University of Anbar

College of Engineering

Chemical and Petrochemical Engineering Department

Chemical Reacior Design

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Lecture No. 12

Reactors of Different Types in Series

If reactors of different types are put in series, such as a mixed flow reactor followed by a plug flow reactor which in turn is followed by another mixed flow reactor, we may write for the three reactors

$$\frac{V_1}{F_0} = \frac{X_1 - X_0}{(-r)_1}, \quad \frac{V_2}{F_0} = \int_{X_1}^{X_2} \frac{dX}{-r}, \quad \frac{V_3}{F_0} = \frac{X_3 - X_2}{(-r)_3}$$

These relationships are represented in graphical form in Fig. 6.12.

Best Arrangement of a Set of Ideal Reactors. For the most effective use of a given set of ideal reactors we have the following general rules:

1. For a reaction whose rate-concentration curve rises monotonically (any nth-order reaction, $n > 0$) the reactors should be connected in series. They should be ordered so as to keep the concentration of reactant as high as possible if the rate-concentration curve is concave ($n > 1$), and as low as possible if the curve is convex ($n < 1$). As an example, for the case of Fig. 6.12 the ordering of units should be plug, small mixed, large mixed, for $n > 1$; the reverse order should be used when $n < 1$.
2. For reactions where the rate-concentration curve passes through a maximum or minimum the arrangement of units depends on the actual shape of curve, the conversion level desired, and the units available. No simple rules can be suggested.
3. Whatever may be the kinetics and the reactor system, an examination of the $1/(-r_A)$ vs. C_A curve is a good way to find the best arrangement of units.

RECYCLE REACTOR

In certain situations it is found to be advantageous to divide the product stream from a plug flow reactor and return a portion of it to the entrance of the reactor. Let the *recycle ratio* $\boldsymbol{R}$ be defined as

$$\boldsymbol{R} = \frac{\text{volume of fluid returned to the reactor entrance}}{\text{volume leaving the system}} \quad \textbf{(15)}$$

This recycle ratio can be made to vary from zero to infinity. Reflection suggests that as the recycle ratio is raised the behavior shifts from plug flow ($\boldsymbol{R} = 0$) to mixed flow ($\boldsymbol{R} = \infty$). Thus, recycling provides a means for obtaining various degrees of backmixing with a plug flow reactor. Let us develop the performance equation for the recycle reactor.

Consider a recycle reactor with nomenclature as shown in Fig. 6.13. Across the reactor itself Eq. 5.18 for plug flow gives

$$\frac{V}{F'_{A0}} = \int_{X_{A1}}^{X_{A2}=X_{Af}} \frac{dX_A}{-r_A} \quad \textbf{(16)}$$

where F'_{A0} would be the feed rate of A if the stream entering the reactor (fresh feed plus recycle) were unconverted. Since F'_{A0} and X_{A1} are not known directly, they must be written in terms of known quantities before Eq. 16 can be used.

The flow entering the reactor includes both fresh feed and the recycle stream. Measuring the flow split at point L (point K will not do if $\varepsilon \neq 0$) we then have

$$F'_{A0} = \begin{pmatrix}\text{A which would enter in an}\\ \text{unconverted recycle stream}\end{pmatrix} + \begin{pmatrix}\text{A entering in}\\ \text{fresh feed}\end{pmatrix}$$
$$= \boldsymbol{R}F_{A0} + F_{A0} = (\boldsymbol{R} + 1)F_{A0} \quad \textbf{(17)}$$

Now to the evaluation of X_{A1}: from Eq. 4.5 we may write

$$X_{A1} = \frac{1 - C_{A1}/C_{A0}}{1 + \varepsilon_A C_{A1}/C_{A0}} \quad \textbf{(18)}$$

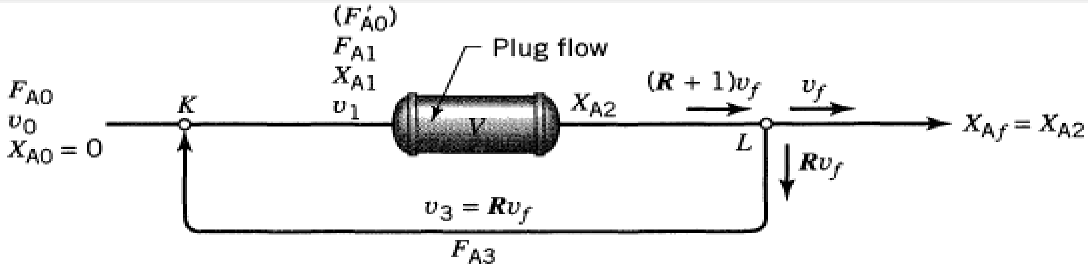

Figure 6.13 Nomenclature for the recycle reactor.

$$C_{A1} = \frac{F_{A1}}{v_1} = \frac{F_{A0} + F_{A3}}{v_0 + \mathbf{R}v_f} = \frac{F_{A0} + \mathbf{R}F_{A0}(1 - X_{Af})}{v_0 + \mathbf{R}v_0(1 + \varepsilon_A X_{Af})} = C_{A0}\left(\frac{1 + \mathbf{R} - \mathbf{R}X_{Af}}{1 + \mathbf{R} + \mathbf{R}\varepsilon_A X_{Af}}\right) \quad \textbf{(19)}$$

Combining Eqs. 18 and 19 gives X_{A1} in terms of measured quantities, or

$$X_{A1} = \left(\frac{\mathbf{R}}{\mathbf{R}+1}\right) X_{Af} \quad \textbf{(20)}$$

Finally, on replacing Eqs. 17 and 20 in Eq. 16 we obtain the useful form for the performance equation for recycle reactors, good for any kinetics, any ε value and for $X_{A0} = 0$.

$$\frac{V}{F_{A0}} = (\mathbf{R} + 1)\int_{\left(\frac{\mathbf{R}}{\mathbf{R}+1}\right) X_{Af}}^{X_{Af}} \frac{dX_A}{-r_A} \quad \ldots \text{any } \varepsilon_A \quad \textbf{(21)}$$

For the special case where density changes are negligible we may write this equation in terms of concentrations, or

$$\tau = \frac{C_{A0}V}{F_{A0}} = -(\mathbf{R} + 1)\int_{\frac{C_{A0} + \mathbf{R}C_{Af}}{\mathbf{R}+1}}^{C_{Af}} \frac{dC_A}{-r_A} \quad \ldots \varepsilon_A = 0 \quad \textbf{(22)}$$

These expressions are represented graphically in Fig. 6.14.

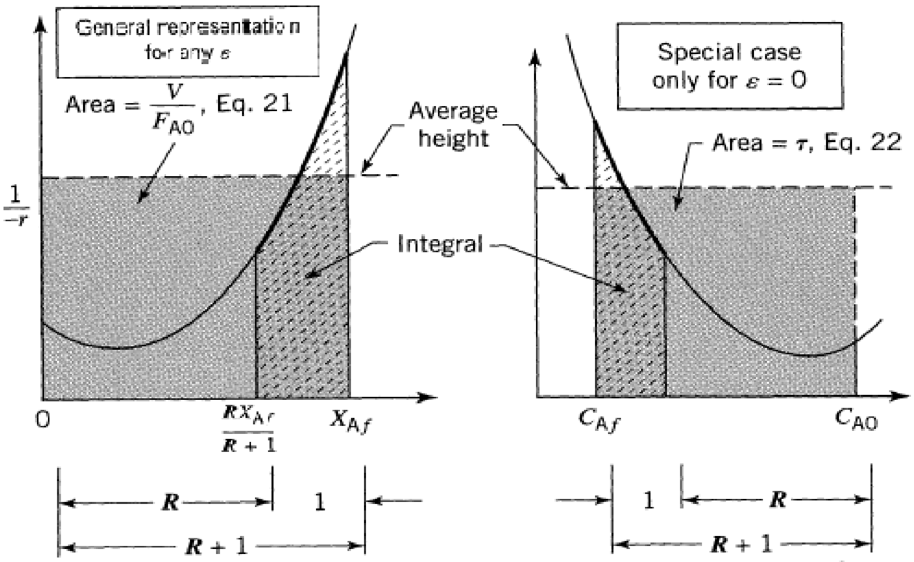

Figure 6.14 Representation of the performance equation for recycle reactors.

For the extremes of negligible and infinite recycle the system approaches plug flow and mixed flow, or

$$\frac{V}{F_{A0}} = (\boldsymbol{R}+1)\int_{\frac{\boldsymbol{R}}{\boldsymbol{R}+1}X_{Af}}^{X_{Af}} \frac{dX_A}{-r_A}$$

$\boldsymbol{R} = 0$ → $\frac{V}{F_{A0}} = \int_A^{X_{Af}} \frac{dX_A}{-r_A}$ (plug flow)

$\boldsymbol{R} = \infty$ → $\frac{V}{F_{A0}} = \frac{X_{Af}}{-r_{Af}}$ (mixed flow)

The approach to these extremes is shown in Fig. 6.15.

Integration of the recycle equation gives, for *first-order reaction*, $\varepsilon_A = 0$,

$$\frac{k\tau}{\boldsymbol{R}+1} = \ln\left[\frac{C_{A0} + \boldsymbol{R}C_{Af}}{(\boldsymbol{R}+1)C_{Af}}\right] \qquad \textbf{(23)}$$

and for *second-order reaction,* 2A → products, $-r_A = kC_A^2$, $\varepsilon_A = 0$,

$$\frac{kC_{A0}\tau}{\boldsymbol{R}+1} = \frac{C_{A0}(C_{A0} - C_{Af})}{C_{Af}(C_{A0} + \boldsymbol{R}C_{Af})} \qquad \textbf{(24)}$$

The expressions for $\varepsilon_A \neq 0$ and for other reaction orders can be evaluated, but are more cumbersome.

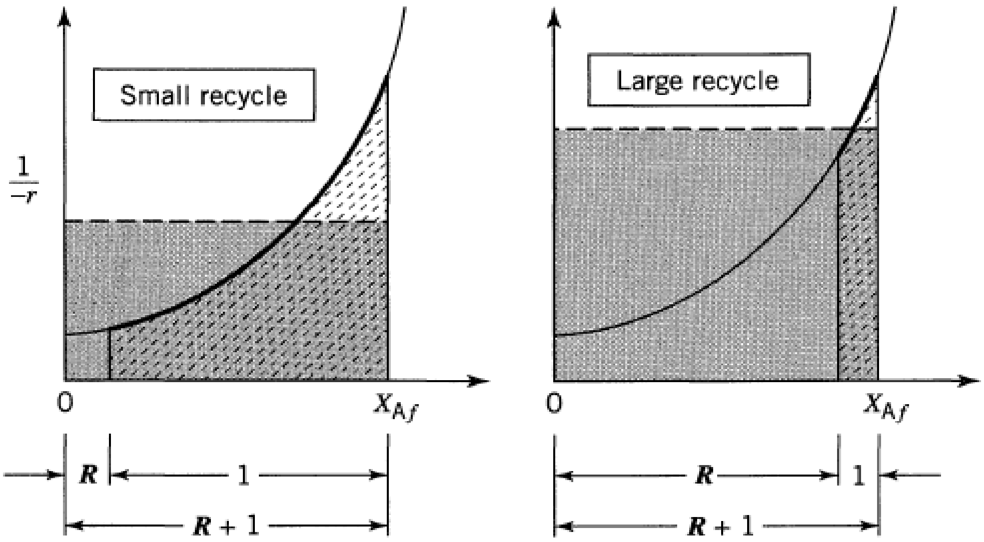

Figure 6.15 The recycle extremes approach plug flow ($\boldsymbol{R} \rightarrow 0$) and mixed flow ($\boldsymbol{R} \rightarrow \infty$).

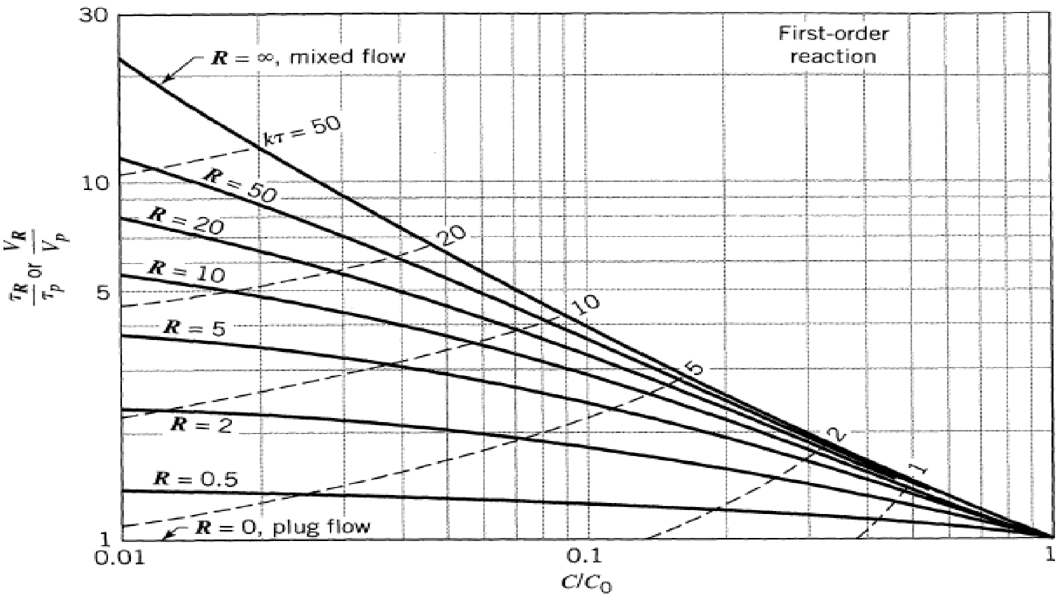

Figure 6.16 Comparison of performance of recycle and plug flow for first-order reactions

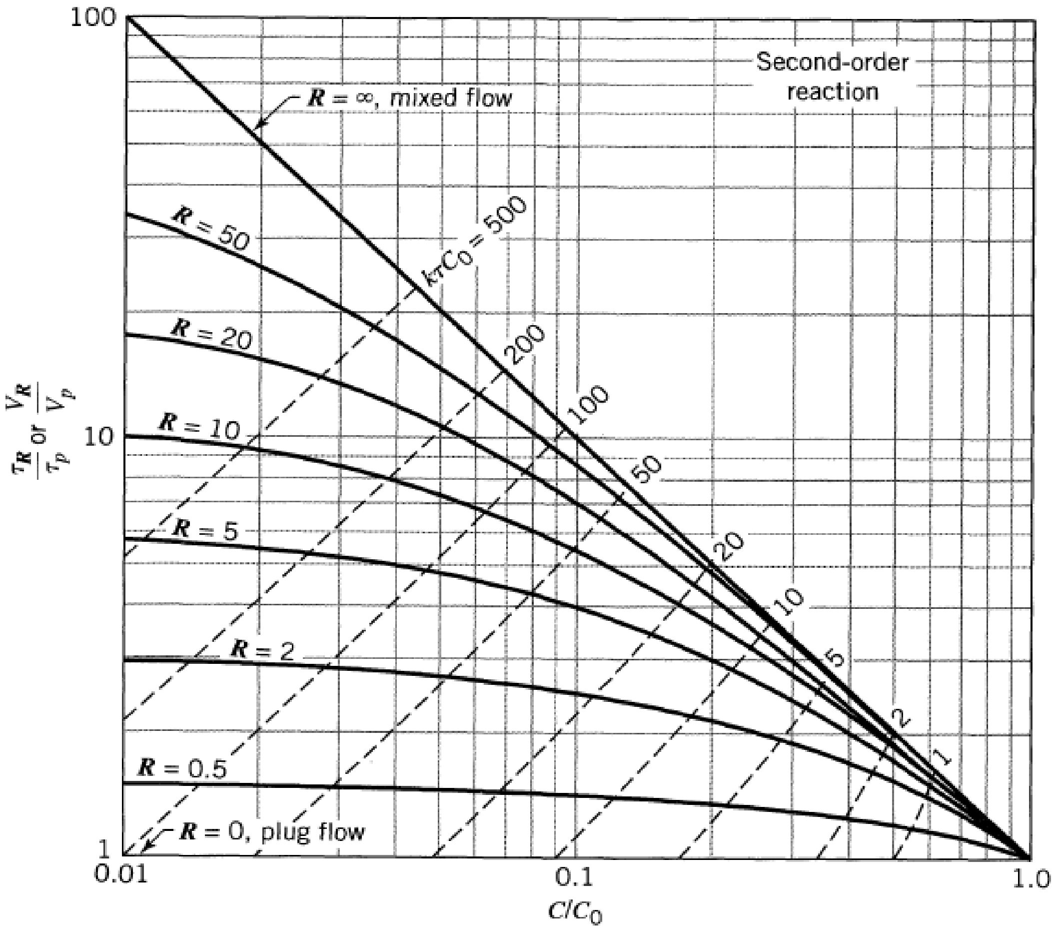

Figure 6.17 Comparison of performance of recycle reactors with plug flow reactors for elementary second-order reactions (Personal communication, from T. J. Fitzgerald and P. Fillesi):

Figures 6.16 and 6.17 show the transition from plug to mixed flow as ***R*** increases, and a match of these curves with those for *N* tanks in series (Figs. 6.5 and 6.6)