9.8 Thermal Expansion

In addition to causing changes in the temperature and the state of a substance, the transfer of heat can also cause a change in the volume of a substance. As its temperature increases, the atoms and molecules of a substance vibrate with greater amplitude. If free to translate, they move faster and have more energetic collisions. Because of their increased motion, the atoms and molecules occupy slightly more space than when moving less vigorously. They are, on the average, spread farther apart when the substance is hot than when cool. Therefore, almost all forms of matter expand when heated and contract when cooled.

Architects and engineers must consider thermal expansion and contraction of metal beams when designing tall buildings and bridges. Expansion joints are usually placed in sidewalks, bridges, and highways to prevent their buckling during summer heat. The road shown in Fig. 9.12 did not have an expansion joint, and as its length increased on a hot summer day, the road buckled. Dentists must use filling materials that expand and contract with temperature change at the same rate as a tooth; otherwise, fillings will become loose.

The change in length—**linear expansion**—ΔL of an object that is warmed or cooled depends on its change in temperature ΔT, on its original length L, and

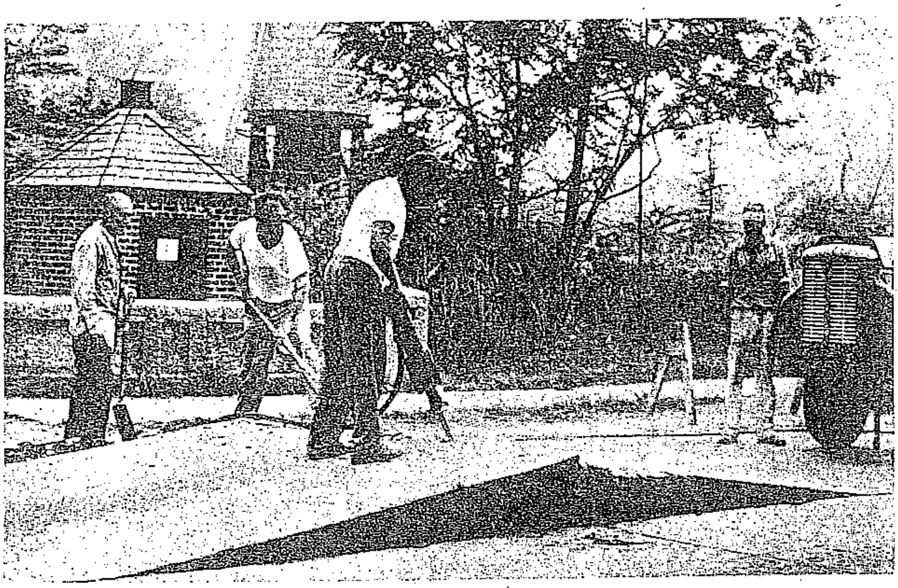

FIG. 9.12. A road that buckled because of expansion during the summer heat. (Courtesy of the New York Department of Transportation.)

TABLE 9.4 Coefficients of Thermal Expansion at 20°C

Substance	Linear α ($C^{\circ -1}$)	Volume γ ($C^{\circ -1}$)
Aluminum	25×10^{-6}	72×10^{-6}
Steel and iron	12×10^{-6}	36×10^{-6}
Glass (Pyrex)	3×10^{-6}	9×10^{-6}
Glass (jar)	$\sim 10 \times 10^{-6}$	$\sim 30 \times 10^{-6}$
Brick and concrete	$\sim 10 \times 10^{-6}$	$\sim 30 \times 10^{-6}$
Rubber	$\sim 80 \times 10^{-6}$	$\sim 240 \times 10^{-6}$
Ethanol	250×10^{-6}	750×10^{-6}
Methanol	400×10^{-6}	1200×10^{-6}
Gasoline	$\sim 300 \times 10^{-6}$	$\sim 900 \times 10^{-6}$
Air		3670×10^{-6}

on the type of material of which it is made. These quantities are related by the equation

$$\Delta L = \alpha L \, \Delta T. \tag{9.11}$$

The quantity α is called the **coefficient of thermal expansion.** From Eq. (9.11) we see that $\alpha = \Delta L/(L\,\Delta T)$ and has units of inverse degrees ($C^{\circ -1}$) because the length units cancel. Table 9.4 lists the values of α for various materials. The coefficient α is not a constant for a particular material but changes slightly with temperature. However, because the change is usually small, we ignore it in our problems and examples.

EXAMPLE 9.11 A steel beam in a bridge extends 25 m across a small stream. What is its change in length from the winter, when its temperature is −20°C, to the summer, when it is 38°C?

EXAMPLE 9.12 The aluminum lid of a jar of dill pickles is stuck to the glass. To loosen the lid so it can be opened, hot water is poured over the lid, causing it to expand. If the temperature increase of the lid and glass is 40 C°, calculate the change in circumference of the lid and of the glass on which it is screwed. The diameter of the lid before heating is 22 cm.

Because a material usually expands uniformly in all directions as it becomes warmer, its volume increases. The change in volume ΔV of a substance depends on its change in temperature, its original volume V, and the material of which it is made:

$$\Delta V = \gamma V \Delta T. \tag{9.12}$$

The quantity γ (the Greek letter gamma) is called the **coefficient of volume expansion;** its value depends on the substance that is expanding or contracting. The units of γ are $C^{\circ -1}$, the same as those of the coefficient of linear expansion. A list of the values of γ for a variety of substances appears in Table 9.4.

The coefficient of volume expansion γ of most substances is about three times the coefficient of linear expansion α of the same substance. This seems reasonable since the volume of an object is the product of three linear dimensions, such as length, height, and width, and each expands as it is heated. Although the mathematics needed to prove this statement are a little more difficult than this simple argument implies, we can see that the statement is true by comparing the values of α and γ in Table 9.4.

EXAMPLE 9.13 During a summer night when the temperature is 20°C, your house contains 453 m^3 of air. What volume of air leaves the house through an open window if the air warms to 40°C on a very hot summer day? Assume that the dimensions of the house experience negligible change and that all other conditions are constant.

The change in volume of air as it warms and cools has significant effects on our atmosphere. As a gas such as air expands, it becomes less dense; its molecules on the average are spaced farther apart than in a cool gas. For this reason a hot (less dense) gas will rise and float on a cool (more dense) gas. This property of gases is very important in cleansing the atmosphere surrounding large cities. Air warmed at the earth's surface rises and carries with it air contaminants. Cool, clean air sinks down from above to replace the warm air.

Occasionally, an inversion occurs. For some reason, the air at the earth's surface remains cool and is covered by warmer air above. The temperature is said to be inverted. The cool, dense air at the surface does not rise, and pollution accumulates until the inversion breaks.

Another interesting environmental consequence of thermal expansion and contraction is related to the freezing of water at the surface of a lake or pond. Why doesn't the 0°C water that is ready to freeze sink to the bottom, allowing slightly warmer water to rise to the surface? This would happen with most substances that expand as they warm and contract as they cool. Water is a

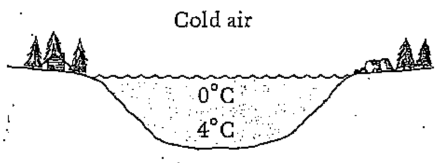

FIG. 9.13. Since water at 4°C is denser than water at 0°C, the warmer water sinks. The cold water freezes at the top of a lake rather than at the bottom.

notable and important exception. When water cools from 4°C to 0°C, it expands and becomes less dense than the slightly warmer water; the 0°C water has less weight per unit volume than the 4°C water. Thus, in a lake or pond, the le dense 0°C water floats at the top while the more dense, slightly warmer wat sinks to the bottom, as depicted in Fig. 9.13. Consequently, a lake freezes from the top down rather than from the bottom up. During the winter, fish remain near the bottom of the lake in the slightly warmer water.

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44. If one steel beam extended the entire height of the Sears Tower in Chicago (434 m), by how much would the beam contract from its summer high temperature of 37°C to its winter low of −20°C?

45. The main steel span of the Golden Gate Bridge is about 1350 m long. By how much will it expand if its temperature is increased from 10°F to 100°F?

46. An interstate highway is made of concrete slabs 25 m long placed end to end. (a) What expansion gap must be left between the slabs to prevent buckling when the temperature changes from 20°C to 50°C? (b) Starting with the gap calculated in part (a), find the gap when the temperature decreases to −20°C.

■ 47. A 100-m-long steel tape is used to measure the length of your property. When measured in the winter at a temperature of 10°C, your property is 85.000 m long. What is the measured length of the property using the same tape in the summer when the temperature is 30°C? Assume that the property does not change dimensions.

48. (a) The Celsius temperature of a 100-m-long aluminum wire originally at 15°C doubles. By how much does its length increase? (b) If the wire is cut in half, how much does the length of each half increase for the same temperature change as in part (a). (c) A 100-m-long aluminum wire with twice the radius as that in part (a) experiences the same temperature change. How much does its length change?

■■ 49. Two concrete roadway slabs 25 m long are accidentally laid without expansion gaps (Fig. 9.14). How high will the slabs buckle up if their temperature increases from 10°C to 50°C?

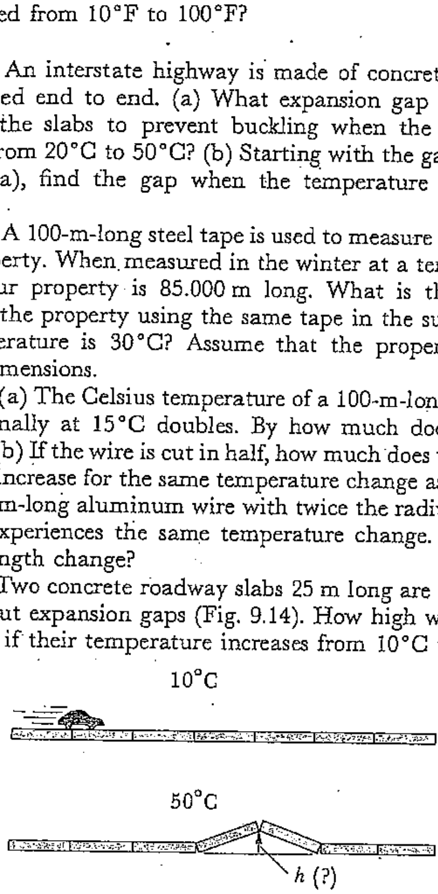

FIG. 9.14

■ 50. The volume of an iron ball of radius r is given by $\frac{4}{3}\pi r^3$. A particular ball has a diameter of 10.00 cm and is 0.01 cm too large to fit through a hole in a metal plate. What temperature change of the ball will allow it to fit through the hole?

■ 51. A 50-gal ($1.9 \times 10^5\ cm^3$) steel drum at 5°C is filled to the brim with gasoline. The drum and its contents are warmed to 40°C. How much gasoline is lost through the open cap of the drum? The drum also expands.

■ 52. The radiator of a car is filled to the overflow level with 5.4 liters of water. The water is warmed from 25°C to 95°C. How much water spills out of the overflow tube? The coefficient of volume expansion of water in this temperature range is $550 \times 10^{-6}\ C°^{-1}$.

■■ 53. (a) Calculate the change in volume of the water in the earth's oceans if it warms from an average temperature of 15°C to 18°C. The present volume is approximately $1.4 \times 10^{18}\ m^3$. (b) Approximately how high will the level of the ocean rise? The coefficient of volume expansion of water at this temperature range is approximately $180 \times 10^{-6}\ C°^{-1}$. [*Note:* You need one other important quantity whose value is probably given in an encyclopedia.]

■■ 54. A rectangular lake that is 2000 m wide, 4000 m long, and 15 m deep contains 1.2×10^{11} kg of water. The lake is warmed by the addition of 2.0×10^{15} J of heat. Calculate its change in volume. For the water temperature in this problem, $\gamma = 210 \times 10^{-6}\ C°^{-1}$.

■■ 55. Prove that the coefficient of volume expansion for a solid cube equals approximately three times the coefficient of linear expansion for one dimension of the cube.

45. 0.81 m
47. 84.980 m
49. 0.71 m
51. 5750 cm^3
53. (a) $7.6 \times 10^{14}\ m^3$, (b) 2 m