Chapter 9

1

Thermal Properties

1

Thermal Expansion

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- When a substance is heated, its volume usually increases, and each dimension increases correspondingly.
- This increase in size can be understood in terms of the increased kinetic energy of the atoms or molecules.
- The additional kinetic energy results in each molecule colliding more forcefully with its neighbours.
- The molecules effectively push each other farther apart, and the material expands.
- This phenomenon plays an important role in many engineering applications, such as the joints in buildings, highways, railroad tracks, bridges . . . etc.
- If the thermal expansion of an object is sufficiently small compared to its initial dimensions, then the change in any dimension (length, width, or thickness) is a linear function of the temperature.

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Thermal Expansion: Linear Expansion

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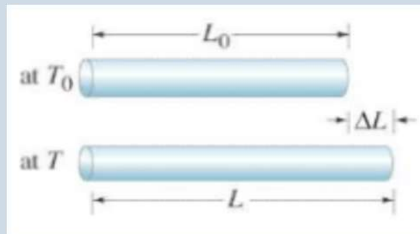
The change in length:

$$\Delta L = \alpha L_{\circ} \Delta T$$

The new length:

$$L = L_{\circ}(1 + \alpha \Delta T\ )$$



3

Thermal Expansion: Linear Expansion

4

- Where:

$$\Delta L = L - L_{\circ}$$
$$\Delta T = T - T_{\circ}$$

  - $L_{\circ}$: the original length (m)
  - L: the new length (m)
  - ΔL: the change in length (m)
  - $T_{\circ}$: the initial temperature (℃) or (K)
  - T: the final temperature (℃) or (K)
  - ΔT: the change in temperature (℃) or (K)
  - α: the **coefficient of linear expansion.**
    - **represents the fractional change in length** $(\Delta L/L_{\circ})$ **per one degree** change in temperature.
    - it has units of $(℃^{-1})$ or (K^{-1}).

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Thermal Expansion: Area Expansion

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The change in area:

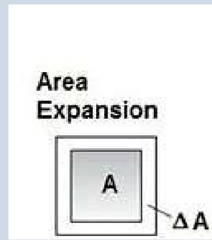
$$\Delta A = \gamma A_\circ \Delta T$$

The new area:

$$A = A_\circ (1 + \gamma \Delta T)$$

For solids:

$$\gamma = 2\alpha$$



Thermal Expansion: Area Expansion

6

- Where:

$$\Delta A = A - A_\circ$$
$$\Delta T = T - T_\circ$$

  - $A_\circ$: the original area (m^2)
  - A: the new area (m^2)
  - ΔA: the change in area (m^2)
  - $T_\circ$: the initial temperature (℃) or (K)
  - T: the final temperature (℃) or (K)
  - ΔT: the change in temperature (℃) or (K)
  - γ: the **coefficient of area expansion.**
    - **represents the fractional change in area** $(\Delta A/A_\circ)$ **per one degree** change in temperature.
    - it has units of $(℃^{-1})$ or (K^{-1}).

Thermal Expansion: Volume Expansion

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The change in volume:

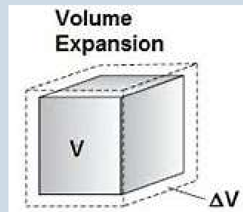
$$\Delta V = \beta V_{\circ} \Delta T$$

The new volume:

$$V = V_{\circ}(1 + \beta \Delta T)$$

For solids:

$$\beta = 3\alpha$$



7

Thermal Expansion: Volume Expansion

8

- Where:

$$\Delta V = V - V_{\circ}$$
$$\Delta T = T - T_{\circ}$$

  - $V_{\circ}$: the original volume (m^3)
  - V: the new volume (m^3)
  - ΔV: the change in volume (m^3)
  - $T_{\circ}$: the initial temperature (°C) or (K)
  - T: the final temperature (°C) or (K)
  - ΔT: the change in temperature (°C) or (K)
  - β: the **coefficient of volume expansion.**
    - **represents the fractional change in volume ($\Delta V / V_{\circ}$) per one degree** change in temperature.
    - it has units of ($°C^{-1}$) or (K^{-1}).

8

Heat Capacity and Specific Heat

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When an object at one temperature is placed near or in contact with another object at a higher temperature, energy is transferred to the cooler object, and its temperature rises.

The ratio of the amount of energy, (ΔQ), transferred to the temperature change, (ΔT), is called the heat capacity.

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

Substances which have a high molar heat capacity, experience relatively small temperature changes when a given amount of heat is transferred.

SI units: J/K

Heat Capacity and Specific Heat

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The **specific heat capacity** (c): is the heat required for a unit temperature change in a unit mass of a substance.

$$c = \frac{C}{M}$$

- (M) is the molar mass.

In terms of c, the heat required for a temperature change (ΔT) in a mass (m) is:

$$\Delta Q = mc\Delta T$$

- When heat energy is added to objects, Q and ΔT are both positive.
- When heat energy is removed from objects, Q and ΔT are both negative.
- SI units: $J/kg.K$

Latent Heat and Phase Changes

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When heat energy is transferred from one substance to another, the temperature of the substance often changes.

However, there are situations in which the transfer of energy does not change the temperature.

Instead, the substance may change from one form to another. Such a change is commonly referred to a phase change.

Latent Heat and Phase Changes

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We consider the following two main common phase changes:

- A phase change from solid to liquid (as ice melting) and from liquid to gas (as water boiling), where heat energy is absorbed while the temperature remains constant.
- A phase change from gas to liquid (as steam condensing) and from liquid to solid (as water freezing), where heat energy is released while the temperature remains constant.

The amount of heat energy per unit mass, L, that must be transferred when a substance completely undergoes a phase change *without changing temperature* is called the **latent heat.**

Latent Heat and Phase Changes

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If a quantity Q of heat energy transfer is required to change the phase of a pure substance of a mass m, then $L = Q/m$ characterizes an important thermal property of that substance. That is:

$$Q = \mp mL$$

- A positive sign is used in this equation when energy enters the system, causing melting or vaporization of the substance,
- while a negative sign corresponds to energy leaving the system such that the substance condenses or solidifies.
- SI units: J/kg

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Latent Heat and Phase Changes

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When a substance experiences a phase change from solid to liquid by absorbing heat, the heat of transformation is called the **latent heat of fusion** L_f.

When the substance releases heat and experiences a phase change from liquid back to solid, the heat of transformation is called the **latent heat of solidification** and is numerically equal to the latent heat of fusion.

In the case of water at its normal melting or freezing temperature, we have:

$$L_f = 3.33 \times 10^5 \ J/kg$$

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Latent Heat and Phase Changes

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When a substance experiences a phase change from liquid to gas by absorbing heat, the heat of transformation is called the **latent heat of vaporization** L_v.

When the gas releases heat and experiences a phase change from gas back to liquid, the heat of transformation is called the **latent heat of condensation** and is numerically equal to the latent heat of vaporization.

For water at its normal boiling and condensation temperatures, we have:

$$L_v = 2.256 \times 10^6 \ J/kg$$

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Mechanisms of Energy Transfer In Thermal Processes

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- We want to know the rate at which energy is transferred.
- There are various mechanisms responsible for the transfer:
  - Conduction
  - Convection
  - Radiation

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Conduction

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- The transfer can be viewed on an atomic scale.
  - It is an exchange of kinetic energy between microscopic particles by collisions.
    - The microscopic particles can be atoms, molecules or free electrons.
  - Less energetic particles gain energy during collisions with more energetic particles.
- Rate of conduction depends upon the characteristics of the substance.

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Conduction, cont.

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- In general, metals are good thermal conductors.
  - They contain large numbers of electrons that are relatively free to move through the metal.
  - They can transport energy from one region to another.
- Poor conductors include paper and gases.
- Conduction can occur only if there is a difference in temperature between two parts of the conducting medium.

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Conduction, equation

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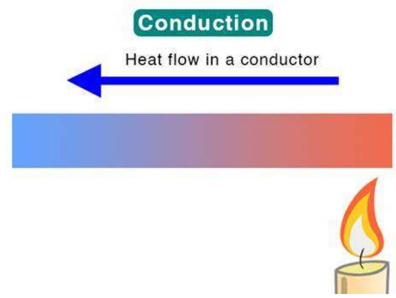
- Heat flows from the region of higher temperature to the region of lower temperature.
- The rate of transfer of energy (The heat flow) is given by:

$$H = \frac{\Delta Q}{\Delta t} = \kappa A \frac{\Delta T}{L}$$



Conduction, equation explanation

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- A is the cross-sectional area. (m^2)
- ΔT is the temperature difference. (K)
- L is the thickness of the slab. (m)
  - Or the length of a rod
- H is the heat flow. (in Watts when Q is in Joules and t is in seconds.)
- $\frac{\Delta T}{L}$ is called the temperature gradient. (K/m)
- κ is the thermal conductivity of the material. $(W/m.K)$
  - Good conductors have high κ values and good insulators have low κ values.

Conduction

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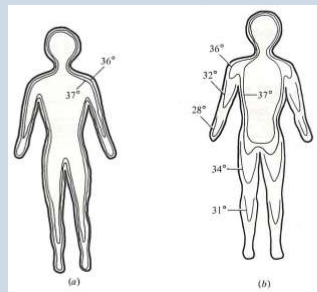
- Body tissue is also a good insulator. When the environment is warm, the interior body temperature is quite uniform. Because body tissues are poor conductors, the inner core of the body can be kept warm in a cold environment.



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Convection

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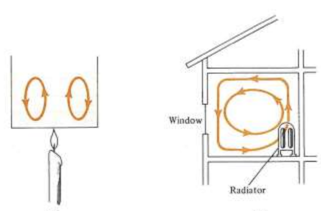
- Some heat is transported by conduction in liquids and gases.
- much larger quantity may be carried by the motion of the fluid itself.
- This is called **convection**.
- the liquid near the heat source is heated and expands slightly, becoming lighter than the overlying cooler fluid.



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Convection

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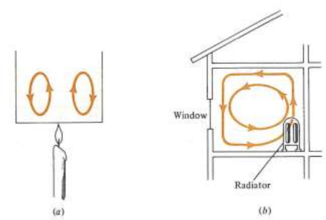
- It then rises and is replaced by cooler, heavier fluid.
- When the warmer fluid arrives at the cooler region of the container, it cools, contracts, and begins to sink again.
- Had the container been heated from the top, convection would not have occurred, and the bulk of the fluid would have been heated by the much slower conduction process.



Convection

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- A hot-water or steam radiator provides another illustration of convection.
- Air near the radiator is heated and rises, while air near the outside walls and the windows is cooled and sinks.
- This establishes the flow pattern shown.
- In still air the rate of convective heat transfer for a surface area A is given approximately by:

$$H = qA\,\Delta T$$

- ΔT is the temperature difference.
- q is the convective heat transfer constant.
- For a human, we use the average value $q = 7.1\ W/m^2.K$.

Radiation

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- Conduction and convection require the presence of some material, be it solid, liquid, or gas.
- We know that heat can also be transmitted through a vacuum, since the sun's energy traverses millions of kilometres of space before reaching the earth.
- The process by which this occurs is called **radiation.**
- Radiant heat transfer also occurs in transparent media.

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Linear Expansion-1

Sunday, 17 October, 2021 21:10

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- [ ] R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- [ ] J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- [ ] H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- [ ] H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.
- [x] Kane

The roadbed of the Golden gate bridge is $1280m$ long. During a certain year the temperature varies from $-12\ ℃$ to $38\ ℃$. What is the difference In the lengths at girders? $(\alpha_{steel} = 1.27 \times 10^{-5}\ \mathrm{K}^{-1})$

Solution

With $\Delta T = 3838°C - (-12°C) = 50°C = 50K$

$$\Delta L = \alpha L \Delta T = (1.27 \times 10^{-5} K^{-1})(1280m)(50K) = 0.81m$$

This substantial change in length must be allowed for in the design of the bridge. If the structure could not alter its length with changes in temperature, huge forces would be developed and sever damage would result.

Volume Expansion-1

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Kane

On a hot day, an oil trucker loaded $37000\ L$ of diesel fuel from an oil station. He encountered cold weather on the way to delivery city, where the temperature was $23\ \mathrm{K}$ lower than in the station. How many liters did he deliver? The coefficient of volume expansion for diesel fuel is $(9.5 \times 10^{-4}\ \mathrm{K}^{-1})$ and the coefficient of linear expansion for his steel truck tank is $(11 \times 10^{-6}\ \mathrm{K}^{-1})$

Solution

The volume of the diesel fuel depends directly on the temperature. Thus, because the temperature decreased, the volume of the fuel did also, We find ΔV:

$$\Delta V = \beta V \Delta T = \left(9.50 \times \frac{10^{-4}}{C}{}^{\circ}\right)(37000L)(-23.0K) = -808L$$

Thus, the amount delivered was

$$V_{del} = V + \Delta V = 37000L - 808L = 36190L$$

Note that the thermal expansion of the steel tank has nothing to do with the problem.

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Kane

How much energy is required to convert a $1.0\ g$ cube of ice at $-30\ ℃$ to steam at $120\ ℃$.

Solution

Part A: on this portion of the curve, the temperature of the ice changes from $-30.0°C$ to $0.0°C$. The temperature varies linearly with the energy added, so the experimental result is a straight line on the graph. Because the specific heat of ice is $2090 J/kg \cdot °C$, we can calculate the amount of energy added by using:

$$Q = m_i c_i \Delta T = (1.00 \times 10^{-3} kg)(2090 J/kg \cdot °C)(30.0°C) = 62.7J$$

Part B: When the temperature of the ice reaches $0.0°C$, the ice–water mixture remains at this temperature, even though energy is being added, until all the ice melts. The energy required to melt 1.00 g of ice at $0.0°C$ is:

$$Q = L_f \Delta m_w = L_f m_i = \left(3.33 \times \frac{10^5 J}{kg}\right)(1.00 \times 10^{-3} kg) = 333J$$

At this point, we have moved to the $396J (= 62.7J + 333J)$ mark on the energy axis in the figure.

Part C: between $0.0°C$ and $100.0°C$, nothing surprising happens. No phase change occurs, and so all energy added to the water is used to increase its temperature. The amount of energy necessary to increase the temperature from $0.0°C$ to $100.0°C$ is

$$Q = m_w c_w \Delta T = (1.00 \times 10^{-3} kg)\left(4.19 \times \frac{10^3 J}{kg} \cdot °C\right)(100.0°C) = 419J$$

Part D: at $100.0°C$, another phase change occurs as the water changes from water at $100.0°C$ to steam at $100.0°C$. Similar to the ice–water mixture in part B, the water– steam mixture remains at $100.0°C$, even though energy is being added, until all the liquid has been converted to steam. The energy required to convert 1.00 g of water to steam at $100.0°C$ is:

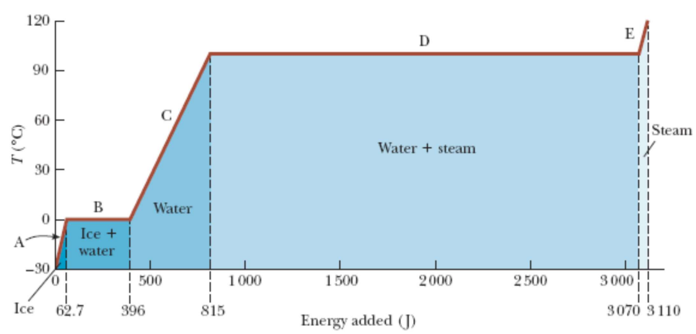
$$Q = L_v \Delta m_s = L_v m_w = (2.26 \times 10^6 J/kg)(1.00 \times 10^{-3} kg) = 2.26 \times 10^3 J$$

Part E: on this portion of the curve, as in parts A and C, no phase change occurs; therefore, all energy added is used to increase the temperature of the steam. The energy that must be added to raise the temperature of the steam from $100.0°C$ to $120.0°C$ is:

$$Q = m_s c_s \Delta T = (1.00 \times 10^{-3} kg)\left(2.01 \times \frac{10^3 J}{kg} \cdot °C\right)(20.0°C) = 40.2J$$

The total amount of energy that must be added to change 1 g of ice at $-30.0°C$ to steam at $120.0°C$ is the sum of the results from all five parts of the curve, which is $3.11 \times 10^3 J$. Conversely, to cool 1 g of steam at

$120.0°C$ to ice at $-30.0°C$, we must remove $3.11 \times 10^3 J$ of energy.



Heat transfer by conduction

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- ☑ Kane

A person walking at a modest speed generates heat at a rate of $280\,W$. If the surface area of the body is $1.5\,m^2$ and if the heat is assumed to be generated $0.03\,m$ below the skin, what temperature difference between the skin and interior of the body would exist if the heat were conducted to the surface? Assume $\kappa = 0.2\,W/m.K$.

Solution

$$H = \kappa A \frac{\Delta T}{\mathrm{L}}$$

$$\Delta T = \frac{\mathrm{L}H}{\kappa A} = \frac{0.03 \times 280}{0.2 \times 1.5} = 28\,K$$

Since the actual temperature difference is only a few degrees, we can conclude that heat is not removed from the body by conduction through tissue from the interior to the exterior of the body. In fact, the flow of warm blood from the interior of the body to the cooler exterior is the major factor in body heat transport.

Heat transfer by convection

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- [x] Kane

In a warm room, a resting person has a skin temperature of $33\ ^\circ\mathrm{C}$. If the room temperature is $29\ ^\circ\mathrm{C}$ and the body surface area is $1.5\ m^2$, what is the rate of heat loss due to convection?

Solution

Using $q = 7.1\ W/\ m^2\ K$, we have:

$$H = qA\ \Delta T$$

$$H = 7.1 \times 1.5 \times 4 = 43\ W$$