)
1	21	100	~0
2	21	100	30
3	10	300	-
4	16	300	-

Lecture 18
Cycle Analysis

Thermodynamic Cycle

- Sequence of processes that begins and ends at the same state → no change in system energy
- Can be single closed device with multiple processes or multiple open devices connected by flow streams

Consider an example closed system power cycle



1 → 2
Compression + Heat Rejection

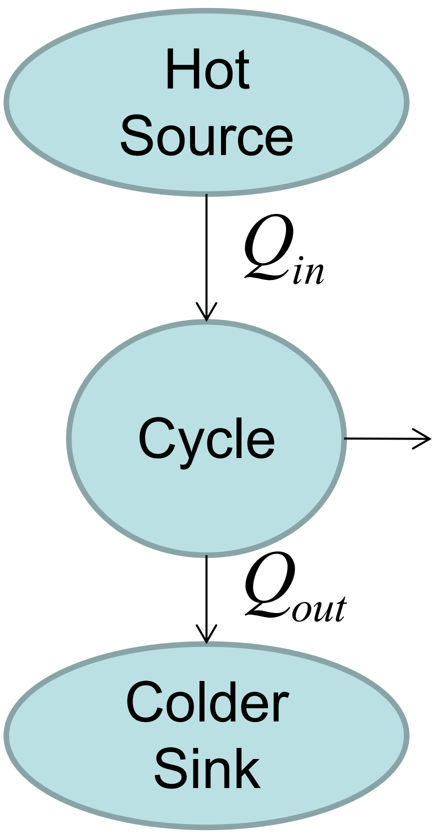
2 → 3
Constant Pressure Expansion + Heat Addition

3 → 1
Constant Volume Heat Rejection

What do the processes look like on a PV diagram? How do you depict the work?

1st Law applied to the complete cycle

For a general power cycle

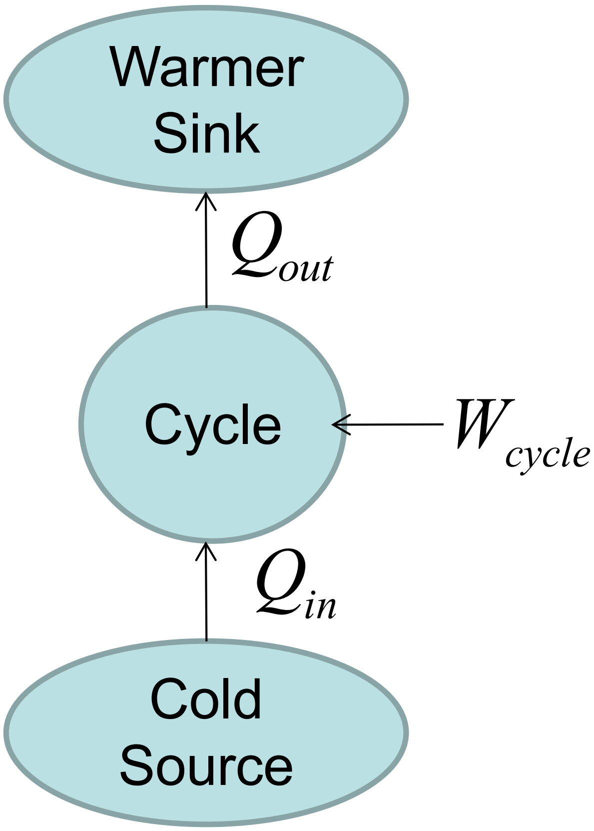


$$W_{cycle} = Q_{in} - Q_{out}$$

<u>Heat Engine Thermal Efficiency</u>

$$\eta = \frac{W_{cycle}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Refrigeration and Heat Pump Cycles



Coefficient of Performance

$$\text{Refrigerator or Air Conditioner:} \quad \beta = \frac{Q_{in}}{W_{cycle}} = \frac{Q_{in}}{Q_{out} - Q_{in}}$$

$$\text{Heat Pump:} \quad \gamma = \frac{Q_{out}}{W_{cycle}} = \frac{Q_{out}}{Q_{out} - Q_{in}}$$

Example

Given: Example closed system 3-Process Cycle with air

1→2: $PV = \text{constant}$

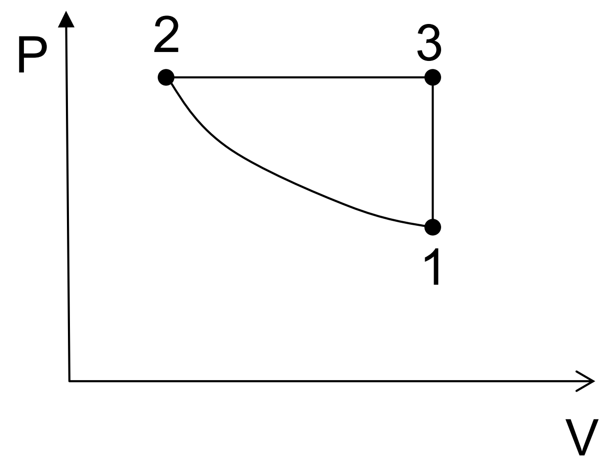
$T_2 = T_1 = 22$ C

$P_1 = 1$ bar, $V_1 = 1.0\ m^3$

$V_2 = 0.2\ m^3$

2→3: $P_3 = P_2$, $V_3 = V_1$

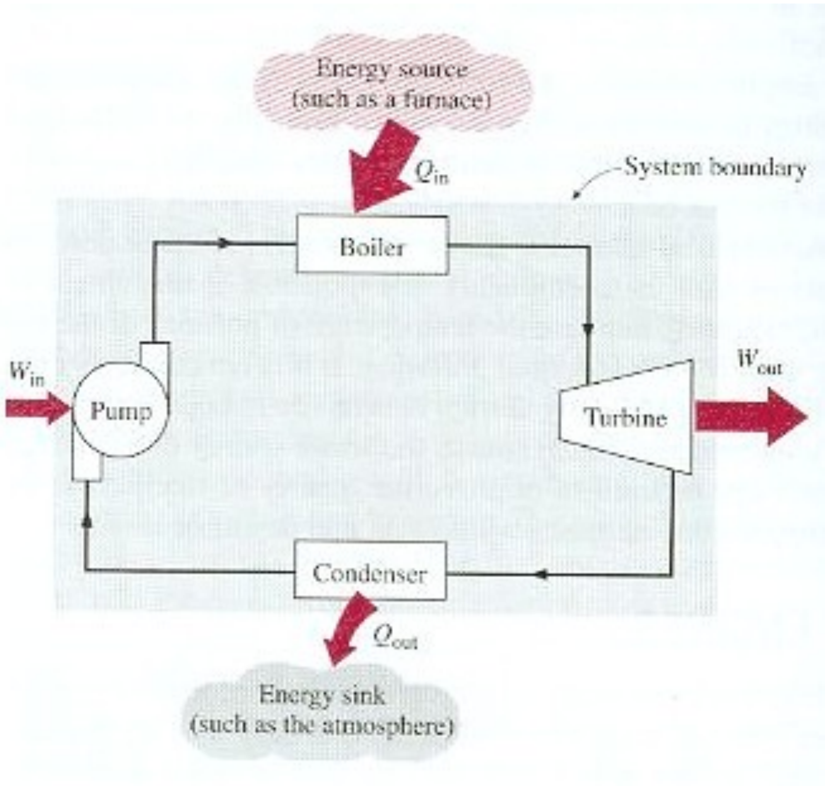
3→1: $V = \text{constant}$



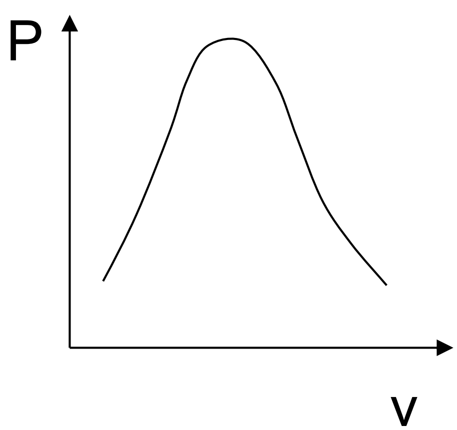
Find: W_{12}, W_{23}, Q_{23}, and η

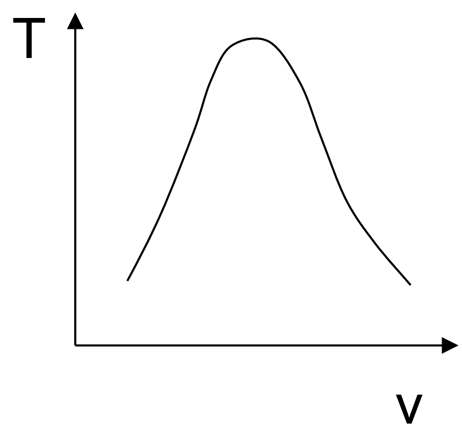
Assumptions:

Steam Power Plant Cycle

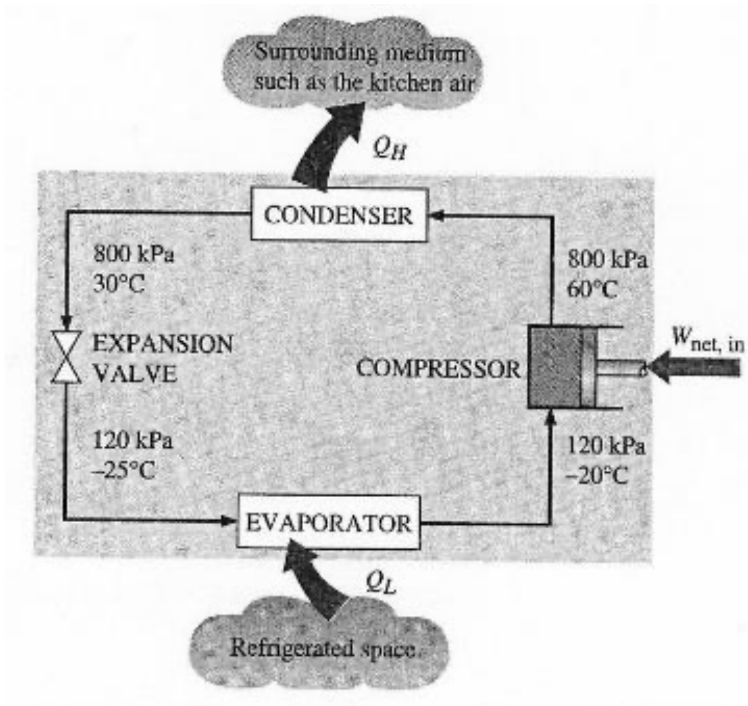


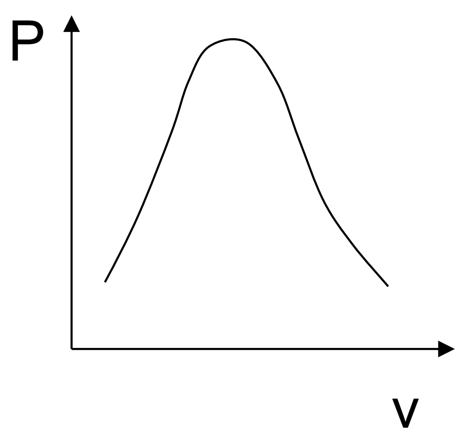
Depiction on P-v and T-v diagrams

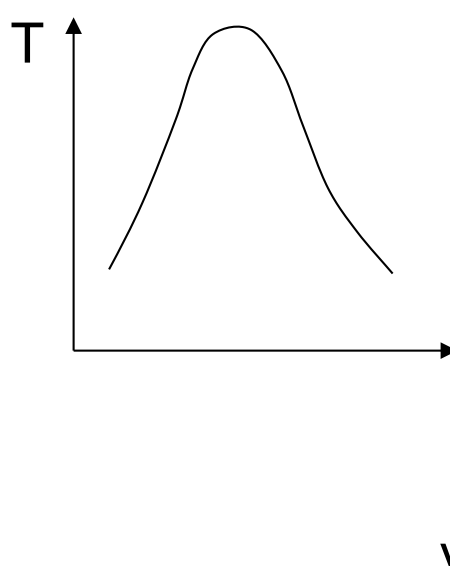




Vapor Compression Heat Pumping Cycle



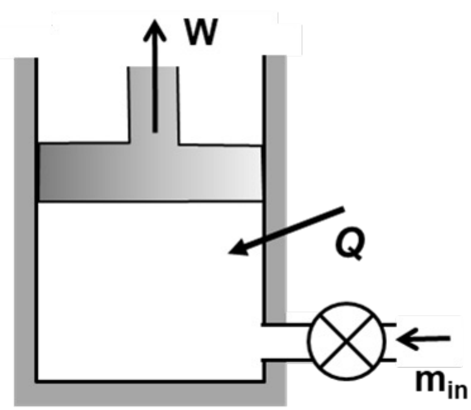




Lecture 19
Transient Open System Analysis

- Most of our closed system analyses have been **"transient"** meaning that the state of the system changed over **time**
- So far our open system analyses have assumed SSSF where system states change spatially from inlet to outlet but don't change with time
- Some systems have both transient and spatial variations

Intake Stroke of Piston-Cylinder Device

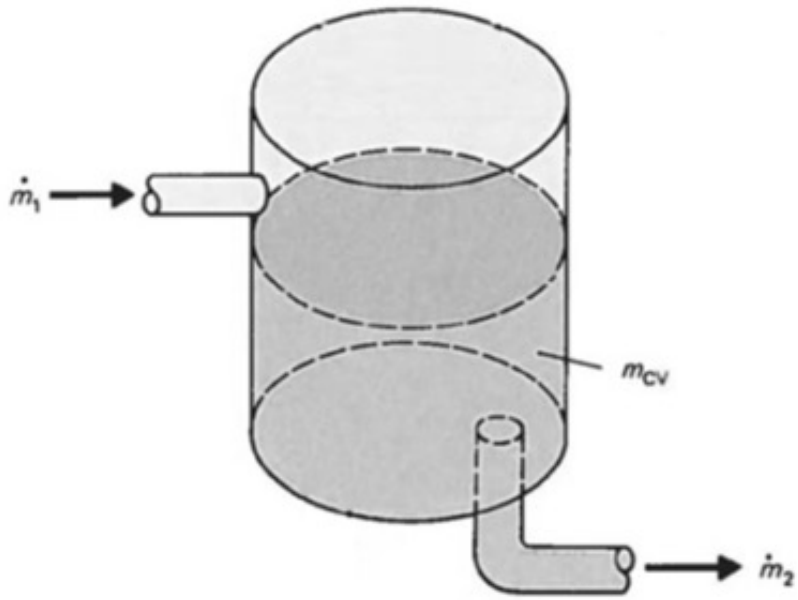


Given: Piston-cylinder undergoes constant pressure process. Steam source at 1.0 MPa & 320°C fills device. Initial state is 0.5 MPa, saturated vapor, and 0.002 m^3. Steam slowly fills volume until the volume is 0.040 m^3, and the mass added is 0.150 kg.

Find: Final state and heat transfer

Oil Tank Filling/Draining

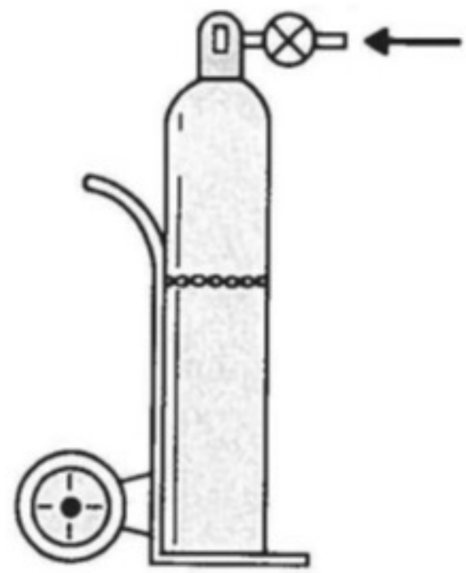
Given: Crude-oil storage tank is 20 m high, holds 2000 m^3, and initially contains 1000 m^3 of oil. Oil is pumped into the tank inlet at a rate of 2 m^3/min and pumped out with a velocity of 1.5 m/s in another pipe of 0.15 m inside diameter.



Find: height and volume of oil in the tank after 24 hours

Air Tank Charging

Given: Tank of volume *V* filled adiabatically with air. Initially tank is evacuated, and air enters from a line at 1.0 MPa and 300 K.



Find: Final temperature when tank is filled to pressure equal to the line pressure. Assume air is an ideal gas with k = 1.40.