Chapter 7. Energy and Energy Balance

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Introduction

- **Energy is expensive….**
  - **Effective use of energy is important task for chemical engineers.**
- **Topics of this chapter**
  - **Energy balance**
  - **Energy and energy transfer**
    - **Forms of energy : Kinetic / Potential / Internal Energy**
    - **Energy transfer : Heat and Work**
  - **Using tables of thermodynamic data**
  - **Mechanical energy balances**

Typical problems

- **Power requirement for a pump → Pure mechanical energy balance**
- **Heat / Work calculation for a desired change**
- **Removal of heat from reactor**
- **Combustion problem**
- **Requirement of energies for each apparatus**

7.1 Forms of Energy
– The First Law of Thermodynamics

- **Forms of energy**
  - **Kinetic energy : due to the motion of the system** $$E_K = \frac{mv^2}{2g_c}$$
  - **Potential energy : due to the position of the system** $$E_p = m\frac{g}{g_c}h$$
  - **Internal energy : due to the motion of internal molecules**
    - **U : from thermodynamic calculation**

- **Forms of energy transfer**
  - **Heat (Q) : energy flow due to temperature difference**
  - **Work (W) : energy flow due to the driving force other than temperature difference (force, torque, voltage, …)**

Energy balance on closed systems

- **Balance equation**

(Final System Energy) – (Initial System Energy) = (Net Energy Transfer)

- **Initial System Energy** $U_i + E_{pi} + E_{ki}$
- **Final System Energy** $U_f + E_{pf} + E_{kf}$
- **Net Energy Transfer** $Q + W$

The first law of thermodynamics for closed systems

$$\Delta U + \Delta E_p + \Delta E_k = Q + W$$

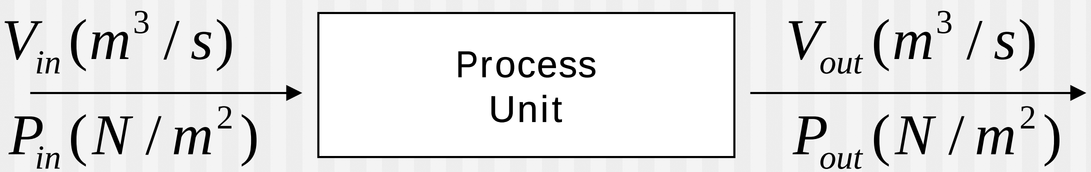
Important points

- **U depends on composition, state, temperature of the system. Nearly independent of pressure for ideal gases, liquids, solids.**
- **Q = 0 → Adiabatic process**
- **If there are no moving parts, W = 0**
- **Potential energy change → due to the changes in height**

7.2 Energy Balances on Open Systems at Steady State

- **Flow work and shaft work**
  - **Flow work : work done on system by the fluid itself at the inlet and the outlet**
  - **Shaft work : work done on the system by a moving part within the system**

$$W = W_s + W_f$$



$$W_f = P_{in}V_{in} - P_{out}V_{out}$$

Specific Properties

- Specific properties
  - (Property) / (Amount (Mass, Mole number,…))
  - Volume , energy, … → Extensive properties
  - Specific volume, specific energy, … → Intensive property
  - Example)
    - Volume : extensive property → depends on system size
    - Specific Volume : intensive property → independent of system size

$V(cm^3), U(kJ), \ldots \longrightarrow$ Extensive properties

$\hat{V}(cm^3/mol), \hat{U}(kJ/mol), \ldots \longrightarrow$ Intensive properties

Enthalpy

- **It is convenient to define the following property for the calculation of energy balance for flowing systems.**
  - **Enthalpy** $H \equiv U + PV$
  - **Specific Enthalpy** $\hat{H} \equiv \hat{U} + P\hat{V}$

The Steady-State Open System Energy Balance

$$\Delta U + \Delta E_p + \Delta E_k = Q + W$$

$$W = W_s + W_f$$

$$W_f = m_{in} P_{in} \hat{V}_{in} - m_{out} P_{out} \hat{V}_{out}$$

$$\Delta E_K = \Delta \frac{mv^2}{2g_c}$$

$$\Delta E_K = \Delta m \frac{g}{g_c} h$$

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

$$\hat{H} \equiv \hat{U} + P\hat{V}$$

$$\Delta H + \Delta E_p + \Delta E_k = Q + W_s$$

7.5 Tables of Thermodynamic Data

- **U, H, S, V,… → Thermodynamic function**
- **Tables of Thermodynamic Data**
  - **Tabulation of values of thermodynamic functions (U, H, V,..) at various condition (T and P)**
  - **It is impossible to know the absolute values of U , H for process materials → Only changes are important (ΔU, ΔH,…)**
  - **Reference state**
    - **Choose a T and P as a reference state and measure changes of U and H from this reference state → tabulation**

Steam Tables

- **Compilation of physical properties of water**

표 B·6. Properties of Superheated Steam[a]

P(bar) (T_{sat}, °C)		Sat'd Water	Sat'd Steam	Temperature (°C) → 50	75	100	150	200	250	300	350
0.0 (—)	$\hat{H}$	—	—	2595	2642	2689	2784	2880	2978	3077	3177
	$\hat{U}$	—	—	2446	2481	2517	2589	2662	2736	2812	2890
	$\hat{V}$	—	—	—	—	—	—	—	—	—	—
0.1 (45.8)	$\hat{H}$	191.8	2584.8	2593	2640	2688	2783	2880	2977	3077	3177
	$\hat{U}$	191.8	2438.0	2444	2480	2516	2588	2661	2736	2812	2890
	$\hat{V}$	0.00101	14.7	14.8	16.0	17.2	19.5	21.8	24.2	26.5	28.7
0.5 (81.3)	$\hat{H}$	340.6	2446.0	209.3	313.9	2683	2780	2878	2976	3076	3177
	$\hat{U}$	340.6	2484.0	209.2	313.9	2512	2586	2660	2735	2811	2889
	$\hat{V}$	0.00103	3.24	0.00101	0.00103	3.41	3.89	4.35	4.83	5.29	5.75
1.0 (99.6)	$\hat{H}$	417.5	2675.4	209.3	314.0	2676	2776	2875	2975	3074	3176
	$\hat{U}$	417.5	2506.1	209.2	313.9	2507	2583	2658	2734	2811	2889
	$\hat{V}$	0.00104	1.69	0.00101	0.00103	1.69	1.94	2.17	2.40	2.64	2.87
5.0 (151.8)	$\hat{H}$	640.1	2747.5	209.7	314.3	419.4	632.2	2855	2961	3065	3168
	$\hat{U}$	639.6	2560.2	209.2	313.8	418.8	631.6	2643	2724	2803	2883
	$\hat{V}$	0.00109	0.375	0.00101	0.00103	0.00104	0.00109	0.425	0.474	0.522	0.571
10 (179.9)	$\hat{H}$	762.6	2776.2	210.1	314.7	419.7	632.5	2827	2943	3052	3159
	$\hat{U}$	761.5	2582	209.1	313.7	418.7	631.4	2621	2710	2794	2876
	$\hat{V}$	0.00113	0.194	0.00101	0.00103	0.00104	0.00109	0.206	0.233	0.258	0.282
20 (212.4)	$\hat{H}$	908.6	2797.2	211.0	315.5	420.5	633.1	852.6	2902	3025	3139
	$\hat{U}$	906.2	2598.2	209.0	313.5	418.4	630.9	850.2	2679	2774	2862
	$\hat{V}$	0.00118	0.09950	0.00101	0.00102	0.00104	0.00109	0.00116	0.111	0.125	0.139

7.6 Energy Balance Procedures

- **Solve material balance → Get all the flow rate of streams**
- **Determine the specific enthalpies of each stream components**
  - **Using tabulated data**
  - **Calculation**
- **Construct energy balance equation and solve it.**

$$\Delta H + \Delta E_p + \Delta E_k = Q + W_s$$

7.7 Mechanical Energy Balances

$$\Delta H + \Delta E_p + \Delta E_k = Q + W_s$$

- **Chemical equipment (Reactor, Distillation column, Evaporator, Heat exchanger,…)**
  - **Heat flow, internal energy changes (enthalpy change) are most important**
  - **Shaft work, kinetic energy, potential energy changes are negligible**

$$\Delta H \approx Q$$

- **Mechanical equipment (Pump, Reservoir, Pipes, Wells, Tanks, Waste Discharge,…)**
  - **Heat flow, internal energy changes are negligible**
  - **Shaft work, kinetic energy, potential energy changes are most important**

$$\Delta E_p + \Delta E_k = W$$

Mechanical Energy Balances

$$\Delta U + \Delta E_p + \Delta E_k = Q + W$$

$$\hat{V}_{in} = \hat{V}_{out} = 1/\rho$$

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \frac{g}{g_c}\Delta z + (\Delta\hat{U} - Q/m) = W_s/m$$

$$F = \Delta\hat{U} - Q/m \quad (\text{friction loss})$$

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \frac{g}{g_c}\Delta z + F = W_s/m$$

$$F = 0, W_s = 0$$

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \frac{g}{g_c}\Delta z = 0$$

Bernoulli Equation

Important equation for the calculation
Of equipments consist of pipes, tanks and pumps