Chapter 5　Design for Single Reactions

(本章為課本的第六章)

§5-1.Size comparison of single reactors

1. Batch reactor 的實用性與優缺點：

(1)Advantage:

❶ small instrumentation cost.

❷ flexibility of operation(may be shut down easily and quickly).

(2)Disadvantage:

❶ high labor and handling cost.

❷ shut down, clean out, refill---等，都是無生產的浪費。

> ●The batch reactor is well suited to produce small amounts of material and to produce many different products from one piece of equipment.

2. Mixed versus plug flow reactors, first- and second-order reactions:

(1)A simple nth-order rate law:

$$-\gamma_A = -\frac{1}{V}\frac{dN_A}{dt} = \mathrm{k}C_A^{\,n}$$

$$C_A = \frac{N_A}{V} = \frac{N_{A0}(1-X_A)}{V_0(1+\varepsilon_A X_A)} = C_{A0}\frac{(1-X_A)}{(1+\varepsilon_A X_A)}$$ ----請看 page 3-21

$$\therefore -\gamma_A = -\frac{1}{V}\frac{dN_A}{dt} = \mathrm{k}C_A^{\,n} = \mathrm{k}C_{A0}^{\,n}\left[\frac{(1-X_A)}{(1+\varepsilon_A X_A)}\right]^n$$

(2)●From page 4-4 or 課本的 Eq. 5-11,

mixed flow: $\tau_m = \dfrac{V}{v_0} = \left(\dfrac{C_{A0}V}{F_{A0}}\right)_\mathrm{m} = \dfrac{C_{A0}X_A}{-\gamma_A} = \dfrac{1}{kC_{A0}^{n-1}}\dfrac{X_A(1+\varepsilon_A X_A)^n}{(1-X_A)^n}$

●From page 4-7 or 課本的 Eq. 5-17,

plug flow: $\tau_p = \dfrac{V}{v_0} = \left(\dfrac{C_{A0}V}{F_{A0}}\right)_\mathrm{p} = C_{A0}\displaystyle\int_0^{X_{Af}}\dfrac{dX_A}{-\gamma_A} = \dfrac{1}{kC_{A0}^{n-1}}\displaystyle\int_0^{X_A}\dfrac{(1+\varepsilon_A X_A)^n dX_A}{(1-X_A)^n}$

◆◆兩式相除 ➔ $$\frac{(\tau C_{A0}^{n-1})_m}{(\tau C_{A0}^{n-1})_p} = \frac{\left(\dfrac{C_{A0}^n V}{F_{A0}}\right)_m}{\left(\dfrac{C_{A0}^n V}{F_{A0}}\right)_p} = \frac{\left[X_A\left(\dfrac{1+\varepsilon_A X_A}{1-X_A}\right)^n\right]_m}{\left[\displaystyle\int_0^{X_A}\left(\dfrac{1+\varepsilon_A X_A}{1-X_A}\right)^n dX_A\right]_p}$$

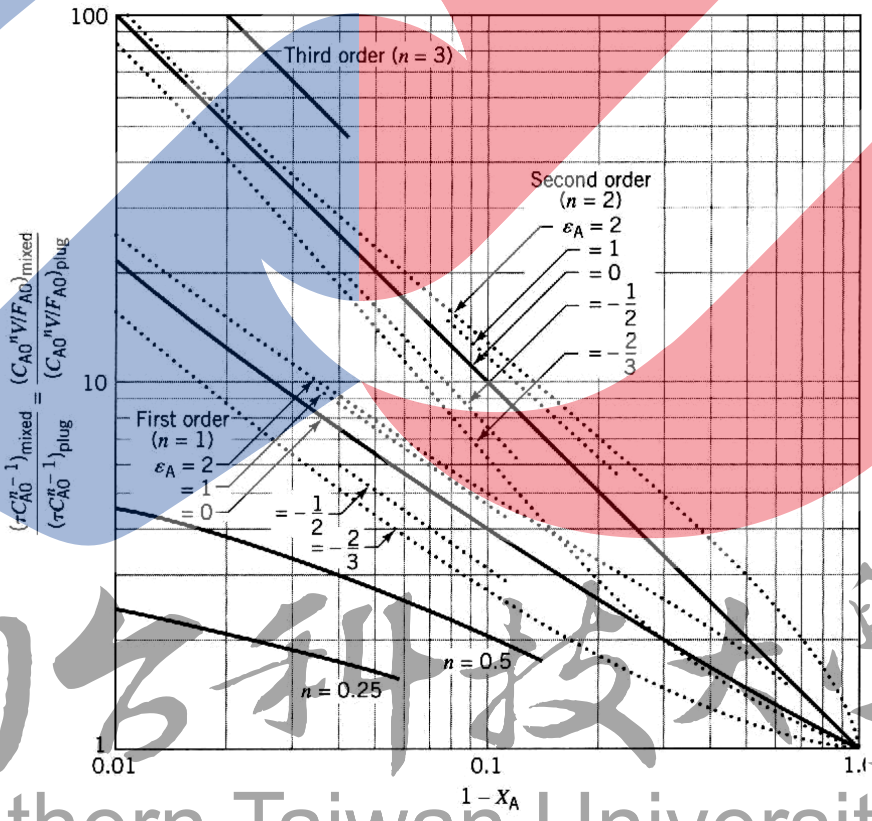
❈With constant density ($\varepsilon_A = 0$)

↳■ n≠1 ➔ $$\frac{(\tau C_{A0}^{n-1})_m}{(\tau C_{A0}^{n-1})_p} = \frac{\left[\dfrac{X_A}{(1-X_A)^n}\right]_m}{\left[\dfrac{(1-X_A)^{1-n}-1}{n-1}\right]_p}$$

■ n = 1 ➔ $$\frac{(\tau C_{A0}^{n-1})_m}{(\tau C_{A0}^{n-1})_p} = \frac{\left[\dfrac{X_A}{(1-X_A)^n}\right]_m}{-\ln(1-X_A)_p}$$

●For identical feed composition C_{A0} and flow rate F_{A0}

↳上兩式代表著二種反應器的體積比。



❈上圖(即課本 Figure 6.1，請參閱課本，課本的圖很清楚)為 nth-order reaction，$\frac{(\tau C_{A0}^{n-1})_m}{(\tau C_{A0}^{n-1})_p}$ 對 1-X_A 的關係。其結論為：

①For all positive reaction orders

↳☸The volume of mixed reactor is always larger than that of the plug reactor

☸The ratio of volumes increases with reaction order.

②When conversion is small

↳ the reactor performance is only slightly affected by flow type.

At high conversion

↳ the reactor performance increases very rapidly.

☞此時，反應器的種類對反應器體積大小的影響較大。

③反應過程，density 的變動會影響設計，但相對於反應器的種類，density 的變動所造成的影響較小。

Example 5-1:

The aqueous reaction A + B → products with known kinetics

$$-\gamma_A = (500\ \text{liter/mol·min})C_AC_B$$

is to take place in a plug flow reactor under the following conditions:

volume of reactor V = 0.1 liter

volumetric feed rate v_0 = 0.05 liter/min.

concentration of reactants in feed, $C_{A0} = C_{B0} = 0.01$ mol/liter

(a)What fractional conversion of reactants can be expected?

(b)For the same conversion as in part (a), what size of mixed flow reactor is needed?

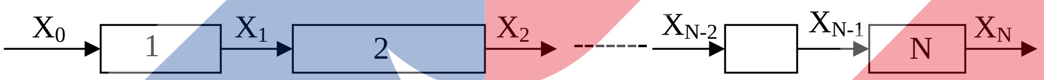
(c)What conversion can be expected in a mixed reactor equal in size to the plug flow reactor?

Example 5-2:

依下列反應，以 100 mol/hr 的速率在 CSTR 反應器中生產 R。而進料的濃度為 C_{A0} = 0.1 mol/liter，成本是 \$0.5/mol A；裝置、儀器、勞工、折舊等成本是 \$0.01/hr‧liter。則反應器體積、進料莫耳速率與轉化率為何時，方能得到最低成本？ A → R $r_R = (0.2\ \text{hr}^{-1})C_A$

§5-2. Multiple-reactor system

1. Plug flow reactors in series and/or in parallel



(1)Consider N plug flow reactors connected in series, and let $X_1, X_2, ---, X_{N-1}, X_N$ be the fractional conversion of component A leaving reactor 1, 2, ---, N-1, N.

第一個 reactor：$\frac{V_1}{F_0} = \int_{X_0}^{X_1}\frac{dX}{-r}$ ； 第二個 reactor：$\frac{V_2}{F_0} = \int_{X_1}^{X_2}\frac{dX}{-r}$

第三個 reactor：---- ；第四個 reactor ：---------

第 N-1 個 reactor：$\frac{V_{N-1}}{F_0} = \int_{X_{N-2}}^{X_{N-1}}\frac{dX}{-r}$

第 N 個 reactor：$\frac{V_N}{F_0} = \int_{X_{N-1}}^{X_N}\frac{dX}{-r}$

∴For the N reactor in series

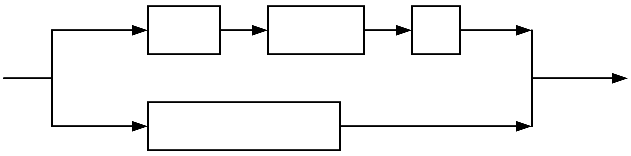
$$\frac{V}{F_0} = \frac{V_1}{F_0} + \frac{V_2}{F_0} + --- + \frac{V_{N-1}}{F_0} + \frac{V_N}{F_0} = \sum_{i=1}^{N}\frac{V_i}{F_0}$$

$$= \int_{X_0}^{X_1}\frac{dX}{-r} + \int_{X_1}^{X_2}\frac{dX}{-r} + --- + \int_{X_{N-2}}^{X_{N-1}}\frac{dX}{-r} + \int_{X_{N-1}}^{X_N}\frac{dX}{-r} = \int_0^{X_N}\frac{dX}{-r}$$

For a plug flow reactor with volume V ➔ $\frac{V}{F_0} = \int_0^{X_N}\frac{dX}{-r}$

●N plug reactors in series with a total volume V gives the same conversion as a single plug flow reactor of volume V.

(2)Consider N plug flow reactors connected in parallel:



❶先將 series 的 reactors 依(1)的方式併成一個反應器。

❷一般而言，進料和出口的轉化率會相等(why?)：

↳X_0、X_1、$-r$ 都相等

由 $\frac{V}{F_A} = \boxed{\int_{X_0}^{X_1} \frac{dX}{-r}}$ 可知

每個平行反應器都相等

- 每個支流的 $\frac{V}{F_A}$ 要一樣 ➔ reactor 的體積大，其通過的流率要高。

Example 5-3:

The reactor setup shown in Fig. A consists of three plug flow reactors in two parallel branches. Branch D has a reactor of volume 50 liters followed by a reactor of volume 30 liters. Branch E has a reactor of volume 40 liters. What fraction of the feed should go to branch D?

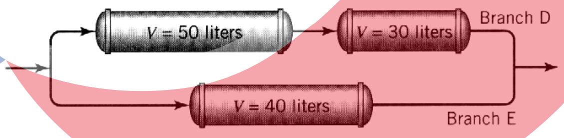


Fig. A

(即課本 Fig E6.1，課本的圖較清楚)

Example 5-4:

Show that n plug flow reactors connected in series with a total volume V gives the same conversion as a single reactor of volume V.

How to distribute the feed for two reactors of volume 60 and 30 liters connected in parallel, in such manner that fluid streams which meet have the same composition?

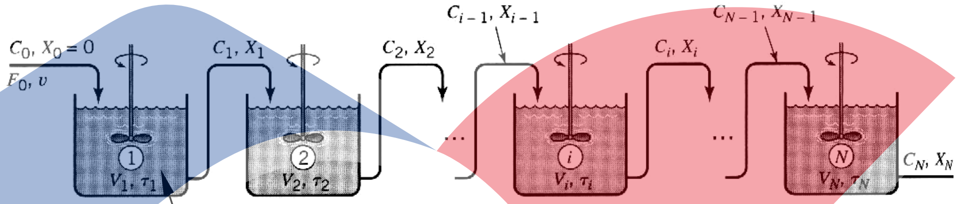
2.(1)❶In plug flow

↳The concentration of reactant decreases progressively through the system.

❷In mixed flow

↳The concentration of reactant drops immediately to a low value.

●反應的 order 越高，使用 PFR 的效率就越高於 CSTR。



請參閱課本 Figure 6-4 (更清晰的圖)

●雖然，進料的濃度是 C_0，但進入反應器後，濃度迅速降爲 C_1，所以，代入 rate eq. 的濃度要代 C_1 而非 C_0。

(2)Consider a series of N equal-size mixed flow reactors. $\varepsilon = 0$ and $t = \tau$.

❶$-r = kC_A$ 型式的 First-order reaction

①∵ $\tau = \dfrac{C_{A0}V}{F_{A0}} = \dfrac{C_{A0}(X_{Af} - X_{Ai})}{(-\gamma_A)_f}$ (page 4-4 or 課本 Eq.5-12)

∴第 i 個 reactor 可寫成 $\tau_i = \dfrac{C_0V_i}{F_0} = \dfrac{V_i}{v} = \dfrac{C_0(X_i - X_{i-1})}{-\gamma_i}$ (不寫 C_{A0} 或 γ_{Ai} 了!)

■考慮 constant-volume system

$$\therefore \tau_i = \frac{C_{i-1} - C_i}{kC_i}$$

or $\dfrac{C_{i-1}}{C_i} = 1 + k\tau_i$

②∵equal-size mixed flow reactors ∴ 每個 reactor 的 τ 都相等。

∴第一個 CSTR ➔ $\dfrac{C_0}{C_1} = 1 + k\tau$；第二個 CSTR ➔ $\dfrac{C_1}{C_2} = 1 + k\tau$

第三個 CSTR ➔ $\dfrac{C_2}{C_3} = 1 + k\tau$ -----------

∴第 N 個 CSTR ➔ $\dfrac{C_{N-1}}{C_N} = 1 + k\tau$

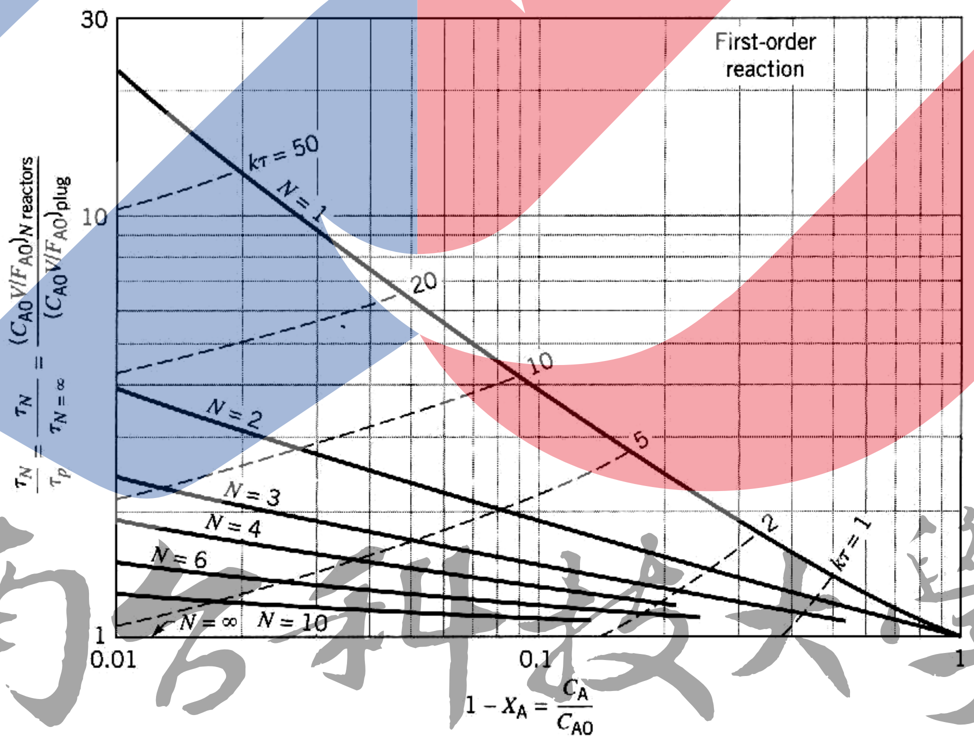
$$\frac{C_0}{C_N} = \frac{1}{1-X_N} = \frac{C_0}{C_1} \text{ x } \frac{C_1}{C_2} \text{ x } \frac{C_2}{C_3} \text{ x --- x } \frac{C_{N-1}}{C_N} = (1 + \text{k}\tau)^{\text{N}}$$

$$\text{or} \quad \tau_{Nreactor} = \text{N}\tau = \frac{N}{k}[(\frac{C_0}{C_N})^{1/N}\text{-1}]$$

❋若 N→∞

$$⇘\ \tau_{Nreactor} = \text{N}\tau = \frac{N}{k}[(\frac{C_0}{C_N})^{1/N}\text{-1}] = \frac{1}{k}\ln\frac{C_0}{C_N} = \text{-}\frac{1}{k}\ln(1-X_N)$$

- ◆與 page 4-8 的 PFR 之 First-order reaction 相同。而事實上，**串聯的 CSTR 越多，其特性越趨近於 PFR。當串聯的 CSTR 數目是∞時，即變成 PFR。**
- ◆比較 N 個 CSTR 與 PFR 的操作狀況可得到下圖 (請參閱課本 Figure 6-5，注意：該圖適用 First-order reaction)：



❷$-r = \text{kC}^2$ 型式的 Second-order reaction

$$\tau = \frac{C_0 V_i}{F_0} = \frac{V_i}{v} = \frac{C_0(X_i - X_{i-1})}{-\gamma_{Ai}}$$

$$\because \varepsilon = 0 \quad \therefore \text{-}\gamma_{Ai} = \text{-}\frac{dC_i}{dt} = kC_i^2$$

$$\therefore \tau_i = \frac{C_0[(1 - C_i/C_0) - (1 - C_{i-1}/C_0)]}{-\gamma_{Ai}} = \frac{C_{i-1} - C_i}{kC_i^2}$$

●第一個 CSTR：$\tau_1=\dfrac{C_0-C_1}{kC_1^2}$ ➔ $kC_1^2\tau_1+C_1-C_0=0$

$$\therefore C_1=\frac{-1+\sqrt{1+4k\tau_1C_0}}{2k\tau_1}$$

●第二個 CSTR：$\tau_2=\dfrac{C_1-C_2}{kC_2^2}$ ➔ $kC_2^2\tau_2+C_2-C_1=0$

$$\therefore C_2=\frac{-1+\sqrt{1+4k\tau_2C_1}}{2k\tau_2}$$

但 $\tau_1=\tau_2=$ -----

$$\therefore C_2=\frac{-1+\sqrt{1+4k\tau\ (\frac{-1+\sqrt{1+4k\tau C_0}}{2k\tau})}}{2k\tau}$$

$$=\frac{1}{2k\tau}[-1+\sqrt{1+(-2+2\sqrt{1+4k\tau C_0})}\,]$$

$$=\frac{1}{2k\tau}[-1+\sqrt{-1+2\sqrt{1+4k\tau C_0}}\ ]$$

$$=\frac{1}{4k\tau}[-2+2\sqrt{-1+2\sqrt{1+4k\tau C_0}}\ ]$$

$$C_3=\frac{-1+\sqrt{1+4k\tau\ C_2}}{2k\tau}\ =\text{----}$$

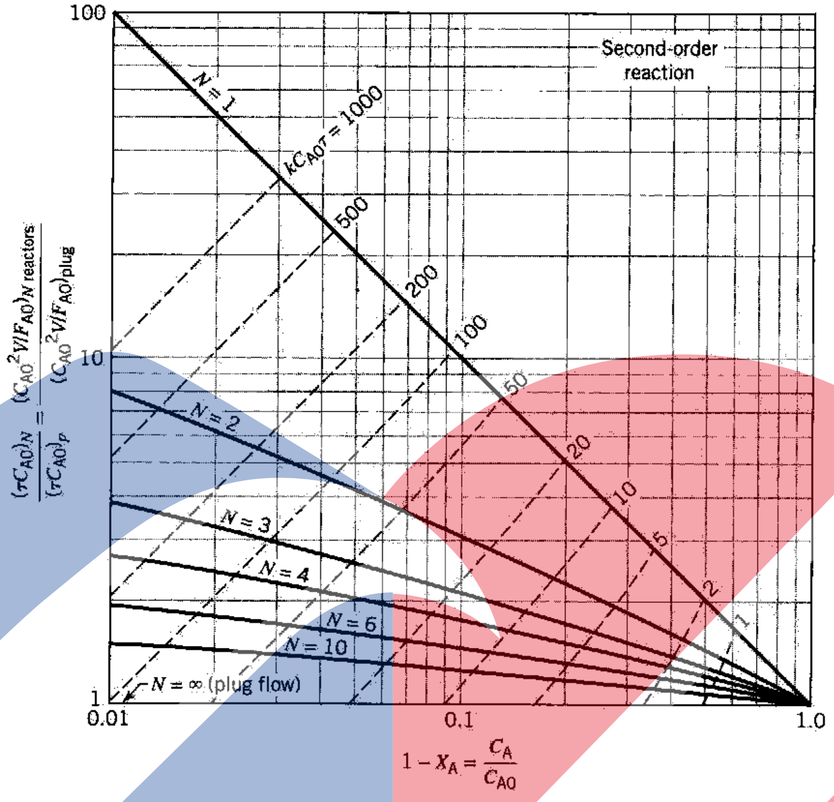
$$=\frac{1}{4k\tau}[-2+2\sqrt{-1+2\sqrt{-1+2\sqrt{1+4k\tau C_0}}}\ ]$$

$$\therefore\ C_N=\frac{1}{4k\tau_i}\left(-2+2\sqrt{\left.\begin{matrix}\vdots\\ -1\cdots+2\sqrt{-1+2\sqrt{1+4C_0k\tau_i}}\end{matrix}\right\}N}\right)$$

❸For plug flow reactor

$$\frac{C_0}{C_N}=1+C_0k\tau_p \quad \text{----}$$

※下圖是 2nd-order reaction 的操作狀況(請參閱課本 Figure 6.6 的圖較清晰)。和前面一樣，**串聯的 CSTR 越多，其特性越趨近於 PFR。當串聯的 CSTR 數目是∞時，即變成 PFR**。



Example 5-5:

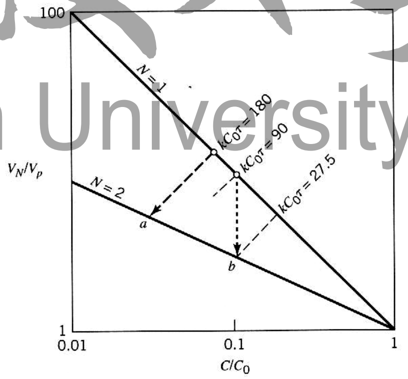
At present 90% of reactant A is converted into product by a second-order reaction in a single mixed flow reactor. We plan to place a second reactor similar to the one being used in series with it.

(a)For the same treatment rate as that used at present, how will this addition affect the conversion of reactant?

$X_A = 0.972$

(b)For the same 90% conversion, by how much can the treatment rate be increased?

N=1 的 6.55 倍



Example 5-6:

A liquid phase, first order reaction was carried out isothermally in three CSTR reactors in series. It was known that the second reactor was as large as the first reactor, and the third reactor was x times larger than the first one. It was also assumed that the density was constant throughout the system. If 30% conversion was achieved in the first reactor, what should the x be in order to achieve a total conversion of 81.95% ?

x = 3.95

Example 5-7:

At present 80% of reactant is converted into product by a first order reaction($A \rightarrow B$) in a single mixed flow reactor. We plan to place a second reactor similar to the one being used in series or in parallel with it. For the same conversion, by how much can the treatment rate be increased if we operate these two units.

(a)in parallel and (b)in series

Example 5-8:

How do you prove that a liquid reaction (A→R) process of using two equal size CSTRs in series (each CSTR has a volume of V) is better than the process using one CSTR of volume 2V or not? If

(a)reaction rate is zero order.

(b)reaction rate is first order.

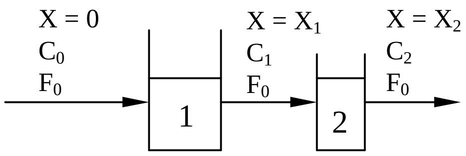
(Note: derive the proof in terms of outlet concentration or conversion)

3.Determineing the best system for a given conversion

(1)Suppose we want to find the minimum size of two mixed flow reactors in series to achieve a specified conversion.

- For the first reactor

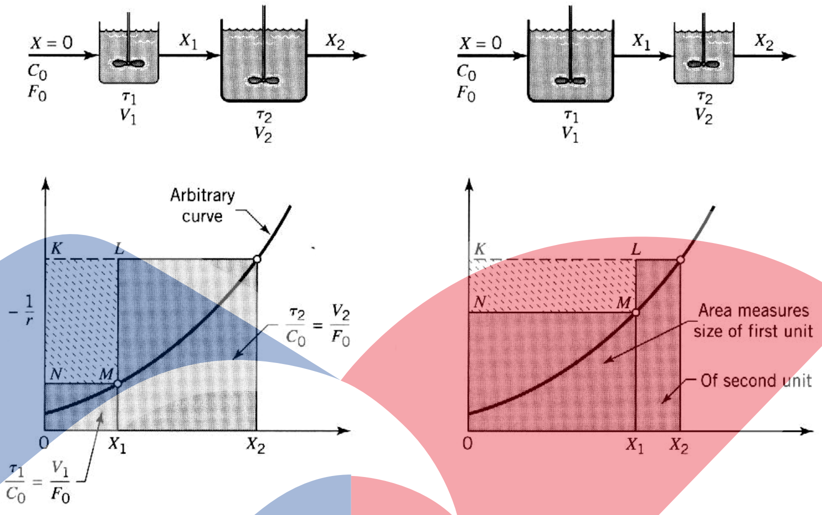
$$\frac{\tau_1}{C_0} = \frac{X_1 - 0}{-r_1}$$



- For the second reactor

$$\frac{\tau_2}{C_0} = \frac{X_2 - X_1}{-r_2}$$

(2)在相同進料條件與得到相同出口轉化率的前提下，大小不同 reactor 的排列方式將影響到 X_1 值與反應器體積的大小。



❶As the intermediate conversion X_1 changes

↳ the size ratio of these two reactors (two shaded areas) }會不同
the total volume of the two vessels (the total shaded area)

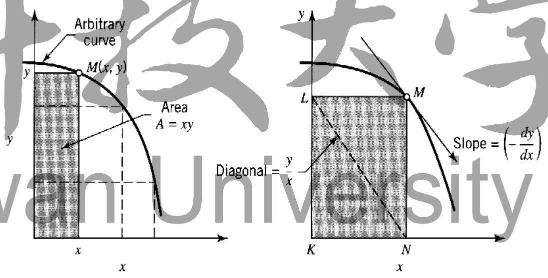
❷The total reactor volume is as small as possible when the rectangle KLMN is as large as possible.

❸We construct a rectangle between the x-y axes and touching the arbitrary curve at point M(x,y).[參考下頁的圖(即課本 Figure 6.11)]

- ●The area of the rectangle is A = xy
- ●The area is maximized when

$$dA = xdy + ydx = 0$$

$$\text{or} \quad -\frac{dy}{dx} = \frac{y}{x}$$



◆此狀況代表

M 點在曲線斜率($-\frac{dy}{dx}$) = 矩形對角線 NL 的斜率($\frac{y}{x}$)時

↳❈其面積為極大。

❈由於曲線種類無限➔此點可能不存在，但也可能不只一點。

❈對 n > 0 的反應動力學而言，常只有一個極值。

❹利用上述方法即可找出串聯的兩個 CSTR 之最佳體積比值。

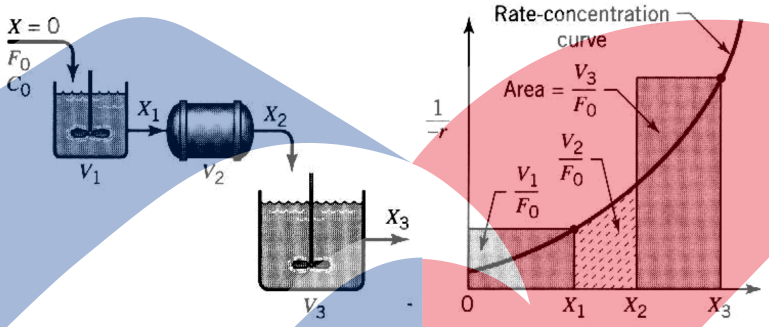
①就 1st-order reaction 而言 ➔ 等容反應器最佳。

②就 n > 1 的 reaction 而言 ➔ 體積較小的反應器放在前面較佳。

③就 n < 1 的 reaction 而言 ➔ 體積較大的反應器放在前面較有利。

4.Reactors of different types in series:

(1)下圖(即課本 Figure 6-12)是不同類型 reactor 串聯的一例：



●reactor 1 ➔ $\frac{V_1}{F_0}=\frac{X_1-X_0}{(-r)_1}$ ●reactor 2 ➔ $\frac{V_2}{F_0}=\int_{X_1}^{X_2}\frac{dX}{(-r)_2}$

●reactor 3 ➔ $\frac{V_3}{F_0}=\frac{X_3-X_2}{(-r)_3}$

(2)一般而言，依下列通則來考慮反應器的排列方式最為理想：

❶若 n > 1 ➔ rate-concentration curve 會下凹 ➔ reactant 濃度需儘可能高 ➔ 所以，排列方式應為 PFR → 小的 CSTR → 大的 CSTR

❷若 n < 1 ➔ rate-concentration curve 會上凸 ➔ reactant 濃度需儘可能低 ➔ 所以，排列方式應為大的 CSTR →小的 CSTR → PFR

(3)真正在解題時，作圖法要會；逐步算出一個一的反應器的結果亦非常重要，這需要靠耐心與熟悉公式了！

Example 5-9:

已知反應 A + R → R + R 的 rate equation, $-r_A = kC_AC_R$，而 rate constant k = 1.0 liter/mol·min。若進料含有 99% 的 A 與 1%的 R，今欲得到含 90% 的 R 之產物且濃度固定為 $C_{A0} + C_{R0} = C_A + C_R = 1.0$ mol/liter。則使用下列反應器所需的滯留時間為何？(A)於 CSTR 中 (B)於 PFR 中 (C)串聯一個 CSTR 與一個 PFR。

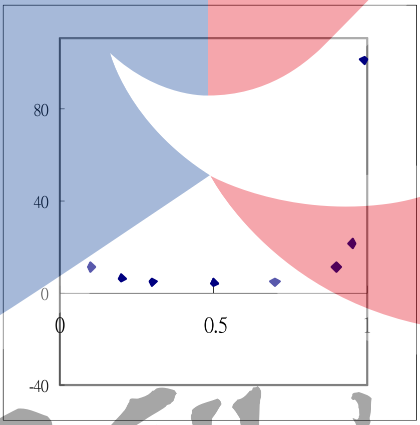
Sol： CSTR ➔ $\tau = \dfrac{C_{A0}V}{F_{A0}} = C_{A0}[\dfrac{X_1 - X_0}{(-r_A)}]$

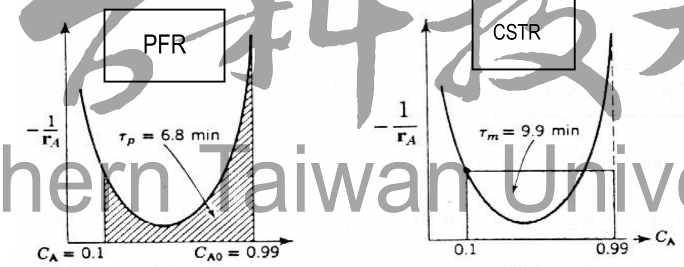
PFR ➔ $\tau = \dfrac{C_{A0}V}{F_{A0}} = C_{A0} \int_{X_0}^{X_1} \dfrac{dX}{(-r_A)}$

但 $-r = kC_AC_R$ ➔ 用計算法並不易得到答案

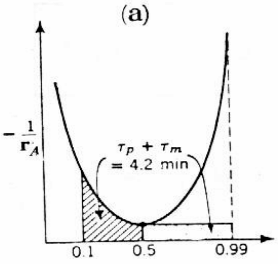
∴使用以 $1/-r_A$ 對 C_A 作圖的圖解法 ➔ 求出 $-r_A = kC_AC_R$

C_A	C_R	$-r_A = kC_AC_R$	$1/(-r_A)$
0.99	0.01	0.0099	101.01
0.95	0.05	0.0475	21.05
0.9	0.1	0.09	11.11
0.7	0.3	0.21	4.76
0.5	0.5	0.25	4
0.3	0.7	0.21	4.76
0.2	0.8	0.16	6.25
0.1	0.9	0.09	11.11





(a) (b)



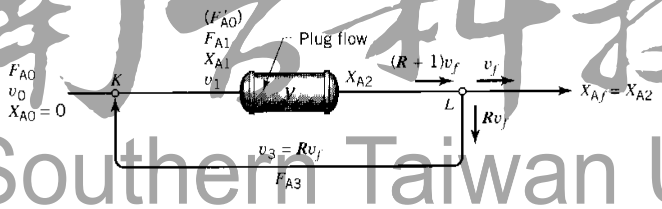
(c)

先 CSTR 再放 PFR
τ_m = 2.0 分鐘； τ_p = 2.2 分鐘

Example 5-10:

An elementary liquid phase reaction $A + B \rightarrow R$ is conducted isothermally in a reactor system with equimolar feed ration of A and B. The reactor system is a mixed flow reactor with a subsequent plug flow reactor of equal size. The reactor system can give 90% final conversion of A. What will be the final conversion of A if reversing the order of the two units, and all else unchanged.

§5-3.Recycle reactor



Recycle reactor 的示意圖
(請詳看課本 Figure 6-13)

1. Recycle reactor: A reactor that divides the product stream from a plug flow reactor and return a portion of it to the entrance of the reactor.

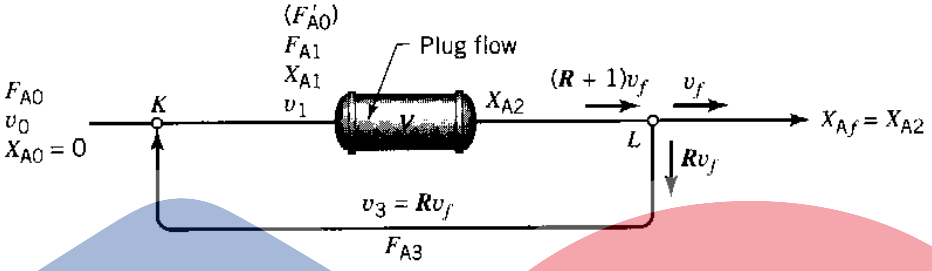
2. Recycle ratio R is defined as

$$R = \frac{\text{Volume of fluid returned to the reactor entrance}}{\text{Volume leaving the system}}$$

●R=0 ➔ Plug flow reactor

●R=∞ ➔ Mixed flow reactor

➔ 循環操作提供 PFR 獲得不同程度逆混合的方法。



3.根據上圖與 PFR 的特性式：

$$\frac{V}{F'_{A0}}=\int_{X_{A1}}^{X_{A2}=X_{Af}}\frac{dX_A}{-r_A} \qquad \text{----(A)}$$

(1) F'_{A0} : the feed rate of A entering the reactor (fresh feed + recycle)

$\therefore F'_{A0}=(R+1)F_{A0}$

(2) $C_A=C_{A0}\dfrac{(1-X_A)}{(1+\varepsilon_A X_A)}$ ➔ $X_{A1}=\dfrac{1-(C_{A1}/C_{A0})}{1+\varepsilon_A(C_{A1}/C_{A0})}$ (B)

(3) $R=\dfrac{v_f}{v_3}$ ➔ $v_3=Rv_f$

$$C_{A1}=\frac{F_{A1}}{v_1}=\frac{F_{A0}+F_{A3}}{v_0+Rv_f}=\frac{F_{A0}+RF_{A0}(1-X_{Af})}{v_0+Rv_0(1+\varepsilon_A X_{Af})}=C_{A0}\left(\frac{1+R-RX_{Af}}{1+R+R\varepsilon_A X_{Af}}\right)$$

代入式(B) $\therefore X_{A1}=\dfrac{1-\dfrac{1+R-RX_{Af}}{1+R+R\varepsilon_A X_{Af}}}{1+\varepsilon_A\left(\dfrac{1+R-RX_{Af}}{1+R+R\varepsilon_A X_{Af}}\right)}$

$$=\frac{(1+R+R\varepsilon_A X_{Af})-(1+R-RX_{Af})}{(1+R+R\varepsilon_A X_{Af})+(\varepsilon_A+\varepsilon_A R-\varepsilon_A RX_{Af})}$$

$$=\frac{R\varepsilon_A X_{Af}+RX_{Af}}{1+R+\varepsilon_A+\varepsilon_A R}=\frac{RX_{Af}(1+\varepsilon_A)}{(1+R)(1+\varepsilon_A)}=\frac{RX_{Af}(1+\varepsilon_A)}{(1+R)(1+\varepsilon_A)}$$

$$=\left(\frac{R}{R+1}\right)X_{Af}$$

(4) $\therefore \dfrac{V}{F'_{A0}}=\displaystyle\int_{X_{A1}}^{X_{A2}=X_{Af}}\frac{dX_A}{-r_A}$ ➔ $\dfrac{V}{(R+1)F_{A0}}=\displaystyle\int_{X_{A1}}^{X_{A2}=X_{Af}}\frac{dX_A}{-r_A}$

$$\rightarrow \frac{V}{F_{A0}} = (R+1)\int_{\left(\frac{R}{R+1}\right)X_{Af}}^{X_{Af}} \frac{dX_A}{-r_A} \qquad \text{------- any } \varepsilon_A \ \& \ X_{A0} = 0$$

$$\tau = C_{A0}\frac{V}{F_{A0}} = -(R+1)\int_{\left(\frac{C_{A0}+RC_{Af}}{R+1}\right)}^{C_{Af}} \frac{dC_A}{-r_A} \qquad \text{-------} \ \varepsilon_A = 0 \ \& \ X_{A0} = 0$$

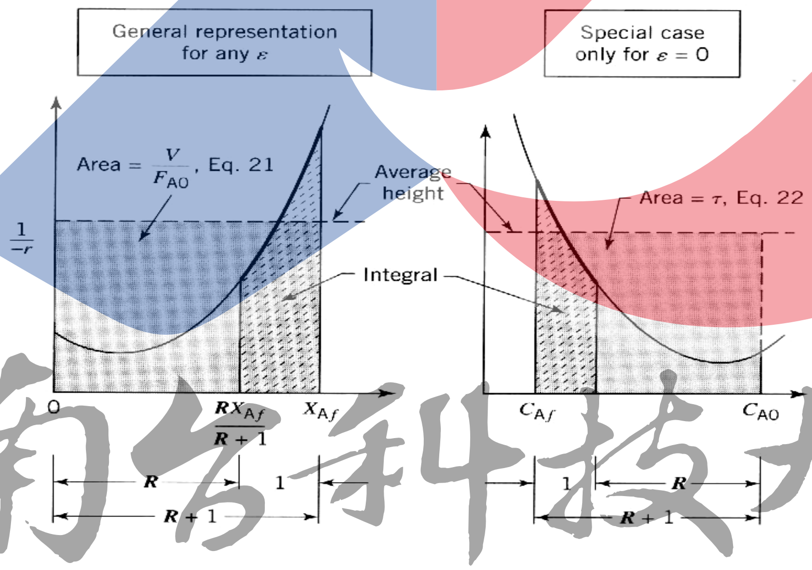
$\varepsilon_A = 0$ 時，(B)式得 $C_{A1} = C_{A0}\left(\frac{1+R-RX_{Af}}{1+R+R\varepsilon_A X_{Af}}\right) = C_{A0}\left(\frac{1+R-RX_{Af}}{1+R}\right)$

但 $X_{Af} = \frac{C_{A0}-C_{Af}}{C_{A0}}$

$$\therefore C_{A1} = C_{A0}\left(\frac{1+R-RX_{Af}}{1+R}\right) = C_{A0}\left(\frac{1+R-R\frac{C_{A0}-C_{Af}}{C_{A0}}}{1+R}\right)$$

$$= \frac{C_{A0}+C_{A0}R-R(C_{A0}-C_{Af})}{1+R} = \frac{C_{A0}+RC_{Af}}{1+R}$$

$$\therefore \tau = C_{A0}\frac{V}{F_{A0}} = -(R+1)\int_{\left(\frac{C_{A0}+RC_{Af}}{R+1}\right)}^{C_{Af}} \frac{dC_A}{-r_A} \qquad \text{-------} \ \varepsilon_A = 0 \ \& \ X_{A0} = 0$$



Example 5-11:

The conversion of an elementary liquid phase second-order reaction 2A → 2R is ⅔ when operated in an isothermal plug flow reactor with a recycle ratio of unity. What will be the conversion if the recycle stream is shut off. 3/4