

For small temperature differences, the rate of cooling, due to conduction, convection, and radiation combined, is proportional to the difference in temperature. It is a valid approximation in the transfer of heat from a radiator to a room, the loss of heat through the wall of a room, or the cooling of a cup of tea on the table.

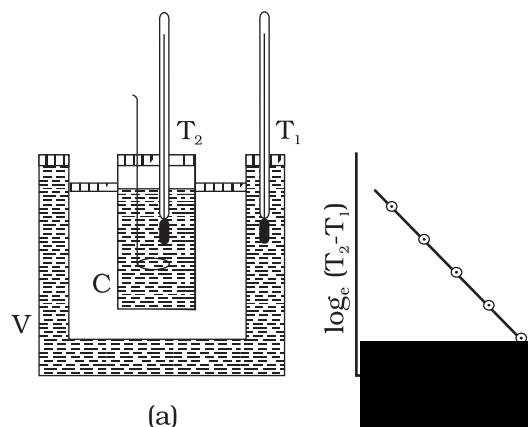


Fig. 11.20 Verification of Newton's law of cooling

Newton's law of cooling can be verified with the help of the experimental set-up shown in Fig. 11.20(a). The set-up consists of a double-walled vessel (V) containing water. The two walls are separated by a layer of air. A copper calorimeter (C) containing hot water is placed inside the double-walled vessel. Two thermometers are used to measure the temperatures T_2 of water in the calorimeter and T_1 of hot water in between the two walls. Temperature of the calorimeter is noted after

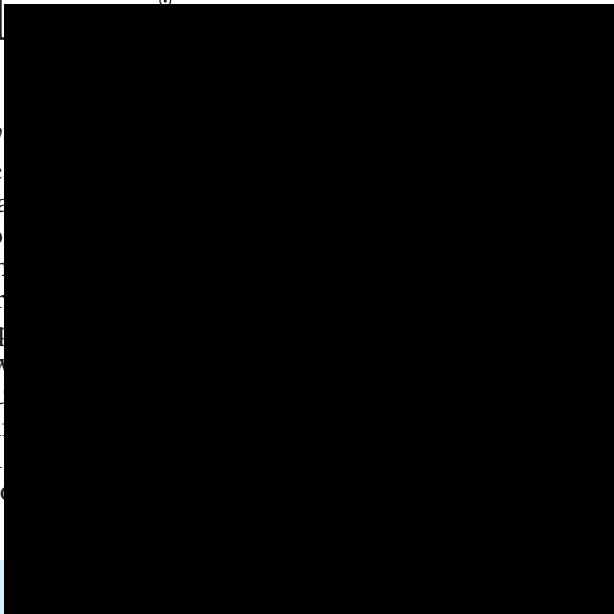
time. A graph is plotted between $\log_e (T_2 - T_1)$ [or $\ln(T_2 - T_1)$] and time (t). The nature of the graph is observed to be a straight line having a negative slope as shown in Fig. 11.20(b). This is in support of Eq. 11.22.

Example 11.8 A pan filled with hot food cools from 94 °C to 86 °C in 2 minutes when the room temperature is at 20 °C. How long will it take to cool from 71 °C to 69 °C?

Answer The average temperature of 94 °C and 86 °C is 90 °C, which is 70 °C above the room temperature. Under these conditions the pan cools 8 °C in 2 minutes.

Using Eq. (11.21), we have

$$\frac{\text{Change in temperature}}{\text{Time}} = K\Delta T$$



and 71 °C is 70 °C, which is 70 °C above the room temperature. K is the same as in the original.

From the two equations, we

1. Heat is a form of energy that flows between a body and its surrounding medium by virtue of temperature difference between them. The degree of hotness of the body is quantitatively represented by temperature.
2. A temperature-measuring device (thermometer) makes use of some measurable property (called thermometric property) that changes with temperature. Different thermometers lead to different temperature scales. To construct a temperature scale, two fixed points are chosen and assigned some arbitrary values of temperature. The two numbers fix the origin of the scale and the size of its unit.
3. The Celsius temperature (t_c) and the Fahrenheit temperature (t_f) are related by

$$t_f = (9/5) t_c + 32$$
4. The ideal gas equation connecting pressure (P), volume (V) and absolute temperature (T) is :

$$PV = \mu RT$$
 where μ is the number of moles and R is the universal gas constant.

5. In the absolute temperature scale, the zero of the scale corresponds to the temperature where every substance in nature has the least possible molecular activity. The Kelvin absolute temperature scale (T) has the same unit size as the Celsius scale (T_c), but differs in the origin :

$$T_c = T - 273.15$$

6. The coefficient of linear expansion (α_l) and volume expansion (α_v) are defined by the relations :

$$\frac{\Delta l}{l} = \alpha_l \Delta T$$

$$\frac{\Delta V}{V} = \alpha_v \Delta T$$

where Δl and ΔV denote the change in length l and volume V for a change of temperature ΔT . The relation between them is :

$$\alpha_v = 3 \alpha_l$$

7. The specific heat capacity of a substance is defined by

$$s = \frac{1}{m} \frac{\Delta Q}{\Delta T}$$

where m is the mass of the substance and ΔQ is the heat required to change its temperature by ΔT . The molar specific heat capacity of a substance is defined by

$$C = \frac{1}{\mu} \frac{\Delta Q}{\Delta T}$$

where μ is the number of moles of the substance.

8. The latent heat of fusion (L_f) is the heat per unit mass required to change a substance from solid into liquid at the same temperature and pressure. The latent heat of vaporisation (L_v) is the heat per unit mass required to change a substance from liquid to the vapour state without change in the temperature and pressure.
9. The three modes of heat transfer are conduction, convection and radiation.
10. In conduction, heat is transferred between neighbouring parts of a body through molecular collisions, without any flow of matter. For a bar of length L and uniform cross section A with its ends maintained at temperatures T_c and T_D , the rate of flow of heat H is :

$$H = K A \frac{T_c - T_D}{L}$$

where K is the thermal conductivity of the material of the bar.

11. Newton's Law of Cooling says that the rate of cooling of a body is proportional to the excess temperature of the body over the surroundings :

$$\frac{dQ}{dt} = -k(T_2 - T_1)$$

Where T_1 is the temperature of the surrounding medium and T_2 is the temperature of the body.

Quantity	Symbol	Dimensions	Unit	Remark
Amount of substance	μ	[mol]	mol	
Celsius temperature	t_c	[K]	°C	
Kelvin absolute temperature	T	[K]	K	$t_c = T - 273.15$
Co-efficient of linear expansion	α_l	[K ⁻¹]	K ⁻¹	
Co-efficient of volume expansion	α_v	[K ⁻¹]	K ⁻¹	$\alpha_v = 3 \alpha_l$
Heat supplied to a system	ΔQ	[ML ² T ⁻²]	J	Q is not a state variable
Specific heat capacity	s	[L ² T ⁻² K ⁻¹]	J kg ⁻¹ K ⁻¹	
Thermal Conductivity	K	[M LT ⁻³ K ⁻¹]	J s ⁻¹ K ⁻¹	$H = -KA \frac{dT}{dx}$

POINTS TO PONDER

- The relation connecting Kelvin temperature (T) and the Celsius temperature t_c

$$T = t_c + 273.15$$

and the assignment $T = 273.16$ K for the triple point of water are exact relations (by choice). With this choice, the Celsius temperature of the melting point of water and boiling point of water (both at 1 atm pressure) are very close to, but not exactly equal to 0 °C and 100 °C respectively. In the original Celsius scale, these latter fixed points were exactly at 0 °C and 100 °C (by choice), but now the triple point of water is the preferred choice for the fixed point, because it has a unique temperature.

- A liquid in equilibrium with vapour has the same pressure and temperature throughout the system; the two phases in equilibrium differ in their molar volume (i.e. density). This is true for a system with any number of phases in equilibrium.
- Heat transfer always involves temperature difference between two systems or two parts of the same system. Any energy transfer that does not involve temperature difference in some way is not heat.
- Convection involves flow of matter *within a fluid* due to unequal temperatures of its parts. A hot bar placed under a running tap loses heat by conduction between the surface of the bar and water and not by convection within water.

EXERCISES

- The triple points of neon and carbon dioxide are 24.57 K and 216.55 K respectively. Express these temperatures on the Celsius and Fahrenheit scales.
- Two absolute scales A and B have triple points of water defined to be 200 A and 350 B. What is the relation between T_A and T_B ?
- The electrical resistance in ohms of a certain thermometer varies with temperature according to the approximate law :

$$R = R_0 [1 + \alpha (T - T_0)]$$

The resistance is 101.6 Ω at the triple-point of water 273.16 K, and 165.5 Ω at the normal melting point of lead (600.5 K). What is the temperature when the resistance is 123.4 Ω ?

- Answer the following :

- The triple-point of water is a standard fixed point in modern thermometry.

Why? What is wrong in taking the melting point of ice and the boiling point of water as standard fixed points (as was originally done in the Celsius scale)?

- (b) There were two fixed points in the original Celsius scale as mentioned above which were assigned the number $0\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ respectively. On the absolute scale, one of the fixed points is the triple-point of water, which on the Kelvin absolute scale is assigned the number 273.16 K . What is the other fixed point on this (Kelvin) scale?
- (c) The absolute temperature (Kelvin scale) T is related to the temperature t_c on the Celsius scale by

$$t_c = T - 273.15$$

Why do we have 273.15 in this relation, and not 273.16?

- (d) What is the temperature of the triple-point of water on an absolute scale whose unit interval size is equal to that of the Fahrenheit scale?

- 11.5** Two ideal gas thermometers A and B use oxygen and hydrogen respectively. The following observations are made:

Temperature	Pressure thermometer A	Pressure thermometer B
Triple-point of water	$1.250 \times 10^5\text{ Pa}$	$0.200 \times 10^5\text{ Pa}$
Normal melting point of sulphur	$1.797 \times 10^5\text{ Pa}$	$0.287 \times 10^5\text{ Pa}$

- (a) What is the absolute temperature of normal melting point of sulphur as read by thermometers A and B ?
- (b) What do you think is the reason behind the slight difference in answers of thermometers A and B ? (The thermometers are not faulty). What further procedure is needed in the experiment to reduce the discrepancy between the two readings?
- 11.6** A steel tape 1 m long is correctly calibrated for a temperature of $27.0\text{ }^{\circ}\text{C}$. The length of a steel rod measured by this tape is found to be 63.0 cm on a hot day when the temperature is $45.0\text{ }^{\circ}\text{C}$. What is the actual length of the steel rod on that day? What is the length of the same steel rod on a day when the temperature is $27.0\text{ }^{\circ}\text{C}$? Coefficient of linear expansion of steel = $1.20 \times 10^{-5}\text{ K}^{-1}$.
- 11.7** A large steel wheel is to be fitted on to a shaft of the same material. At $27\text{ }^{\circ}\text{C}$, the outer diameter of the shaft is 8.70 cm and the diameter of the central hole in the wheel is 8.69 cm. The shaft is cooled using 'dry ice'. At what temperature of the shaft does the wheel slip on the shaft? Assume coefficient of linear expansion of the steel to be constant over the required temperature range:
 $\alpha_{\text{steel}} = 1.20 \times 10^{-5}\text{ K}^{-1}$.
- 11.8** A hole is drilled in a copper sheet. The diameter of the hole is 4.24 cm at $27.0\text{ }^{\circ}\text{C}$. What is the change in the diameter of the hole when the sheet is heated to $227\text{ }^{\circ}\text{C}$? Coefficient of linear expansion of copper = $1.70 \times 10^{-5}\text{ K}^{-1}$.
- 11.9** A brass wire 1.8 m long at $27\text{ }^{\circ}\text{C}$ is held taut with little tension between two rigid supports. If the wire is cooled to a temperature of $-39\text{ }^{\circ}\text{C}$, what is the tension developed in the wire, if its diameter is 2.0 mm? Co-efficient of linear expansion of brass = $2.0 \times 10^{-5}\text{ K}^{-1}$; Young's modulus of brass = $0.91 \times 10^{11}\text{ Pa}$.
- 11.10** A brass rod of length 50 cm and diameter 3.0 mm is joined to a steel rod of the same length and diameter. What is the change in length of the combined rod at $250\text{ }^{\circ}\text{C}$, if the original lengths are at $40.0\text{ }^{\circ}\text{C}$? Is there a 'thermal stress' developed at the junction? The ends of the rod are free to expand (Co-efficient of linear expansion of brass = $2.0 \times 10^{-5}\text{ K}^{-1}$, steel = $1.2 \times 10^{-5}\text{ K}^{-1}$).

- 11.11** The coefficient of volume expansion of glycerine is $49 \times 10^{-5} \text{ K}^{-1}$. What is the fractional change in its density for a 30°C rise in temperature?
- 11.12** A 10 kW drilling machine is used to drill a bore in a small aluminium block of mass 8.0 kg. How much is the rise in temperature of the block in 2.5 minutes, assuming 50% of power is used up in heating the machine itself or lost to the surroundings. Specific heat of aluminium = $0.91 \text{ J g}^{-1} \text{ K}^{-1}$.
- 11.13** A copper block of mass 2.5 kg is heated in a furnace to a temperature of 500°C and then placed on a large ice block. What is the maximum amount of ice that can melt? (Specific heat of copper = $0.39 \text{ J g}^{-1} \text{ K}^{-1}$; heat of fusion of water = 335 J g^{-1}).
- 11.14** In an experiment on the specific heat of a metal, a 0.20 kg block of the metal at 150°C is dropped in a copper calorimeter (of water equivalent 0.025 kg) containing 150 cm^3 of water at 27°C . The final temperature is 40°C . Compute the specific heat of the metal. If heat losses to the surroundings are not negligible, is your answer greater or smaller than the actual value for specific heat of the metal?
- 11.15** Given below are observations on molar specific heats at room temperature of some common gases.

Gas	Molar specific heat (C_v) ($\text{cal mol}^{-1} \text{ K}^{-1}$)
Hydrogen	4.87
Nitrogen	4.97
Oxygen	5.02
Nitric oxide	4.99
Carbon monoxide	5.01
Chlorine	6.17

The measured molar specific heats of these gases are markedly different from those for monatomic gases. Typically, molar specific heat of a monatomic gas is 2.92 cal/mol K . Explain this difference. What can you infer from the somewhat larger (than the rest) value for chlorine?

- 11.16** A child running a temperature of 101°F is given an antipyryn (i.e. a medicine that lowers fever) which causes an increase in the rate of evaporation of sweat from his body. If the fever is brought down to 98°F in 20 minutes, what is the average rate of extra evaporation caused, by the drug. Assume the evaporation mechanism to be the only way by which heat is lost. The mass of the child is 30 kg. The specific heat of human body is approximately the same as that of water, and latent heat of evaporation of water at that temperature is about 580 cal g^{-1} .
- 11.17** A 'thermacole' icebox is a cheap and an efficient method for storing small quantities of cooked food in summer in particular. A cubical icebox of side 30 cm has a thickness of 5.0 cm. If 4.0 kg of ice is put in the box, estimate the amount of ice remaining after 6 h. The outside temperature is 45°C , and co-efficient of thermal conductivity of thermacole is $0.01 \text{ J s}^{-1} \text{ m}^{-1} \text{ K}^{-1}$. [Heat of fusion of water = $335 \times 10^3 \text{ J kg}^{-1}$]
- 11.18** A brass boiler has a base area of 0.15 m^2 and thickness 1.0 cm. It boils water at the rate of 6.0 kg/min when placed on a gas stove. Estimate the temperature of the part of the flame in contact with the boiler. Thermal conductivity of brass = $109 \text{ J s}^{-1} \text{ m}^{-1} \text{ K}^{-1}$; Heat of vaporisation of water = $2256 \times 10^3 \text{ J kg}^{-1}$.
- 11.19** Explain why :
- a body with large reflectivity is a poor emitter
 - a brass tumbler feels much colder than a wooden tray on a chilly day
 - an optical pyrometer (for measuring high temperatures) calibrated for an ideal black body radiation gives too low a value for the temperature of a red hot iron piece in the open, but gives a correct value for the temperature when the same piece is in the furnace

- (d) the earth without its atmosphere would be inhospitably cold
- (e) heating systems based on circulation of steam are more efficient in warming a building than those based on circulation of hot water

11.20 A body cools from $80\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$ in 5 minutes. Calculate the time it takes to cool from $60\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$. The temperature of the surroundings is $20\text{ }^{\circ}\text{C}$.

ADDITIONAL EXERCISES

- 11.21** Answer the following questions based on the P - T phase diagram of carbon dioxide:
- (a) At what temperature and pressure can the solid, liquid and vapour phases of CO_2 co-exist in equilibrium ?
 - (b) What is the effect of decrease of pressure on the fusion and boiling point of CO_2 ?
 - (c) What are the critical temperature and pressure for CO_2 ? What is their significance ?
 - (d) Is CO_2 solid, liquid or gas at (a) $-70\text{ }^{\circ}\text{C}$ under 1 atm, (b) $-60\text{ }^{\circ}\text{C}$ under 10 atm, (c) $15\text{ }^{\circ}\text{C}$ under 56 atm ?
- 11.22** Answer the following questions based on the P - T phase diagram of CO_2 :
- (a) CO_2 at 1 atm pressure and temperature $-60\text{ }^{\circ}\text{C}$ is compressed isothermally. Does it go through a liquid phase ?
 - (b) What happens when CO_2 at 4 atm pressure is cooled from room temperature at constant pressure ?
 - (c) Describe qualitatively the changes in a given mass of solid CO_2 at 10 atm pressure and temperature $-65\text{ }^{\circ}\text{C}$ as it is heated up to room temperature at constant pressure.
 - (d) CO_2 is heated to a temperature $70\text{ }^{\circ}\text{C}$ and compressed isothermally. What changes in its properties do you expect to observe ?