Chapter 3 The First Law of Thermodynamics in Open Systems

§3-1. Energy balance for closed system

1. For a closed system:
   (1) No streams enter or leave the system.
   (2) No internal energy is transported across the boundary of the system.

2.在 system 與 surroundings 之間只以 heat 與 work 的形式進行能量交換。

$\therefore \Delta$(Energy of the system) = Q + W

↳ $\Delta U = Q + W$ for a closed system

or $dU = dQ + dW$ for a closed system

----常見的 the first law of thermodynamics 數學表示式。

§3-2. Closed system *vs.* open system

1. Closed system:

一個 tank 裝了 200 liter 的 H_2O，若其溫度從 20 升到 60℃，則

❶水吸收熱 __________

❷水的 internal energy 增加 __________

❸外界需供給 __________的熱給水(system)。

2. Open system:

(1)以 200 liter/min 的流量將 20℃ 的 H_2O 注入一個 tank，若水流出 tank 後，流量仍爲 200 liter/min 但溫度已升到 60℃，則

❶水吸收熱 __________

❷水的 internal energy 增加 __________

❸外界需供給 __________的熱給水(system)。

(2) 200 liter/min、20℃ 的 H_2O 和 100 liter/min、25℃ 的 H_2O 同時注入一個 tank，若水流出 tank 後，流量爲 300 liter/min 但溫度已升到 60℃，則

❶水吸收熱 __________

❷外界需供給 __________的熱給水(system)。

◆open system 的計算仍要建立在 closed system 的基礎上！

§3-3. Mass and energy balances for open systems --- 要考慮 time 了

1. Measures of flow:

(1) Mass flowrate, $\dot{m}$: g/sec; kg/sec; g/min; lb/sec -----.

(2) Molar flowrate, $\dot{n}$: mole/sec; mole/min; lb-mole/sec -----.

(3) Volumetric flowrate, v: cm^3/sec; m^3/sec; cm^3/hr; ft^3/sec ----.

(4) Velocity, u: cm/sec; m/sec; cm/min; ft/sec; ft/hr ----.

❈❈flowrate ➔ 慣稱為 "流量"； Velocity ➔ 在此慣稱為 "流速"

流速大 ➔ 不代表流量就大。

● $\dot{m} = M \times \dot{n}$ M = molar mass

$v = u \times A$ A = the cross-sectional area of a conduit

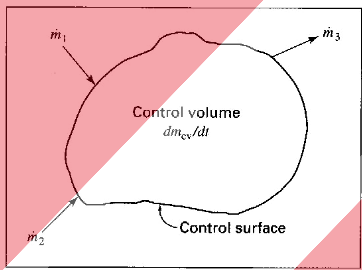
● $\dot{m} = uA\rho$ ρ = specific density (g/cm^3; ------------)

$\dot{n} = uA\rho$ ρ = molar density ($mole/cm^3$ -----------)

2. Mass Balance for Open Systems:

(1)control volume:

control surface:



(2)❶Two streams with flow rates $\dot{m}_1$ and $\dot{m}_2$ are shown directed into the control volume, and one stream with flow rate $\dot{m}_3$ is directed out.

❷Since mass is conserved, the rate of change of mass within the control volume, dm_{cv}/dt, equals the net rate of flow of mass into the control volume.

●Flow directed into the control volume ➔ positive "+".

●Flow directed out the control volume ➔ negative "-".

$$\frac{dm_{acc}}{dt} + \Delta(\dot{m})_{fs} = 0 \quad \text{or} \quad \frac{dm_{acc}}{dt} + \Delta(\rho A u)_{fs} = 0 \qquad \text{Eq. (2.25)}$$

Mass balance 的 continuity equation

where

$$\Delta(\dot{m})_{fs} = \dot{m}_3 - \dot{m}_2 - \dot{m}_1$$

❸At steady state ➔ The control volume contains a constant mass of fluid, and the first or accumulation term of Eq. (2.25) is zero,

$\therefore \quad \Delta(\rho A u)_{fs} = 0$

●The term "steady state" does not necessarily imply that flowrates are constant, merely that the inflow of mass is exactly matched by the outflow of mass.

❹Steady state, single entrance and a single exit stream:

$\rho_2 A_2 u_2 - \rho_1 A_1 u_1 = 0$ or $\dot{m} = const = \rho_2 A_2 u_2 = \rho_1 A_1 u_1$

$$\text{or}\quad \dot{m} = \frac{u_1 A_1}{V_1} = \frac{u_2 A_2}{V_2} = \frac{uA}{V}$$

$$V_1 = \frac{1}{\rho_1}\ ;\quad V_2 = \frac{1}{\rho_2}$$ ----- 單位質量的體積 (如：cm^3/g、m^3/kg ---)

3. The General Energy Balance:

(1)The rate of change of energy within the control volume equals the net rate of energy transfer into and out of the control volume.

(2)Streams flowing into and out of the control volume contain the changes of:

❶internal energy ❷potential energy ❸kinetic energy

∴Each unit mass of a stream carries with it a total energy = $\hat{U} + ½u^2 + gh$

↳Each stream transports energy at the rate $(\hat{U} + ½u^2 + gh)\dot{m}$

(3)Heat that added to the system or removed from the system should be considered: $\dot{Q}$ ------ heat transfer rate

(4)The work done on the system or on the surroundings: work rate, including

❶單位質量流體在管路中流動，有被其後面流體推擠的現象，此可想像成被一個活塞以 P 的壓力推擠

↳ ∴the net work done on the system: $-\Delta[(P\hat{V})\dot{m}]_{fs}$

❷shaft work: 如 pump 抽送液體、攪拌器攪拌及 control volume 膨脹或收縮的功 ----等，以 $\dot{W}_s$ 表示。

(5)Heat of chemical reaction: 本書目前尚不討論。

(6)∴ $$\frac{d(m\hat{U})_{acc}}{dt} = -\Delta[(\hat{U} + (½)u^2 + gh)\dot{m}]_{fs} + \dot{Q} + \text{work rate}$$

$$= -\Delta[(\hat{U} + (½)u^2 + gh)\dot{m}]_{fs} + \dot{Q} - \Delta[(P\hat{V})\dot{m}]_{fs} + \dot{W}_s$$

$$= -\Delta[(\hat{H} + (½)u^2 + gh)\dot{m}]_{fs} + \dot{Q} + \dot{W}_s$$

$$\text{or}\quad \frac{d(m\hat{U})_{acc}}{dt} + \Delta[(\hat{H} + (½)u^2 + gh)\dot{m}]_{fs} = \dot{Q} + \dot{W}_s$$

◆上述的 open system 能量平衡式除了要背外，懂得其意義才可能解決問題！

◆有的人用下列的式子就可搞定了！

$$\frac{dU_{acc}}{dt} + \Delta[(\hat{H}+\hat{K}+\hat{P})\dot{m}] = \dot{Q} + \dot{W}$$

(7) closed system

↳Matter cannot pass through the boundary between the system and its surroundings, but energy can pass through it.

$$\therefore \quad \dot{m} = 0 \quad \Rightarrow \quad \frac{d(m\hat{U})_{acc}}{dt} + \Delta[(\hat{H} + (½)u^2 + gh)\dot{m}]_{fs} = \dot{Q} + \dot{W}_s$$

$$d(mU)_{acc} = \dot{Q}\,dt + \dot{W}\,dt$$

$$\int_{t1}^{t2} d(mU)_{acc} = \int_{t1}^{t2} \dot{Q}\,dt + \int_{t1}^{t2} \dot{W}\,dt$$

$$\therefore \Delta U = Q + W$$

(8) Energy Balances for Steady-State Flow Processes:

❶At steady state ➔ $\frac{d(m\hat{U})_{acc}}{dt} = 0$

$$\therefore \Delta[(\hat{H} + (½)u^2 + gh)\dot{m}]_{fs} = \dot{Q} + \dot{W}_S \quad \text{(only shaft work)}$$

❷When the control volume has only one entrance and one exit:

$$\Delta[(\hat{H} + (½)u^2 + gh)\dot{m}]_{fs} = \dot{Q} + \dot{W}_S$$

$$\therefore \Delta(\hat{H} + (½)u^2 + gh) = \dot{Q}/\dot{m} + \dot{W}_S/\dot{m} \Rightarrow \Delta\hat{H} + \frac{\Delta u^2}{2} + g\Delta h = Q + W_S$$

Example 3-1:

將 5℃的水自 40 m 深的井底以 1100 liters/hr 的流量抽至離地面 25 m 高的水槽中，此時水的出口速度爲 2 m/sec，溫度爲 12℃。爲防止水的凍結，於輸送過程中加入 40500 kJ/hr 的熱量，又對整個系統而言，熱量以 28500 kJ/hr 的速率在散失。若汲水 pump 的效率可達 75%，則需要多大的馬力方可達此目標？

1 hp = 746 w = 746 J/sec；水的 $\hat{C}p$ = 4.18 J/g·K

Example 3-2:

Water at 366.65 K is pumped from a storage tank at the rate of 3.15 x 10^{-3} m^3/s. The motor for the pump supplies work at the rate of 1.5 kW. The water goes through a heat exchanger, giving up heat at the rate of 700 kW, and is delivered to a second storage tank at an elevation 15 m above the first tank. What is the temperature of the water delivered to the second tank? (The density of water is 958 kg/m^3 at 366.65 K)

Example 3-3:

Air at 1 bar and 25℃ enters a compressor at low velocity, discharges at 3 bar, and enters a nozzle in which it expands to a final velocity of 600 ms^{-1} at the initial conditions of pressure and temperature. If the work of compression is 240 kJ per kilogram of air, how much heat must be removed during compression?

Example 3-4:

A small, high-speed turbine operating on compressed air produces 0.1 kW. The inlet and exit conditions are 400 kPa, 25℃ and 100 kPa, -50℃, respectively. Assuming the velocities to be low, find the required mass flow rate of air.

$\hat{C}_p$ for air = 29.17 J/mol•K

Example 3-5:

An ideal gas is flowing in steady state through a horizontal tube which has nonconducting wall. No heat is added, nor is any shaft work done. The cross-section area of the tube changes with length, and this causes the velocity to change. Drive an expression relating the temperature and velocity of the gas.

If nitrogen at 270^{o}F flows past one section of the tube at a velocity of 50 ft/s, what will be its temperature at another section where the velocity is 1200 ft/s?

Cp = 7 BTU/lb-mole·^{o}F

◆ F = ma

❶ m = 10 kg；a = 2 m/s^2

F = ma = 10 x 2 = 20 kg-m/s^2 = 20 Nt

❷ m = 10 lb；a = 2 ft/s^2 ✸10 lb 也常被寫成 10 lb$_m$

F = ma = 10 x 2 = 20 lb$_m$-ft/s^2 ---- 不被 American Engineering system 所接受。

●Define:

F = 1 lbm x 32.174 ft/s^2 = 32.174 lbm-ft/s^2 = 1 lb$_f$

∴ F = ma = 10 x 2 = 20 lb$_m$-ft/s^2 = $\frac{20}{32.174}$ lb$_f$

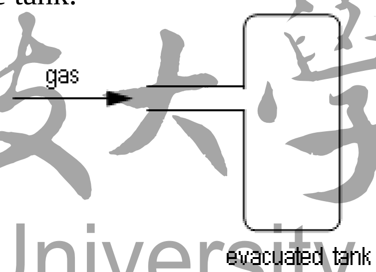
而 1 BTU = 778 lb$_f$-ft

❸ KE = $\frac{1}{2}$mu^2 ➔ KE = $\frac{1}{2g_c}$mu^2 SI: $g_c = 1\ \frac{kg\cdot\frac{m}{s^2}}{Nt}$

PE = mgh ➔ PE = m$\frac{g}{g_c}$h 美工程制: $g_c = 32.174\ \frac{lb_m\cdot\frac{ft}{s^2}}{lb_f}$

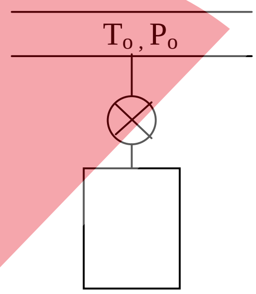
Example 3-6:

An evacuated tank is filled with gas from a constant-pressure line. What is the relation between the enthalpy of the gas in the entrance line and the internal energy of the gas in the tank? Neglect heat transfer between the gas and the tank.



Example 3-7:

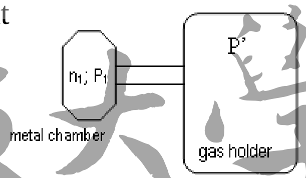
A gas at temperature T_o and pressure P_o is flowing through a pipe. A small amount is bled off into an evacuated cylinder as shown in the figure below. The bleeding continues until the pressure in the tank is equal to the pressure in the pipe P_o. If the cylinder is perfectly insulted and the gas is ideal with C_p and C_v independent of temperature and pressure, find the temperature T in the cylinder at the end of the process.



Example 3-8:

A thick-wall insulated metal chamber contains n_1 mole of He at high pressure P_1. It is connected through a valve with a large, almost empty gasholder in which the pressure is maintained at a constant value P’, very nearly atmosphere. The valve is opened slightly, and the helium flows slowly and adiabatically into the gas holder until the pressures on the two sides of valve are equalized. Prove that

$$\frac{n_2}{n_1} = \frac{\hat{U}_1 - H'}{\hat{U}_2 - H'}$$



where n_2 = number of moles of helium left in the chamber,

$\hat{U}_1$ = initial molar internal energy of helium in the chamber,

$\hat{U}_2$ = final molar internal energy of helium in the chamber,

H’ = molar enthalpy of helium in the gasholder.

Example 3-9:

An insulated, electrically heated tank for hot water contains 190 kg of liquid water at 60℃ when a power outage occurs. If water is withdrawn from the tank at a steady rate of $\dot{m} = 0.2\ \mathrm{kgs^{-1}}$, how long will it take for the temperature of the water in the tank to drop from 60 to 35℃? Assume that cold water enters the tank at 10℃, and that heat losses from the tank are negligible. For liquid water let $\hat{C}_v = \hat{C}_p = C$, independent of T and P.