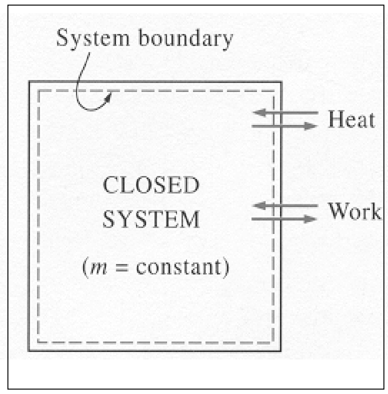
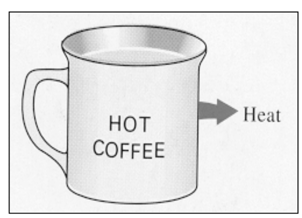
First Law of Thermodynamics

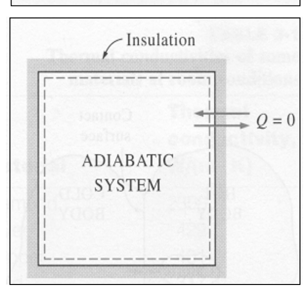
- During an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings.
- Energy can cross the boundary of a closed system in two distinct forms: ***heat*** and ***work***.



Heat Transfer

- Heat is a form of energy that is transferred between a system and its surroundings by virtue of a temperature difference.
- A process during which there is no heat transfer is called an adiabatic process.
- An adiabatic process should not be confused with an isothermal process.



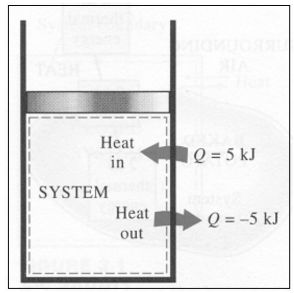


Heat: Units & Direction

- Heat has energy units, kJ (or Btu).
- The amount of heat transferred during a process between two states is denoted by Q_{12} or just Q.
- Heat transfer per unit mass of a system is denoted q as:

$$q = \frac{Q}{m} \qquad \text{kJ/kg}$$

- Heat is a directional quantity. Heat transfer ***to*** a system is ***positive***, and heat transfer **from** a system is ***negative*** .



Modes of Heat Transfer

- Heat can be transferred in three different ways: ***conduction, convection***, and ***radiation***.
- All modes of heat transfer require the existence of a temperature difference.
- All modes of heat transfer are from the high-temperature medium to a lower temperature one.

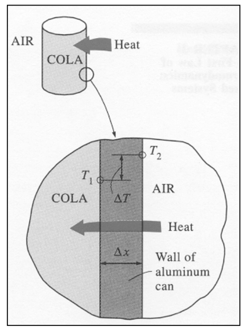
Conduction Heat Transfer

Fourier's Law:

$$\dot{Q}_{cond} = kA\frac{\Delta T}{\Delta x}$$

or

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \quad \text{(W)}$$

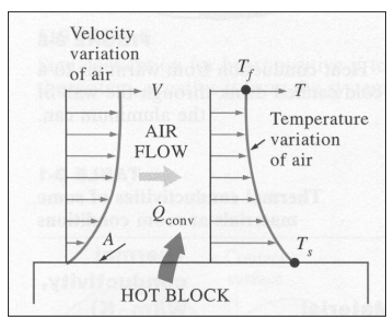


Thermal Conductivity

Material	Thermal conductivity, W/(m · K)
Diamond	2300
Silver	429
Copper	401
Gold	317
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

Convection Heat Transfer

- Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas which is in motion.
- It involves the combined effects of conduction and fluid motion.

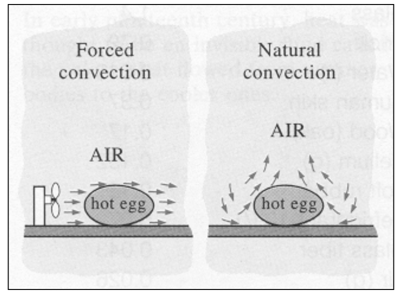


- The faster the fluid motion, the greater the convection heat transfer.

Forced vs.Natural Convection

- Convection is called ***forced convection*** if the fluid is forced to flow by external means such as a fan, or a pump,

- Convection is called ***free** or **natural convection*** if the fluid motion is caused by buoyancy forces that are induced by density differences.



$$\dot{Q}_{conv} = hA(T_s - T_f)$$

Heat Transfer Coefficient, h

$$\dot{Q}_{conv} = hA(T_s - T_f)$$

- h is a function of surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity.
- Typical values of h, in W/(m^2 .K):
  - 2-25 free convection of gases,
  - 50-1000 free convection of liquids,
  - 25-250 forced convection of gases,
  - 50-20,000 forced convection of liquids,
  - 2500-100,000 convection in boiling and condensation processes.

Radiation Heat Transfer

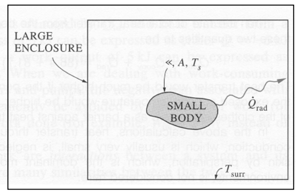
- Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

Stefan-Boltzmann Law:

$$\dot{Q}_{emit,\max} = \sigma A T_s^4$$

$$\dot{Q}_{rad} = \varepsilon \sigma A (T_s^4 - T_{surr}^4)$$

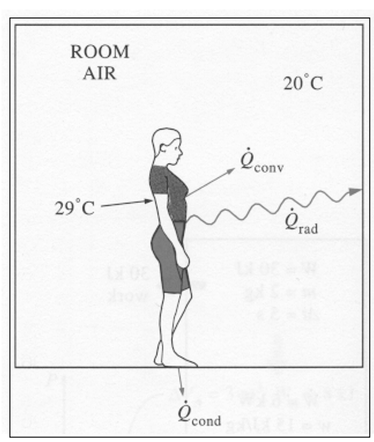
- $\sigma = 5.67 \times 10^{-8}$ W/(m^2 .K^4)
- $0 \leq \varepsilon \leq 1$
- Temperatures are **absolute!**



Material	Emissivity
Aluminum foil	0.07
Polished silver	0.02
Black paint	0.98
Asphalt pavement	0.85–0.93
Human skin	0.95

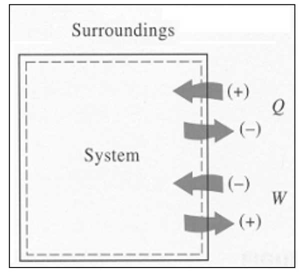
Example

- Given:
  - A = 1.9 m^2
  - h = 6 W/m^2.C
- Calculate total rate of heat transfer.



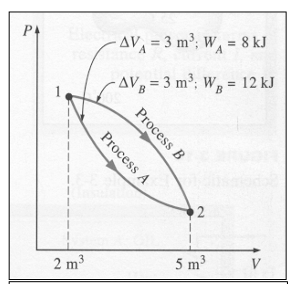
Work

- Work is an energy interaction which is not caused by a temperature difference.
- Work is associated with a force acting through a distance (rising piston, rotating shaft, electric wire crossing the system boundaries).
- Work done by a system is positive, and work done on a system is negative.



Similarities

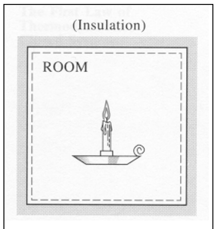
- Both heat and work are boundary phenomena.
- Systems possess energy, but not heat or work. That is, heat and work are transfer phenomena.
- Both are associated with a process, not a state.
- ***<u>Both are path functions.</u>***



$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

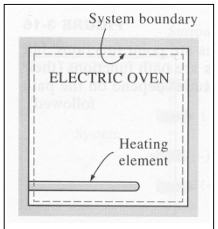
$$\int_1^2 \delta W = W_{12} \quad \text{NOT} \quad \Delta W$$

Examples



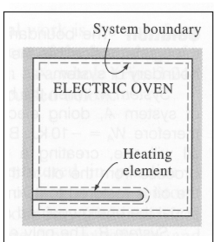
$$Q = 0$$

$$\Delta U = 0$$



$$Q = 0$$

$$W < 0$$



$$Q > 0$$

$$W = 0$$

Electrical Work

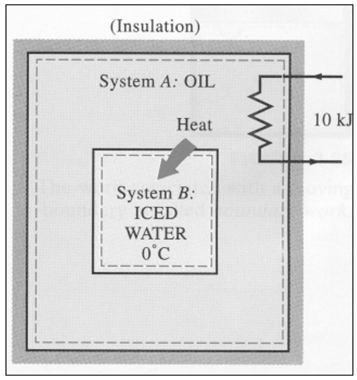
- In an electric field, electrons in a wire move under the effect of electromotive forces, doing work.

$$W_e = V\,N \quad \text{(kJ)} \qquad \dot{W}_e = V\,I \quad \text{(kW)}$$

$$W_e = \int_1^2 V\,I\,dt \quad \text{(KJ)}$$

$$\boxed{W_e = V\,I\,\Delta t \quad \text{(KJ)}}$$

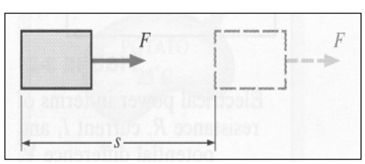
Example



- Discuss the heat and work interactions for system A, B, and the combined system.

Mechanical Work

- Work is force times displacement.



$$W = \int_1^2 F\,ds$$

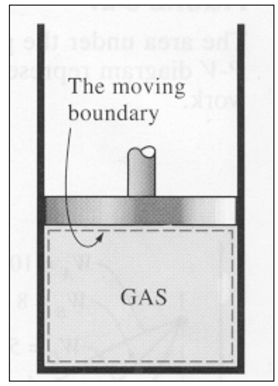
Requirements for a work interaction:

(1) There must be a force acting on the boundary, and

(2) The boundary must move.

Moving Boundary Work

- It is associated with the expansion or compression of a gas in a piston-cylinder device,
- It is also called ***boundary work*** or ***PdV*** work,
- Moving boundary work is the primary form of work involved in automobile engines.



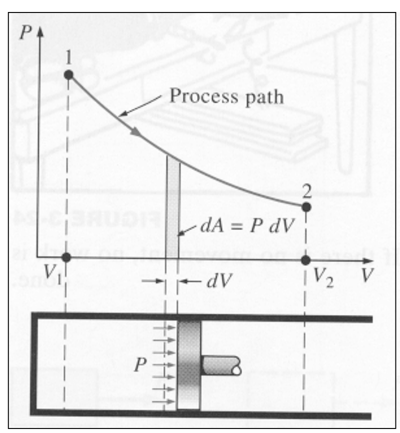
Boundary Work

(Quasi-Equilibrium Process)

$$\delta W_b = F\,ds = P\,A\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV$$

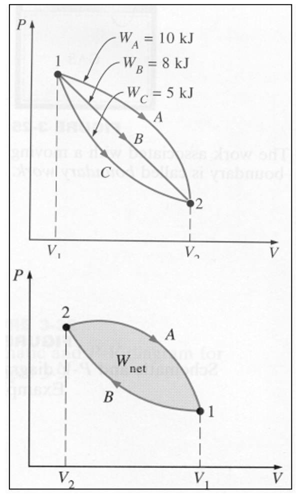
$$area = A = \int_1^2 dA = \int_1^2 P\,dV$$



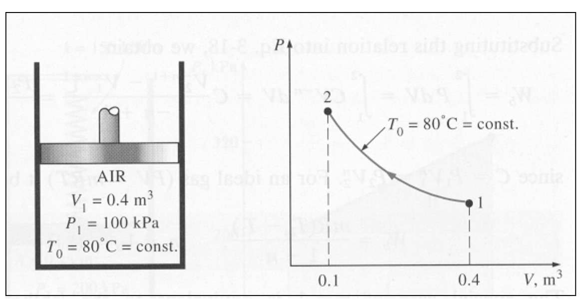
Boundary Work

(Quasi-Equilibrium Process)

- The boundary work done during a process depends on the path followed as well as the end states.
- The net work done during a cycle is the difference between the work done by the system and the work done on the system.

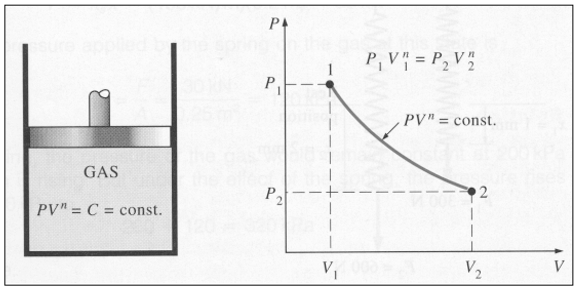


Example



- Determine the work done during this process.

Polytropic Process



$$W_b = \int_1^2 P\,dV = \int_1^2 C\,V^{-n}dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

$$W_b = \frac{mR(T_2 - T_1)}{1-n}, \qquad n \neq 1$$

Spring Work

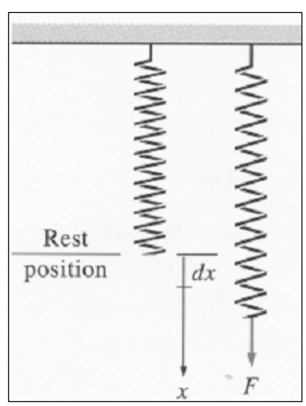
$$\delta W_{spring} = F\,dx \quad \text{(kJ)}$$

- For linear elastic springs:

$$F = k_s x \quad \text{(kN)}$$

k_s = Spring constant (kN/m)

$$W_{spring} = \tfrac{1}{2}k_s(x_2^2 - x_1^2)$$



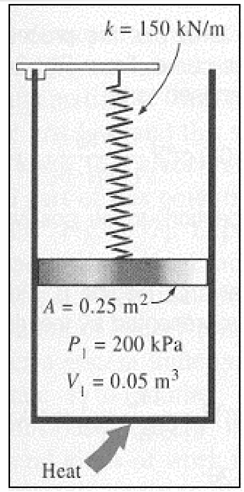
Example

Determine:

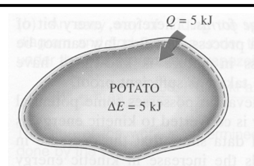
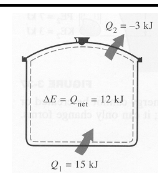
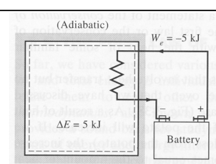
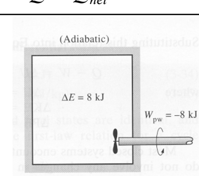
(a) Final pressure inside the cylinder,

(b) Total work done by the gas, and

(c) Fraction of this work done against the spring to compress it.



First Law of Thermodynamics

 $Q = \Delta E$	 $Q = Q_{net} = \Delta E$
 $-W_e = \Delta E$	 $-W_{PW} = \Delta E$

$Q = \Delta E \quad \text{when } W = 0$

$-W = \Delta E \quad \text{when } Q = 0$

First Law of Thermodynamics

$$\begin{bmatrix}\text{Net energy transfer to (or from)} \\ \text{the system as heat and work}\end{bmatrix} = \begin{bmatrix}\text{Net increase (or decrease) in the} \\ \text{total energy of the system}\end{bmatrix}$$

$$Q - W = \Delta E \quad \text{(kJ)}$$

Where:

$$Q = \sum Q_{in} - \sum Q_{out}$$
$$W = \sum W_{out} - \sum W_{in}$$
$$\Delta E = E_2 - E_1$$

First Law of Thermodynamics

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

Where
$$\begin{cases}\Delta U = m(u_2 - u_1) \\ \Delta KE = 1/2m(v_2^2 - v_1^2) \\ \Delta PE = mg(z_2 - z_1)\end{cases}$$

For ***Stationary Systems:***

$$Q - W = \Delta U$$

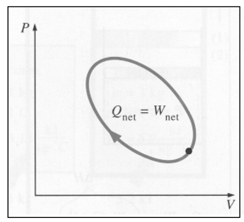
Other Forms of the First Law

Per unit mass: $q - w = e \qquad \text{(kJ/kg)}$

In rate form: $\dot{Q} - \dot{W} = \frac{dE}{dt} \qquad \text{(kW)}$

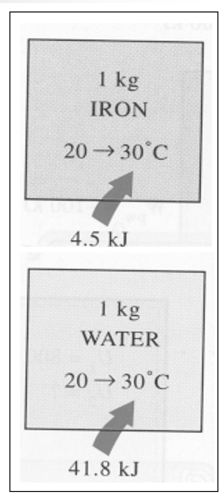
For ***cyclic processes***:

$$Q - W = 0 \quad \text{(kJ)}$$



Specific Heats

- ***Specific heat*** is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.
- Specific heat depends on how the process is executed.
- Specific heat at constant pressure C_P is always greater than specific heat at constant volume C_V.



Specific Heats

For a stationary closed system undergoing a constant-volume process:

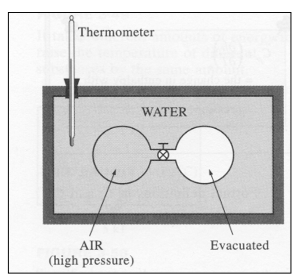
$$\delta q - \delta w_{other} = du \qquad C_v dT = du$$

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v \qquad C_p = \left(\frac{\partial h}{\partial T}\right)_p$$

- Note that C_v and C_p are thermodynamic properties. They are both state functions.

U, h, and C for Ideal Gases

Joule's Experiment:



$$u = u(T)$$

$$h = u + Pv$$

$$Pv = RT \quad \rightarrow h = u + RT$$

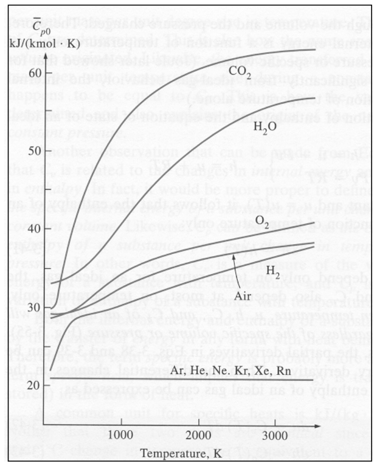
$$h = h(T)$$

$$du = C_v(T)\,dT \qquad \Delta u = u_2 - u_1 = \int_1^2 C_v(T)\,dT$$

$$dh = C_p(T)\,dT \qquad \Delta h = h_2 - h_1 = \int_1^2 C_p(T)\,dT$$

Specific Heats of Ideal Gases

- Specific heats of gases with complex molecules are higher and increase with temperature.
- Variation of specific heats with temperature may be approximated as linear over small temperature intervals.
- Ideal-gas specific heats of monatomic gases remain constant over the entire temperature range.



Specific Heats of Ideal Gases

$$h = u + RT \quad \Rightarrow \quad dh = du + R\,dT$$

$$\boxed{C_p = C_v + R \quad \text{(kJ/kg.K)}}$$

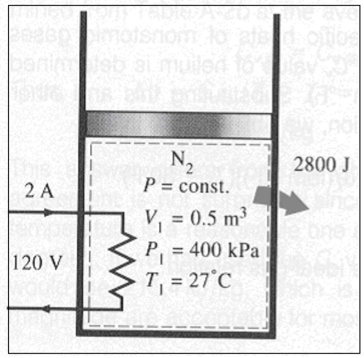
On a molar basis:

$$\boxed{\overline{C}_p = \overline{C}_v + R_u \quad \text{(kJ/kmol.K)}}$$

Specific Heat Ratio: $k = \dfrac{C_p}{C_v} \begin{cases} k = 1.667 & \text{Monatomic Gases (Ar)} \\ k = 1.4 & \text{Diatomic Gases (Air)} \end{cases}$

Example

- Determine the final temperature of the nitrogen.



Example

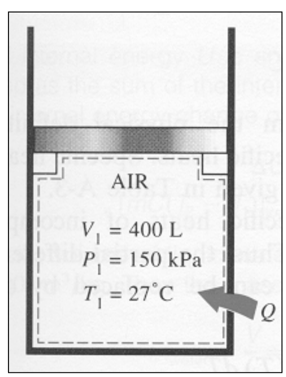
Determine:

(a) Final temperature,

(b) Work done by the air,

(c) Total heat added.

- 350 kPa pressure is required to move the piston.



u, h, and C of Solids and Liquids

- Solids and liquids are essentially incompressible.

$$\boxed{C_p = C_v = C \quad \text{(Solids \& Liquids)}}$$

$$du = C_v dT = C(T)dT \quad \Rightarrow \qquad \Delta u = u_2 - u_1 = \int_1^2 C(T)dT$$

$$h_2 - h_1 = (u_2 - u_1) + v(P_2 - P_1) \quad \Rightarrow \qquad \Delta h = \Delta u + v\Delta P$$

- The term ($v\Delta P$) is often small compared with the first term (Δu) and can be neglected without significant loss in accuracy.

Example

- Determine the temperature when thermal equilibrium is reached.