normal evaporation and cooling of the body. As some evaporation occurs from the body, the air next to the skin becomes saturated, and no further cooling can occur. If a fan is used, we feel more comfortable because the fan blows the saturated air next to our skin away and replaces it with air that is slightly less saturated. Hence, the evaporation process can continue while the fan is in operation and the body cools itself. Another way to cool the human body in the summer is to use an air conditioner. The air conditioner not only cools the air to a lower temperature, but it also removes a great deal of water vapor from the air, thereby decreasing the relative humidity of the air and permitting the normal evaporation of moisture from the skin. (Note that if the air conditioner did not remove water vapor from the air, cooling the air would increase the relative humidity making us even more uncomfortable.)

In the hot summertime, people enjoy swimming as a cooling experience. Not only the immersion of the body in the cool water is so satisfying, but when the person comes out of the water, evaporation of the sea or pool water from the person adds to the cooling. It is also customary to wear loose clothing in the summertime. The reason for this is to facilitate the flow of air over the body and hence assist in the evaporation process. Tight fitting clothing prevents this evaporation process and the person feels hotter. If you happen to live in a dry climate (low relative humidity), then you can feel quite comfortable at 85 °F, while a person living in a moist climate (high relative humidity) is very uncomfortable at the same 85 °F.

What many people do not realize is that you can also feel quite uncomfortable even in the wintertime, because of the humidity of the air. If the relative humidity is very low in your home then evaporation occurs very rapidly, cooling the body perhaps more than is desirable. As an example, the air temperature might be 70 °F but if the relative humidity is low, say 30%, then evaporation readily occurs from the skin of the body, and the person feels cold even though the air temperature is 70 °F. In this case the person can feel more comfortable if he or she uses a humidifier. A humidifier is a device that adds water vapor to the air. By increasing the water vapor in the air, and hence increasing the relative humidity, the rate of evaporation from the body decreases. The person no longer feels cold at 70 °F, but feels quite comfortable. If too much water vapor is added to the air, increasing the relative humidity to near a 100%, then evaporation from the body is hampered, the body is not able to cool itself, and the person feels too hot even though the temperature is only 70 °F. Thus too high or too low a relative humidity makes the human body uncomfortable.

We should also note that the evaporation process is also used to cool the human body for medical purposes. If a person is running a high fever, then an alcohol rub down helps cool the body down to normal temperature. The principle of evaporation as a cooling device is the same, only alcohol is very volatile and evaporates very rapidly. This is because the saturation vapor pressure of alcohol at 20 °C is much higher than the saturation vapor pressure of water. At 20 °C, water has a saturation vapor pressure of 17.4 mm of Hg, whereas ethyl alcohol has a saturation vapor pressure of 44 mm of Hg. The larger the saturation vapor pressure of a liquid, the greater is the amount of its vapor that the air can hold and hence the greater is the rate of vaporization. Because the alcohol evaporates much more rapidly than water, much greater cooling occurs than when water evaporates. Ethyl ether and ethyl chloride have saturation vapor pressures of 442 mm and 988 mm of Hg, respectively. Ethyl chloride with its very high saturation vapor pressure, evaporates so rapidly that it freezes the skin, and is often used as a local anesthetic for minor surgery.

The Language of Physics

Thermal expansion
Most materials expand when heated (p. 425).

Charles' law
The volume of a gas at constant pressure is directly proportional to the absolute temperature of the gas (p. 432).

Gay-Lussac's law
The absolute pressure of a gas at constant volume is directly proportional to the absolute temperature of the gas (p. 433).

Boyle's law
The product of the pressure and volume of a gas at constant temperature is equal to a constant (p. 434).

The ideal gas law
The general gas law that contains Charles', Gay-Lussac's, and Boyle's law as special cases. It states that the product of the pressure and volume of a gas divided by the absolute temperature of the gas is a constant (p. 434).

Mole
One mole of any gas is that amount of the gas that has a mass in grams equal to the atomic or molecular mass of the gas. One mole of any gas at a temperature of 0 °C and a pressure of one atmosphere, has a volume of 22.4 liters (p. 435).

Avogadro's number
Every mole of a gas contains the same number of molecules, namely, 6.022×10^{23} molecules. The mass of one molecule is equal to the molecular mass of that gas divided by Avogadro's number (p. 435).

Kinetic theory of gases
The analysis of a gas at the microscopic level, treated by Newton's laws of motion. The kinetic theory shows that the absolute temperature of a gas is a measure of the mean translational kinetic energy of the molecules of the gas (p. 438).

Summary of Important Equations

Linear expansion
$$\Delta L = \alpha L_0 \Delta t \tag{15.1}$$

Area expansion
$$\Delta A = 2\alpha A_0 \Delta t \tag{15.3}$$

Volume expansion
$$\Delta V = 3\alpha V_0 \Delta t \tag{15.5}$$

Coefficient of volume expansion for solids
$$\beta = 3\alpha \tag{15.6}$$

Volume expansion
$$\Delta V = \beta V_0 \Delta t \tag{15.7}$$

Ideal gas law
$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \tag{15.20}$$
$$pV = nRT \tag{15.23}$$

Number of molecules
$$N = nN_A \tag{15.24}$$

Absolute pressure
$$p_{abs} = p_{gauge} + p_{atm} \tag{15.25}$$

Temperature and mean kinetic energy
$$\tfrac{3}{2}kT = \tfrac{1}{2}mv^2_{avg} \tag{15.45}$$

rms speed of a molecule
$$v_{rms} = \sqrt{\frac{3kT}{m}} \tag{15.46}$$

Mass of a molecule
$$m = \frac{M}{N_A} \tag{15.47}$$

Total mass of the gas
$$m_{total} = nM$$

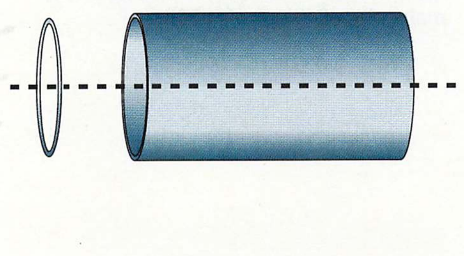
Questions for Chapter 15

1. Describe the process of expansion from a microscopic point of view.
2. Explain why it is necessary to make a temperature correction when measuring atmospheric pressure with a barometer.
†3. In the very upper portions of the atmosphere there are extremely few molecules present. Discuss the concept of temperature as it would be applied in this portion of the atmosphere.
4. Explain the introduction of the Kelvin temperature scale in the application of Charles' law.
5. Describe the meaning and application of gauge pressure.
†6. Would you expect the ideal gas equation to be applicable to a volume that is of the same order of magnitude as the size of a molecule?
7. If a gas is at an extremely high density, what effect would this have on the assumptions underlying the kinetic theory of gases?
8. From the point of view of the time between collisions of a gas molecule and the walls of the container, what happens if the container is reduced to half its original size?
9. From the point of view of the kinetic theory of gases, explain why there is no atmosphere on the moon.
10. When an astronomer observes the stars at night in an observatory, the observatory is not heated but remains at the same temperature as the outside air. Why should the astronomer do this?

Problems for Chapter 15

15.1 Linear Expansion of Solids

1. An aluminum rod measures 2.00 m at 10.0 °C. Find its length when the temperature rises to 135 °C.
2. A brass ring has a diameter of 20.0 cm when placed in melting ice at 0 °C. What will its diameter be if it is placed in boiling water?
3. A steel ring of 2.00-in. diameter at 0 °C is to be heated and slipped over a steel shaft whose diameter is 2.003 in. at 0 °C. To what temperature should the ring be heated? If the ring is not heated, to what temperature should the shaft be cooled such that the ring will fit over the shaft?



4. An aluminum ring, 7.00 cm in diameter at 5.00 °C, is to be heated and slipped over an aluminum shaft whose diameter is 7.003 cm at 5.00 °C. To what temperature should the ring be heated? If the ring is not heated, to what temperature should the shaft be cooled such that the ring will fit over the shaft?
5. The iron rim of a wagon wheel has an internal diameter of 80.0 cm when the temperature is 100 °C. What is its diameter when it cools to 0.00 °C?
6. A steel measuring tape, correct at 0.00 °C measures a distance L when the temperature is 30.0 °C. What is the error in the measurement due to the expansion of the tape?
7. Steel rails 50.0 ft long are laid when the temperature is 0.00 °C. What separation should be left between the rails to allow for thermal expansion when the temperature rises to 40.0 °C? If the cross-sectional area of a rail is 30.0 in.^{2}, what force is associated with this expansion?
8. Steel rails 20.0 m long are laid when the temperature is 5.00 °C. What separation should be left between the rails to allow for thermal expansion when the temperature rises to 38.5 °C? If the cross-sectional area of a rail is 230 cm^2, what force is associated with this expansion?

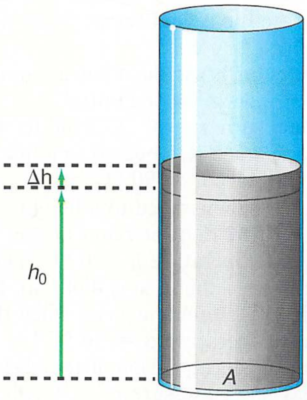
15.2 Area Expansion of Solids

9. A sheet of aluminum measures 10.0 ft by 5.00 ft at 0.00 °C. What is the area of the sheet at 150 °C?
10. A sheet of brass measures 4.00 m by 3.00 m at 5.00 °C. What is the area of the sheet at 175 °C?
11. If the radius of a copper circle is 20.0 cm at 0.00 °C, what will its area be at 100 °C?
12. A piece of aluminum has a hole 0.850 cm in diameter at 20.0 °C. To what temperature should the sheet be heated so that an aluminum bolt 0.865 cm in diameter will just fit into the hole?

15.3 Volume Expansion of Solids and Liquids

13. A chemistry student fills a Pyrex glass flask to the top with 100 cm^3 of Hg at 0.00 °C. How much mercury will spill out of the tube, and have to be cleaned up by the student, if the temperature rises to 35.0 °C?

14. A tube is filled to a height of 20.0 cm with mercury at 0.00 °C. If the tube has a cross-sectional area of 25.0 mm^2, how high will the mercury rise in the tube when the temperature is 30.0 °C? Neglect the expansion of the tube.



15. Since the volume of a material changes with a change in temperature, show that the density ρ at any temperature is given by

$$\rho = \frac{\rho_0}{1 + \beta \Delta t}$$

where ρ_0 is the density at the lower temperature.

15.7 The Ideal Gas Law

16. If 2.00 g of oxygen gas are contained in a tank of 500 cm^3 at a pressure of 20.0 psi, what is the temperature of the gas?

17. What is the pressure produced by 2 moles of gas at 20.0 °C contained in a volume of 0.500 liters?

18. One mole of hydrogen is at a pressure of 2.00 atm and a volume of 0.25 m^3. What is its temperature?

19. Compute the number of molecules in a gas contained in a volume of 50.0 cm^3 at a pressure of 2.00 atm and a temperature of 300 K.

20. An automobile tire has a volume of 4500 $in.^3$ and contains air at a gauge pressure of 32.0 $lb/in.^2$ when the temperature is 0.00 °C. What is the gauge pressure when the temperature rises to 35.0 °C?

21. An automobile tire has a volume of 0.0800 m^3 and contains air at a gauge pressure of 2.48×10^5 N/m^2 when the temperature is 3.50 °C. What is the gauge pressure when the temperature rises to 37.0 °C?

22. (a) How many moles of gas are contained in 0.300 kg of H_2 gas? (b) How many molecules of H_2 are there in this mass?

23. Nitrogen gas, at a pressure of 150 N/m^2, occupies a volume of 20.0 m^3 at a temperature of 30.0 °C. Find the mass of this nitrogen gas in kilograms.

24. One mole of nitrogen gas at a pressure of 1.00 atm and a temperature of 300 K expands isothermally to double its volume. What is its new pressure? (Isothermal means at constant temperature.)

25. An ideal gas occupies a volume of 4.00 liters at a pressure of 1.00 atm and a temperature of 273 K. The gas is then compressed isothermally to one half of its original volume. Determine the final pressure of the gas.

26. The pressure of a gas is kept constant while 3.00 m^3 of the gas at an initial temperature of 50.0 °C is expanded to 6.00 m^3. What is the final temperature of the gas?

27. The volume of O_2 gas at a temperature of 20.0 °C is 4.00 liters. The temperature of the gas is raised to 100 °C while the pressure remains constant. What is the new volume of the gas?

28. A balloon is filled with helium at a pressure of 1.50 atm, a temperature of 25.0 °C, and occupies a volume of 3.00 m^3. The balloon rises in the atmosphere. When it reaches a height where the pressure is 0.500 atm and the temperature is −20.0 °C, what is its volume?

†29. An air bubble of 32.0 cm^3 volume is at the bottom of a lake 10.0 m deep where the temperature is 5.00 °C. The bubble rises to the surface where the temperature is 20.0 °C. Find the volume of the bubble just before it reaches the surface.

30. One mole of helium is at a temperature of 300 K and a volume of 10.0 liters. What is its pressure? The gas is warmed at constant volume to 600 K. What is its new pressure? How many molecules are there?

15.8 The Kinetic Theory of Gases

31. Find the rms speed of a helium atom at a temperature of 10.0 K.

32. Find the kinetic energy of a single molecule when it is at a temperature of (a) 0.00 °C, (b) 20.0 °C, (c) 100 °C, (d) 1000 °C, and (e) 5000 °C.

33. Find the mass of a carbon dioxide molecule (CO_2).

34. Find the rms speed of a helium atom on the surface of the sun, if the sun's surface temperature is approximately 6000 K.

35. At what temperature will the rms speed of an oxygen molecule be twice its speed at room temperature?

36. The rms speed of a gas molecule is v at a temperature of 300 K. What is the speed if the temperature is increased to 900 K?

†37. Find the total kinetic energy of all the nitrogen molecules in the air in a room 7.00 m by 10.0 m by 4.00 m, if the air is at a temperature of 22.0 °C and 1 atm of pressure.

38. If the rms speed of a monatomic gas is 445 m/s at 350 K, what is the atomic mass of the atom? What gas do you think it is?

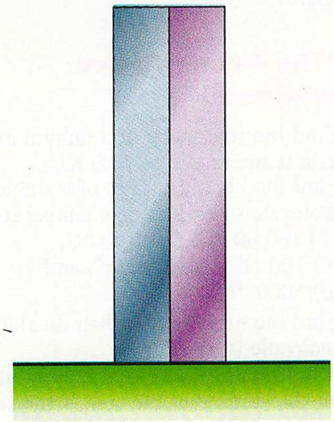
Additional Problems

39. A barometer reads normal atmospheric pressure when the mercury column in the tube is at 76.0 cm of Hg at 0.00 °C. If the pressure of the atmosphere does not change, but the air temperature rises to 35.0 °C, what pressure will the barometer indicate? The tube has a diameter of 5.00 mm. Neglect the expansion of the tube.

40. Find the stress necessary to give the same strain that occurs when a steel rod undergoes a temperature change of 120 °C.

†41. The symbol π is defined as the ratio of the circumference of a circle to its diameter. If a circular sheet of metal expands by heating, show that the ratio of the expanded circumference to the expanded diameter is still equal to π.

42. A 15.0-cm strip of steel is welded to the left side of a 15.0-cm strip of aluminum. When the strip undergoes a temperature change Δt, will the combined strip bend to the right or to the left?



†43. A 350-g mass is connected by a thin brass rod 25.0 cm long to a rotating shaft that is rotating at an initial angular speed of 5.00 rad/s. If the temperature changes by 35 °C, (a) find the change in the moment of inertia of the system and (b) using the law of conservation of angular momentum, find the change in the rotational energy of the system.

44. The focal length of a polished aluminum spherical mirror is given by $f = R/2$, where R is the radius of curvature of the mirror, and is 23.5 cm. Find the new focal length of the mirror if the temperature changes by 45.0 °C.

†45. A 50.0-g silver ring, 12.0 cm in diameter, is spinning about an axis through its center at a constant speed of 11.4 rad/s. If the temperature changes by 185 °C, what is the change in the angular momentum of the ring? The coefficient of linear expansion for silver is $1.90 \times 10^{-5}/°C$.

†46. An aluminum rod is at room temperature. To what temperature would this rod have to be heated such that the thermal expansion is enough to exceed the elastic limit of aluminum? Compare this temperature with the melting point of aluminum. What conclusion can you draw?

47. A steel pendulum is 60.0 cm long, at 20.0 °C. By how much does the period of the pendulum change when the temperature is 35.0 °C?

48. Find the number of air molecules in a classroom 10.0 m long, 10.0 m wide, and 3.5 m high, if the air is at normal atmospheric pressure and a temperature of 20.0 °C.

49. A brass cylinder 5.00 cm in diameter and 8.00 cm long is at an initial temperature of 380 °C. It is placed in a calorimeter containing 0.120 kg of water at an initial temperature of 5.00 °C. The aluminum calorimeter has a mass of 0.060 kg. Find (a) the final temperature of the water and (b) the change in volume of the cylinder.

†50. Dalton's law of partial pressure says that when two or more gases are mixed together, the resultant pressure is the sum of the individual pressures of each gas. That is,

$$p = p_1 + p_2 + p_3 + p_4 + \cdots$$

If one mole of oxygen at 20.0 °C and occupying a volume of 2.00 m^3 is added to two moles of nitrogen also at 20.0 °C and occupying a volume of 10.0 m^3 and the final volume is 10.0 m^3, find the resultant pressure of the mixture.

†51. The escape velocity from the earth is $v_E = 1.12 \times 10^4$ m/s. At what temperature is the rms speed equal to this for: (a) hydrogen (H_2), (b) helium (He), (c) nitrogen (N_2), (d) oxygen (O_2), (e) carbon dioxide (CO_2), and (f) water vapor (H_2O)? From these results, what can you infer about the earth's atmosphere?

†52. The escape velocity from the moon is $v_M = 0.24 \times 10^4$ m/s. At what temperature is the rms speed equal to this for (a) hydrogen (H_2), (b) helium (He), (c) nitrogen (N_2), (d) oxygen (O_2), (e) carbon dioxide (CO_2), and (f) water vapor (H_2O)? From these results, what can you infer about the possibility of an atmosphere on the moon?

†53. Show that the velocity of a gas molecule at one temperature is related to the velocity of the molecule at a second temperature by

$$v_2 = \sqrt{\frac{T_2}{T_1}}\, v_1$$

†54. A room is filled with nitrogen gas at a temperature of 293 K. (a) What is the average kinetic energy of a nitrogen molecule? (b) What is the rms speed of the molecule? (c) What is the rms value of the momentum of this molecule? (d) If the room is 4.00 m wide what is the average force exerted on the wall by this molecule? (e) If the wall is 4.00 m by 3.00 m, what is the pressure exerted on the wall by this molecule? (f) How many molecules moving at this speed are necessary to cause a pressure of 1.00 atm?

†55. Two isotopes of a gaseous substance can be separated by diffusion if each has a different velocity. Show that the rms speed of an isotope can be given by

$$v_2 = \sqrt{\frac{m_1}{m_2}}\, v_1$$

where the subscript 1 refers to isotope 1 and the subscript 2 refers to isotope 2.

Interactive Tutorials

56. A copper tube has the length L_0 = 1.58 m at the initial temperature t_i = 20.0 °C. Find its length L when it is heated to a final temperature t_f = 100 °C.

57. A circular brass sheet has an area A_0 = 2.56 m^2 at the initial temperature t_i = 0 °C. Find its new area A when it is heated to a final temperature t_f = 90 °C.

58. A glass tube is filled to a height h_0 = 0.762 m of mercury at the initial temperature t_i = 0 °C. The diameter of the tube is 0.085 m. How high will the mercury rise when the final temperature t_f = 50 °C? Neglect the expansion of the glass.

59. A gas has a pressure p_1 = 1 atm, a volume V_1 = 4.58 m^3, and a temperature t_1 = 20.0 °C. It is then compressed to a volume V_2 = 1.78 m^3 and a pressure p_2 = 3.57 atm. Find the final temperature of the gas t_2.

60. Find the number of moles and the number of molecules in a gas under a pressure p = 1 atm and a temperature t = 20.0 °C. The room has a length L = 15.0 m, a width W = 10.0 m, and a height h = 4.00 m.

61. Kinetic theory. Oxygen gas is in a room under a pressure p = 1 atm and a temperature of t = 20.0 °C. The room has a length L = 18.5 m, a width W = 12.5 m, and a height h = 5.50 m. For the oxygen gas, find (a) the kinetic energy of a single molecule, (b) the total kinetic energy of all the oxygen molecules, (c) the mass of an oxygen molecule, and (d) the speed of the oxygen molecule. The molecular mass of oxygen is M_{O_2} = 32.0 g/mole.

62. Ideal Gas Equation Calculator.