Ch.2
Conservation of Mass / Energy

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Outline

1. Conservation and The Balance Equation
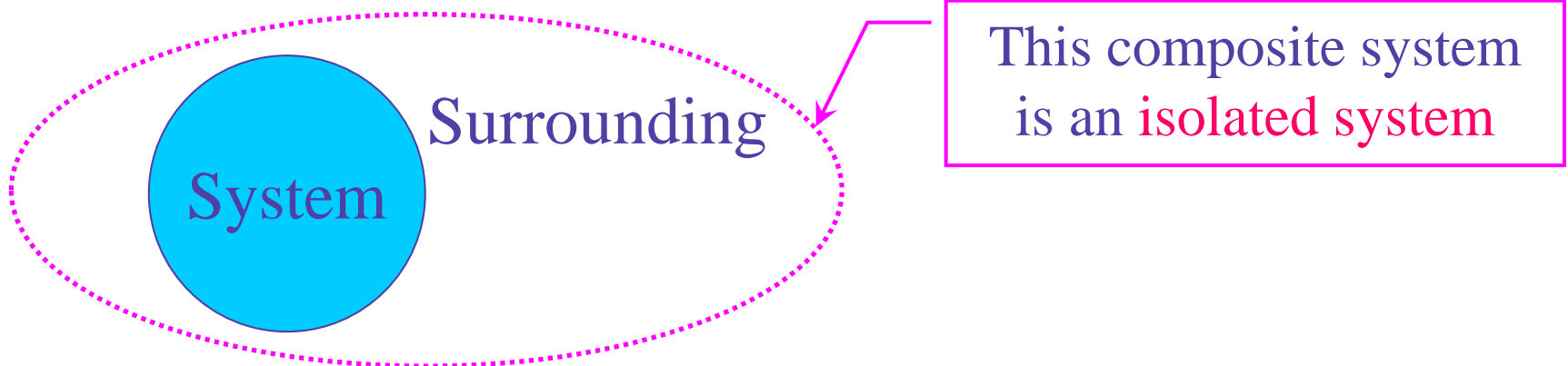
2. Mass Balance

3. Energy Balance

4. Thermodynamic Properties of Matter

- For isolated systems in the absence of nuclear reactions,
  - mass is conserved.
  - energy is conserved.

- Consequently, the Balance Concept is applicable for nonisolated systems.

Surrounding

System

This composite system is an isolated system

Conserved Quantity and Balance

- Systems
  - Matters of interest, separated from surrounding.
  - Boundary, real or imaginary, separates a system from its surrounding.
  - Can have interactions with surroundings.

- Types of systems
  - Closed systems / Open systems.   Mass Flow?
  - Adiabatic systems / Diathermal systems.   Heat Flow?
  - Rigid systems / Deformable systems   Work Flow?
  - Isolated systems.
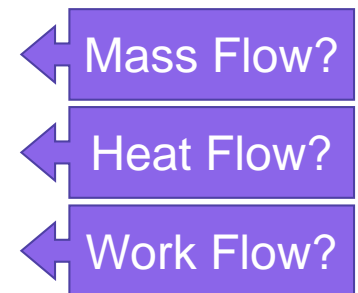
The General Balance Equation

- Within a specified time span, changes in the conserved quantity of the system of interest must be due to
  - Exchange of the quantity with the surrounding.
  - Chemical reactions (?).

- For the system of interest, balance of quantity θ from time t to t + Δt,
  - Accumulation = Input – Output + Generation.

Integral form of the general balance equation

$$\begin{pmatrix} \text{amount of } \theta \text{ in the} \\ \text{system at time t} + \Delta t \end{pmatrix} - \begin{pmatrix} \text{amount of } \theta \text{ in the} \\ \text{system at time t} \end{pmatrix} =$$

$$\begin{pmatrix} \text{amount of } \theta \text{ that entered the} \\ \text{system from time t to t} + \Delta t \end{pmatrix} - \begin{pmatrix} \text{amount of } \theta \text{ that left the} \\ \text{system from time t to t} + \Delta t \end{pmatrix} + \begin{pmatrix} \text{amount of } \theta \text{ generated within} \\ \text{the system at time t} + \Delta t \end{pmatrix}$$

- From the integral form balance equation to the differential form balance equation,
  - "Accumulation = Input – Output + Generation".
  - Divide the equation by Δt, and let $\Delta t \rightarrow 0$, we get "Accumulation rate = Input rate – Output rate + Generation rate".

$$\frac{d\theta}{dt} = \lim_{\Delta t \to 0} \frac{\theta(t+\Delta t) - \theta(t)}{\Delta t} = \begin{pmatrix} \text{rate of change of} \\ \theta \text{ in the system} \end{pmatrix} =$$
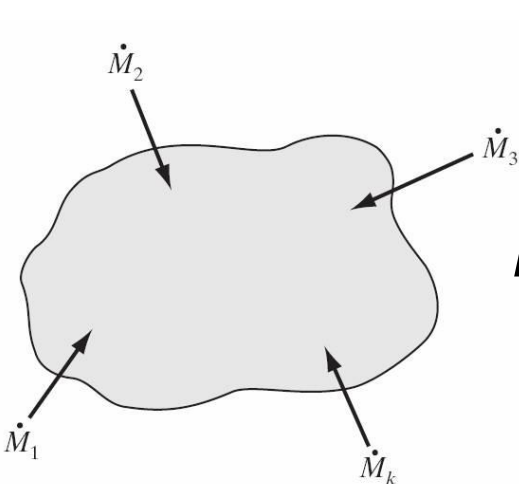
$$\begin{pmatrix} \text{rate at which } \theta \\ \text{enters the system} \end{pmatrix} - \begin{pmatrix} \text{rate at which } \theta \\ \text{leaves the system} \end{pmatrix} + \begin{pmatrix} \text{rate at which } \theta \text{ is generated} \\ \text{within the system} \end{pmatrix}$$

$$\begin{pmatrix} \text{rate of} \\ \text{accumulation} \end{pmatrix} = \begin{pmatrix} \text{rate of} \\ \text{input} \end{pmatrix} + \begin{pmatrix} \text{rate of} \\ \text{output} \end{pmatrix} + \begin{pmatrix} \text{rate of} \\ \text{generation} \end{pmatrix}$$

Differential form or rate form of the general balance equation

- Total mass is conserved for isolated systems. Therefore, the balance equation is applicable for "total mass".
  - "total mass" cannot be "generated" unless via nuclear reaction.
  - For systems not involving nuclear reaction, the "generation of total mass" is zero.

$$\frac{dM}{dt} = \sum_{k=1}^{K} \dot{M}_k \quad \text{for input, } \dot{M}_k > 0; \text{ for output, } \dot{M}_k < 0$$

$$M(t_1 + \Delta t) - M(t_1) = \int_{t_1}^{t_1 + \Delta t} \frac{dM}{dt} dt = \sum_{k=1}^{K} \int_{t_1}^{t_1 + \Delta t} \dot{M}_k dt = \sum_{k=1}^{K} \Delta M_k$$

$\dot{M}_2$

$\dot{M}_3$

$\dot{M}_1$

$\dot{M}_k$

NOTE: If steady state is attained, "accumulation" is zero.

Mass Balance Equation

- ## Ex.2.2-1

  A tank of volume 25 m^3 contains 1.5×10^4 kg of water. Over a two-day period the inlet to the tank delivers 2.0×10^3 kg, 1.3×10^3 kg leaves the tank through the outlet port, and 50 kg of water leaves the tank by evaporation. How much water is in the tank at the end of the two-day period?

- Ex.

    Analyze the change of your body weight from wake up to lunch time.

    Analyze your bank account balance from Sept.1 till Sept. 20.

    c.f., continuous process / noncontinuous process
        batch / semibatch process

Mass Balance Equation

- Ex.2.2-4

  An open cylinder with a base area of 1 m² and a height of 10 m contains 5 m³ of water. As a result of corrosion, the tank leaks at its bottom at a rate following

  leak rate (m³/s) = $0.5\sqrt{\Delta P}$

  where ∆P is the pressure difference in bar between the fluid at the base of the tank and the atmosphere. Determine the amount of water in the tank at any time.

  c.f., differential (rate) form of balance eqn
  semibatch process

Table 2.2-1 The Mass Conservation Equation

	Mass Basis	Molar Basis
Rate-of-change form of the mass balance		
General equation	$\dfrac{dM}{dt} = \sum\limits_{k=1}^{K} \dot{M}_k$	$\dfrac{dN}{dt} = \sum\limits_{k=1}^{K} \dot{N}_k$
Special case:		
Closed system	$\dfrac{dM}{dt} = 0$	$\dfrac{dN}{dt} = 0$
	$M = \text{constant}$	$N = \text{constant}$
Difference form of the mass balance *		
General equation	$M_2 - M_1 = \sum\limits_{k=1}^{K} \Delta M_k$	$N_2 - N_1 = \sum\limits_{k=1}^{K} \Delta N_k$
Special cases:		
Closed system	$M_2 = M_1$	$N_2 = N_1$
Steady flow	$M_2 - M_1 = \sum\limits_{k=1}^{K} \dot{M}_k \, \Delta t$	$N_2 - N_1 = \sum\limits_{k=1}^{K} \dot{N}_k \, \Delta t$

Only for systems without reaction

Q: steady state?

*Here we have used the abbreviated notation $M_i = M(t_i)$ and $N_i = N(t_i)$.

$$\frac{dN_j}{dt} = F_{j,o} - F_j + \int r_j \cdot dV$$

Independent variable : t

Dependent variables : N_j , F_j , r_j , V

\# Initial condition

- Ex. 2.3-2

  At high temperature, acetaldehyde dissociates into methane and CO, by $CH_3CHO \rightarrow CH_4 + CO$. At 520 ^oC the rate is found as $\dfrac{dN_{CH_3CHO}}{dt} = -0.48C_{CH_3CHO}^2 \dfrac{m^3}{kmol \cdot s}$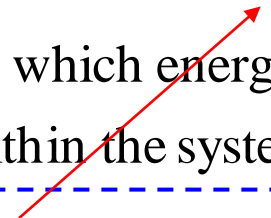 where C is in kmol/m^3. The reaction occurs in a constant-volume 1-liter vessel and the initial concentration of acetaldehyde is 10 kmol/m^3.

  a. If 5 moles of the acetaldehyde reacts, how much methane and CO is produced?

  b. Develop expressions for the amounts of acetaldehyde, methane, and CO present at any time, and determine how long it would take for 5 mol of acetaldehyde to have reacted.

Energy Balance Equation

- Total energy is conserved for isolated systems although the forms of energy may change. Therefore, the balance equation is applicable for "total energy".
  - "total energy" cannot be "generated" unless via nuclear reaction.
  - What forms of energy need to be considered?

$$\frac{d\theta}{dt} = \frac{d}{dt}\left(U + M(v^2/2 + \Psi)\right) = \begin{pmatrix} \text{rate of change of} \\ \text{energy in the system} \end{pmatrix} =$$

$$\begin{pmatrix} \text{rate at which energy} \\ \text{enters the system} \end{pmatrix} - \begin{pmatrix} \text{rate at which energy} \\ \text{leaves the system} \end{pmatrix} + \begin{pmatrix} \text{rate at which energy is generated} \\ \text{within the system} \end{pmatrix}$$

Energy Balance Equation

System - Surrounding Interaction

Mass Flow

Heat Flow

Work Flow

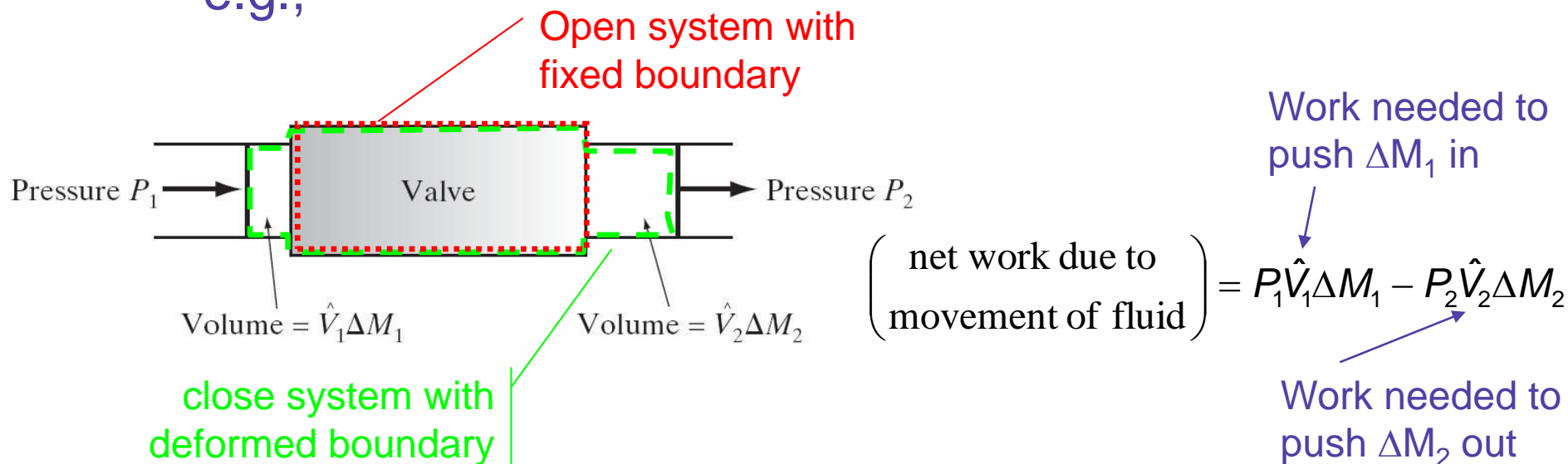$$\sum_{k=1}^{K} \dot{M}_k (\hat{U} + \frac{v^2}{2} + \Psi) \qquad \dot{Q} = \sum_{j=1}^{J} \dot{Q}_j \qquad \dot{W} = \sum_{i=1}^{I} \dot{W}_i = \sum_{i=1}^{I} F_i \frac{dL_i}{dt}$$

All three are related to Energy Flow.

- Heat and work
  - Have the same unit as "energy"
  - Are considered as one form of energy during energy transition.

- Matters
  - Contain energy which is classified into kinetic energy, potential energy , and internal energy

- Work flows (exchanges):
  - Shaft work, W_S, the mechanical energy flow that occurs without the deformation of the system boundaries, e.g., turbine. Electrical energy can also be included.
  - Work resulted from the movement of the system boundaries, which can be expressed in terms of PdV, e.g.,

Open system with
fixed boundary

Pressure P_1

Valve

Pressure P_2

Volume $= \hat{V}_1 \Delta M_1$

Volume $= \hat{V}_2 \Delta M_2$

close system with
deformed boundary

Work needed to
push ΔM_1 in

$$\left(\begin{array}{c} \text{net work due to} \\ \text{movement of fluid} \end{array} \right) = P_1 \hat{V}_1 \Delta M_1 - P_2 \hat{V}_2 \Delta M_2$$

Work needed to
push ΔM_2 out

- **In general, work flows** $= \dot{W}_s - P\dfrac{dV}{dt} + \displaystyle\sum_{k=1}^{K} \dot{M}_k (P\hat{V})_k$

- **Consequently, the energy balance equation is**

$$\frac{d}{dt}\left\{ U + M\left(\frac{v^2}{2} + \Psi \right) \right\} = \sum_{k=1}^{K} \dot{M}_k (\hat{U} + \frac{v^2}{2} + \Psi)_k + \dot{Q} + \dot{W}_s - P\frac{dV}{dt} + \sum_{k=1}^{K} \dot{M}_k (P\hat{V})_k$$

  – Define H = U + PV, and we have

$$\frac{d}{dt}\left\{ U + M\left(\frac{v^2}{2} + \Psi \right) \right\} = \sum_{k=1}^{K} \dot{M}_k (\hat{H} + \frac{v^2}{2} + \Psi)_k + \dot{Q} + \dot{W}$$

  – In molar basis

$$\frac{d}{dt}\left\{ U + Nm\left(\underbrace{\frac{v^2}{2} + \Psi} \right) \right\} = \sum_{k=1}^{K} \dot{N}_k \left\{ \underline{H} + m\left(\underbrace{\frac{v^2}{2} + \Psi} \right) \right\}_k + \dot{Q} + \dot{W}$$

First Law of Thermodynamics

Usually small and negligible, esp. for gases

Table 3.1-1 Differential Form of the Energy Balance

General equation

$$\frac{d}{dt}\left\{U + M\left(\frac{v^2}{2} + \psi\right)\right\} = \sum_{k=1}^{K} \dot{M}_k\left(\hat{H} + \frac{v^2}{2} + \psi\right)_k + \dot{Q} + \dot{W} \qquad (a)$$

Special cases:

(i) Closed system

$$\dot{M}_k = 0, \qquad \frac{dM}{dt} = 0$$

so

$$\frac{dU}{dt} + M\frac{d}{dt}\left(\frac{v^2}{2} + \psi\right) = \dot{Q} + \dot{W} \qquad (b)$$

(ii) Adiabatic process

in Eqs. a, b, and d

$$\dot{Q} = 0 \qquad (c)$$

(iii) Open and steady-state system

$$\frac{dM}{dt} = 0, \qquad \frac{dV}{dt} = 0, \qquad \frac{d}{dt}\left\{U + M\left(\frac{v^2}{2} + \psi\right)\right\} = 0$$

so

$$0 = \sum_{k=1}^{K} \dot{M}_k\left(\hat{H} + \frac{v^2}{2} + \psi\right)_k + \dot{Q} + \dot{W}_s \qquad (d)$$

(iv) Uniform system

In Eqs. a and b

$$U = M\hat{U} \qquad (e)$$

Note: To obtain the energy balance on a molar basis, make the following substitutions:

Table 3.1-2 Difference Form of the Energy Balance

General equation

$$\left\{ U + M\left(\frac{v^2}{2} + \psi\right)\right\}_{t_2} - \left\{ U + M\left(\frac{v^2}{2} + \psi\right)\right\}_{t_1} = \sum_{k=1}^{K} \int_{t_1}^{t_2} \dot{M}_k \left(\hat{H} + \frac{v^2}{2} + \psi\right)_k dt + Q + W \quad \text{(a)}$$

Special cases:

(i) Closed system

$$\left\{ U + M\left(\frac{v^2}{2} + \psi\right)\right\}_{t_2} - \left\{ U + M\left(\frac{v^2}{2} + \psi\right)\right\}_{t_1} = Q + W \quad \text{(b)}$$

and

$$M(t_1) = M(t_2)$$

(ii) Adiabatic process

In Eqs. a and b
$$Q = 0 \quad \text{(c)}$$

(iii) Open system, flow of fluids of constant thermodynamic properties

$$\sum_{k=1}^{K} \int_{t_1}^{t_2} \dot{M}_k \left(\hat{H} + \frac{v^2}{2} + \psi\right)_k dt = \sum_{k=1}^{K} \Delta M_k \left(\hat{H} + \frac{v^2}{2} + \psi\right)_k \quad \text{(d)}$$

in Eq. a

(iv) Uniform system
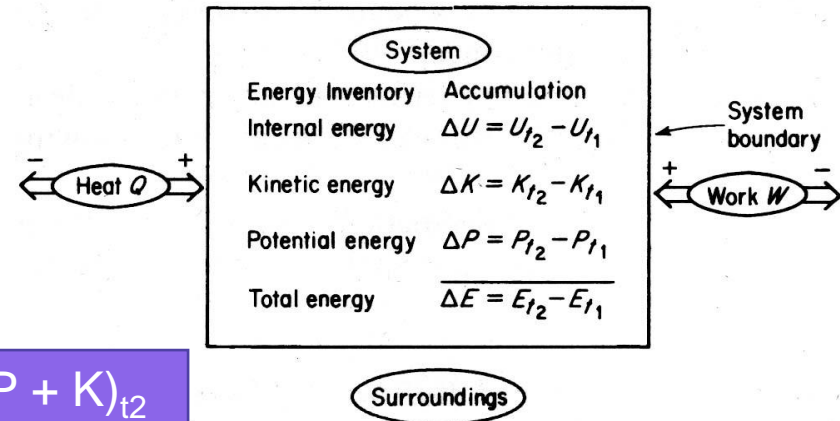
$$\left\{ U + M\left(\frac{v^2}{2} + \psi\right)\right\} = M\left(\hat{U} + \frac{v^2}{2} + \psi\right) \quad \text{(e)}$$

in Eqs. a and b

Note: To obtain the energy balance on a molar basis, make the following substitutions:

Acc = In – Out + Gen

System
Energy Inventory   Accumulation
Internal energy $\Delta U = U_{t_2} - U_{t_1}$ System boundary
Kinetic energy $\Delta K = K_{t_2} - K_{t_1}$
Heat Q Work W
Potential energy $\Delta P = P_{t_2} - P_{t_1}$
Total energy $\overline{\Delta E = E_{t_2} - E_{t_1}}$
Surroundings

$$= E_{t2} - E_{t1} = (U + P + K)_{t1} - (U + P + K)_{t2}$$

$$\Delta E = \sum_{in} m_i(\hat{U}_i + \hat{K}_i + \hat{P}_i) - \sum_{out} m_j(\hat{U}_j + \hat{K}_j + \hat{P}_j) + Q + W + \sum_{in} m_i P_i \hat{V}_i - \sum_{out} m_j P_j \hat{V}_j$$

Work due to shaft work, electrical work or others.

PV work

$$\Delta E = \sum_{in} m_i(\hat{U}_i + \hat{K}_i + \hat{P}_i + P_i\hat{V}_i) - \sum_{out} m_j(\hat{U}_j + \hat{K}_j + \hat{P}_j + P_j\hat{V}_j) + Q + W$$

Integral form:
$$\Delta E = \sum_{in} m_i(\hat{H}_i + \hat{K}_i + \hat{P}_i) - \sum_{out} m_j(\hat{H}_j + \hat{K}_j + \hat{P}_j) + Q + W$$

Rate form:
$$\Delta \dot{E} = \sum_{in} \dot{m}_i(\hat{H}_i + \hat{K}_i + \hat{P}_i) - \sum_{out} \dot{m}_j(\hat{H}_j + \hat{K}_j + \hat{P}_j) + \dot{Q} + \dot{W}$$
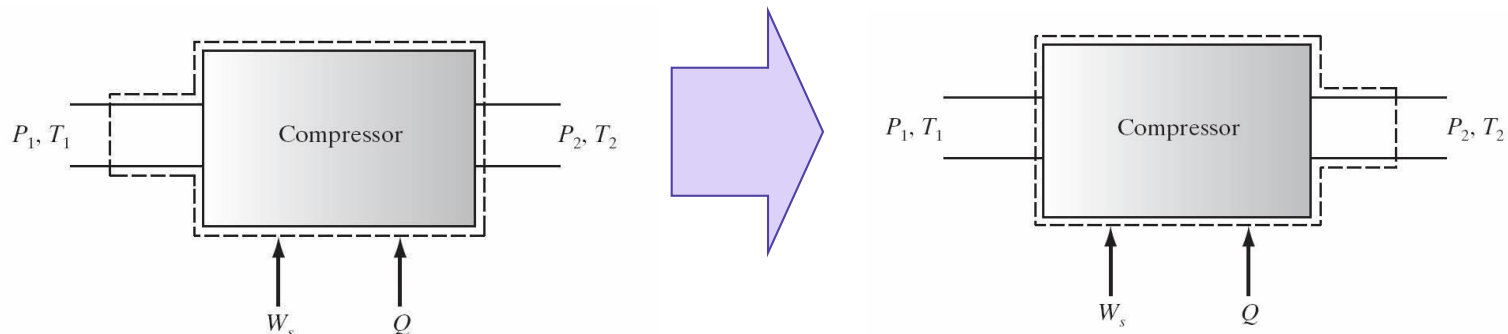
- Ex. 3.2-1

  A compressor is operating in a continuous, steady-state manner to produce a gas at temperature T_2 and pressure P_2 from one at T_1 and P_1. Show that for the time interval Δt,

  $$Q + W_s = (\hat{H}_2 - \hat{H}_1)\Delta M$$

  Establish this result by (a) writing the balance equation for a closed system, and then (b) writing the balance equation for an open system.

- ## Ex. 3.2-2

    A mass M of gas is to be compressed from a temperature T_1 and pressure P_1 to T_2 and P_2 in (a) a one-step process in a frictionless piston and cylinder, and (b) a continuous process in which the mass M of gas is part of the feed stream to the compressor of the previous example. Compute the sum Q + W for each process.

(a)

P_1, T_1 ⟹ P_2, T_2

(b)

P_1, T_1 → Compressor → P_2, T_2

W_s Q
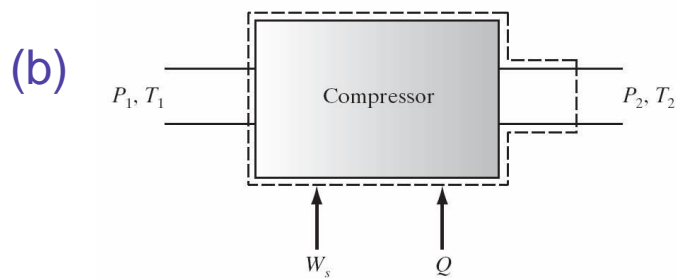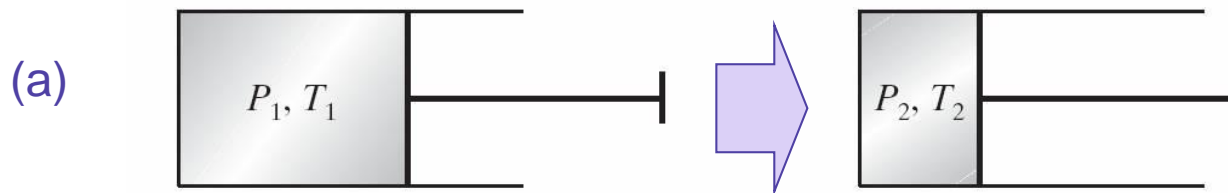
A compressor

- Ex. 3.2-3 (Joule-Thomson or Isenthalpic expansion)

  A gas at pressure P_1 and temperature T_1 is steadily exhausted to the atmosphere at pressure P_2 through a pressure-reducing valve. Find the expression relating the downstream gas temperature T_2 to P_1, P_2 and T_1 . Since the gas flows through the valve rapidly, one can assume that there is no heat transfer to the gas. Also, the potential and kinetic energy terms can be neglected.

$T_1, P_1 \longrightarrow \qquad \longrightarrow T_2 = ?, P_2$
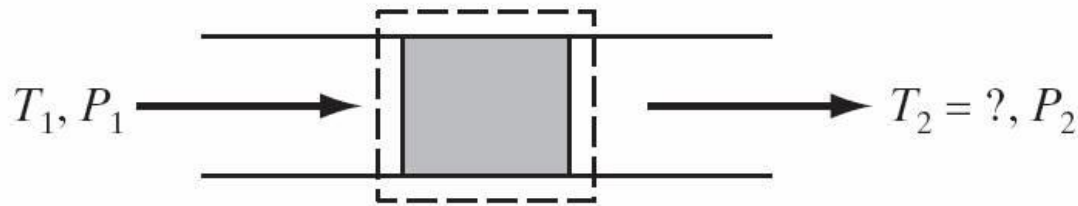
- Energy associated with matters
  - Per unit mass, $\hat{E} = \hat{U} + \dfrac{v^2}{2} + \Psi$
  - The value depends on the state of matters (in the system)

- The state of a system
  - Can be specified by 2 independent intensive variables for single-component, single-phase system.
  - T and P are the preferred intensive variables.
  - Equation of state (EOS) of matter is important.
  - The correlation between energy (e.g., $\hat{U}$ and $\hat{H}$) and the two independent variables (e.g., T, P) is important.

$$\hat{U} = \hat{U}(T, \hat{V}) \quad \hat{U} = \hat{U}(T, P) \quad \text{or} \quad \hat{U} = \hat{U}(P, \hat{V})$$

Properties of Matters

- EOS:
  - For ideal gases, $P\underline{V} = RT$
  - For van der Waal gases, $(P + \dfrac{a}{\underline{V}^2})(\underline{V} - b) = RT$
  - For others, (will be discussed in Ch.6)

- Energy
  - Usually, $\underline{U} = \underline{U}(T, \underline{V})$ and $\underline{H} = \underline{H}(T, P)$
  - Define heat capacity (from experimental observation) as

$$C_V(T, V) = \left(\frac{\partial \underline{U}}{\partial T} \right)_V \qquad C_P(T, P) = \left(\frac{\partial \underline{H}}{\partial T} \right)_P$$

NOTE: The heat capacity concept can be verified using the energy balance

- For ideal gases (and only for ideal gases),
  - EOS, $P\underline{V} = RT$
  - $\underline{U} = \underline{U}(T)$ and $\underline{H} = \underline{H}(T)$
  - $C_P^*(T) = \dfrac{d\underline{H}}{dT}$ and $C_V^*(T) = \dfrac{d\underline{U}}{dT}$

$$C_P^* = \frac{d\underline{H}}{dT} = \frac{d(\underline{U} + P\underline{V})}{dT} = \frac{d(\underline{U} + RT)}{dT} = C_V^* + R$$

$$C_P^*(T) = a + bT + cT^2 + dT^3 + ...$$

$$\underline{H}^{IG}(T_2) = \underline{H}^{IG}(T_1) + \int_{T_1}^{T_2} C_P^* dT$$

$$\underline{U}^{IG}(T_2) = \underline{U}^{IG}(T_1) + \int_{T_1}^{T_2} C_V^* dT$$

NOTE: For matters other than IG, follow the definitions and try to find EOS.

- For solids and liquids (incompressible matters), molecules are close to each other.

  – Molar volume is usually small.

  – $\underline{U} \approx \underline{H}$ because $P\underline{V} \ll \underline{U}$ (unless at very high P)

  – $\left(\dfrac{d\underline{V}}{dP}\right)_T \approx 0$

  – U, C_p, and C_v are functions of T only. For solids, the following empirical correlation (DuLong-Petit law) is found : $C_P = 3NR = 24.942N\dfrac{J}{mol \cdot K}$ @25 ºC ?

  – EOS is very different from the ideal gas law.

Properties of Matters

- For gases not following the ideal gas law (non-ideal gases),
  - EOS different from the ideal gas law can be found, e.g.,
    - Using the compressibility factor (called the corresponding state), i.e., $PV = ZnRT$.
    - van der Waal EOS (one kind of cubic EOS).
    - Cubic EOS.
    - Varial EOS.
  - Thermodynamic properties are usually expressed as functions of (T,P), or (T,V), or (P,V)

Properties of Matters

- For convenience, thermodynamic properties (and their dependency on T,P) are frequently expressed as
  - Diagrams, e.g., P-H diagrams (Fig. 3.3-2, 3.3-3, 3.3-4), T-S diagrams (Fig. 3.3-1).
  - Database, e.g., in Tables (steam table is a most frequently used one), in computerized data.

THERMODYNAMIC PROPERTIES OF METHANE
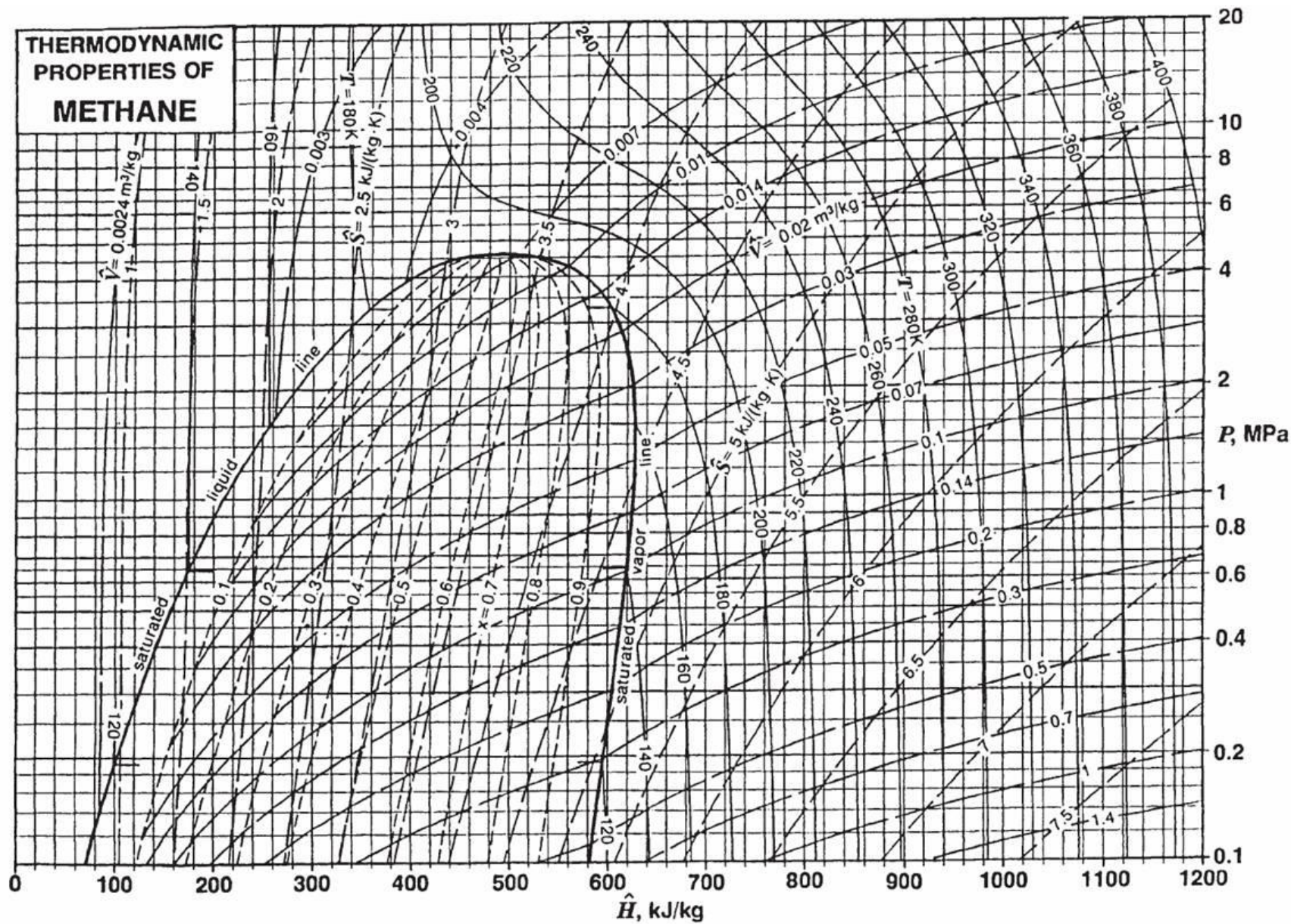
- ## Ex. 3.4-1 (Joule-Thompson calculation)

  Steam at 400 bar and 500 ^{o}C undergoes a Joule-Thompson expansion to 1 bar. Determine the temperature of the steam after the expansion using (a) Fig. 3.3-1 and (b) steam tables (Appendix A.III).

- Ex. 3.4-2

  An adiabatic steady-state turbine is being designed to serve as an energy source for a small electrical generator. The inlet to the turbine is steam at 600 ^{o}C and 10 bar, with a mass flow rate of 2.5 kg/s through an inlet pipe that is 10 cm in diameter. The conditions at the turbine exit are 400 ^{o}C and 1 bar. The outlet pipe is 25 cm in diameter. Estimate the rate at which work can be obtained from this turbine.

$T_1 = 600°C$
$P_1 = 10$ bar

$T_2 = 400°C$
$P_2 = 1$ bar

$\dot{W}_s$
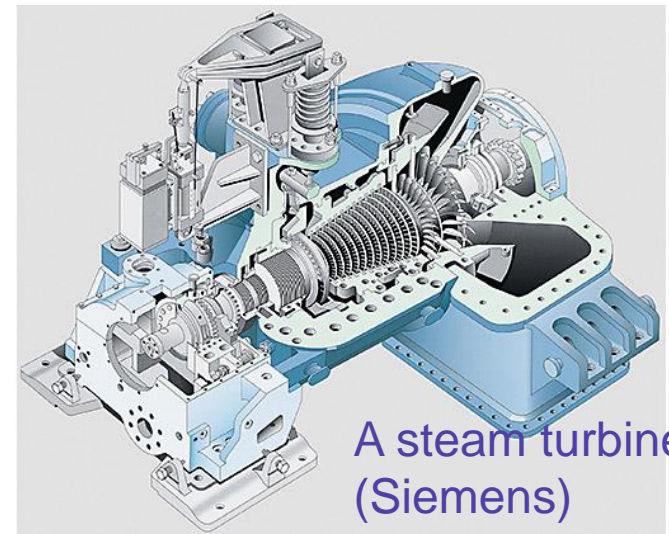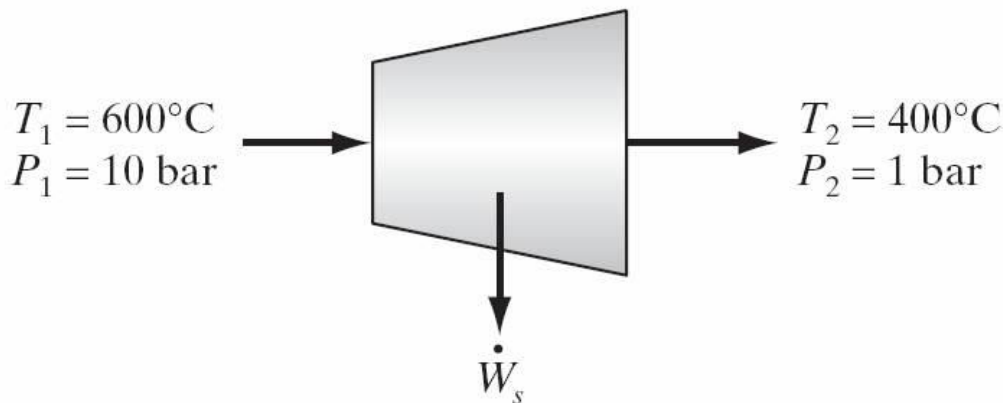
A steam turbine (Siemens)

- Ex. 3.4-3

  A compressed-air tank is to be pressurized to 40 bar by connecting to a high-pressure line containing air at 50 bar and 20 °C. The repressurization occurs so quickly that the process can be considered as adiabatic. Assume air as an ideal gas with C_v = 21 J/(mol K). (a) If the tank initially contains air at 1 bar and 20 °C, what will be the temperature of the air in the tank at the end of the filling process? (b) After long-enough time, the gas in the tank can return to room temperature because of heat exchange between the tank and the atmosphere. What is the new pressure of air in the tank?

  50 bar
  20°C
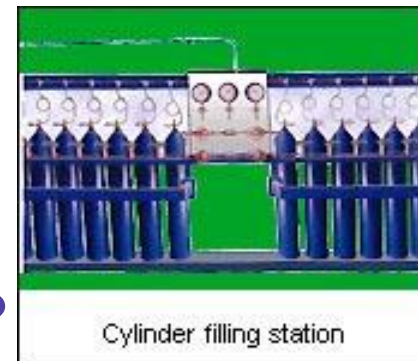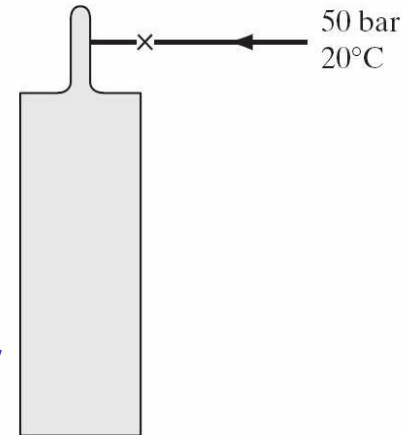
  Cylinder filling station

- Ex. 3.4-4

  A compressor is a gas pumping device that takes in gas at low pressure and discharges it at a higher pressure. Since the process occurs quickly compared to heat transfer, it is usually assumed to be adiabatic. Assuming that the inlet to the compressor is air (as an ideal gas with C_P =29.3 J/mol K) at 1 bar and 290 K and that the discharge is at 10 bar, estimate the temperature of the exit gas and the rate at which work is done on the gas for a gas flow of 2.5 mol/s.
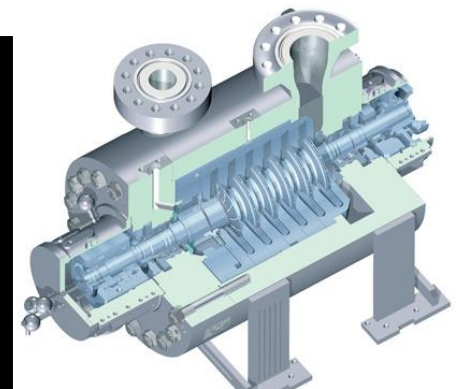
- Ex. 3.4-5

  A gas cylinder of 1 m^3 volume containing N$_2$ initially at a pressure of 40 bar and 200 K is connected to another cylinder of 1 m^3 that is evacuated. A valve between the two cylinders is opened until the pressure in the cylinders equalize. Find the final temperature and pressure in each cylinder if no heat flows into or out of the cylinders or between the gas and the cylinder. You may assume that the gas is ideal with a constant-pressure heat capacity of 29.3 J/mol K.

- Ex. 3.4-6

   It is possible to go from a given initial equilibrium state of a system to a given final equilibrium state by different paths. One gram mole of a gas at a temperature of 25 °C and 1 bar is to be heated and compressed in a frictionless piston and cylinder to 300 °C and 10 bar. Compute the heat and work along each of the following paths.

   (a) Isothermal compression to 10 bar and then isobaric heating to 300 °C.

   (b) Isobaric heating to 300 °C following by isothermal compression to 10 bar.

   (c) A compression in which PV^γ = constant, where $\gamma = C_P/C_V$, followed by an isobaric cooling or heating, if necessary, to 300 °C.

   NOTE: The internal energy is a state property and is independent of the path. The heat and work are, however, path-dependent quantities.
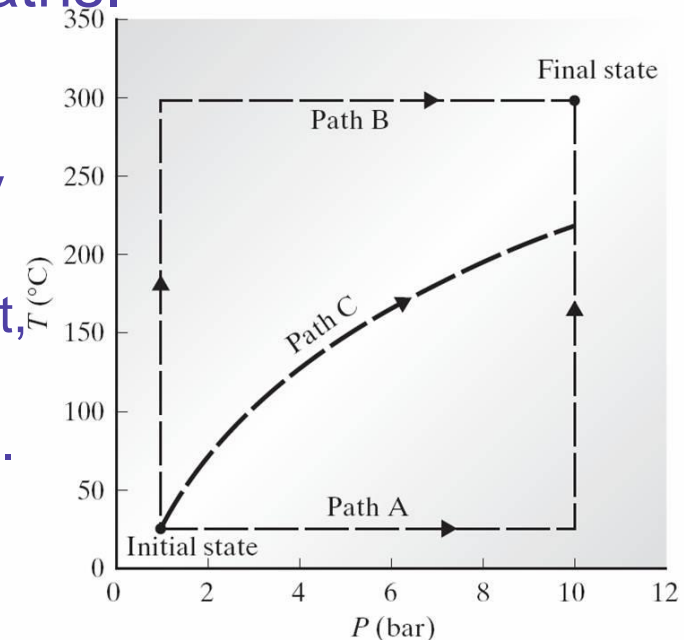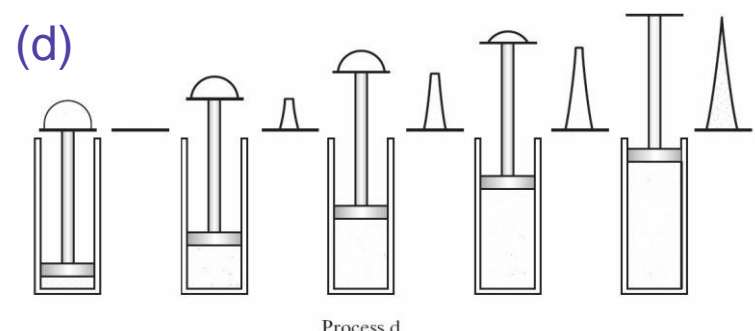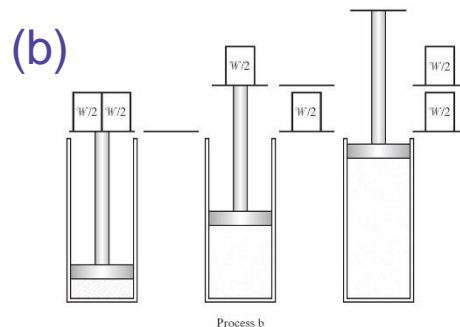
- Ex. 3.4-7

  An initial pressure of 2.043 bar is maintained on a I mol of air contained in a piston and cylinder system by a set of weight $\mathcal{W}$. Work is obtained by removing some of the weights and allowing the air to isothermally expand at 25 ^{o}C. The process is repeated until all the weight s have been removed. The piston has a mass of 5 kg and an area of 0.01 m2. The air can be considered as an ideal gas. and 1 bar. Compute the work obtained from the isothermal expansion for each of the following:

  (a) The weight $\mathcal{W}^o$ is taken off in one step.

  (b) The weight is taken off in two steps, $\mathcal{W}^o/2$ removed each time.

  (c) The weight is taken off in four steps, $\mathcal{W}^o/4$ removed each time.

  (d) The weight is replaced by a pile of sand and the grains of sand are removed one at a time.

(b)

Process b

(d)

Process d

EX. 3.4-7: All 4 processes have the same initial state, the same final state, but different paths. U is a state property while Q and W are path-dependent.
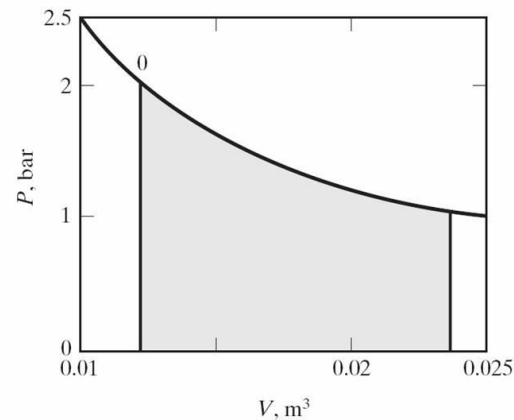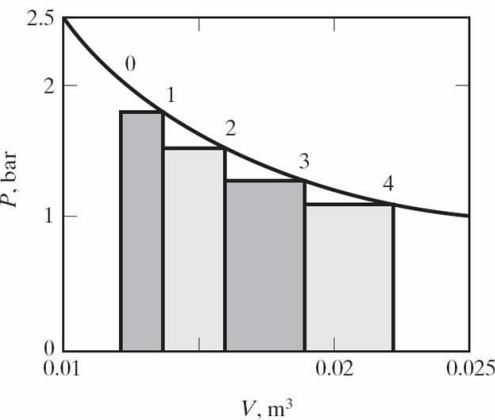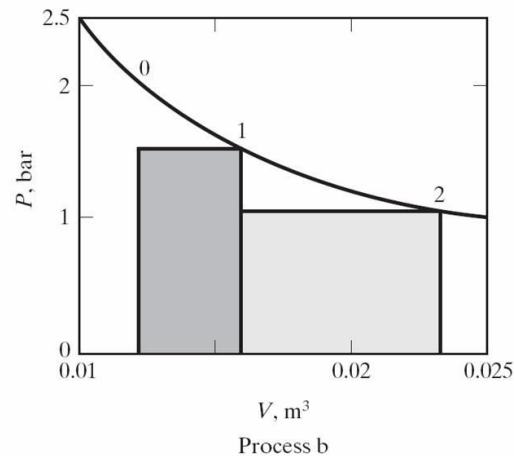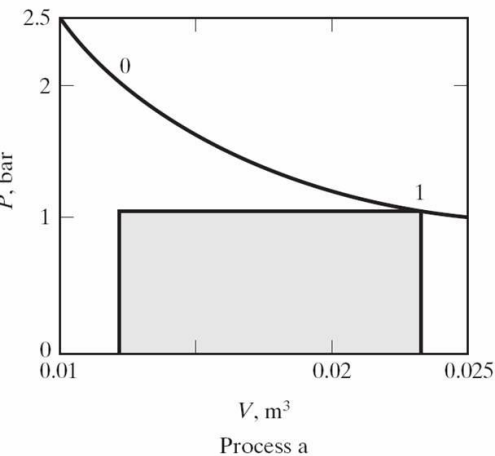
Process a

Process b

Closed system,
U = Q - W

Table 1

Process	$-W^{NET} = Q^{NET}$ (J)	Q (J)	$-W_{fr}$ (J)
a	1190.5	1622.5	432.0
b	1378.7	1622.5	243.8
c	1493.0	1622.5	129.5
d	1622.5	1622.5	0

- Ex. 3.4-8

    Consider the cylinder filled with air and with the piston and spring arrangement shown below. The external atmospheric pressure is 1 bar, the initial temperature of the air is 25 ^{o}C, the no-load length of the spring is 50 cm, the spring constant is 40000 N/m, the frictionless piston weighs 500 kg, and the constant-colume heat capacity of air can be taken as 20.3 J/mol^{o}C. Compute (a) the initial pressure of the gas in the cylinder, and (b) How much heat must be added to the gas in the cylinder for the spring to compress by 2 cm.

55 cm

15 cm

30 cm