Thermodynamics

- **Thermodynamics** deals with the conversion of energy from one form to another and the availability of energy for doing work

- **Internal energy** – the total kinetic energy and potential energy of atoms and molecules of the system

- **Temperature** – a measure of the hotness or coldness of an object

- **Heat** – the process of energy transfer from one body or system to another as a result of a difference in temperature

Thermodynamics

- Three methods of heat transfer:

- Convection – involves the bulk motion of a fluid and is usually caused by a hot fluid (with less dense) rising and displacing colder fluid

- Conduction – the transfer of heat in solids and liquids from a region of higher temperature to a region of lower temperature, primarily by collisions and vibrations between particles

- Radiation – includes the emission and absorption of electromagnetic radiation

Thermodynamics

- <u>Temperature</u> – the important thermodynamic property

Two objects in thermal contact will be at the same temperature, if there is no flow of heat between these two objects (*thermodynamics equilibrium*)

- **If there is a flow of heat energy from one object to the second one, then the object that is the source of heat, must be at a higher temperature than the object that accepts the heat energy**

- **The Celsius temperature scale uses the freezing point of distilled water (defined as 0° C) and its boiling point (100° C) as the two fixed points and divides the scale between them into 100 degrees (at standard atmospheric pressure)**

Thermodynamics

- **The thermodynamic temperature scale (Kelvin scale) is based on the measurement of the amount of heat flowing between bodies at different temperatures**
- **This scale is based on the temperature at which no body can give off heat (absolute zero 0)**
- **Relation between these two scales: $T = 273.15 + t$,**
- **T – temperature in kelvins (K), t – temperature in Celsius degrees (°C)**
- **The value 273.15 – the temperature of the melting point of ice in kelvins**

- **the temperature difference $\Delta T = T_2 - T_1$ in kelvins is exactly equal to the temperature difference $\Delta t = t_2 - t_1$ in Celsius degrees:**
- **$\Delta T = \Delta t$**

Thermodynamics

- **<u>Thermal expansion of solids and liquids (expansivity)</u>**
- ***Linear expansion***
- **If the temperature of a metal rod of length l_1 is increasing from t_2 to t_1 ($\Delta t = t_2 - t_1$) its length expands by an amount $\Delta l = l_1 \alpha \Delta t$**

- **Constant α – the coefficient of linear expansion of the material**
- **The value of α depends on the material - unit $[\alpha] = K^{-1}$**
- **Different materials expand at different rates when heated**

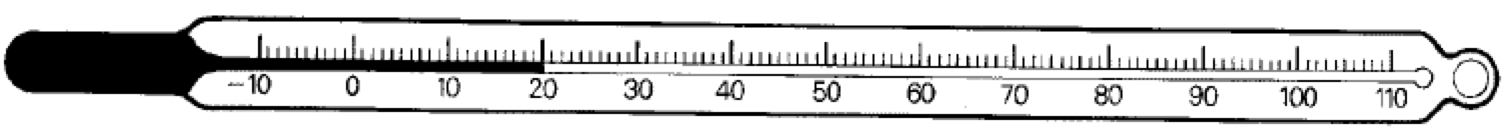
- **The total length of rod l_2 after increasing temperature:**
- $l_2 = l_1 + \Delta l = l_1 (1 + \alpha \Delta t)$

Thermodynamics

- **<u>Thermal expansion of solids and liquids (expansivity)</u>**
- ***Volume expansion***
- **Analogically to the previous one dimensional case, the volume expansion concerns all three dimensions of solids or liquids**
- **the volume expands with increasing temperature:** $\Delta V = V_1\, \beta\, \Delta t$
- ΔV **– increase in volume**
- V_1 **– initial volume (for temperature** t_1**)**
- $\Delta t = t_2 - t_1$ **– change of temperature**
- $\beta = 3\alpha$ **– coefficient of volume expansion**
- **The volume of body after change in temperature**
- $V_2 = V_1 + \Delta V = V_1\,(1 + \beta\, \Delta t)$

Thermodynamics

- *Application*
- <u>Temperature measurement</u>
- The basis of a thermometer can be any property that changes with temperature
- A liquid thermometer takes advantage of the fact that the liquid expands as the temperature rises, usually using mercury or alcohol
- These thermometers consist of a glass bulb filled with liquid that is connected to a partially filled capillary tube. As the liquid heats up, it expands and a column of liquid rises up the capillary tube – see Fig.



Mercury thermometer

Thermodynamics

Example 7.1:

Calculate at what change in temperature Δt the steel strip l_1 = 50 m long will extend by a length Δl = 1 mm. The coefficient of linear expansion of the steel is $\alpha = 1.2 \cdot 10^{-5}\ K^{-1}$.

[Δt = 1.7 °C]

Thermodynamics

Heat

- Heat – internal energy that can be transferred from one body to another if one body has a higher temperature than the other

- Heat *Q* – a form of energy $\Rightarrow$ it is measured in joules [*Q*] = J

If there is a flow of heat from one body to another, then the body that is the source of the heat, must have a higher temperature than the body that is receiving the heat energy

- The temperature of the heat source decreases and the temperature of the object receiving the heat energy increases, heat is transferred until the two temperatures are equal – *thermodynamic equilibrium*

- If an amount of heat *Q* is added to a body of mass *m*, the temperature rises by Δt

Thermodynamics

$C = \frac{Q}{\Delta t}$ **– the *heat capacity of body* – the heat required to produce a unit temperature rise**

- SI unit of heat capacity [*C*] = $J \cdot K^{-1}$

$c = \frac{Q}{m\,\Delta t}$ **– the *specific heat capacity* of a substance – the heat required to produce a unit temperature rise per unit mass of substance**

- SI unit of specific heat capacity [*c*] = $J \cdot kg^{-1} \cdot K^{-1}$

- If the temperature of a body of mass *m* and specific heat capacity *c* increases by the temperature difference Δt, a quantity of heat *Q* must be supplied: $Q = c\, m\, \Delta t$

Thermodynamics

Calorimetrical Equation

- If we combine the hot and cold substances (masses m_1, m_2 , specific heat capacities c_1, c_2 and temperatures $t_2 > t_1$), everything settles at the final temperature t ($t_2 > t > t_1$) – *thermodynamic equilibrium*

- Then, assuming that there is no conversion of heat to other forms of energy, and assuming that there is no heat loss to the surroundings (insulated system), the total energy is conserved - the *Principle of conservation of energy*

- The heat given off by the warmer substance Q_2 is equal to the heat received by the cooler substance Q_1:

$$Q_1 = Q_2 \Leftrightarrow m_1\, c_1\, (t - t_1) = m_2\, c_2\, (t_2 - t)$$

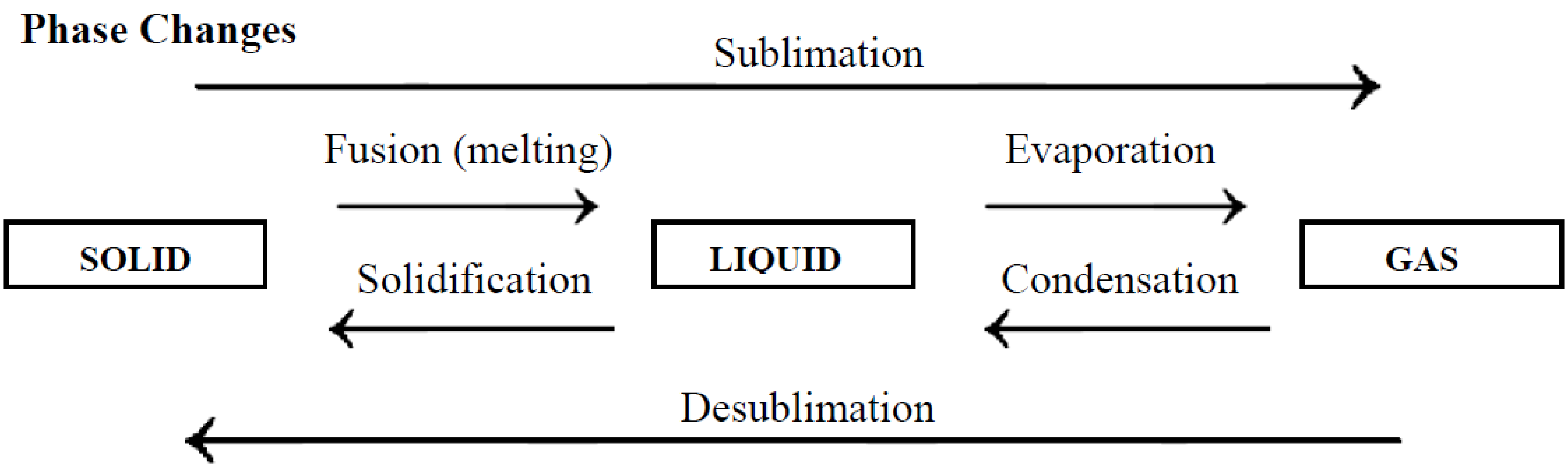
Thermodynamics

Example 7.6:

Water with mass m_1 = 500 g and temperature t_1 = 17 °C was in a calorimeter with heat capacity C = 25 J·K^{-1}. A metal sample of mass m_2 = 200 g heated to a temperature of t_2 = 100 °C was placed in the water in the calorimeter. The temperature of the water in the calorimeter was then stabilised at t = 20 °C. Determine the specific heat capacity of the metal c_2. The specific heat capacity of water is c_1 = 4200 J·kg^{-1}·K^{-1}.

[c_2 = 398 J·kg^{-1}·K^{-1}]

Thermodynamics



Thermodynamics

- When a solid is heated, its temperature rises to the temperature at which the solid begins to melt
- The supplied energy is used to change the solid into a liquid without changing the temperature
- Similarly - when a liquid is heated, its temperature rises until the liquid begins to boil – the change from liquid to gas takes place without a change in temperature
- Latent heat *Q*: the amount of heat absorbed by a substance during the change of phase
- $l = \frac{Q}{m}$ – specific latent heat: the heat per unit mass of a substance required (or released) to convert one phase (solid, liquid or gas) to another at a constant temperature
- SI unit of specific latent heat $[l]$ = $J \cdot kg^{-1}$

Thermodynamics

Example **- Phase changes – ice, water, steam:**

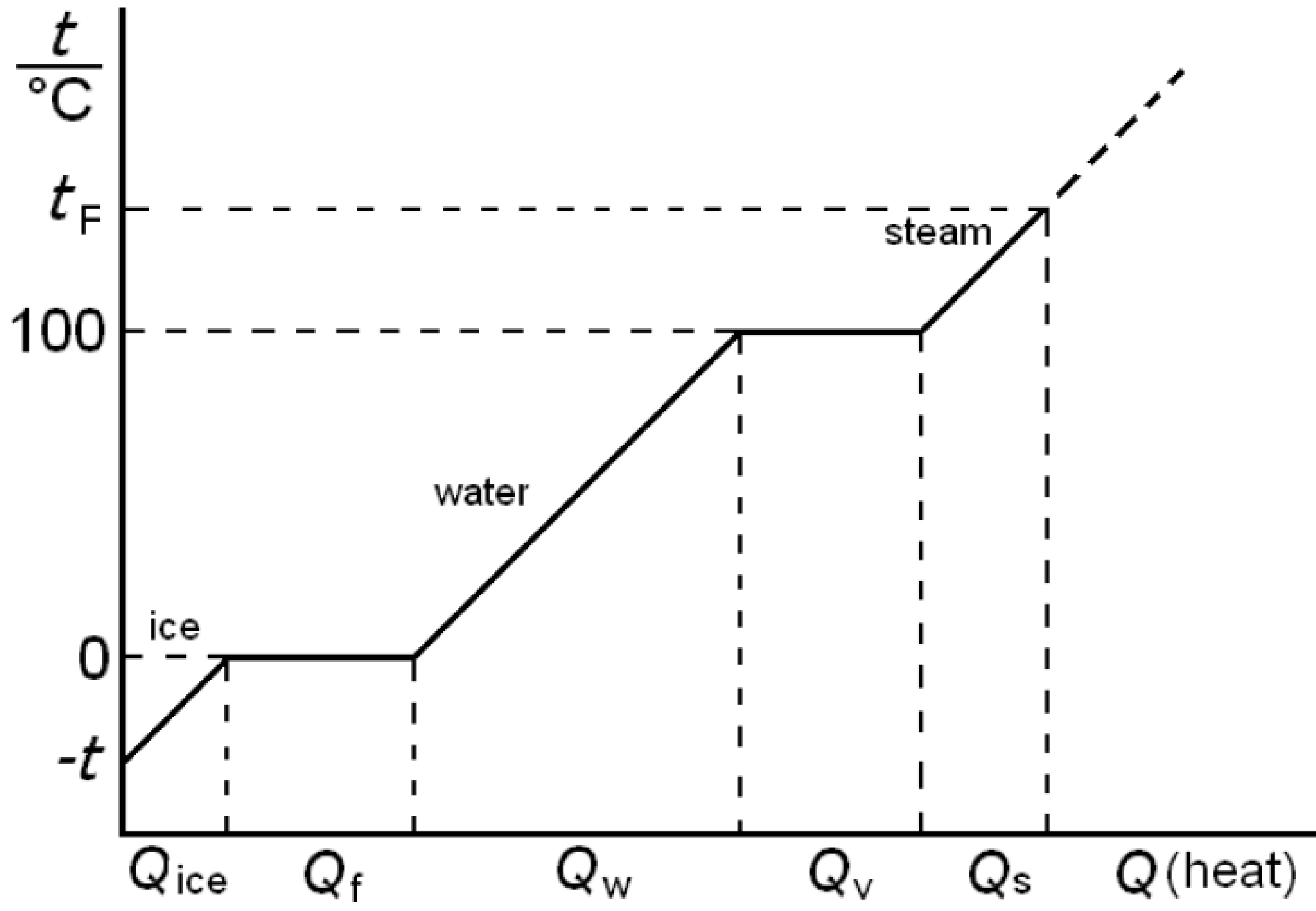


Diagram of phase changes

Thermodynamics

- When the ice is heated, its temperature rises until it starts to melt (fusion) Q_{ice} – the amount of heat required to change the temperature of ice from initial negative temperature t to 0 °C (melting point):

$Q_{\mathrm{ice}} = m_{\mathrm{ice}} \,.\, c_{\mathrm{ice}} \,.\, (0 - t)$

t – negative temperature of ice

m_{ice} – mass of ice

c_{ice} – specific heat capacity of ice ($c_{\mathrm{ice}} = 2100\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)

- Then the latent heat of fusion Q_{f} is required to change the ice at 0 °C to water at 0 °C: $Q_{\mathrm{f}} = m_{\mathrm{ice}} \,.\, l_f$

l_f – specific latent heat of fusion of ice ($l_f = 330\ \mathrm{kJ \cdot kg^{-1}}$)

Thermodynamics

- The heat Q_w is required to change the temperature of the water from 0 °C to 100 °C (bowling point): $Q_w = m_w \, . \, c_w \, . \, (100 - 0)$

m_w – mass of water ($m_w = m_{ice}$)

c_w – specific heat capacity of water (c_w = 4200 J·kg^{-1}·K^{-1})

- Then the latent heat of vaporization Q_v is required to change the water at 100 °C to steam at 100 °C: $Q_v = m_w \, l_w$

l_w – specific latent heat of vaporization of water (l_w = 2200 kJ·kg^{-1})

- The heat Q_s is required to change the temperature of the steam from 100 °C to final temperature t_F: $Q_s = m_s \, c_s \, (t_F - 100)$

m_s – mass of steam ($m_s = m_w$)

c_s – specific heat capacity of steam (c_s = 730 J·kg^{-1}·K^{-1})

Thermodynamics

Application

- The large specific heat capacity of water causes a temperate climate -

a slow and small change in water and air temperature near large bodies of water (sea)

- It is a difference from continental climate over dry areas

Thermodynamics

Gases

- The properties of gases from a macroscopic view are described by physical quantities: pressure *p* (Pa), volume *V* (m^3) and temperature *T* (K)

- The relation for an ideal gas – ideal gas equation:

$\frac{p\,V}{T} = const.$, **or for two states of gas:** $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$

- If one quantity is constant, then only two quantities of the same amount of gas can be changed:

1 – at constant temperature (*T* = const.), *isothermal process*: $p\,V = const.$

2 – at constant pressure (*p* = const.), *isobaric process*: $\frac{V}{T} = const.$

3 – at constant volume (*V* = const.), *isochoric process*: $\frac{p}{T} = const.$

Thermodynamics

- If the state of gas is under normal conditions,

pressure p_n = 101.325 · 10^3 Pa and temperature t_n = 0 °C ⇒ T_n = 273.15 K,

then one mole of any gas occupies volume V_{mn} = 22.414 · 10^{-3} m^3:

$\frac{p_n V_{mn}}{T_n} = R_m$ **= 8.314 J·mol^{-1}·K^{-1} , R_m – universal gas constant**

- The ideal gas equation can be written in the form:

$p V = n R_m T$ (n – number of moles)

- One mole is the number of atoms in 12 g of carbon $^{12}_{6}C$

- This number is called *Avogadro's number* N_A = 6.023.10^{23} mol^{-1}

- All gases contain the same number of molecules or atoms when they occupy the same volume at constant conditions (pressure and temperature)

Thermodynamics

Adiabatic process

If $\Delta Q = 0 \Rightarrow Q$ = const. $\Rightarrow$ system is isolated $\Rightarrow$ no changes of heat between the system and surroundings – *adiabatic process*:

$$p\,V^{\kappa} = const.$$

$\kappa = \frac{c_{mp}}{c_{mV}}$ – Poisson's constant of gas – rate of the molar heat capacities of a gas at constant pressure c_{mp} and at constant volume c_{mV}

Thermodynamics

Example 7.10:

The compressor compressed air of volume V_1 = 100 l, temperature t = 10 °C and pressure p_1 = 10^5 Pa to pressure p_2 = 5 · 10^5 Pa. The air was cooled so that its temperature did not change. What volume V_2 did the air occupy after compression?

[V_2 = 20 l]