Chemical Process Calculations CL204
Module-5
Energy balance

Tutorials

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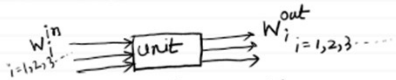
Energy balance

Macroscopic view.



Conservation of Energy

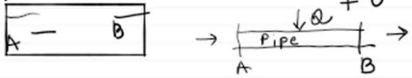
Rate of Accumulation of Energy = rate of Energy in − rate of Energy + Potential Source

at Steady State

rate of energy in − rate of energy out + Source = 0

Total energy = kinetic energy + Potential Energy + mechanical Energy + internal Energy.

Energy/unit mass } $\rightarrow E = \frac{1}{2}v^2 + gh + \frac{PV}{m} + U$



at Steady State $\Sigma\, \text{energy}_A - \Sigma\, \text{energy}_B + Q = 0$

$u + \frac{PV}{m}$ = Enthalpy / unit mass.

$u + \frac{P}{\rho} = H_i$ (enthalpy/unit mass)

(internal + mechanical) energy = Enthalpy

ρ = density (kg/m³)

E = kJ/kg

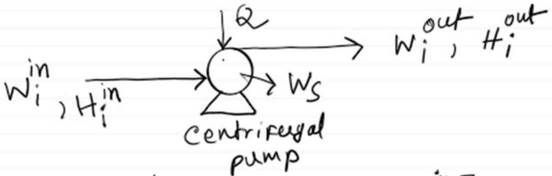
W (kg/hr)

$$E_i = \frac{1}{2}v_i^2 + gh_i + H_i$$

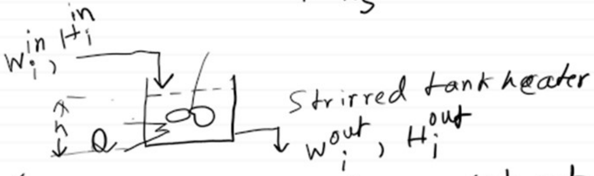
$$\Sigma W_i^{in} E_i - \Sigma W_i^{out} E_i + Q = 0$$

$\frac{kJ}{hr}$ / hr   kJ/hr $\frac{kJ}{hr} \simeq$ Watt

$\frac{kJ \times 1000}{3600} \simeq$ kWatt



$$Q + \Sigma W_i^{in} \left[H_i^{in} + \frac{1}{2}v_i^{in} + gh^{in} \right] =$$
$$= \Sigma W_i^{out} \left[H_i^{out} + \frac{1}{2}v_i^{out} + gh^{out} \right] + W_S$$



h ≤

$$Q + \Sigma W_i^{in} H_i^{in} = \Sigma W_i^{out} H_i^{out}.$$

in case of negligible change of mechanical Energy. $\left(\frac{PV}{m}\right) \rightsquigarrow \frac{P}{\rho}$

$$Q + \Sigma U_i^{in} W_i^{in} = \Sigma U_i^{out} W_i^{out}$$

internal Energy } $U = f(T)$.

$= f(m c_p T)$

$$Q + \Sigma T_i^{in} c_{p_i}^{in} W_i^{in} = \Sigma T_i^{out} c_{p_i}^{out} W_i^{out}$$

Energy balance

Conservation of energy.

↳ Accumulation of energy = Energy in − Energy out + Source.

∴ Total energy, E = kinetic energy → $\frac{1}{2}mv^2$

+ potential energy → mgh.

+ mechanical energy → PV

+ internal energy → $U(V,T)$.

at constant volume

$U = U(T)$.

$$E = \frac{1}{2}mv^2 + mgh + PV + U$$

∴ Energy per unit mass = specific energy

$$(J) = (N \times m) = kg\,\frac{m}{s^2} \times m = kg \cdot \frac{m^2}{s^2}$$

J/s = Watt = W.

total specific energy $\hat{E} = \frac{E}{m}$.

$$\hat{E} = \frac{1}{2}v^2 + gh + \frac{PV}{m} + \hat{U}.$$

$$= \frac{1}{2}v^2 + gh + \frac{P}{\rho} + \hat{U}. \quad (m^2/s^2) \text{ or } \frac{J}{kg}.$$

$$\therefore \overset{\text{specific}}{\text{Enthalpy}} = \frac{P}{\rho} + \hat{U}.$$

$$= \hat{H}\cdot (J/kg) \; [H = \text{enthalpy } (J)]$$

$$\hat{E} = \frac{1}{2}v^2 + gh + \hat{H}.$$

If the body is not moving with its axis $v = 0$,

and it is in reference level of elevation (ground level)

$$gh = 0.$$

$$\therefore \Delta\hat{E} = \Delta\hat{H}.$$

stagnant body.
h = ground level.

$$\therefore \Delta \tfrac{1}{2}v^2 = 0$$

$$\Delta gh = 0$$

$$\therefore \Delta H = \Delta\left(\frac{P}{\rho}\right) + \Delta\hat{U}$$

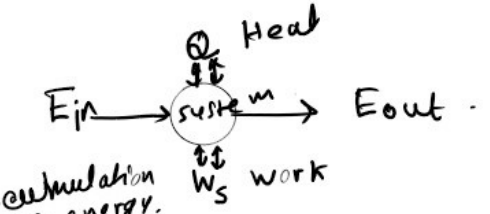
$\therefore$ temperature is constant.

$$\Delta\hat{U} = 0$$

$$\Delta H = \Delta\left(\frac{P}{\rho}\right)$$ change of mechanical energy.

$$\Delta\hat{E} = \Delta\left(\frac{P}{\rho}\right).$$

$\therefore$

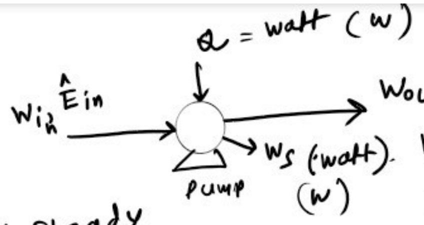


accumulation of energy.

$$\Delta E = Q + W_S - \Delta\left(\hat{H} + \tfrac{1}{2}v^2 + gh\right)$$

at steady state when no energy accumulation. $\Delta E = 0$.

$$\therefore \Delta\left(\hat{H} + \tfrac{1}{2}v^2 + gh\right) = Q + W_S.$$



W_s = shaf

w (kg/s).

$\hat{E}$ (J/kg).

at steady state

∴ Energy in − Energy out + source = 0
(watt) watt watt.

$$\Rightarrow W_{in}\hat{E}_{in} - W_{out}\hat{E}_{out} + Q - W_s$$

$\frac{\cancel{kg}}{s} \times \frac{J}{\cancel{kg}}$ = (Watt) watt

$$\underbrace{W_{in}\hat{E}_{in}}_{\text{total inlet energy}} + \overset{\swarrow}{Q} = \underbrace{W_s + W_{out}\hat{E}_{out}}_{\text{total outlet energy}}$$

W_s = shaft work
(the work is done by the pump).

Q = Power of pump
(the energy is done on the pump)

$\hat{U} = \hat{U}(T)$ at constant volume

$\hat{U} = \int_{T_1}^{T_2} C_V \, dT$ $\quad c_V = $ J kg^{-1} K^{-1},
J kmol^{-1} K^{-1}.

$$\underline{C_p - C_V = R}$$

$$\overline{C_V} = C_p - R.$$

$$C_p = \frac{5}{2} R.$$

$$\therefore C_V = \frac{5}{2} R - R$$

$$\underline{C_V = \frac{3}{2} R}$$

real gases

$$\Delta H = \int_{T_1}^{T_2} C_p \, dT + \int_{P_1}^{P_2} \left[\hat{V} - T \left(\frac{\partial \hat{V}}{\partial T} \right)_P \right] dP$$

$$= \left(\frac{d\hat{H}}{dT} \right)_P dT + \left(\frac{d\hat{H}}{dP} \right)_T dP \, ,$$

at constan pressure $dP = 0$

$$\Delta H = \int_{T_1}^{T_2} C_p \, dT$$

$$C_p = a + bT + cT^2$$

$$= a + bT$$

a, b, c are constant

C_p - J/(kg)(K)

J/kg(°C)

BTU/(lb)(°F)

BTU/(lb-mol)(°F).

$\Delta \underline{H} = \Delta \underline{\hat{U}} + \Delta \frac{P}{V}$

$\frac{}{V} \to 0$ mechanical energy $= 0$

$\underline{\underline{\Delta H = \Delta \hat{U}}}$

$$\boxed{\Delta T_k = \frac{\Delta T_{°R}}{1.8}}$$

$\underline{T_{°R} = T_{°F} + 460}$

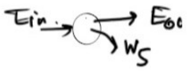
A frictionless piston expanded from $0.1\ m^3$ to $0.2\ m^3$ at 300k and with ideal gas.
Initial pressure of piston was. 200 kPa. Find work done.

$\Delta\left(\frac{1}{2}v^2 + gh + \frac{P}{\rho} + \hat{U}\right) + Q + W_s = 0$.

$\therefore$ $v = 0$, $h = 0$,

isothermal process. $\Delta \hat{U} = 0$.

$Q = 0$.



$\acute{E}_{in} - E_{out} - W_s = 0$

$E_{out} - E_{in} = -W_s$.

$\therefore W_s = E_{in} - E_{out}$

$P = \text{constant} = 200\ kPa. = 200 \times 10^3\ Pa$

$= \bar{P}V_{in} - \bar{P}V_{out}$.

$= 200\ (V_{in} - V_{out})$

$= 200\ (\overset{m^3}{0.1} - \overset{m^3}{0.2}) \times 10^3\ J$

$= -0.1 \times 200 \times 10^3\ J$

$= -20\ \underline{\underline{kJ}}$

$\underline{\text{ideal gas}}$ $PV = nRT$

$n = \frac{PV}{RT} = \frac{200 \times 0.1^3}{300k \times 8.314}$.

$= 0.00802$ kgmol

$W = -\int_{V_1}^{V_2} P\, dV$.

$= -\int_{V_1}^{V_2} \frac{nRT}{V}\, dV$.

$$\boxed{W = -nRT \ln \frac{V_2}{V_1}.}$$

at $\underline{\text{constant}}$ P, and T.

$W = -0.00802 \times 8.314 \times 300 \times \ln 2$

$= \underline{-13.86\ kJ}$

Horizontal pipeline $\quad V_{out} = V_{in}$

$\Delta \frac{1}{2} v^2 = 0$

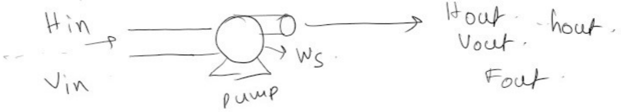
$\Delta h = 0 \therefore h_{out} - h_{in} = 0$

$\Delta \frac{1}{2} v^2 = 0$; Δ Potential energy $= 0$

$\Delta H = \text{-----}$

$H_{in} - H_{out} = 0$ at steady state.

$\downarrow Q = Q\,wat = 1\,hp$



$$F_{in}\left[h_{in} g + H_{in} + \frac{1}{2} V_{in}^2\right] + Q$$

$$\Delta H = \int_{T_1}^{T_2} (a + bT + cT^2)\, dT$$

$$= \left[aT + \frac{b}{2}T^2 + \frac{c}{3}T^3\right]_{T_1}^{T_2}$$

K → °C → °F → °R.

$K = °C + 273.15$

$= T°C + 273.15$

$\frac{C}{5} = \frac{F-32}{9}$

$\Rightarrow C = \frac{F-32}{1.8} \rightarrow 9/5$

$= \frac{T_{°F} - 32}{1.8} + 273.15$

$°R = °F + 460$

$°R - 460 = °F$

$$T_K = \frac{T_{°R} - 460 - 32}{1.8} + 273.15$$

$$F_{in}\left[h_{in} g + H_{in} + \frac{1}{2} V_{in}^2\right] + Q$$

inlet

$$= W_s + F_{out}\left[h_{out} g + H_{out} + \frac{1}{2} V_{out}^2\right]$$

if $\quad h_{in} = h_{out}$ $\quad$ Δ Potential $= 0$

$\quad V_{out} = V_{in}$ $\quad$ Δ kinetic $= 0$

Heat transfer

$Q = UA\Delta T$ (watt) W.

U = heat transfer coefficient overall ($W/(m^2)(°C)$) $=$ $W/((m^2)(K))$.

A = surface area, m^2

ΔT = °C or K

$\Delta °C = \Delta K$.

Human body $\xrightarrow{\text{heat transfer}}$ Atmosphere 25°C

T_b 29°C

$A_b = 1.6\ m^2$

$U = 7\ W/(m^2)(°C)$

$$Q = UA\Delta T$$
$$= 7 \times 1.6 \times (25-29)$$
$$= -44.8 \text{ watt (W)}.$$

—ve sign heat is done by the system

Energy balance with chemical reaction

Exothermic reaction.

heat is removed from the process.

$3H_2^{(g)} + N_2^{(g)} \rightleftharpoons 2NH_3^{(g)} + \text{heat}$

$\Delta H = -ve$

Endothermic reaction

heat is absorbed by the system

$CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(s) - \text{heat}$

$C_6H_2O_6 + 6H_2O \rightarrow 12H_2 + 6CO_2 - \text{heat}$

endothermic reaction

$\Delta H = +ve$

heat of reaction $\Delta H = 627$ kJ/mol glucose

To produce 10 mol of glucose

627 x 10 kJ energy must be required.

= 6270 kJ

exothermic reaction

$\Delta H = -600$ kJ/mol.

10 mol Total heat = 600 x 10 kJ

= 6000 kJ

cooling will be required.

heat of reaction is equivalent to enthalpy.

Standard heat of formation

(enthalpy)' ΔH_f^0 0 dentes standard state
25°C & 1 atm

It refers the enthalpy change associated with the formation of 1 mol of compound from the reactants and other products at standard state.

$$1\,C\,(s) + 1\,O_2\,(g) \longrightarrow 1\,CO_2\,(g).$$

$$\Delta H_f^0 = \underbrace{1 \times \Delta H^0_{f,CO_2}}_{\text{Product}} - \underbrace{1 \times \Delta H^0_{f,C} - 1 \times \Delta H^0_{f,O_2}}_{\text{reactant}}$$

[Hess's Law]

$$= \sum_i n_i \Delta H^0_{f,\text{product}} - \sum_i n_i \Delta H^0_{f,\text{reactant}}$$

for stable element (O_2, N_2, C ...

$$\underline{\Delta H^0_{f,\text{stable element}} = 0}$$

$$\Delta H^0_{f,} = \Delta H^0_{f,CO_2} - 1 \times 0 - 1 \times 0$$

$$\underline{\Delta H^0_{f.}} = \Delta H^0_{f,CO_2} = -393.51 \text{ kJ/g mol}.$$

Heat of formation of reaction at standard state

$C + O_2 \rightarrow CO_2$

$\Delta H = -393.51$ kJ/g-mol

Other than endothermic & exothermic.

∴ $\Delta H_f^0 = 0$

$\Rightarrow [n\Delta H_F]_{\text{Reactant}} = [n\,\Delta H_F]_{\text{product}}$.

$CH_2(NH_3)COOH\,(s) + \frac{15}{2}O_2 \rightarrow 2CO_2(g) + \frac{5}{2}H_2O(g)$

glycine ∴ $\Delta H_f^0 = 0$ $+ HNO_3(g)$.

$\sum \Delta H_{F,\text{ product}} = \sum \Delta H_{F,\text{ reactant}}$

∴ $1\times\Delta H_{F,\text{glycine}} = 2\Delta H_{F,CO_2} + \frac{5}{2}\Delta H_{F,H_2O}$

$= 2(-393.51) + \frac{5}{2}\times(-241.826)$

$+ 1\times(-173.23)$.

$= -1202.08$ kJ/gm-mol. of glycine

∴ $\frac{-1202.08}{15/2 \rightarrow \nu_{O_2}}$ kJ/gm-mol O_2

A) $C(s) + O_2(g) \rightarrow CO_2$; $\Delta H = -393.51$ kJ/gmmol

Ⓑ $CO + \frac{1}{2} O_2(g) \rightarrow CO_2$; $\Delta H = -282.99$ kJ/g mol

$$\Delta H^0_A = \cancel{\Delta H^0_{CO_2}} - 0 - 0$$

$$\Delta H^0_B = \cancel{\Delta H^0_{CO_2}} - \Delta H^0_{CO}$$

$$\underline{\quad - \qquad\qquad - \qquad\qquad + \quad}$$

$$\Delta H^0_{CO} = \Delta H^0_A - \Delta H^0_B$$

$$= -393.51 - (-282.99)$$

$$= \underline{-110.52 \text{ kJ/gmol}}$$

$$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g).$$

$$\Delta H^0_{rxn} = 4\,\Delta H^0_{f,NO} + 6 \times \Delta H^0_{H_2O} - 4 \times \Delta H^0_{NH_3}$$

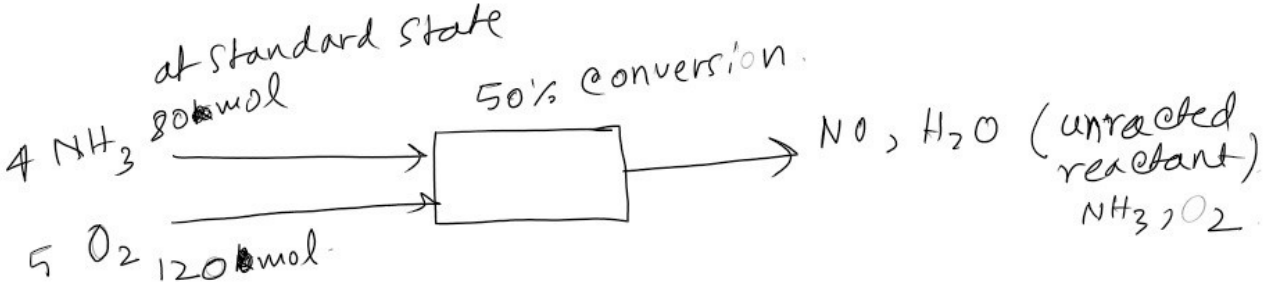
$$= 4 \times (90.374) + 6 \times (-241.826)$$
$$- 4 \times (-46.191).$$

$$\Delta H^0_{rxn} = -904.696 \text{ kJ}$$

$$\Delta H^0_{rxn} = -\frac{904.696}{4} \text{ kJ/gm-mol } NH_3$$

$$= -226.174 \text{ kJ/ gmmol } NH_3$$

The heat of reaction so far calculated for 100% conversion.



$$\xi = \frac{-x \times n_{\text{Limiting reactant}}}{\nu_{\text{Limiting reactant}}} =$$

$$= -\frac{0.5 \times 80}{(-4)} = 10$$

$$\therefore \boxed{\Delta H^0_{rxn} = \xi \times \Delta H^0_{rxn}\ (\text{at } 100\%)}$$

$$= 10 \times (-226.174)\ \text{kJ/gmmol } NH_3$$

$$= -2260.174\ \underline{\text{kJ/gmmol } NH_3}$$

If reaction is carried out at different state than standard state

$$3H_2 + N_2 \overset{350°C}{\rightleftharpoons} 2NH_3 + \text{Heat}$$

$\Delta H < 0$ negative

$T_{reaction} > T_{25°C}$

$P > P_{atm}$

$$\Delta H^{\text{at constant } P} = \int_{T_1}^{T_2} C_p \, \Delta T$$

$$\Delta H^{\text{at constant } T} = \cancel{\int_{P_1}^{P_2} \left[\hat{V} - T\left(\frac{\partial \hat{V}}{\partial T}\right)_P \right] dP}$$

$$\Delta H^{\text{at constant pressure}} = \int_{T_1}^{T_2} C_p \, dT$$

$$C_p = a + bT + cT^2 .$$

$$\underline{\Delta H_{rxn}(T)} = \sum_i^{\text{Product}} n_i \overbrace{\left[H_i(T_{product}) - H_i^0(25°) \right]}^{\Delta H_{product}} - \sum_i^{\text{reactant}} n_i \overbrace{\left[H_i(T_{reactant}) - H_i^0(25°) \right]}^{\Delta H_{reactant}} + \Delta H^0_{rxn}(25°)$$

$$H_i(T_{product}) - H_i^0(25°) = n_i \underbrace{\int_{25°}^{T_{product}} C_{p,i} \, dT}_{\text{sensible heat}} + \underbrace{\cancel{n_i \Delta \hat{H}_{i,\text{phase change}}}}_{\text{Latent heat}}$$

neglect phase change

$$H_i(T_{reactant}) - H_i^0(25°) = n_i \int_{25°}^{T_{reactant}} C_{p,i} \, dT + n_i \Delta \hat{H}_{i,\text{phase change}}$$

$$\boxed{\underset{\checkmark}{\Delta H_{rxn}^{(T)}} = \underbrace{\sum_i^{\text{Product}} n_i \int_{25°}^{T_{product}} C_{p,i} \, dT}_{\text{unknown } f(T_{product})} - \sum_i^{\text{Reactants}} n_i \underset{\checkmark}{\int_{25°}^{T_{reactant}} C_{p,i} \, dT} + \underset{\checkmark}{\Delta H^0_{rxn}} .}$$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

1° inlet → 1·5 gmol CO_2

→ 4 " H_2 → Limitin

Sensible heat → due to $\int_{T_1}^{T_2}$ change

$$\left.\begin{array}{lll} \text{reactant} \rightarrow H_2 & 4 \times \int_{25°}^{100} C_{p,H_2}\, dT \\ \hookrightarrow CO_2 & 1\cdot5 \times \int_{25°}^{700°C} C_{p,CO_2}\, dT \end{array}\right\} \text{Sensible heat}$$

$$\left.\begin{array}{lll} \text{Product} & H_2 & 1\cdot6 \times \int_{25°}^{500} C_{p,H_2}\, dt \\ & CO_2 & 0\cdot9 \times \int_{25°}^{500} C_{p,CO_2}\, dT \\ & CH_4 & 0\cdot6 \times \int_{25}^{500} C_{p,CH_4}\, dT \end{array}\right\} \text{Sensible heat}$$

$$H_2O \quad 1\cdot2 \times \int_{25}^{500} C_{p,H_2O}\, dT$$

$$\Delta H_{rxn} = \sum \text{Sensible heat}_{product}$$

$$- \sum \text{sensible heat}_{reactant}$$

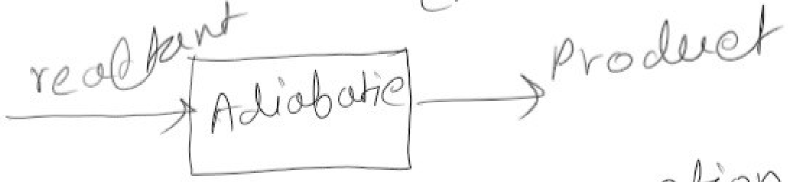
$$+ \underline{\Delta H^{\circ}}$$

$$= 75\cdot3 - 54\cdot955 + (-99\cdot161)$$

$$= \underline{-78\cdot85 \text{ kJ / gmol of } CO_2}$$

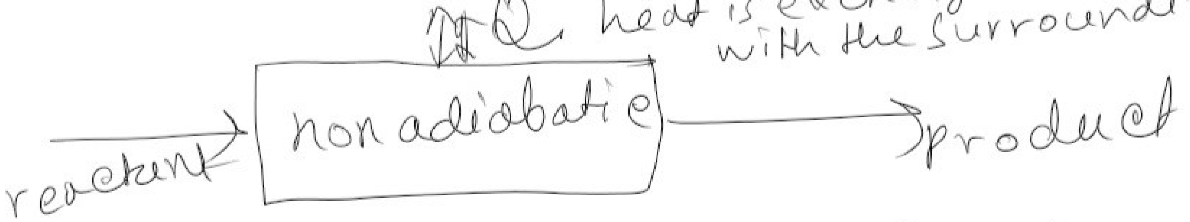
(adiabatic system.)

no heat exchange with the surrounding.



exothermic reaction
reactor temperature ↑ → accident melting of reactor.

endothermic reaction
reactor temperature ↓ stop reaction.



heat is exchanged with the surrounding

T of reactor is controlled by cooling or heating.

$$Q + \frac{x_A F_A^{in}}{-\upsilon_A}\left[-\sum \upsilon_i H_i^{out}\right] = \sum_{i}^{\text{reactant}} F_i^{in} \int_{T_{in}}^{T_{out}} C_{p,i}\, dT$$

$$= \sum F_i^{in}\left[H(T_{out}) - H(T_{in})\right]$$

For adiabatic system $Q = 0$

$$\sum \upsilon_i H_i^{out} = \sum \upsilon_i H_f^{0} + \sum \upsilon_i \int_{25^{0}}^{T_{out}} C_p\, dT$$

$$= \Delta H_{rxn}^{0} + \sum \upsilon_i \int_{25^{0}}^{T_{out}} C_p\, dT$$

$$\Rightarrow \quad Q + \left[\Delta H_{rxn} + \sum_{\substack{\text{All}\\ \text{inlet}}} \upsilon_i \int_{25^{\circ}C}^{T_{out}} C_{p,i}\, dT\right]\left[\frac{x_A F_A^{in}}{-\upsilon_A}\right][-1]$$

$$= \sum_{\substack{\text{all}\\ \text{inlet}}} F_i^{in} \int_{T_{in}}^{T_{out}} C_{p,i}\, dT$$

One hundred gram moles of CO at 300°C are burned with 100 g mol of O2 which is at 100°C; the exit gases leave at 400°C. What is the heat transfer to or from the system in kilojoules?

inelet comosition

$$2CO + O_2 \rightarrow 2CO_2$$

300°C 100°C 400

100gm mol 100 gm mol

$Q = 0$

$$\Delta H_{rxn} = \Delta H^{0}_{rxn} + \sum \text{sensible heat of Product} + \sum \text{sensible heat of reactant}$$

$$= \Delta H^{0}_{rxn} + \int_{25}^{400} C_{P,CO_2}\, 100\, dT - \int_{25}^{100} 100\, C_{P,O_2}\, dT - \int_{25}^{300} 100\, C_{P,CO}\, dT$$

$$\downarrow$$

$a + bT + cT^2 + dT^3$

J / (gm mol)(°C) → K

↑

J / (gm)(°C) × MW_i

10^{-3} × kJ

10 gm mol CO

convert

$$\frac{\Delta H_{rxn}}{2} \times 10 \text{ kJ}$$

Energy balance in Unit process. (chemical reactor)

↳ Macroscopic view.

First come to material balance of reactor

$$\begin{array}{c} n_i^{in} \\ F_i^{in} \end{array} \longrightarrow \overset{\downarrow Q}{\boxed{\text{Reactor}}} \longrightarrow \begin{array}{c} n_i^{out} \\ F_i^{out} \end{array} \qquad Q = \text{heat duty.}$$

$$F_i^{out} = F_i^{in} + \xi \upsilon_i \quad \text{— (i)}$$

$$F_i^{out} = F_i^{in} + \frac{x_A F_A^{in}}{(-\upsilon_A)} \upsilon_i \quad \text{— (ii)}$$

A = Limiting reactant

$$\xi = \frac{x_A F_A^{in}}{(-\upsilon_A)} = f(x_A)$$

F_A^{in} = molar flow rate of limiting reactant in the reactor inlet.

x_A = conversion of limiting reactant

υ_A = Stoichiometric coefficient of limiting reactant.

Energy balance.

$$Q + \Sigma F_i^{in} H_i^{in}(T^F, P^F) = \Sigma F_i^{out} H_i^{out}(T^{out}, P^{out}) \quad \text{— (iii)}$$

Q + total rate of heat in = total rate of heat out.

T^F, P^F = Feed Temperature & Pressure

T^{out}, P^{out} = outlet temperature & pressure.

H = enthalpy.

replace equation ◯ (F_i^{out}) in equation (iii)

$$Q + \Sigma F_i^{in} H_i^{in} = \Sigma \left[F_i^{in} + \frac{x_A F_A^{in}}{(-\upsilon_A)} \upsilon_i \right] H_i^{out}$$

$$Q - \Sigma \frac{x_A F_A^{in}}{(-\upsilon_A)} \upsilon_i H_i^{out} = \Sigma F_i^{in} (H_i^{out} - H_i^{in})$$

$$Q + \frac{x_A F_A^{in}}{(-\upsilon_A)} \left[-\Sigma \upsilon_i H_i^{out} \right] = \Sigma F_i^{in} (H_i^{out} - H_i^{in})$$

(iv)

In case of ideal solution ⟶ $\Delta H = \int_{T_1}^{T_2} C_p \, dT$

$$H_i^{out} - H_i^{in} = \int_{T_F}^{T_{out}} C_p \, dT$$

$$Q + \frac{x_A F_A^{in}}{(-\upsilon_A)} \left[-\Sigma \upsilon_i H_i^{out} \right] = \Sigma \int_{in}^{out} F_i^{in} c_p \, dT$$

$$Q + \frac{x_A F_A^{in}}{(-\upsilon_A)} \left[-\Sigma \upsilon_i H_i^{out} \right] = \Sigma F_i^{in} \int_{T_F}^{T^{out}} c_p \, dT \quad \text{— (v)}$$

in case of adiabatic operation

$$Q = 0$$

References

- Himmelblau, D.M., Riggs, J.B., Basic Principles and Calculation in chemical engineering, Prentice Hall.