Heat, Temperature, and Power for AP Physics B

Summary: energy transfer in gases can do measurable work on large objects. Thermodynamics is the study of heat energy and its consequences.

Key ideas:

- Internal energy is the energy possessed by a substance due to the vibration of molecules. A substances internal energy depends on its temperature
- Heat is a transfer of thermal energy
- When a an object's temperature increases, it expands
- The ideal gas law relates three important thermodynamic values: pressure, volume and temperature.
- Kinetic theory explains how the motion of many individual atoms in a gas leads to measurable properties such as temperature.
- The first law of thermodynamics is a statement of conservation of energy.
- The first law of thermo is usually applied when a gas's state is represented on a Pressure vs Volume [PV] diagram
- First law of thermodynamics:
    - Internal energy can be determined using the ideal gas law, and PV values from the diagram
    - Work done on a gas or by a gas can be determined from the area under the graph
    - Heat added or removed from the gas CANNOT be determined directly from the diagram, but rather only from the first law.
- The efficiency of an engine is determined as work output divided by energy input.
- The efficiency of an **ideal engine** is NOT 100%
- Efficiency of an ideal engine is determined from the Carnot formula

Equations

1-d expansion: $\Delta L = \alpha L_o \Delta T$ 2-d expansion $\Delta A = 2 \alpha A_o \Delta T$ 3-d expansion: $\Delta V = 3 \alpha V_o \Delta T$

Ideal gas law $PV = nRT$

Internal energy of an ideal gas: $U = 3/2 \, nRT = 3/2 \, PV$

RMS speed of a gas molecule $V_{rms} = \sqrt{[\, 3k_B T/m\,]}$

First law of thermodynamics $\Delta U = Q + W$

Efficiency of any heat engine: $e = W/Q_H$

Efficiency of Carnot engine: $e_{carnot} = \dfrac{T_H - T_C}{T_H}$

Rate of heat transfer $H = \dfrac{kA\Delta T}{L}$

Thermodynamic is the study of what heat is and how it gets transferred.
This unit is very different from other topics we have studied because we will be looking at systems of molecules of gases.

Heat, represented by the variable Q, is a type of energy that can be transferred from one body to another.
       Heat is measured in joules, because it is a form of **energy.**

Be careful - Energy must be *transferred* in order to be called heat.
Remember: heat can be gained or lost, but **not   possessed.**

It is ***incorrect*** to say, "a gas **has** 3000 J of heat."

Internal energy , U.

Internal energy is the sum of the energies of all of the molecules in a substance.
Internal energy is   measured in joules,

It *is* **correct** to say, "a gas **has** 3000 J of internal energy."

Temperature is related to the average kinetic energy per molecule of a substance. Temperature is measured in **kelvins** or degrees Celsius.

Do NOT say   " 114 degrees kelvin";   just say "114 kelvins."

To convert between kelvins and degrees Celsius   use the following formula:

$$T_{Celsius} = T_{Kelvin} - 273.$$

Problem 1: :   room temperature is about 23°C, what is room temperature in kelvins?

It is important to note that *two bodies that have the same temperature do not necessarily contain the same amount of internal energy*.

For example, consider a huge hunk of metal at 20°C and a tiny speck of the same type of metal, also at 20°C. The huge hunk contains a lot more internal energy—it has a lot more molecules moving around—than the tiny speck.

By the same logic, you could have two items with very different temperatures that contain exactly the same amount of internal energy.

$$Power = \frac{work}{time}$$

Power is measured in joules/second, or watts: 1 W = 1 J/sec.

Power is not an idea limited to thermodynamics.   We talked about power in   mechanics.

Power = $\frac{work}{time}$ = $\frac{forceX\ distance}{time}$ or   power = force X velocity

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recall **work-energy theorem**   horizontal motion: Work = ΔKE   vertical motion: Work = ΔPE

Problem 2   How much power is needed to raise a block of mass 20 kg a distance of 10 meters in forty seconds?"

Problem 3: In a warehouse, a 200 kg container breaks loose from a forklift. The container slides along the floor at 5 m/sec. The force of friction between the block and the floor produces thermal energy [heat] at a rate of 10 watts. How far does the block travel before coming to rest?

THERMAL EXPANSION
Objects get slightly bigger when they are heated.In a thermometer, mercury expands when heat is added.
1-D thermal expansion: $\Delta L = \alpha L_o \Delta T$

$\alpha =$ coefficient of thermal expansion [α is a material property determined experimentally]
L_o = initial length
ΔL = final length – initial length
$\Delta T = T_{final} - T_{initial}$

Linear expansion describes the change in length of a "1-D" object such as a wire, ring, pipe, or a bar, or rod or pole.

Area expansion describes the change in area for a 2-D object such as a plate or disk
2-D thermal expansion: $\Delta A = 2\alpha A_o \Delta T$

Volume expansion describes the change in volume of a 3-D object, such as sphere, cube
3-D thermal expansion: $\Delta V = 3\alpha V_o \Delta T$

Problem 4: You need to slide an aluminum ring onto a cylindrical aluminum bar. At room temperature [20°C] the diameter of the ring is 50.0 mm and the diameter of the bar is 50.1 mm.
    a)   Should you heat or cool the ring to make it fit?
    b)   If the coefficient of thermal expansion for aluminum is $\alpha = 2.5 \times 10^{-5}$ /°C , at what temperature will the ring fit on the bar?

Note :Thermal expansion assumes the length changes will be small compared to the size of the object.[An object will NOT double in size for example due to thermal expansion.]

RATE OF HEAT TRANSFER

Heat will flow across a material when there is a temperature difference between 2 points on the material.

Heat ALWAYS flows from high temperature to low temperature.

Heat will flow until the object is in **thermal equilibrium** [the same temperature everywhere]

If the temperature difference is large, the rate of heat transfer is large.

Properties of a material determine rate of heat transfer:

k: Type of material [metals conduct heat better than nonmetals]

A: Cross-sectional area [larger area = easier heat flow]

L: Distance between the positions of different temperature [if distance longer, transfer is slower]

H = heat transferred = $\dfrac{kA\, \Delta T}{L}$

k is the thermal conductivity of the substance $\qquad$ A = cross sectional area
L = length of material $\qquad\qquad\qquad\qquad\qquad$ ΔT = temperature difference

Problem 5: The heat flow per unit area through a wood slab 50 mm thick, whose inner and outer surface temperatures are 40°C and 20°C, respectively, has been determined to be 40 W/m². What is the thermal conductivity of the wood?

$$H = \frac{kA\Delta T}{L} \qquad \text{becomes} \qquad \frac{H}{A} = \frac{kDT}{L}$$

IDEAL GAS LAW
Recall from chemistry at standard temperature and pressure,   1 mole of any gas occupies 22.4 liters
$\qquad$ 1 liter = 0.1 m X 0.1 m X 0.1 m = .001m³

$\qquad$ The gas laws for constant number of moles of gas in a container:
$\qquad$ **Charles law: $V_1 / T_1 = V_2 / T_2$**
$\qquad$ **Boyles law $P_1 V_1 = P_2 V_2$**
$\qquad$ **Gay-Lussac law: $P_1 / T_1 = P_2 / T_2$**
$\qquad$ **Combined gas law: $\dfrac{P_1 V_1}{T_1} = \dfrac{P_2 V_2}{T_2}$**

Problem 6:   on the   draw a sketch for
a)   Charles' law   b) Boyle's law   c) Gay-Lussac's law

V| P | P |

                              T   V   T

Ideal gas law: must be used when number of moles not constant

PV = nRT

P = pressure , in N/m^2 or pascals

V = volume, in m^3

n = number of moles

R = ideal gas constant   R = 8.31 Joule
                                        [mole-Kelvin]

 T = temperature in **kelvins**

nR = Nk$_B$

      n = number of moles   R = ideal gas constant

      N = number of molecules   k$_B$ = Boltzmann's constant

Ideal gas law can also be expressed as   PV = Nk$_B$T

k$_B$ = Boltzmann's constant k$_B$ = 1.38×10^{-23} Joule
                                                              kelvin

Problem 7: The rigid frame of a dirigible holds 5000 m^3 of hydrogen. On a warm day [20 ^{o}C] the hydrogen is as atmospheric pressure. What is the pressure of the hydrogen if the temperature drops to 0°C?

KINETIC THEORY OF GASES

Kinetic theory is a series of assumptions about the behavior of ideal gases.

- Molecules move in continuous random motion, with great variety of speeds.
- There is a huge number of molecules in any container of gas
- The separation between the molecules is very large compared to the size of the molecules [mostly empty space]
- Molecules do not attract or repel each other.
- All collisions between molecules or between molecules and the walls of the container are perfectly elastic

The results of kinetic theory:

1) relationship between the internal energy of a gas and its temperature is given by $U = 3/2\ nRT$

2) the root-mean-square [rms] speed of gas molecules is given by $v_{rms} = \sqrt{[3k_BT/m]}$

problem 8: what is V_{rms} of a sample of oxygen at $0°C$?

Problem 9: Calculate the internal energy of the air in a typical room with volume $40\ m^3$.

First law of thermodynamics

Recall heat is not the same as internal energy.
Mechanical work is done when a force is applied through a distance.

The first law of thermodynamics is
$\Delta U = Q + W$
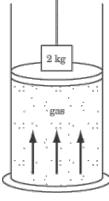ΔU = change in internal energy
Q= heat
W = Work

If **heat is ADDED** to a gas, **Q is +**   If **heat is REMOVED** from a gas, **Q is −**
If **work** is **done ON** a gas , **W is +**   If work is **done BY** a gas, **W is −**

REMEMBER: for positive signs: *heat added to plus work done on*

If temperature is constant, then $\Delta U = 0$
initial internal energy = U_i = 3/2 nRT_i   **final internal energy = U_f = 3/2 nRT_f**
                    $\Delta U = U_f − U_i = 0$ if $T_i = T_f$

problem 10: a gas in a cylinder can be compressed if a piston is pushed down. You add 2500 J of heat to the system and then push the piston 1.0 m down with a constant force of 1800N. What is the change in the gas's internal energy?

Problem 11: Problem 11: some heat is added to a gas container that is topped by a movable piston. The piston is weiged down by a 2 kg mass. The piston rises a distance of 0.2 m at constant velocity. Throughout the process the temperature of the gas remains constant. What is the amount of heat added to the container?