Thermodynamics Lecture Series

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Gas Mixtures – Properties and Behaviour

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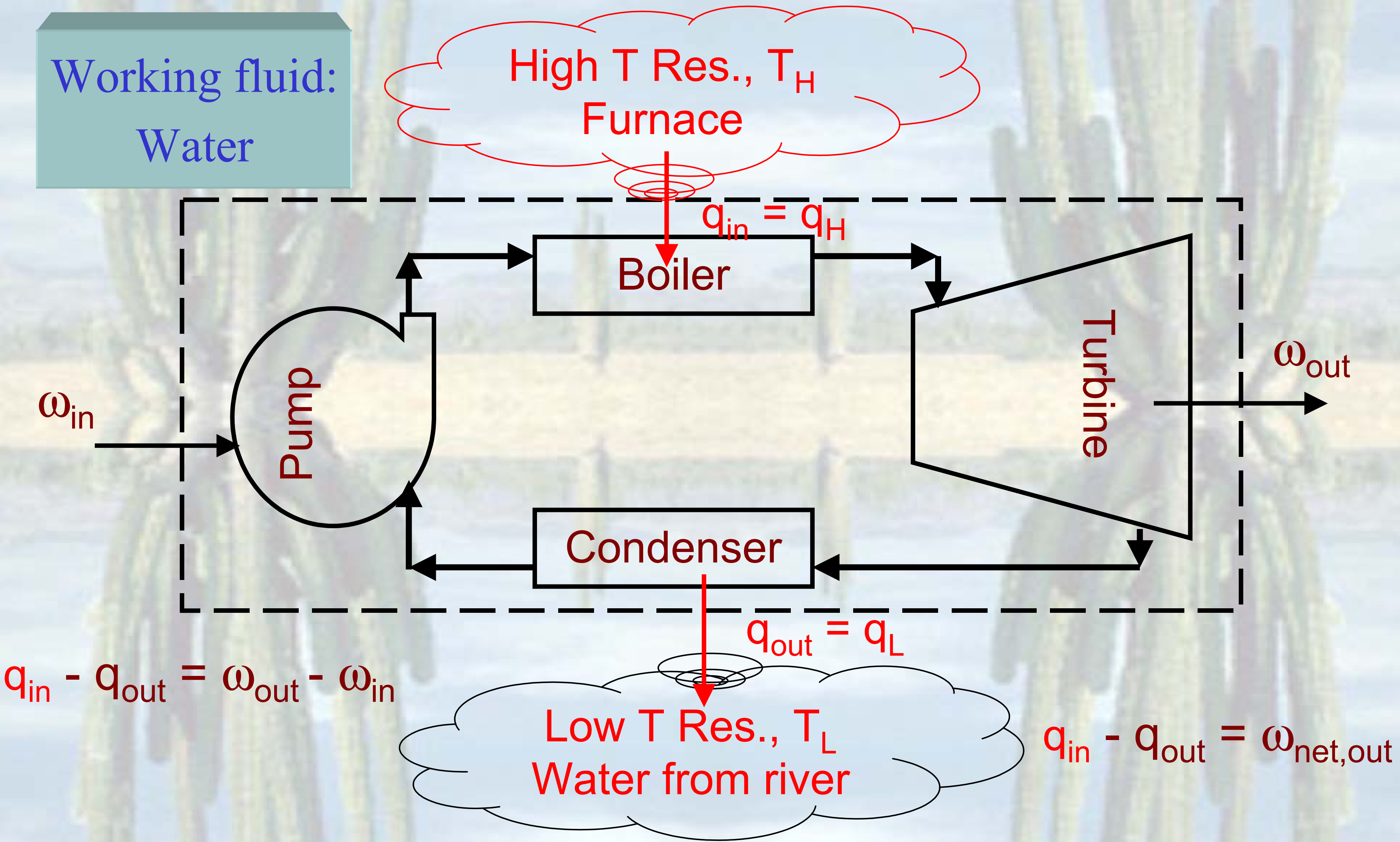
Review – Steam Power Plant

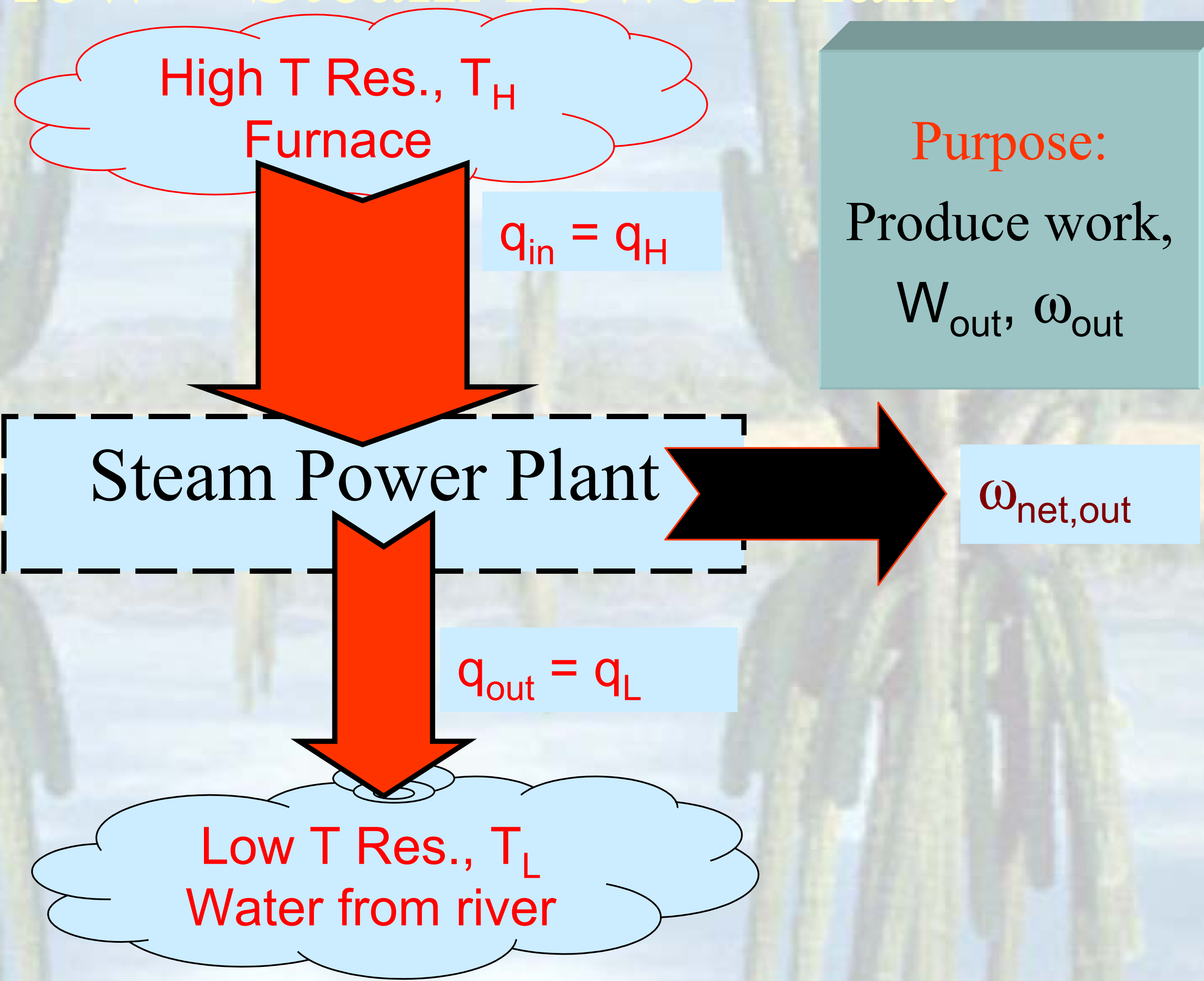


A Schematic diagram for a Steam Power Plant

Review - Steam Power Plant

Working fluid:
Water

Purpose:
Produce work, W_{out}, ω_{out}



An Energy-Flow diagram for a SPP

Review - Steam Power Plant

Thermal Efficiency for steam power plants

$$\eta = \frac{desired\ \ output}{required\ \ input} = \frac{\omega_{net,out}}{q_{in}}$$

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{q_L}{q_H}$$

$$\eta_{rev} = 1 - \frac{T_L}{T_H}$$

For real engines, need to find q_L and q_H.

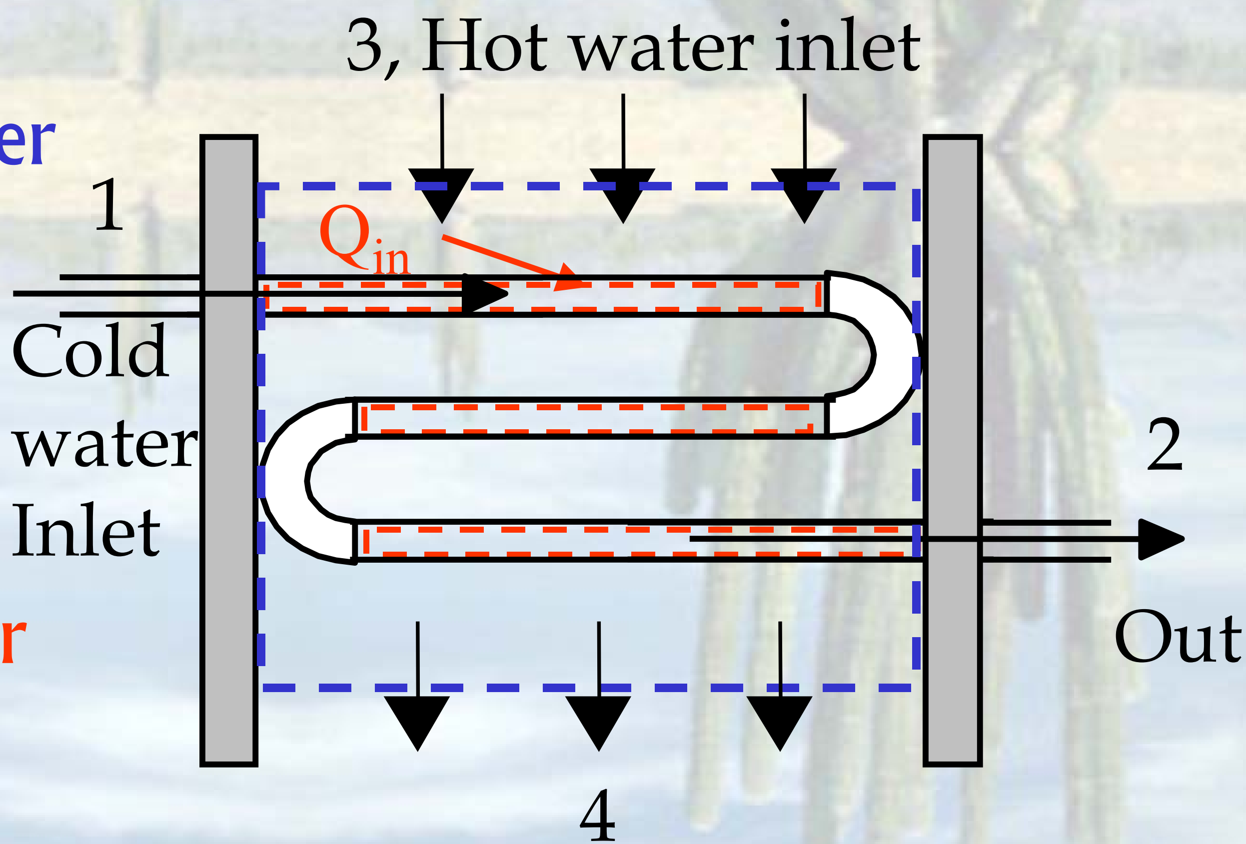
Review - Entropy Balance

Entropy Balance –Steady-flow device

Heat exchanger

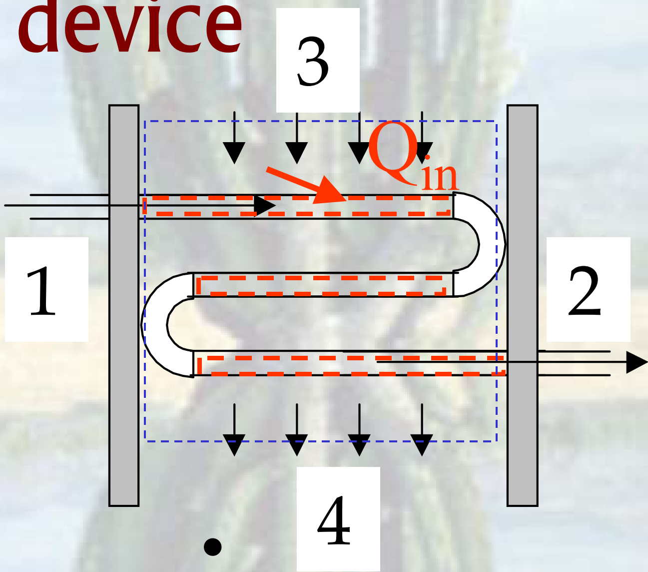
Case 1 – blue border

Case 2 – red border



Review - Entropy Balance

Entropy Balance –Steady-flow device



Heat exchanger: energy balance;

where $\dot{m}_4 = \dot{m}_3 \quad \dot{m}_2 = \dot{m}_1$

Assume $\Delta ke_{mass} = 0, \Delta pe_{mass} = 0$

Case 1 $\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = (\dot{m}\vartheta)_{exit} - (\dot{m}\vartheta)_{inlet}$, kW

$$0 = \dot{m}_4 h_4 - \dot{m}_3 h_3 + \dot{m}_2 h_2 - \dot{m}_1 h_1, kW$$

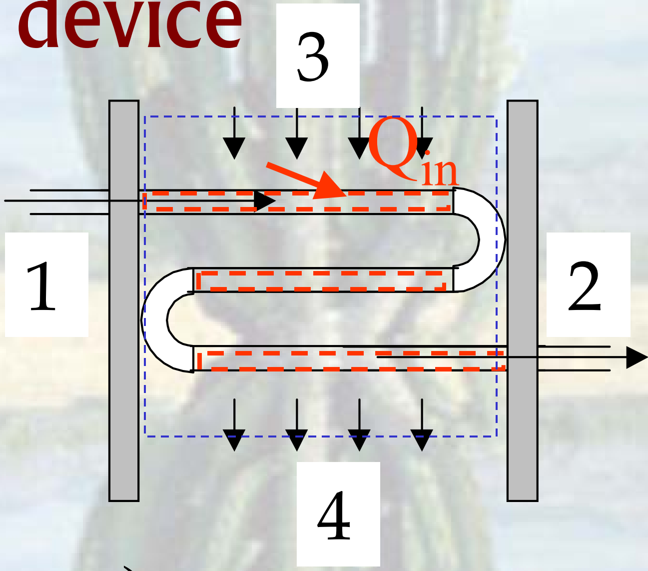
$$\dot{m}_4 (h_4 - h_3) = \dot{m}_2 (h_1 - h_2), kW$$

Review - Entropy Balance

Entropy Balance –Steady-flow device

Heat exchanger: energy balance;

where $\dot{m}_4 = \dot{m}_3 \quad \dot{m}_2 = \dot{m}_1$



Assume $\Delta ke_{mass} = 0, \Delta pe_{mass} = 0$

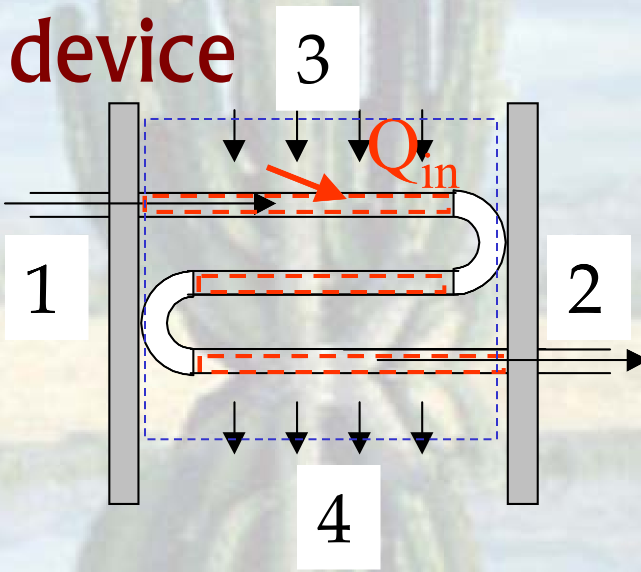
Case 1 $\quad \dot{m}_4 (h_4 - h_3) = \dot{m}_2 (h_1 - h_2), kW$

Case 2 $\quad \dot{Q}_{in} - \dot{Q}_{out} = \dot{m}_2 \theta_2 - \dot{m}_1 \theta_1, kW$

$$\dot{Q}_{in} - 0 = \dot{m}_2 (h_2 - h_1), kW$$

Review - Entropy Balance

Entropy Balance –Steady-flow device



Heat exchanger:

Entropy Balance

where $\dot{m}_4 = \dot{m}_3 \quad \dot{m}_2 = \dot{m}_1$

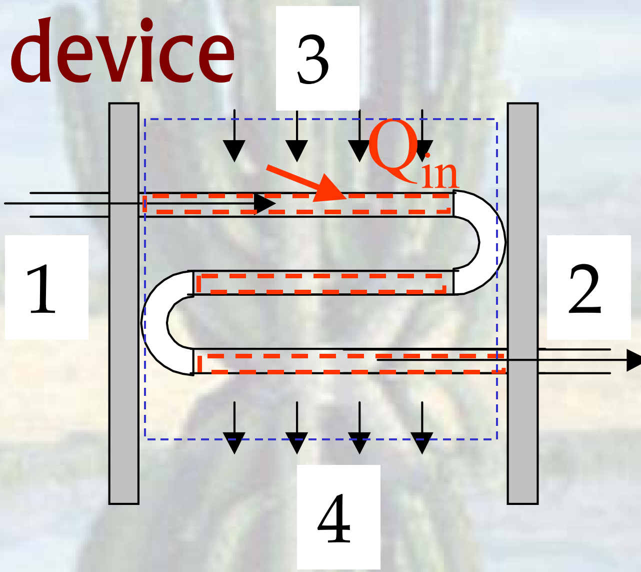
Case 1

$$\dot{S}_{gen} = 0 - 0 + \dot{m}_4 s_4 - \dot{m}_3 s_3 + \dot{m}_2 s_2 - \dot{m}_1 s_1, \ \frac{kW}{K}$$

$$\dot{S}_{gen} = \dot{m}_4 (s_4 - s_3) + \dot{m}_2 (s_2 - s_1), \ \frac{kW}{K}$$

Review - Entropy Balance

Entropy Balance –Steady-flow device



Heat exchanger:

Entropy Balance

where $\dot{m}_4 = \dot{m}_3 \quad \dot{m}_2 = \dot{m}_1$

Case 2

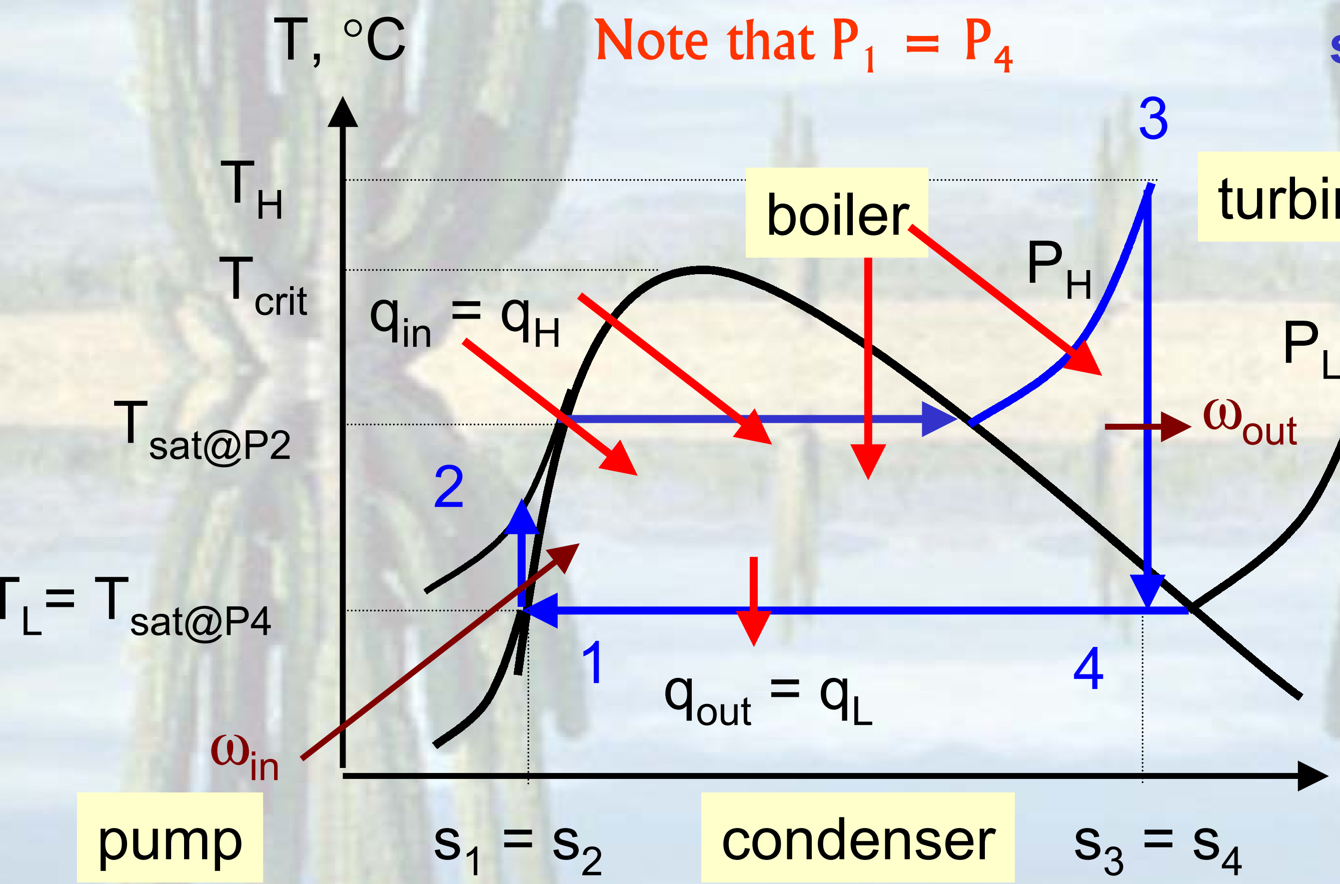
$$\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{out}} - \frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_2 s_2 - \dot{m}_1 s_1, \quad \frac{kW}{K}$$

$$\dot{S}_{gen} = 0 - \frac{\dot{Q}_{in}}{T_{in}} + \dot{m}_2 (s_2 - s_1), \quad \frac{kW}{K}$$

Vapor Cycle – Ideal Rankine Cycle

T- s diagram for an Ideal Rankine Cycle

Note that $P_1 = P_4$



$s_1 = s_{f@P1}$ $h_1 = h_{f@P1}$

$s_3 = s_{@P3,T3}$

$h_3 = h_{@P3,T3}$

$s_4 = [s_f + x s_{fg}]_{@P4} = s_3$

$$x = \frac{s_3 - s_{f@P4}}{s_{fg@P_4}}$$

$h_4 = [h_f + x h_{fg}]_{@P4}$

$h_2 = h_1 + \nu_2(P_2 - P_1)$; where $\nu_2 \cong \nu_1 = \nu_{f@P_1}$

Review – Ideal Rankine Cycle

Energy Analysis

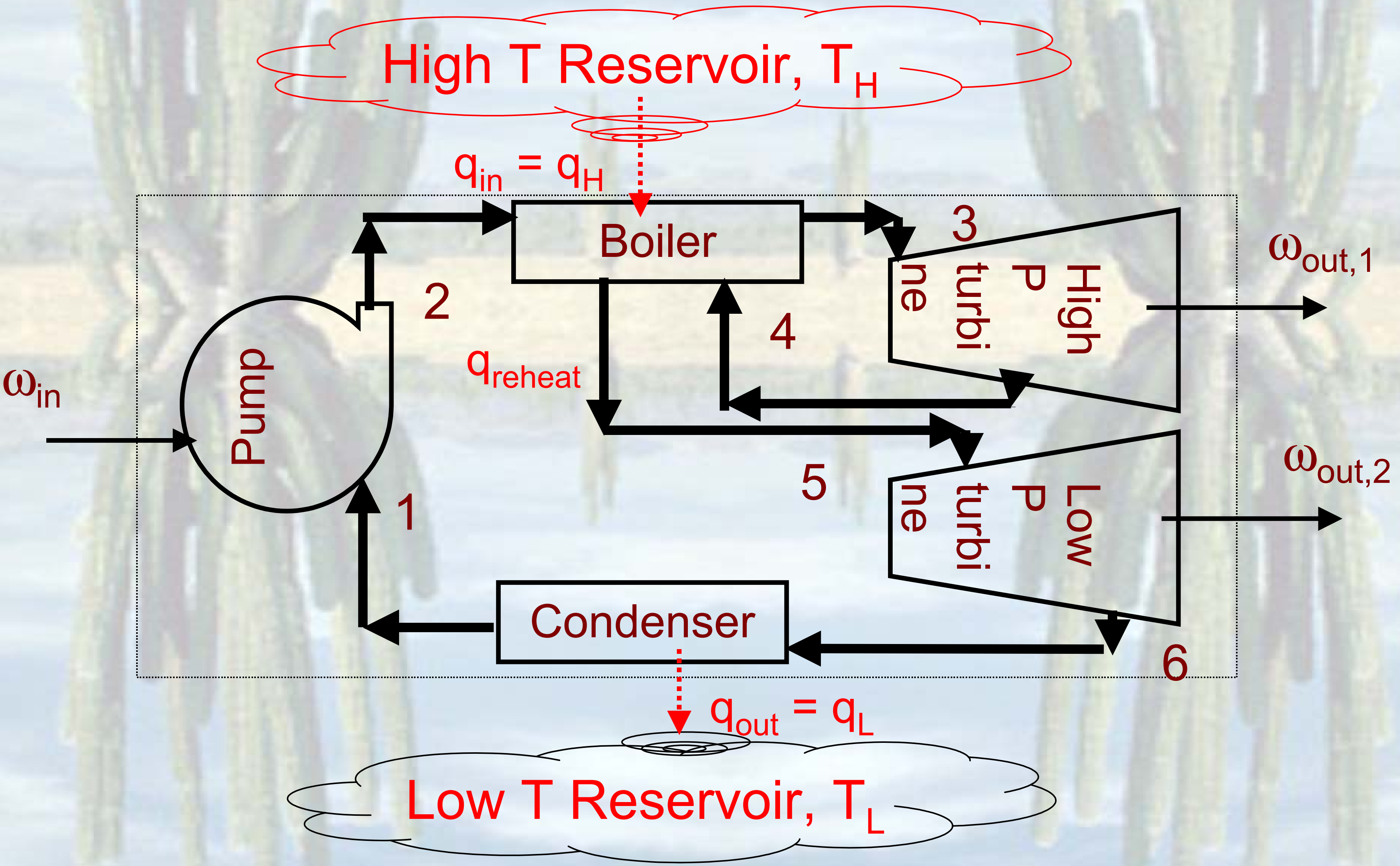
Efficiency

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{h_3 - h_2 - (h_4 - h_1)}{h_3 - h_2}$$

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{\omega_{out} - \omega_{in}}{q_{in}} = \frac{h_3 - h_4 - (h_2 - h_1)}{h_3 - h_2}$$

$$\eta == \frac{h_3 - h_4 - h_2 + h_1}{h_3 - h_2}$$

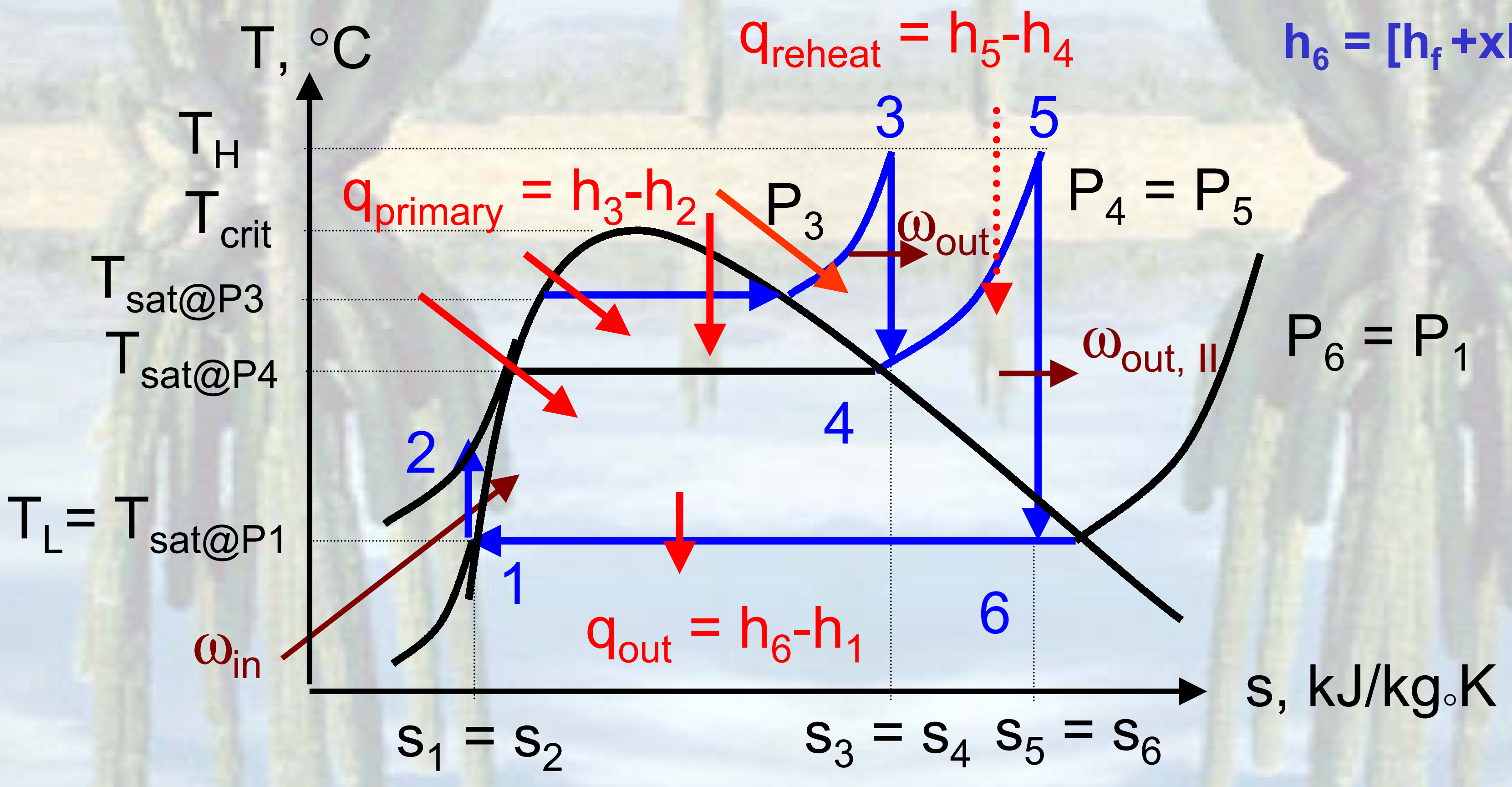
Review – Reheat Rankine Cycle



Review – Reheat Rankine Cycle

Reheating increases η and reduces moisture in turbine

$s_6 = [s_f + x s_{fg}]_{@P6}$. Use $x = 0.896$ and $s_5 = s_6$



Review – Reheat Rankine Cycle

Energy Analysis

$q_{in} = q_{primary} + q_{reheat} = h_3 - h_2 + h_5 - h_4$ $q_{out} = h_6 - h_1$

$\omega_{net,out} = \omega_{out,1} + \omega_{out,2} = h_3 - h_4 + h_5 - h_6$

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{h_3 - h_2 + h_5 - h_4 - (h_6 - h_1)}{h_3 - h_2 + h_5 - h_4}$$

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{\omega_{out1} + \omega_{out2}}{q_{in}} = \frac{h_3 - h_4 + h_5 - h_6}{h_3 - h_2 + h_5 - h_4}$$

Gas Mixtures – Ideal Gases

Vapor power cycles – Rankine cycle

- Water as working fluid
  - cheap
  - Easily available
  - High latent heat of vaporisation, h_{fg}.
- Use property table to determine properties

Gas Mixtures – Ideal Gases

Non-reacting gas mixtures as working fluid

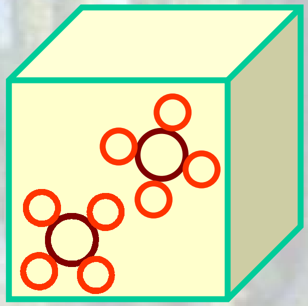
- Properties depends on
  - Components (constituents) of mixtures
  - Amount of each component
  - Volume of each component

  Pressure each component exerts on container walls
- Extended properties may not be tabulated
- Treat mixture as pure substances
- Examples: Air, CO_2, CH_4 (methane),
  C_3H_8 (Propane)

Gas Mixtures – Ideal Gases

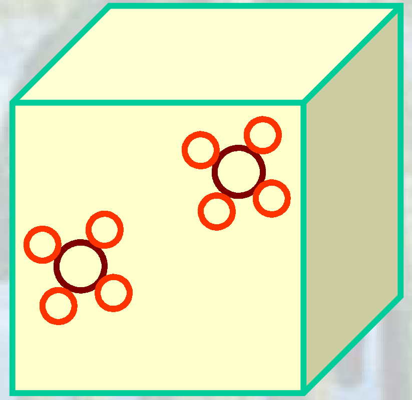
Ideal Gases

- Low density (mass in 1 m^3) gases
  Molecules are further apart



High density

- Real gases satisfying condition
  $P_{gas} << P_{crit}$; $T_{gas} >> T_{crit}$,
  have low density and can be treated as ideal gases



Low density

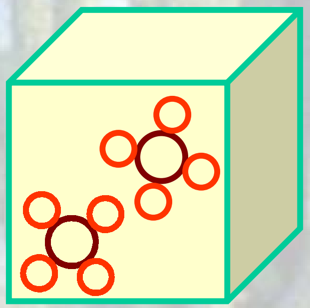
Molecules far apart

Gas Mixtures – Ideal Gases

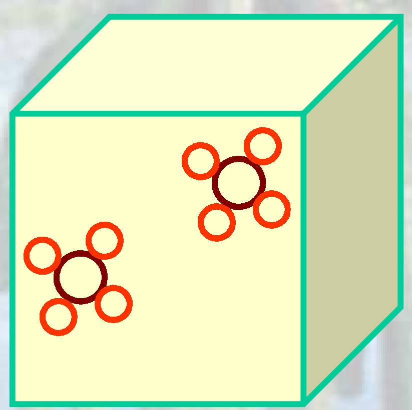
Ideal Gases

- **Equation of State** - P-ν-T behaviour

  $P\nu = RT$ (energy contained by 1 kg mass) where ν is the specific volume in m^3/kg, R is gas constant, kJ/kg∘K, T is absolute temp in Kelvin.



High density



Low density

Molecules far apart

Gas Mixtures – Ideal Gases

Ideal Gases

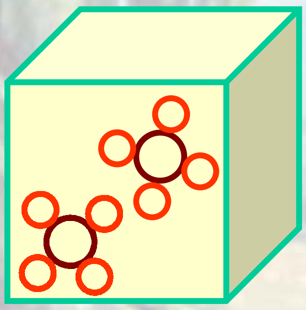
- **Equation of State** - P-ν-T behaviour

  $P\nu = RT$, since $\nu = V/m$ then,

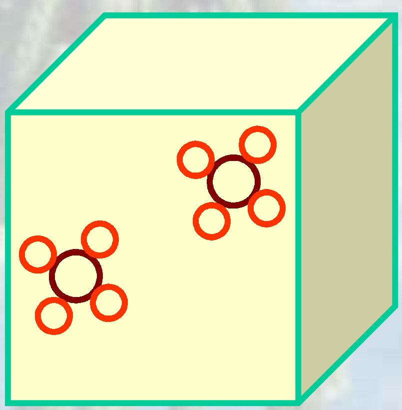
  $P(V/m) = RT$. So,

  $PV = mRT$, in $kPa \cdot m^3 = kJ$.

  Total energy of a system.



High density



Low density

Gas Mixtures – Ideal Gases

Ideal Gases

- **Equation of State** - P-v-T behaviour

  $PV = mRT = NMRT = N(MR)T$

  Hence, can also write $PV = NR_uT$

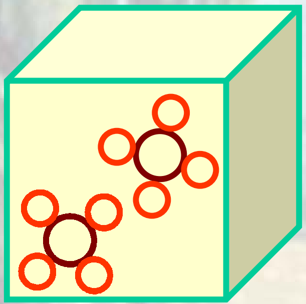
  where

  N is no of kilomoles, kmol,

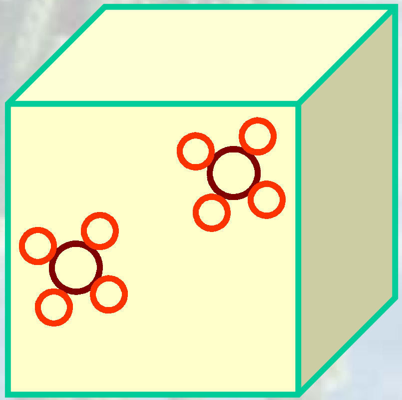
  M is molar mass in kg/kmole and

  R_u is universal gas constant; $R_u = MR$.

  $R_u = 8.314$ kJ/kmol.K



High density



Low density

Gas Mixtures – Ideal Gases

Ideal Gases

- **Equation of State** for mixtures

$P_{mix} v_{mix} = R_{mix} T_{mix}$, $P_{mix} V_{mix} = m_{mix} R_{mix} T_{mix}$

$P_{mix} V_{mix} = N_{mix} R_u T_{mix}$ where $m_{mix} = M_{mix} N_{mix}$

R_{mix} is apparent or mixture gas constant, kJ/kg∘K,

T_{mix} is absolute temp in Kelvin, N_{mix} is no of kilomoles,

M_{mix} is molar mass of mixture in kJ/kmole and

R_u is universal gas constant; $R_u = MR$.

$R_u = 8.314$ kJ/kmol∘K

Gas Mixtures – Ideal Gases

Composition of gas mixtures

- Specify by mass (gravimetric analysis) or volume (volumetric or molar analysis)

mass = Molar mass * Number of kilomoles

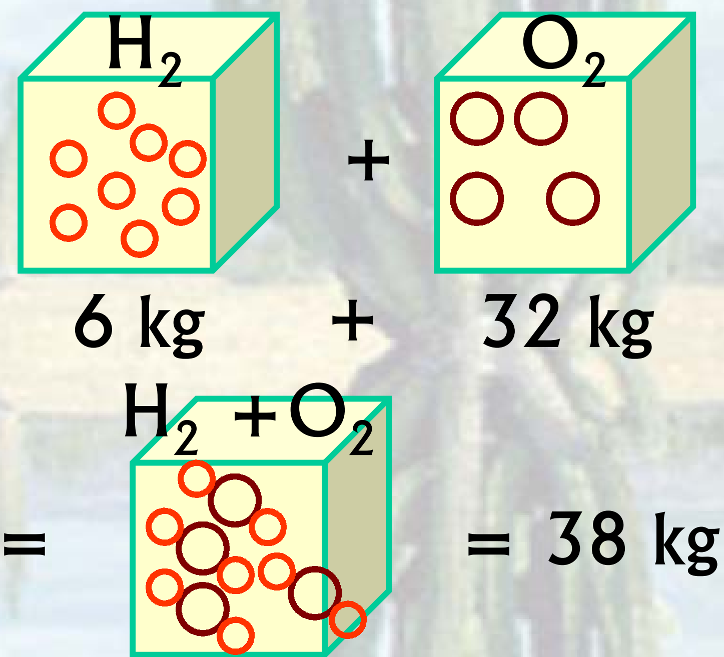
Mass is $m = MN$, in kg

Number of kilomoles is $N = \frac{m}{M}$, in kmole

Gas Mixtures – Composition by Mass

Gravimetric Analysis

- Composition by weight or mass
- Mass of components add to the total mass of mixtures



$$m_{mix} = m_{H_2} + m_{O_2}$$

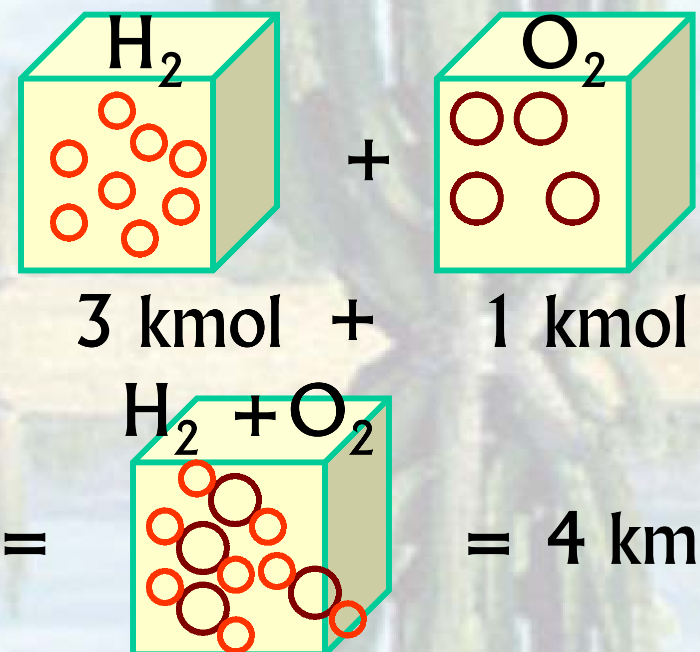
Mass fraction of components

$$mf_{H_2} = \frac{m_{H_2}}{m_{mix}} = \frac{6}{38} = 0.1579 = 15.8\%$$

$$mf_{O_2} = \frac{m_{O_2}}{m_{mix}} = \frac{32}{38} = 0.8421 = 84.2\%$$

Gas Mixtures – Composition by Moles

Volumetric Analysis



- Composition by kilomoles
- Number of kilomoles of components add to the total number of kilomoles of mixtures

$$N_{mix} = N_{H_2} + N_{O_2}$$

= 4 kmol

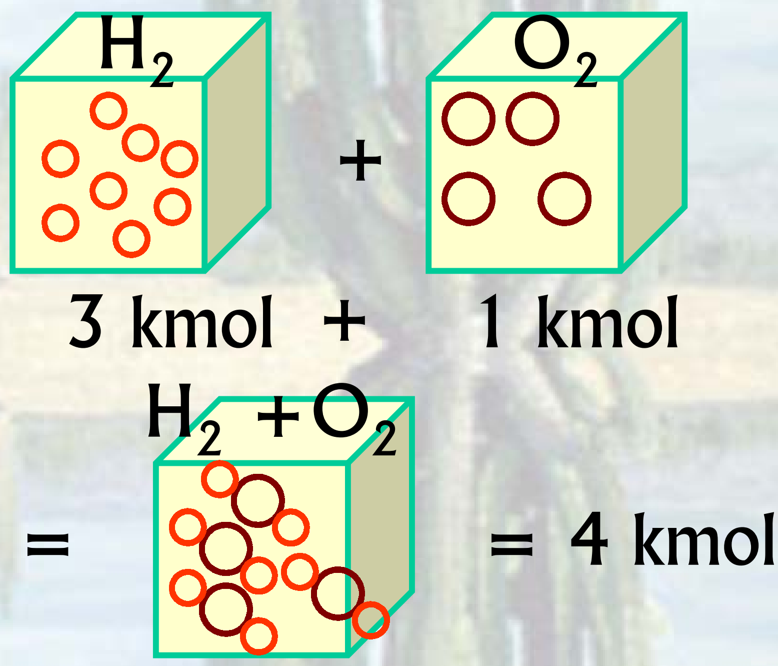
Number of kilomoles is $N = \frac{m}{M}$

Hence,

$$\left(\frac{m}{M}\right)_{mix} = \left(\frac{m}{M}\right)_{H_2} + \left(\frac{m}{M}\right)_{O_2}$$

Gas Mixtures – Composition by Moles

Volumetric Analysis



Mole fraction of components

$$N_{H_2} = \frac{6\ kg}{2\ kg/\ kmol} = 3\ kmol$$

$$N_{O_2} = \frac{32\ kg}{32\ kg/\ kmol} = 1\ kmol$$

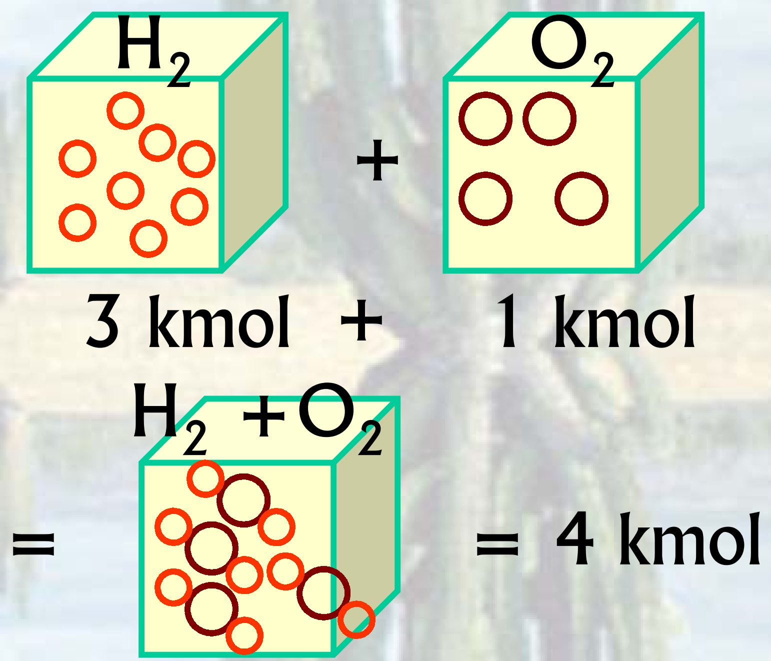
Hence

$$y_{H_2} = \frac{N_{H_2}}{N_{mix}} = \frac{3}{4} = 0.75 = 75\ \%$$

$$y_{O_2} = \frac{N_{O_2}}{N_{mix}} = \frac{1}{4} = 0.25 = 25\ \%$$

Gas Mixtures – Composition by Moles

Composition Summary



Gravimetric Analysis

$$m_1 + m_2 = m_{mix}$$

$$mf_1 + mf_2 = 1 \text{ or } 100\%$$

where $$mf_i = \frac{m_i}{m_{mix}}$$

Volumetric Analysis

$$N_1 + N_2 = N_{mix}$$

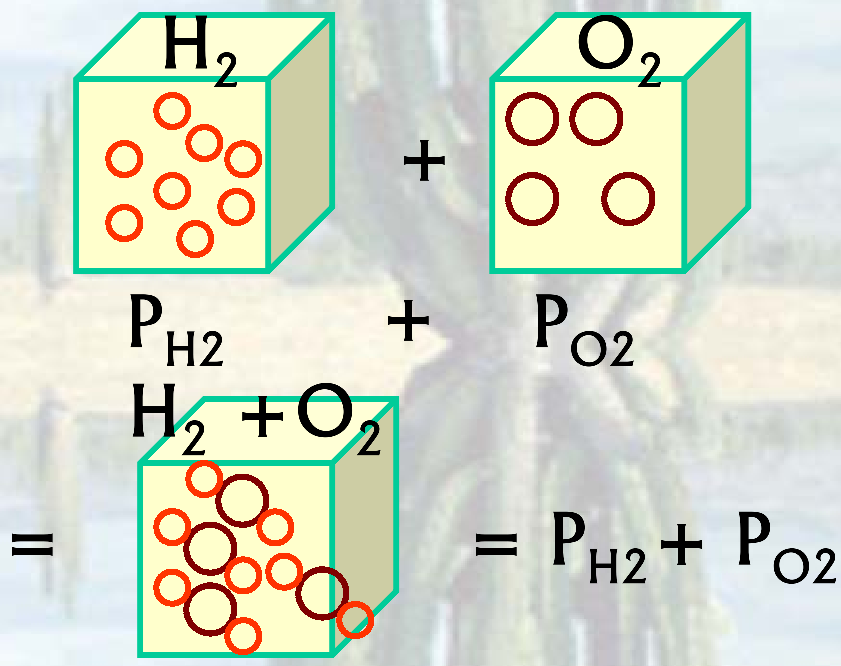
$$y_1 + y_2 = 1 \text{ or } 100\%$$

where $$y_i = \frac{N_i}{N_{mix}}$$

Gas Mixtures – Additive Pressure

Dalton's Law

- The total pressure exerted in a container at volume V and absolute temperature T, is the sum of component pressure exerted by each gas in that container at V, T.



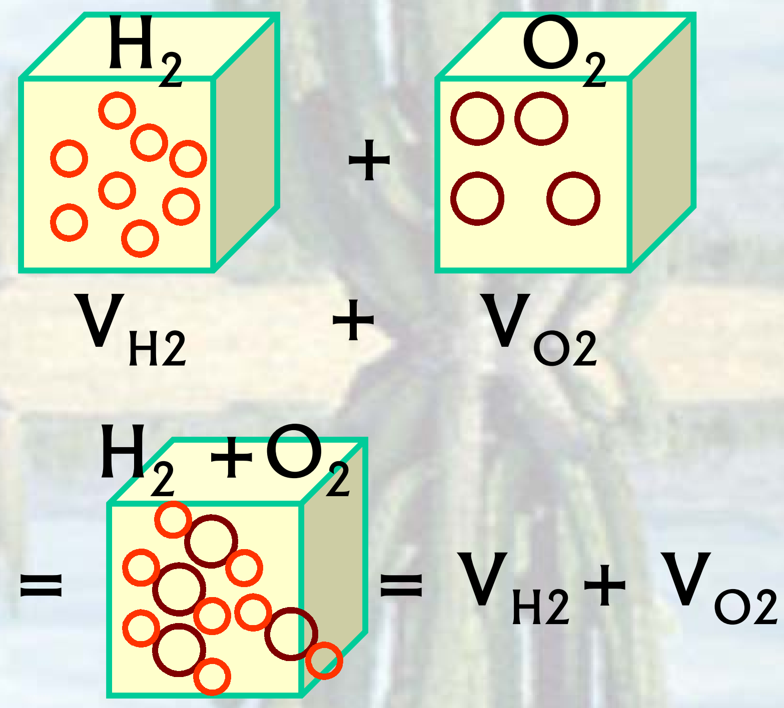
$$P_{mix} = P_1 + P_2$$

$$P_{mix} = \sum_{i=1}^{k} P_i\,(V_{mix}, T_{mix});k$$ is total number of components

Gas Mixtures – Additive Volume

Amagat's Law

- The total volume occupied in a container at pressure P_{mix} and absolute temperature T_{mix}, is the sum of component volumes occupied by each gas in that container at P_{mix}, T_{mix}.



$$V_{mix} = V_1 + V_2$$

$$V_{mix} = \sum_{i=1}^{k} V_i \, (P_{mix}, T_{mix});$$ k is total number of components

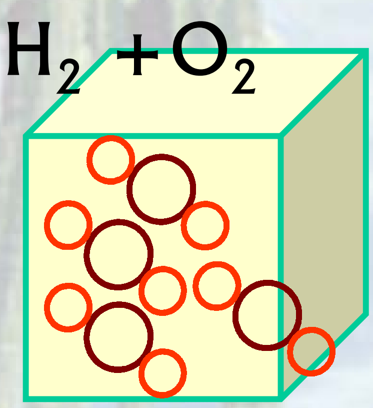
Gas Mixtures –Pressure Fraction

Partial Pressure

Since $P_{mix} V_{mix} = N_{mix} R_U T_{mix}$; $P_1 V_{mix} = N_1 R_U T_{mix}$

- The pressure fraction for each gas inside the container is

$$\frac{P_1}{P_{mix}} = \frac{N_1 R_u \frac{T}{V}}{N_{mix} R_u \frac{T}{V}} = \frac{N_1}{N_{mix}} = y_1$$



Hence the partial pressure is $P_1 = y_1 P_{mix}$

In general, $P_i = y_i P_{mix}$

Gas Mixtures –Volume Fraction

Partial Volume

Since $P_{mix} V_{mix} = N_{mix} R_U T_{mix}$; $P_{mix} V_1 = N_1 R_U T_{mix}$

- The volume fraction for each gas inside the container is

$$\frac{V_1}{V_{mix}} = \frac{N_1 R_u \frac{T}{P}}{N_{mix} R_u \frac{T}{P}} = \frac{N_1}{N_{mix}} = y_1$$

Hence the partial volume is $V_1 = y_1 V_{mix}$

In general, $V_i = y_i V_{mix}$