Physics I Lecture19-The First Law of Thermodynamics-I

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Outline

1. Heat and Internal Energy
2. Specific Heat and Calorimetry
3. Latent Heat
4. Work and Heat in Thermodynamics
5. The First Law of Thermodynamics
6. Some Applications of The 1st Law
7. Thermal Energy Transfer

1. HEAT AND INTERNAL ENERGY

Internal energy: It is the total energy that includes the translational energy, the rotational energy, and the vibrational energy of all atoms belonging to the system.

Heat: It is one kind of energy transfer process. It stands for energy transfer from high temperature substances to low temperature substances.

Heat is either a transfer of energy due to an entropy change. In a microscopic viewpoint, it originates from an increase or a decrease of the number of microstates.

Units of heat: A calorie is the heat energy to raise the temperature of 1-g water from 14.5 to 15.5°C.

Mechanical equivalent of heat – Joule's experiment: It is experimentally confirmed that the mechanical energy of 4.18 J is equivalent to 1 calorie of heat energy. It is known as the mechanical equivalence of heat.

1 cal = 4.186 J, 1 Cal = 1000 cal

1. HEAT AND INTERNAL ENERGY

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

$$E = 2000\ Cal = 2000 \times 1000 \times 4.186 = 8.37 \times 10^6\ J$$

$$E_{lift} = 50 \times 9.8 \times 2 = 980\ J$$

$$N = \frac{E}{E_{lift}} = \frac{8.37 \times 10^6}{980} = 8540$$

https://giphy.com/gifs/TTPi3fB9F5Aqs

2. SPECIFIC HEAT AND CALORIMETRY

Specific heat: A quantity of energy ΔQ is transferred to a mass m of a substance and changing its temperature by ΔT.

The heat capacity c: $c = \Delta Q / \Delta T$

The specific heat per unit mass $C_m = c/m = \Delta Q / m\Delta T$

The specific heat: J kg^{-1} K^{-1}

Fe	Cu	Ag	Al	Steel	Wood	Water	Air
470	390	230	900	500	1800	4186	1000

Calorimetry: measurement of the specific heat of unknown substances

place the hot object of temperature T_h and mass m_x into a vessel containing cold water of temperature T_c, mass m_w and measure the equilibrium temperature T_{eq}.

$$m_w C_{m,w} \left(T_{eq} - T_c\right) = m_x C_{m,x} \left(T_h - T_{eq}\right) \qquad C_{m,x} = \frac{m_w C_{m,w} \left(T_{eq} - T_c\right)}{m_x \left(T_h - T_{eq}\right)}$$

2. SPECIFIC HEAT AND CALORIMETRY

Example: The temperature of a 0.0500-kg ingot of metal is raised to 200°C and the ingot is then dropped into a light, insulated beaker containing 0.400 kg of water initially at 20.0°C. If the final equilibrium temperature of the mixed system is 22.4°C, find the specific heat of the metal.

$$m_x = 0.05, m_w = 0.4, T_h = 200^0C, T_c = 20^0C, T_{eq} = 22.4^0C$$

$$C_{m,w} = 4186\frac{J}{kg\ K}$$

$$C_{m,x} = \frac{m_w c_w\left(T_{eq} - T_c\right)}{m_x\left(T_h - T_{eq}\right)} = \frac{(0.4)(4186)(22.4 - 20)}{(0.05)(200 - 22.4)} = 453\frac{J}{kg\ K}$$

3. LATENT HEAT

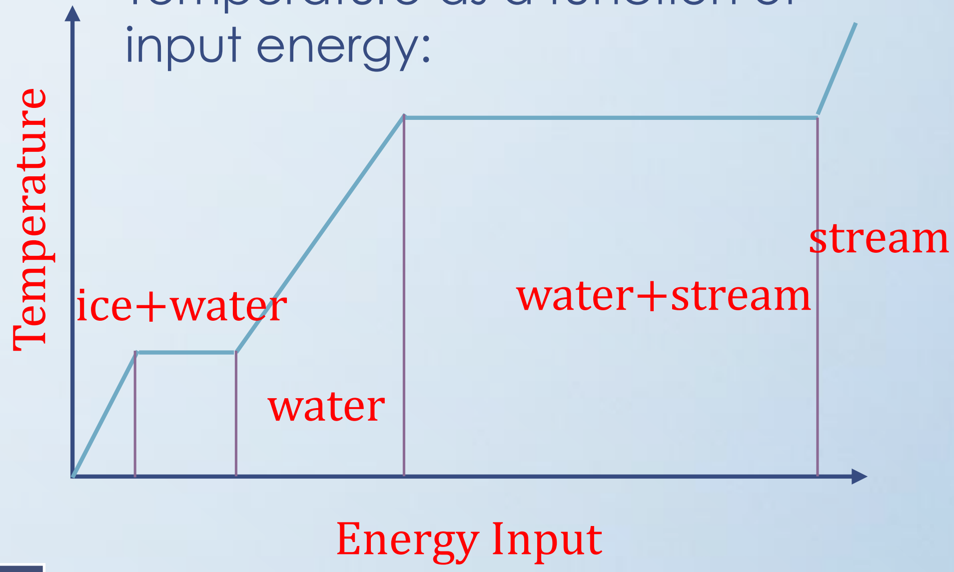
Latent heat: It is the heat energy required for the phase transition from a solid to a liquid phase or from a liquid to a gas phase for substances.

Latent heat: $L = \Delta Q/m$

Latent heat of fusion: L_f

Latent heat of vaporization: L_v

Temperature as a function of input energy:

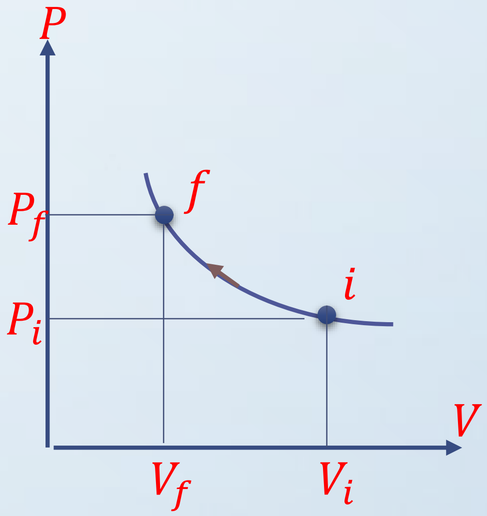


Substance	**Melting point**	L_f	**Boiling point**	L_v**(J / kg)**
He	0.95 K		4.22 K	2.09X10^4
H_2	14.15 K		20.15 K	
N_2	63.15 K		77.35 K	2.01X10^5
water	0°C	3.33X10^5	100°C	2.26X10^6
Pb	327.3°C		1750°C	
Al	660°C		2450°C	

4. WORK AND HEAT IN THERMODYNAMICS

If the gas is compressed quasi-statically (slowly enough) to be remained in thermal equilibrium at all times, the work done on the gas is

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



dy is in the direction of volume expansion
F is in the volume compression direction

$$\Delta W = W = -\int_{V_i}^{V_f} PdV$$

Consider a compression of the volume of gas, its work is positive.
A positive work means an increase of energy in the gas system.

4. WORK AND HEAT IN THERMODYNAMICS

Example: An ideal gas is taken through two processes in which $P_f = 1.0 \times 10^5$ Pa, $V_f = 2.0$ m^3, $P_i = 0.20 \times 10^5$ 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?

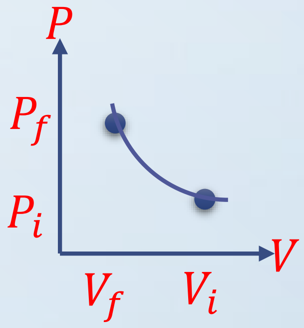
$$P_i V_i = P_f V_f = 2.0 \times 10^5\ J$$

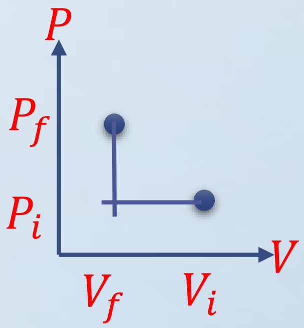
Process 1: $\Delta W = -\int_{V_i}^{V_f} P\,dV = -\int_{10}^{2} \frac{2.0\times10^5}{V}\,dV$

$$W_1 = -2.0 \times 10^5 \ln\left(\frac{2.0}{10}\right) = 3.2 \times 10^5\ J$$

Process 2: $\Delta W = -P_i \int_{V_i}^{V_f} dV = -\left(0.2 \times 10^5\right)(2.0 - 10)$

$W_2 = 1.6 \times 10^5\ J$ $\qquad \frac{W_1}{W_2} = 2$

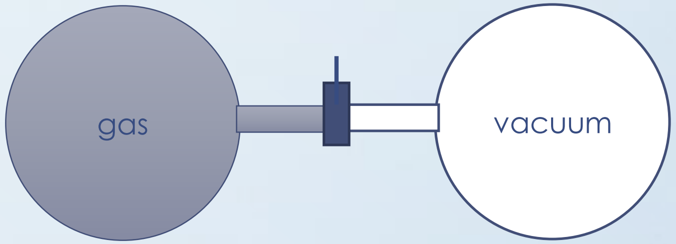




4. WORK AND HEAT IN THERMODYNAMICS

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.



$$PV = nRT = const \rightarrow P = \frac{nRT}{V}$$

The two kinds of expansions give the same results of a decrease of work energy and an increase of heat energy.

Note that here the absorption of heat energy originates from an increase of microstates due to the volume expansion.

$$\Delta W = W = -\int_{V_i}^{V_f} \frac{nRT}{V} dV = nRT \ln\left(\frac{V_i}{V_f}\right), \Delta E = 0 \rightarrow \Delta Q = -\Delta W$$

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5. THE FIRST LAW OF THERMODYNAMICS

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

$$\Delta E_{int} = \Delta Q + \Delta W$$

The change of internal energy is independent of the path.

A cyclic process which starts and ends at the same state gives no changes of its internal energy.

$$\Delta E_{int} = 0 \rightarrow \Delta Q + \Delta W = 0 \rightarrow \Delta Q = -\Delta W$$

In the cyclic process, the net work done on the system per cycle equals the area enclosed by the path representing the process on the P-V diagram

6. SOME APPLICATIONS OF THE 1ST LAW

Equations for an ideal gas:

$$PV = Nk_BT = nRT \qquad \Delta W = -P\Delta V = -\int PdV \qquad \Delta E_{int} = \Delta Q + \Delta W$$

In Chapter 20, we will learn that the total energy is $E = 3Nk_BT/2$.

Adiabatic process: $\Delta Q = 0 \rightarrow \Delta E_{int} = \Delta W$

Isothermal process: $\Delta E_{int} = 0, PV = const \rightarrow \Delta Q = -\Delta W$

Isovolumetric process: $\Delta V = 0 \rightarrow \Delta W = 0 \rightarrow \Delta E_{int} = \Delta Q$

Isobaric process: $\Delta P = 0 \rightarrow \Delta W = -P\Delta V, \Delta E_{int} = \Delta Q + \Delta W$

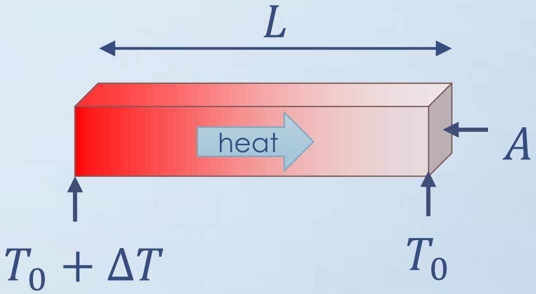
7. THERMAL ENERGY TRANSFER

The three typical types of energy transfer are conduction, convection, and 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.

$$R_{heat} = I_{heat} = \frac{\Delta Q}{\Delta t} = P \propto \Delta T = \left(T_{body} - T_{surrounding}\right)$$

Thermal conduction:

$$I_{heat} = P = kA\frac{\Delta T}{L}$$



k: thermal conductivity, 1/k: thermal resistivity

$$\Delta T = I_{heat}\left(\frac{1}{k}\right)\frac{L}{A}$$ compare with $V = IR, R = \rho\frac{L}{A}$

Connected in series: $R = R_1 + R_2 + \cdots$

Connected in parallel: total conductance = sum of each conductance, $G = G_1 + G_2 + \cdots, \left(\frac{1}{R}\right) = \left(\frac{1}{R_1}\right) + \left(\frac{1}{R_2}\right) + \cdots$

7. THERMAL ENERGY TRANSFER

Thermal conductivity of materials in the unit of Wm^{-1}K^{-1}:

Fe	**Cu**	**Ag**	**Al**	**Steel**	**Wood**	**Water**	**Air**
80	401	429	210	46	0.13	0.58	0.026

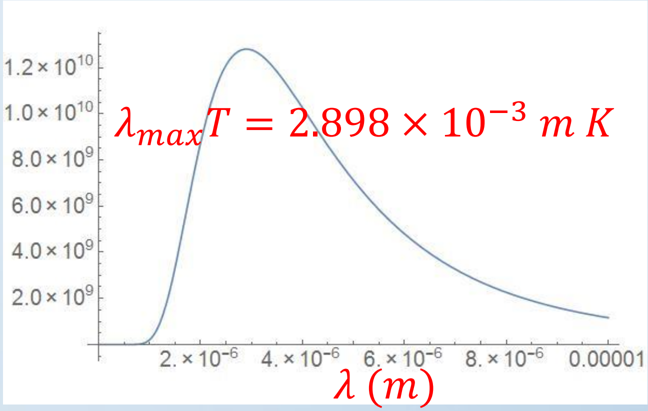
Note that the mass specific heat for Fe and Water are 470 and 4186 J kg^{-1}K^{-1}.

Thermal radiation: Stephan-Boltzmann law: $P = \sigma A e T^4$, where $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$ is the universal constant (Stephan's constant) and e is the emissivity of the object. The value of the emissivity is between 0 and 1.

Newton's coffee cooling:

$$T = T_0 + \Delta T$$

$$\Delta P = \sigma A e\left(T^4 - T_0^4\right) \cong 4\sigma A e T_0^3 \Delta T$$

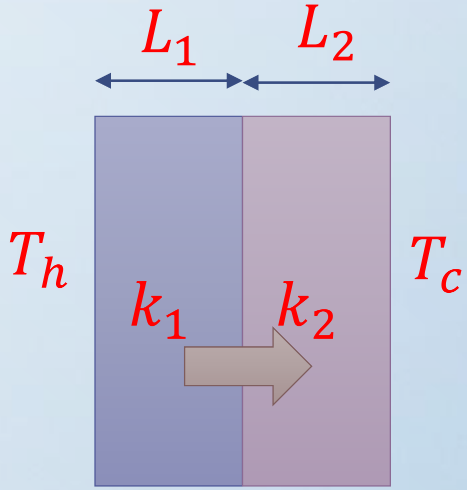


$$\lambda_{max} T = 2.898 \times 10^{-3}\ m\ K$$

7. THERMAL ENERGY TRANSFER

Example: Two slabs of the same area A, 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.

assume the temperature T at the interface between the two slabs



$$P_1 = \frac{k_1 A(T - T_c)}{L_1} = P_2 = \frac{k_2 A(T_h - T)}{L_2} \rightarrow k_1 L_2 (T - T_c) = k_2 L_1 (T_h - T)$$

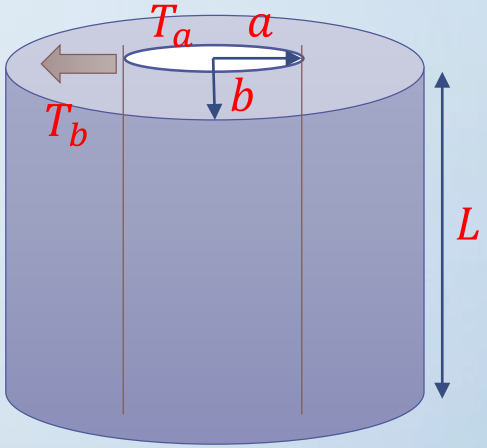
$$T = \frac{k_1 L_2 T_c + k_2 L_1 T_h}{k_1 L_2 + k_2 L_1}, P_1 = P_2 = \frac{A(T_h - T_c)}{\frac{L_1}{k_1} + \frac{L_2}{k_2}}$$

$$I_{heat} = \frac{\Delta T}{R_{heat}}, R_{heat} = \frac{L}{kA} \qquad R_t = R_1 + R_2 = \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A}$$

$$I_{heat} = P_1 = P_2 = \frac{T_h - T_c}{\frac{L_1}{k_1 A} + \frac{L_2}{k_2 A}}$$

7. THERMAL ENERGY TRANSFER

Example: 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 cylinder has a length of L and thermal conductivity k. Ignoring end effects, please calculate the rate of energy transfer from the inner to the outer surface.



confirm that the thermal resistances are connected in series

$$\Delta T = I_{heat}\left(\frac{1}{k}\right)\frac{L}{A}$$

$$R_{heat} = \frac{L}{kA}$$

$$dR = \frac{dr}{k(2\pi rL)} \rightarrow R = \int_a^b \frac{dr}{k(2\pi rL)} = \frac{\ln(b/a)}{2\pi kL}$$

$$P = I_{heat} = \frac{\Delta T}{R} = \frac{2\pi kL(T_a - T_b)}{\ln(b/a)}$$

7. THERMAL ENERGY TRANSFER

Example: 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 10.0 cm long with a radius of 0.0500 mm. The emissivity of the filament is 1.

$$P = \sigma A e T^4$$

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}, e = 1$$

$$A = 2\pi r L = 2\pi \left(5.0 \times 10^{-5}\right)\left(1.0 \times 10^{-1}\right) = 3.14 \times 10^{-5}\ m^2$$

$$T = \left(\frac{P}{\sigma A e}\right)^{1/4} = 2740\ K$$

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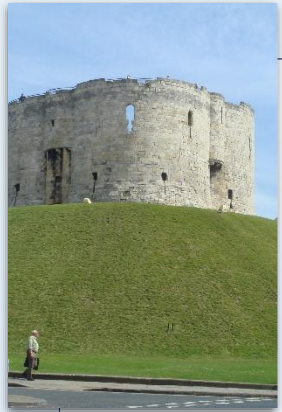

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