IOP Concise Physics

Thermal Properties of Matter

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Chapter 7

Summary of equations

Relationship between the celsius and kelvin temperature scales:

$$T_K = T_C + 273.15.$$

Thermal expansion:

$$\Delta L = L_0 \alpha \Delta T.$$

Expansion in three dimensions:

$$\Delta V = V_0 \beta \Delta T.$$

Relationship between linear and three-dimensional expansion coefficients:

$$\beta = 3\alpha.$$

Rate of heat transfer:

$$H = kA\frac{T_H - T_C}{L}.$$

Thermal resistance:

$$R = \frac{L}{k}.$$

Rate of heat transfer using thermal resistance:

$$H = A\frac{(T_H - T_C)}{R}.$$

$$H = A\frac{(T_H - T_C)}{R_1 + R_2 + \cdots}.$$

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Heat capacity:

$$C = \frac{Q}{\Delta T}.$$

Relationship between heat capacity and specific heat:

$$C = c \times m.$$

Heat transferred to the object:

$$Q = mc\Delta T.$$

Molar heat transferred to the object:

$$Q = nc\Delta T.$$

Heating power:

$$\text{power} = (\text{energy transferred})/\text{time}$$

$$P = \frac{mc\Delta T}{t}.$$

Latent heat of fusion:

$$Q = mL.$$

First law of thermodynamics:

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

Ideal gas law:

$$PV = nRT.$$

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$$PV = \frac{nM\langle v^2\rangle}{3}.$$

Root mean square velocity:

$$v_{\text{rms}} = \sqrt{\langle v^2\rangle} = \sqrt{\frac{3RT}{M}}.$$

Molar mass:

$$M = mN_{\text{A}}$$

Molecular or atomic average kinetic energy:

$$\text{KE}_{\text{ave}} = \frac{3}{2}\frac{R}{N_{\text{A}}}T.$$

Definition of Boltzmann's constant:

$$\frac{R}{N_{\text{A}}} \equiv k_{\text{B}} = 1.38 \times 10^{-23}\ \text{J K}^{-1}.$$

Answers

2.1 Increases. Explained with the same reasoning as the ball and ring demonstration given in chapter 2.
2.2 The diameter of the hollow sphere will be larger. The same heat will raise the hollow sphere to a higher temperature because there is less metal to heat.
2.3 The alcohol thermometer because it has a larger thermal expansion coefficient.
2.4 The glass bulb that contains mercury expands to a slightly larger volume before the mercury has had time to increase in temperature.
2.5 Yes, dental fillings should have the same thermal expansion coefficients as teeth. If they do not then the filling can break the bonds with the tooth and can come out the first time you eat something that is either hot or cold.
2.6 The lid diameter expands.
2.7 5.64×10^{-5} m^2.
2.8 6.3 mm. Use the formula 2.4 for expansion in three dimensions.
3.1 Although the carpet and floor are the same temperature, the stone floor is more thermally conducting and therefore conducts heat away from the sole of your foot much faster than the carpet. So the stone floor feels colder.
3.2 Wood and glass are both poor thermal conductors, so you will not get burnt.
3.3 Metal has a higher thermal conductivity than potatoes.
3.4 They are a result of convection where hot air from ground level rises.
3.5 Convective currents stir the water.
3.6 Although aluminium foil is a good thermal conductor the batt is isolated from thermal conduction by being embedded in the wooden frames in the roof. However, metal is a good radiation reflector.
3.7 21 kW. This is unbelievable since a resting person only produces about 200 W. Other factors will limit the exit of heat from the body than simple conduction across the skin. See if you can find out what they are.
3.8 232 W.
5.1 3344.8 s or 0.929 h. Although this is a long time, it is still too short in practice since as the temperature of the water rises there will be heat lost due to conduction, convection, and radiation.
5.2 The first law of thermodynamics is a conservation of energy equation. If a device is made that produces a certain amount of energy, then that same amount was used to set the device in motion. If a fraction of this energy is fed back into the device, then it cannot keep operating since it is less than the amount required to keep it operating. You can argue that you do not want any useful energy out—just feed back the output energy into the device to keep it running. In practice this cannot work since the energy out is always less than the energy in because there is no such thing as a 100% efficient device. So it will eventually stop.
5.3 No, this will not work. Although it might feel cool as you stand in front of the refrigerator door, in fact the room will start to heat up as work is done

by the refrigerator motor to extract heat from the room. This work appears as heat in the back of the refrigerator that will heat the room. Another way of stating this is that the first law of thermodynamics states that the work done by a system (the motor of the refrigerator in this case doing work on the air in the room) thus raises the internal energy of the room and therefore raises its temperature.

6.1 Pressure is force applied divided by area. In this case, the force is your weight, $m \times g$, where m is your mass in kg and $g = 9.8$ m s^{-2}, which is the acceleration due to gravity on the Earth's surface. The area is that of the soles of your feet when you are standing up, and the area of your body that is in contact with the ground. So the answer depends on how much you weigh and your size. For example, say your mass is 60 kg and the area of each sole is 200 cm^2 or 0.02 m^2. Then the total pressure you apply on the ground is equal to

$$\text{pressure} = \frac{mg}{A} = \frac{60 \times 9.8}{0.02} = 2.94 \times 10^4 \text{ Pa}$$

Recall that 1 atmosphere is equal to a pressure of 1.01×10^5 Pa. That is, the pressure you apply on the ground while standing up is less than that applied by the atmosphere on the ground. You can also calculate the pressure you apply while lying down. This will be left as an exercise for you to estimate your area, but you still use the same mass in the pressure equation. You must obtain a pressure that is much less than the one calculated for standing up.

6.2 The root mean square speed, v_{rms} is inversely proportional to the square root of the atomic or molecular mass, M,

$$v_{\text{rms}} \propto \frac{1}{\sqrt{M}}.$$

Because hydrogen and helium have smaller masses than oxygen or nitrogen, their v_{rms} is higher for the same temperature. This means they can escape from the Earth's atmosphere at a higher rate. As a result, their concentration will be less over time.

6.3 Oxygen has a mass of 15.999 amu (atomic mass units). That means one oxygen atom has a mass of

$$15.999 \times 1 \text{ amu} = 15.999 \times 1.66 \times 10^{-27} = 26.56 \times 10^{-27} \text{ kg}$$

That means molecular oxygen, O_2, has twice the mass and is equal to 53.11×10^{-27} kg. One mole is given by Avogadro's number ($N_A = 6.023 \times 10^{23}$) of oxygen molecules. Therefore, the mass of two moles of oxygen molecules is given by

$$\text{mass of two moles of } O_2 = 53.11 \times 10^{-27} \times 2 \times N_A$$
$$= 53.11 \times 10^{-27} \times 2 \times 6.023 \times 10^{23} = 0.064 \text{ kg.}$$

6.4 $PV = nRT$, where n is the number of moles given by N/N_A, where N is the number of particles. So the ideal gas law can be rewritten as

$$\frac{N}{V} = \frac{PN_A}{RT} = \frac{1.01 \times 10^5 \times 6.023 \times 10^{23}}{8.314 \times 300}$$

$$= 2.44 \times 10^{25} \text{ molecules per cubic metre.}$$

Summary of constants

Gas constant: $R = 8.314$ J mol^{-1}. K^{-1}
Boltzmann constant: $k_B = 1.38 \times 10^{-23}$ J K^{-1}
Avogadro's number: $N_A = 6.023 \times 10^{23}$
Boiling point of liquid nitrogen: −196 °C
Freezing point of water at one atmosphere of pressure: 0 °C
Boiling point of water at one atmosphere of pressure: 100 °C
Latent heat of fusion of ice: $L_v = 333$ kJ kg^{-1}
Speed of light: $c = 3.00 \times 10^8$ m s^{-1}
Stefan's constant: $\sigma = 5.67 \times 10^8$ W m^{-2} K^{-4}
Acceleration due to gravity: $g = 9.8$ m s^{-2}
One atmosphere of pressure: 101 325 Pa
One atomic mass unit (1 amu): $1.660\,54 \times 10^{27}$ kg