Lecture 19 The First Law of Thermodynamics

1. developing the concept of heat
2. extending our concept of work to thermal processes
3. introducing the first law of thermodynamics

19.1 Heat and Internal Energy

Internal energy:

is the energy associated with the microscopic components of a system – atoms and molecules. It includes kinetic and potential energy associated with the random translational, rotational, and vibrational motion of the atoms or molecules that make up the system as well as an intermolecular potential energy.

Heat:

is a mechanism by which energy is transferred between a system and its environment because of a temperature difference between them. It is also the amount of energy Q transferred by this mechanism.

Units of Heat:

The calorie is the heat necessary to raise the temperature of 1 g water from 14.5° to 15.5°C.

The Mechanical Equivalent of Heat

Joule's Experiment:
The result that 4.184 J of mechanical energy is equivalent to 1 cal of heat energy is known as the mechanical equivalence of heat.

$1 \cdot cal = 4.186 \cdot J$, $1 \cdot Calorie = 1000 \cdot calorie$

Example: Losing weight that hard way

A student eats a dinner containing 2000 Calories of energy. He wishes to do an equivalent amount of work in the gymnasium by lifting a 50-kg object. How many times must he raise the object to expend this much energy? Assume that he raise it a distance of 2 m each time.

$E = 2000000 \cdot 4.186 = 8372000J$, $\frac{8372000}{50 \cdot 9.8 \cdot 2} = 8.5 \times 10^3$, 8.5 x 10^3 times

19.2 Specific Heat and Calorimetry

a quantity of energy Q is transferred to a mass m of a substance and changing its temperature by ΔT,

The heat capacity: 熱容量

C is defined as $C = \frac{Q}{\Delta T}$

The specific heat: 比熱

c is defined as $c = \frac{Q}{m\Delta T}$

Calorimetry: 熱量計

place the object into a vessel containing water and measure the change of temperature

$$m_W c_W (T - T_W) = m_x c_x (T_x - T)$$

$$c_x = \frac{m_W c_W (T - T_W)}{m_x (T_x - T)}$$

Example: Cooling a Hot Ingot

The temperature of a 0.05-kg ingot of metal is raised to 200ºC and the ingot is then dropped into a light, insulated beaker containing 0.4 kg of water initially at 20ºC. If the final equilibrium temperature of the mixed system is 22.4ºC, find the specific heat of the metal.

$$c = \frac{400 \cdot (22.4 - 20)4.186}{50 \cdot (200 - 22.4)} = 0.45(\frac{J}{g \cdot {}^O C})$$

19.3 Latent Heat 潛熱

latent heat: $L = \dfrac{Q}{m}$

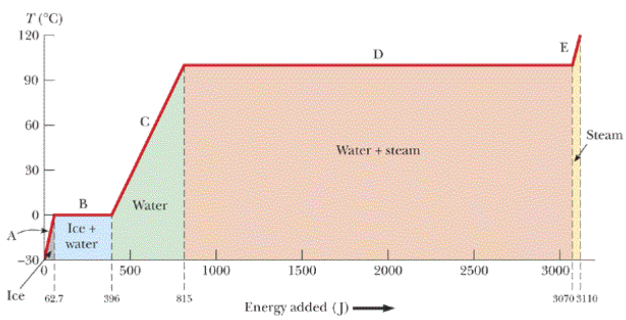
latent heat of fussion: L_f

latent heat of vaporization: L_v

Substance	Melting Point	Latent Heat of Fusion	Boiling Point	Latent Heat of Vaporization (J/kg)
He	0.95 K		4.22 K	2.09×10^4
H_2	14.15 K		20.15 K	
N_2	63.15 K		77.35 K	2.01×10^5
O_2	58.75 K		89.19	
Alcohol				
Water	0 °C	3.33×10^5	100 °C	2.26×10^6
Pb	327.3 °C		1750 °C	
Al	660 °C		2450 °C	
Ag	960.8 °C		2193 °C	
Au	1063 °C		2660 °C	
Cu	1083 °C		1187 °C	
W	3422 °C		5555 °C	

important data for thermal evaporation

Serway/Jewett; Principles of Physics, 3/e
Figure 17.3



Part A:

$$Q = mc_{ice}\Delta T$$

Part B:

$$Q = mL_f$$

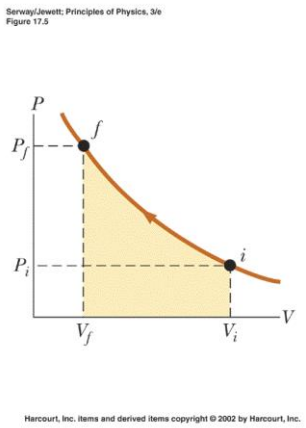
19.4 Work and Heat in Thermodynamics

state variables:

pressure, volume, temperature, and internal energy

transfer variables associated with a change in the state of the system

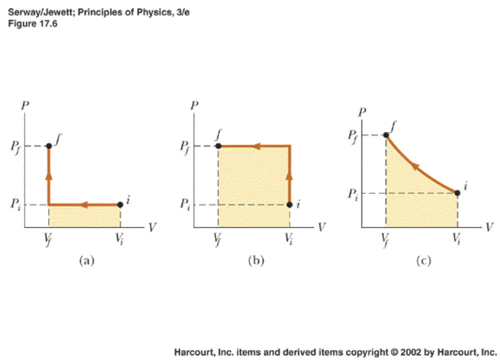
if the gas is compressed quasi-statically, that is, slowly enough to allow the system to remain in thermal equilibrium at all times



$$dW = \vec{F} \cdot d\vec{r} = -Fdy = -PAdy = -PdV$$

$$W = -\int_{V_i}^{V_F} PdV$$ 對氣體做功？

in PV diagram, The work done on a gas in a quasi-static process that takes the gas from an initial state to a final state is the negative of the area under the curve on a PV diagram, evaluated between the initial and final states.



Example: Comparing processes

An ideal gas is taken through two processes in which $P_f = 1 \times 10^5$ Pa, $V_f = 2\ m^3$, $P_i = 0.2 \times 10^5$ Pa, and $V_i = 10\ m^3$. For process 1, the temperature remains constant. For process 2, the pressure remains constant and then the volume remains constant. What is the ratio of the work W_1 done on the gas in the first process to the work W_2 done in the second process?

$$P_i V_i = P_f V_f = C = 2 \times 10^5$$

$$W_1 = -\int_{Vi}^{Vf} \frac{C}{V} dV = \int_{Vf}^{Vi} \frac{C}{V} dV = C \ln \frac{V_i}{V_f} = 2 \times 10^5 \ln(\frac{10}{2}) = 3.2 \cdot 10^5$$

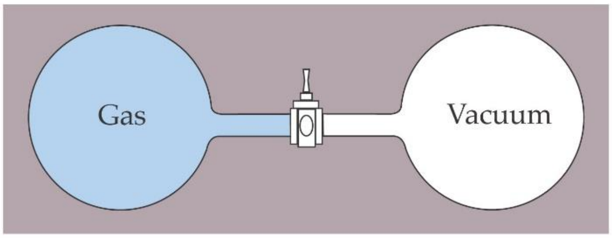
$$W_2 = P_i(V_f - V_i) = P_i(V_i - V_f) = 0.2 \cdot 10^5 (10-2) = 1.6 \cdot 10^5, \quad \frac{W_1}{W_2} = 2$$

Isothermal Expansion:

A gas at temperature T expands slowly while absorbing energy from a reservoir to maintain the constant temperature.

Free Expansion:

A gas expands rapidly into an evacuated region after a membrane is broken.



Energy transfer by heat, like work done, depends on the initial, final, and intermediate states of the system.

19.5 The First Law of Thermodynamics

The first law of thermodynamics is a special case of the law of conservation of energy.

The quantity Q+W is independent of the path.

$\Delta E_{\text{int}} = Q + W$ 暫時不談位能

$dE_{\text{int}} = dQ + dW$

cyclic process: a process that starts and ends at the same state

$\Delta E_{\text{int}} = 0$, $Q = -W$

in a cyclic process, the net work done on the system per cycle equals the area enclosed by the path representing the process on a PV diagram

19.6 Some Applications of the First Law of

Thermodynamics

Energy Conservation:

$\Delta E_{\text{int}} = Q + W$, $W = -P\Delta V$

Adiabatic Process:

$Q = 0$ → $\Delta E_{\text{int}} = W$

Isobaric Process:

$W = -P(V_f - V_i)$

Isovolumetric Process:

$W = 0$ → $\Delta E_{\text{int}} = Q$

Isothermal Process:

A process that occurs at a constant temperature is called an isothermal process.

Isothermal Expansion of an Ideal Gas:

$PV = nRT$, $W = -\int_{Vi}^{Vf} PdV$

→ $P = -\dfrac{nRT}{V}$

→ $W = -\int_{Vi}^{Vf} \dfrac{nRT}{V} dV = -nRT \ln\left(\dfrac{V_f}{V_i}\right) = nRT \ln\left(\dfrac{V_i}{V_f}\right)$

19.7 Energy Transfer Mechanisms

1. Conduction
2. Convection
3. Radiation

In all mechanisms of heat transfer, the rate of cooling of a body is approximately proportional to the temperature difference between the body and its surrounding.

$Rate \propto \Delta T$

Thermal conduction:

$$I^q = \frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x} = kA\frac{T_H - T_C}{L} \quad (I^q \equiv \Delta Q/\Delta t \text{, 熱流 } \rightarrow \ \Delta T = (I\Delta x)/(kA) = I^q R^q \text{,}$$

R^q: 熱阻)

For a compound slab containing several materials of thickness L_1, L_2,... and thermal conductivities k_1, k_2,…, the rate of energy transfer through the slab at steady state is

$$I^q = \frac{A(T_h - T_c)}{\sum_i L_i / k_i} \quad (\Delta T = I^q R_1 + I^q R_2 + ... = I^q \sum_i R_i \ \rightarrow \ I^q = \frac{\Delta T}{\sum_i R_i} = \frac{A\Delta T}{\sum_i L_i / k_i})$$

Example:

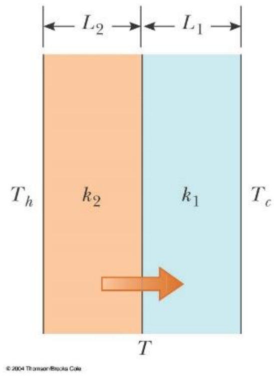
Two slabs of thickness L_1 and L_2 and thermal conductivities k_1 and k_2 are in thermal contact with each other. The temperature of their outer surfaces are T_c and T_h, respectively, and $T_h > T_c$. Determine the temperature at the interface and the rate of energy transfer by conduction through the slabs in the steady-state condition.

$$I_1^q = k_1 A\frac{T - T_c}{L_1}, \quad I_2^q = k_2 A\frac{T_h - T}{L_2}$$

when a steady state is reached,

$$k_2 A\frac{T_h - T}{L_2} = k_1 A\frac{T - T_c}{L_1}$$

$$T = \frac{L_1 T_h k_2 + L_2 T_c k_1}{k_1 L_2 + k_2 L_1}, \quad I^q = \frac{A(T_h - T_c)}{L_1/k_1 + L_2/k_2}$$



EX: The inside (radius a) of a hollow cylinder is maintained at a temperature T_a while the outside (radius b) is a lower temperature , T_b. The wall of the cylinder has a thermal conductivity k. Ignoring end effects, show that the rate of energy conduction from the inner to the outer surface in the radial direction is

$$I^q = \frac{dQ}{dt} = 2\pi Lk\left[\frac{T_a - T_b}{\ln(b/a)}\right].$$

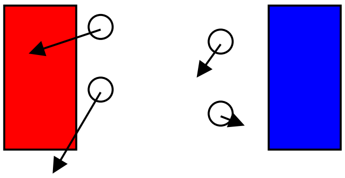
$$I^q = \frac{dQ}{dt} = \frac{k\Delta T}{\sum_i L_i / A_i} \ \rightarrow \ \frac{dQ}{dt}\int_a^b \frac{dr}{2\pi r L} = k(T_a - T_b)$$

$$\rightarrow \ I^q = \frac{dQ}{dt} = 2\pi Lk\frac{T_a - T_b}{\ln(b/a)}$$

Home Insulation

Convection:

It is transport of energy as heat by the transport of the material medium itself.



Radiation:

electromagnetic radiation

Stephan-Boltzmann law: $P = \sigma A e T^4$

A is the area, σ is a universal constant called Stephan's constant

$\sigma = 5.6703 X 10^{-8}$ W/(m^{2}K^4)

e is the emissivity of the object. Its value is between 0 and 1.

Example: The temperature of a lightbulb filament

Estimate the order of magnitude of the temperature of the filament of a 100 W lightbulb when it is operating. To model the filament as a cylinder 10 cm long with a radius of 0.050 mm.

$$T = \sqrt[4]{\frac{P}{\sigma A e}} = \sqrt[4]{\frac{100}{5.67 \cdot 10^{-8}(2 \cdot \pi \cdot 5 \cdot 10^{-5} \cdot 10 \cdot 10^{-2})(1)}} = 2.7 \cdot 10^3 K$$

Melt?

Blackbody radiation??

$$\lambda_{\max} = \frac{2.898}{T}(mm)$$

$$P = e\sigma A\left(T^4 - T_0^4\right) = e\sigma A\left(T^2 + T_0^2\right)\left(T + T_0\right)\left(T - T_0\right)$$

If $T \sim T_0$ → $P = 4e\sigma A T_0^3 \Delta T$ ($\Delta P = \left.\frac{dP}{dT}\right|_{T=T_0} \Delta T = 4e\sigma A T_0^3 \Delta T$) Newton's coffee cooling law

The Dewar Flask