MULTIPHASE REACTORS

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Contents

Summary

The chapter describes basic issues in the selection, design and operation of multiphase reactors. Industrial applications of multiphase reactors are discussed. The up-to-date information on current research and future developments in the field is provided.

1. Introduction

Chemical reactors form the heart of any chemical plant. Here, the raw materials are chemically converted into the final products. On the efficiency of this conversion depends not only the economy but also the environmental performance of the entire

production process. Contrary to some common misconceptions, most industrially important chemical reactions are not carried out in a single phase. Vast majority of those reactions involve two or more phases, including liquids, gases and/or solids, in contact. The phases can play various roles in the reactor, not only as the source or storage of the reactants to be converted but also as catalysts for the reactions or simply as means to improve mixing or transport processes in the reactor.

All those roles of the phases are discussed in this chapter. Section 2 provides the reader with basic understanding of the phase contacting in the chemical reactors. In Section 3 some fundamental design issues in multiphase reactors are discussed, including the selection of the optimum type of multiphase reactor, based on the assumed selection criteria. In Section 4 basic types of multiphase reactors are described. Those basic types of multiphase reactors and the corresponding phase contacting patterns are listed in Figure 1. Finally, Section 5 brings up-to-date information on current research developments and future outlook in the field of multiphase reactors.
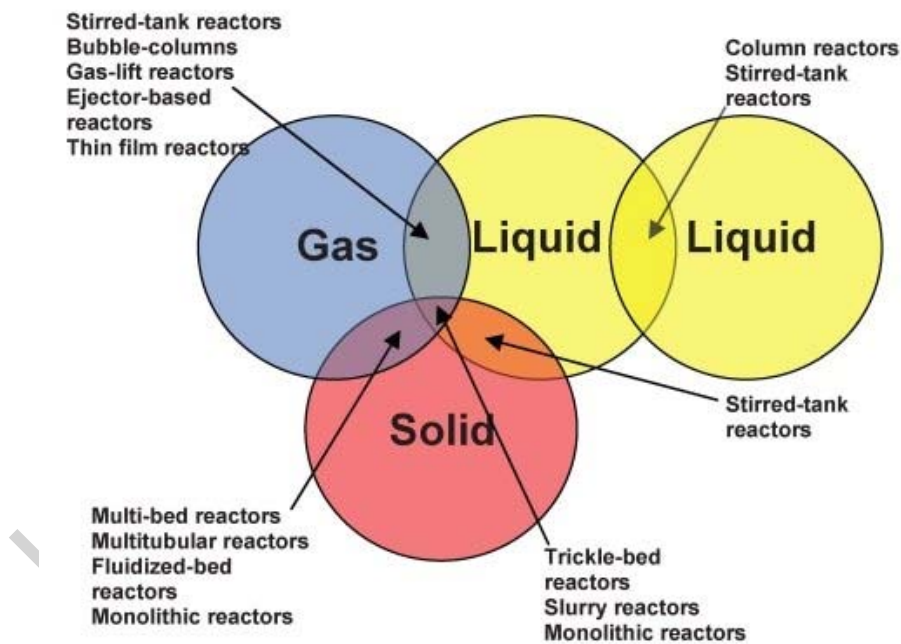

Figure 1. Most important types of multiphase reactors and phase contacting patterns discussed in this chapter.

2. Fundamentals of Phase Contacting in Chemical Reactors

Basically, in single-phase reactors the only physical process influencing the efficiency of chemical conversion is the mixing of reacting components with each other and sometimes also with a homogeneous catalyst. In multiphase reactors the situation is much more complex. Here, not only the reacting components must be efficiently mixed, but also conditions have to be created to transport those components efficiently across the interfaces between the phases, such as surface of a gas bubble or a surface of a solid

catalyst particle.

The most important mass transfer theory in chemical engineering, the so-called "film-theory" represents the barrier to mass transport across the interface by a thin film, in which the concentration of the transported components drops due to diffusional resistance. For instance, in contacting gas phase (e.g. in form of a bubble) with liquid, two diffusional films on both sides of the interface can be distinguished, as it is shown in Figure 2.

In the film theory, the rate, at which component "i" is transported from the bulk of one phase to another can be generally expressed by the following equation:

$$N_i = k_c.a.\Delta c_i \tag{1}$$

where

N_i : mass transfer rate [mol/m^3/s]
k_c : mass transfer coefficient [m/s]
a : specific interfacial area [m^2/m^3]
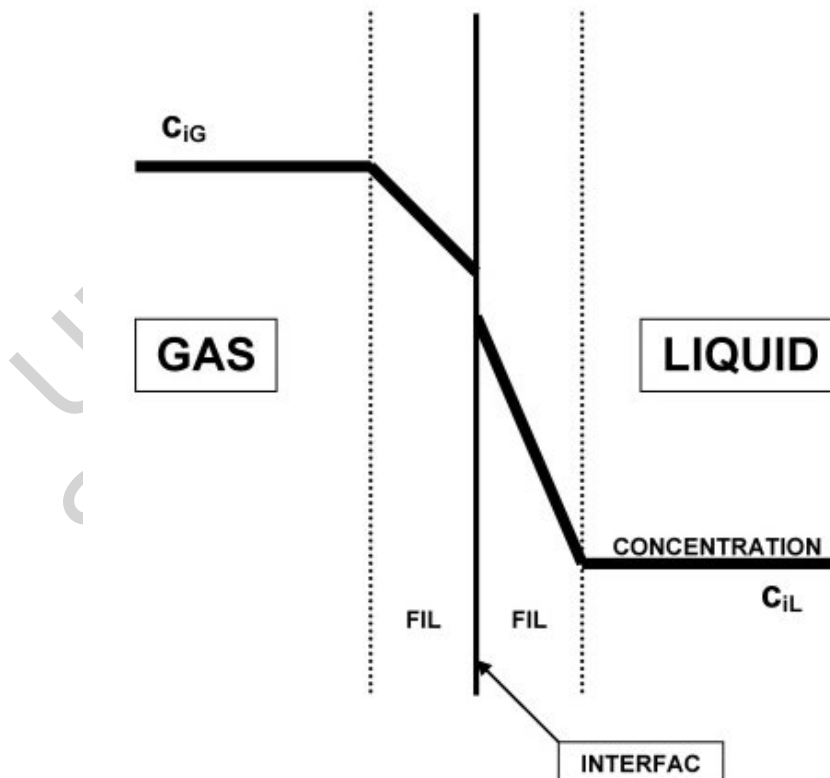ΔC_i : concentration difference [mol/m^3]

Figure 2. Mass transfer films at the gas-liquid interface. Concentration of component "i" drops as a result of diffusional resistance.

The mass transfer coefficient depends primarily on the hydrodynamic conditions and the physico-chemical properties of the phases involved. The engineering formulas correlating the mass transfer coefficients with system hydrodynamics and physico-chemical properties are usually expressed by the dimensionless numbers in general form:

$$Sh = A.Re^n.Sc^m \tag{2}$$

where

Sh is Sherwood Number $= (K_c L / D_i)$
Re is Reynolds Number $= (u \rho L / \mu)$
Sc is Schmidt Number $= (\mu / \rho D_i)$

L denotes the characteristic length (e.g. diameter), D_i – diffusivity, u – velocity, μ and ρ – fluid dynamic viscosity and density, respectively.

In gas-liquid or liquid-liquid systems also the specific interfacial area depends on system hydrodynamics and physico-chemical properties. The interfacial area between fluid and solid is obviously dependent on the size and geometrical form of the solid phase.

As one can see from the above considerations, basic steps that can be undertaken in order to improve the mass transfer rate from one phase to another include:

- In fluid-fluid systems: intensify hydrodynamics to increase mass transfer coefficient and specific interfacial area;
- In fluid-solid systems: intensify hydrodynamics to increase mass transfer coefficient and modify size/form of the solid phase to enhance interfacial area;
- In all systems: increase the concentration difference (for instance by increasing the partial pressure of the component "i" in the gaseous phase if the transport is to take place from gas to liquid).

The above briefly described issues are obviously of fundamental importance to the efficiency of the multiphase reactor operation. If the reaction kinetics is fast compared to the rate, at which one or more components are transported from the given phase to the reacting phase, one speaks about a *mass transfer-limited reaction regime*. Often used terms to describe the degree of mass transfer-limitation in a multiphase reacting system are the so-called *effectiveness factors* for fluid-solid systems and *enhancement factors* for gas-liquid systems. For instance, the effectiveness factor describing the limitation of a gas-solid catalytic reaction caused by the diffusion resistance inside the catalyst pellet is defined as:

$$\eta = \frac{\text{reaction rate observed}}{\underset{\text{(without diffusion resistances)}}{\text{reaction rate under conditions of pellet surface}}} \tag{3}$$

As one can expect, such defined effectiveness factor is strongly dependant on the ratio

between the kinetic reaction rate constant and the effective diffusivity in the catalyst pellet. This strong dependence for a first-order reaction in a flat-plate geometry of catalyst pellet is shown in Figure 2. Here ϕ denotes the so-called *Thiele modulus* defined as:

$$\phi = L \cdot \left(k_A / D_e \right)^{1/2} \tag{4}$$

where L denotes the characteristic length (e.g. plate thickness or particle diameter), k_A is the reaction rate constant and D_e is the effective diffusivity in the pellet.

The above figure let us see clearly how an increase of the plate thickness (or, similarly, catalyst pellet diameter) may result in a slow-down of the reaction in the catalyst.

Similarly, in gas-liquid systems the concept of so-called "effectiveness factor" has been introduced. The effectiveness factor is defined as:
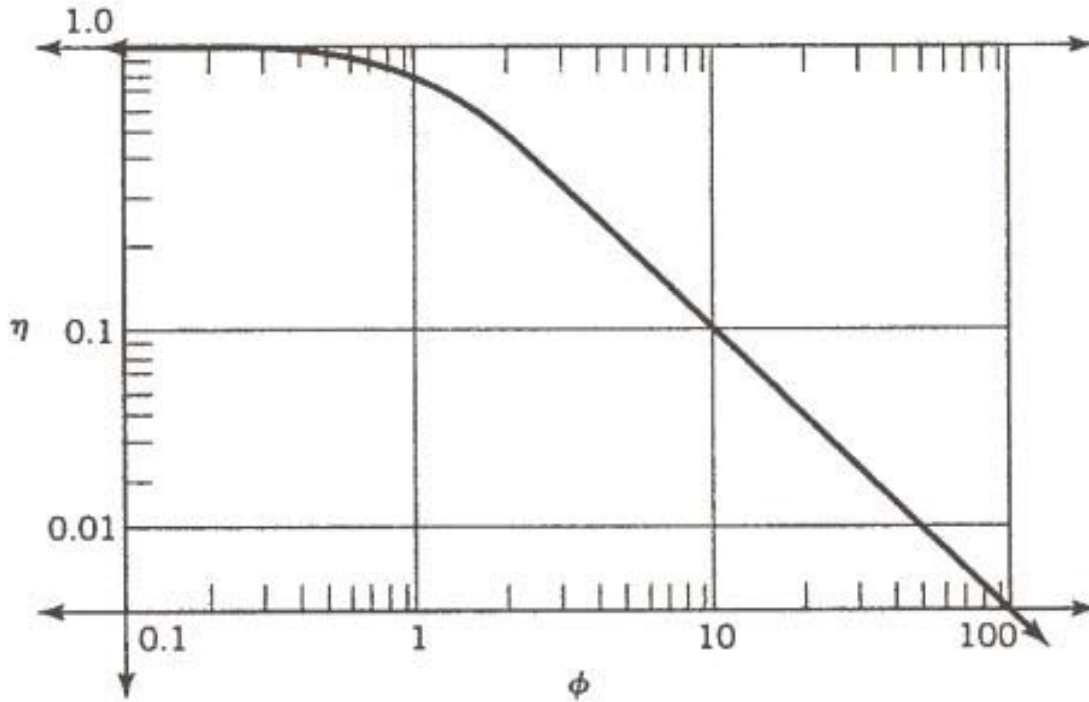

Figure 3. Gas-solid catalytic reaction. Dependence of the effectiveness factor on Thiele modulus for first-order kinetics and flat-plate geometry.

$$E = \frac{\text{rate of reaction of flux A}}{\text{maximum rate of the mass transfer of A through the liquid film}} \tag{5}$$

For instance, for a fast irreversible reaction taking place in the liquid mass transfer film only, the enhancement factor is expressed as a function of the so-called Hatta number as:

$$E = \frac{Ha}{\tanh(Ha)} \tag{6}$$

where

$$Ha = \delta_L (k_A / D_{AL}) \tag{7}$$

In the above equation δ_L denotes the thickness of the liquid mass transfer film.

In reacting systems involving gas, liquid and solid phases the mass transfer issues become even more complex. A reactant contained in the gaseous phase has to get across two interfaces and diffuse into the solid catalyst, where the chemical reaction takes place (Figure 4).
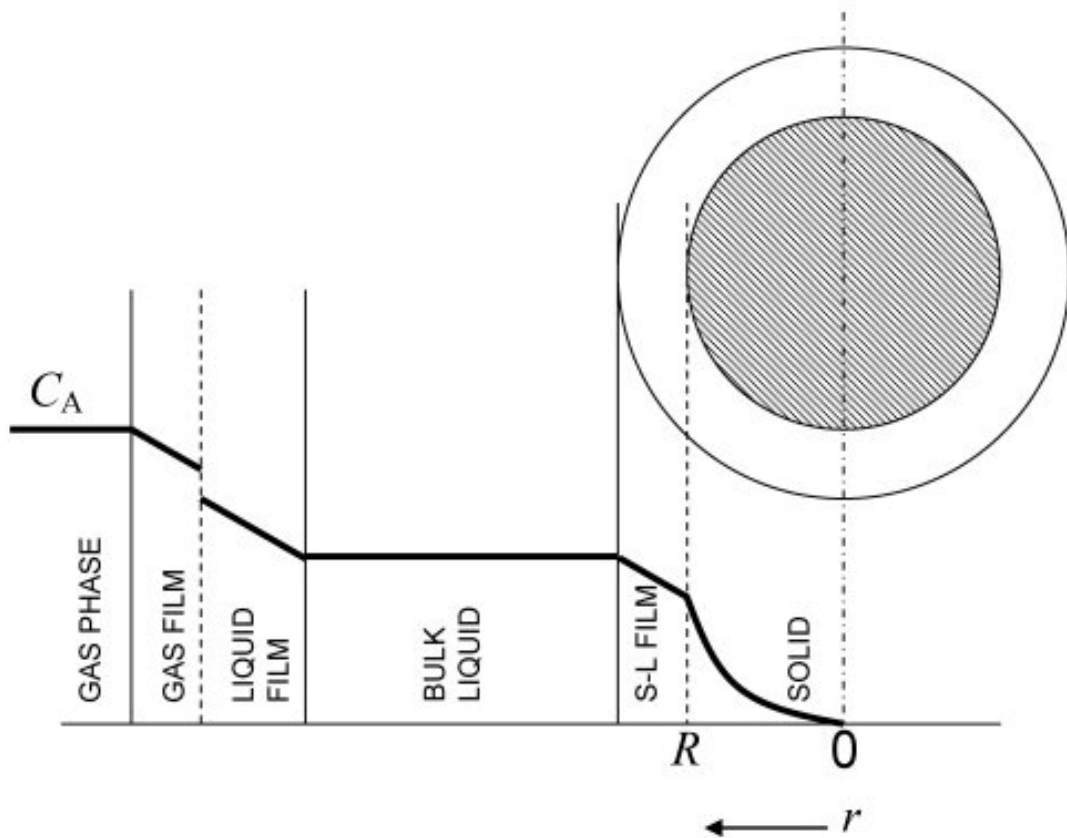

Figure 4. Mass transfer steps in gas-liquid-solid reactors.

Full analysis of the mass transfer limitations in other multiphase systems exceeds the scope of this chapter. Detailed information can be found in literature references listed at the end of the chapter.

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Biographical Sketch

Andrzej Stankiewicz is Professor of Process Intensification at Delft University of Technology. With 30 years of industrial and academic research experience, he is author or co-author of ca. 100 papers on chemical reaction engineering, industrial catalysis and process intensification, and holds several patents in the field. He is Chairman of the Dutch national Process Intensification Network (PIN-NL), and Chairman of the Working Party on Process Intensification at the European Federation of Chemical Engineering. He is co-author and co-editor of the world's first book on Process Intensification: "Re-Engineering the Chemical Processing Plant" (Marcel Dekker, 2004) and editor of Elsevier's journal "Chemical Engineering and Processing: Process Intensification". Andrzej Stankiewicz received his M.Sc. degree in chemical engineering from Warsaw University of Technology and a Ph.D. degree from the Industrial Chemistry Research Institute in Warsaw. He is Fellow of the Alexander von Humboldt Foundation in Germany and member of several national and international professional organizations.