29.2: Temperature and Thermal Equilibrium

On a cold winter day, suppose you want to warm up by drinking a cup of tea. You start by filling up a kettle with water from the cold water tap (water heaters tend to add unpleasant contaminants and reduce the oxygen level in the water). You place the kettle on the heating element of the stove and allow the water to boil briefly. You let the water cool down slightly to avoid burning the tea leaves or creating bitter flavors and then pour the water into a pre-heated teapot containing a few teaspoons of tea; the tea leaves steep for a few minutes and then you enjoy your drink.

When the kettle is in contact with the heating element of the stove, energy flows from the heating element to the kettle and then to the water. The conduction of energy is due to the contact between the objects. The random motions of the atoms in the heating element are transferred to the kettle and water via collisions. We shall refer to this conduction process as 'energy transferred thermally'. We can attribute different degrees of "hotness" (based on our experience of inadvertently touching the kettle and the water). Temperature is a measure of the "hotness" of a body. When two isolated objects that are initially at different temperatures are put in contact, the "colder" object heats up while the "hotter" object cools down, until they reach the same temperature, a state we refer to as thermal equilibrium. Temperature is that property of a system that determines whether or not a system is in thermal equilibrium with other systems.

Consider two systems A and B that are separated from each other by an adiabatic boundary (adiabatic = no heat passes through) that does not allow any thermal contact. Both A and B are placed in thermal contact with a third system C until thermal equilibrium is reached. If the adiabatic boundary is then removed between A and B, no energy will transfer thermally between A and B. Thus

Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.

Thermometers and Ideal-Gas Temperature

Any device that measures a thermometric property of an object, for instance the expansion of mercury, is called a thermometer. Many different types of thermometers can be constructed, making use of different thermometric properties; for example: pressure of a gas, electric resistance of a resistor, thermal electromotive force of a thermocouple, magnetic susceptibility of a paramagnetic salt, or radiant emittance of blackbody radiation.

Gas Thermometer

The gas thermometer measures temperature based on the pressure of a gas at constant volume and is used as the standard thermometer, because the variations between different gases can be greatly reduced when low pressures are used. A schematic device of a gas thermometer is shown in Figure 29.1. The volume of the gas is kept constant by raising or lowering the mercury reservoir so that the mercury level on the left arm in Figure 29.1 just reaches the point I . When the bulb is placed in thermal equilibrium with a system whose temperature is to be measured, the difference in height between the mercury levels in the left and right arms is measured. The bulb pressure is atmospheric pressure plus the pressure in mercury a distance h below the surface (Pascal's Law). A thermometer needs to have two scale points, for example the height of the column of mercury (the height is a function of the pressure of the gas) when the bulb is placed in thermal equilibrium with ice water and in thermal equilibrium with standard steam.

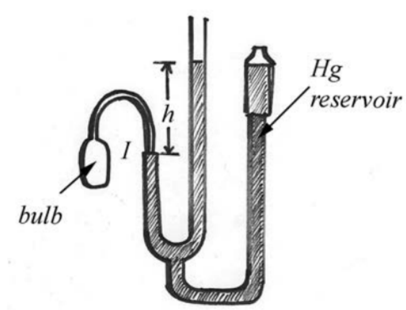

Figure 29.1 Constant volume gas thermometer

At constant volume, and at ordinary temperatures, the pressure of gases is proportional to the temperature,

$$T \propto P$$

We define a linear scale for temperature based on the pressure in the bulb by

$$T = aP$$

where a is a positive constant. In order to fix the constant a in Equation (29.1.3), a standard state must be chosen as a reference point. The standard fixed state for thermometry is the triple point of water, the state in which ice, water, and water vapor coexist. This state occurs at only one definite value of temperature and pressure. By convention, the temperature of the triple point of water is chosen to be exactly 273.16 K on the Kelvin scale, at a water-vapor pressure of 610 Pa. Let P_{TP} be the value of the pressure P at the triple point in the gas thermometer. Set the constant a according to

$$a = \frac{273.16\mathrm{K}}{P_{\mathrm{TP}}}$$

Hence the temperature at any value of P is then

$$T(P) = aP = \frac{273.16\mathrm{K}}{P_{\mathrm{TP}}} P$$

The ratio of temperatures between any two states of a system is then measured by the ratio of the pressures of those states,

$$\frac{T_1}{T_2} = \frac{P_1}{P_2}$$

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Ideal-Gas Temperature

Different gases will have different values for the pressure P, hence different temperatures T(P). When the pressure in the bulb at the triple point is gradually reduced to near zero, all gases approach the same pressure reading and hence the same temperature. The limit of the temperature T(P) as $P_{\mathrm{TP}} \rightarrow 0$ is called the *ideal-gas* temperature and is given by the equation

$$T(P) = \lim_{P_{\mathrm{TP}} \rightarrow 0} \frac{273.16\mathrm{K}}{P_{\mathrm{TP}}} P$$

This definition of temperature is independent of the type of gas used in the gas thermometer. The lowest possible temperatures measured in gas thermometers use ^{3}He because this gas becomes a liquid at a lower temperature than any other gas. In this way, temperatures down to 0.5K can be measured. We cannot define the temperature of absolute zero, 0K, using this approach.

Temperature Scales

The commonly used Celsius scale employs the same size for each degree as the Kelvin scale, but the zero point is shifted by 273.15 degrees so that the triple point of water has a Celsius temperature of 0.01 $^{\mathrm{o}}$C.

$$T\left({}^{\circ}\mathrm{C}\right) = \theta(\mathrm{K}) - 273.15^{\circ}\mathrm{C}$$

and the freezing point of water at standard atmospheric pressure is $^{\mathrm{o}}$C . The Fahrenheit scale is related to the Celsius scale by

$$T\left({}^{\circ}\mathrm{F}\right) = \frac{9}{5} T\left({}^{\circ}\mathrm{C}\right) + 32^{\circ}\mathrm{F}$$

The freezing point of pure water at standard atmospheric pressure occurs at $^{\mathrm{o}}$C and 32 $^{\mathrm{o}}$F . The boiling point of pure water at standard atmospheric pressure is 100 $^{\mathrm{o}}$C and 212 $^{\mathrm{o}}$F.