CHARLES M. THATCHER

FUNDAMENTALS OF CHEMICAL ENGINEERING

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for many years of encouragement and friendship

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PREFACE

This book presents the fundamentals of chemical engineering in an introductory but quantitative manner. Its purpose is to provide the prospective chemical engineer with a firm foundation for further development in his chosen field by making him aware of *all* its aspects, so as to leave him both better prepared and better motivated for a meaningful learning experience. It is also intended to initiate the development of those skills which are so essential to his immediate and ultimate success: the ability to reason logically and independently, to make quantitative calculations, and to exercise engineering judgment.

Just as the practicing engineer is often called upon to submit a quick, approximate solution to a comprehensive problem, so this book is a first approximation to the study of chemical engineering. Its scope is wholly consistent with this role, depth of treatment having been made subordinate to breadth. This is not to say that the treatment is superficial. The development of basic principles—the mass balance, first and second law thermodynamics, the rate concept, and economic considerations—is rigorous and complete, and the quantitative application of these principles in the solution of practical problems is repeatedly exemplified. But, like all engineering approximations, the book leaves many details for subsequent consideration.

The first four chapters identify the types of problems the chemical engineer is expected to solve, the nature of the specialized knowledge he applies in solving such problems, and the qualitative and quantitative methods he utilizes in effecting their solution. The basic principles listed above are successively emphasized in the middle chapters, which also include a discussion of properties and property relationships. In the concluding chapters the analysis and solution of comprehensive problems pertaining to various unit operations and complex chemical processes are given primary attention.

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C. M. Thatcher

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PART I

Introduction to Chemical Engineering

Most readers of this text have already decided upon chemical engineering as a career. Unfortunately, the choice of any career is all too frequently based on inaccurate or incomplete information. Even those who consider themselves to be well informed may actually have little more than a very vague idea of what a chemical engineer is and does. Therefore, this introductory examination of the profession will insure that all readers are equally well prepared for the more advanced material which follows.

A chemical engineer can be characterized by the type of problems he is expected to solve, by the specialized knowledge he applies in solving such problems, and, in common with other branches of engineering, by the method he uses in effecting their solution. The first three chapters of this book detail each of these characteristic features in turn. The fourth chapter considers the adroit use of quantitative numerical calculations in chemical engineering.

CHAPTER 1

Definition of Chemical Engineering

Chemical engineering is closely related to the field of pure chemistry on the one hand, and to its sister branches of engineering on the other. The latter relationship properly deserves initial attention, for the chemical engineer is first and foremost an engineer. It will accordingly be advantageous to characterize the profession of engineering in general before prefixing the adjective "chemical." With the chemical engineer's identity as an engineer well established, we can then examine his role as a chemical specialist within the field of engineering.

1.1 The Engineering Profession

Even engineers themselves are not in complete agreement as to the proper definition of engineering. Fortunately, an official definition has recently been proposed by the Engineers' Council for Professional Development:*

"Engineering is the Profession in which a knowledge of the mathematical and natural sciences gained by study, experience and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the progressive well being of mankind."

* Engineers' Council for Professional Development, "26th Annual Report for the Year Ending September 30, 1958" (report of the Recognition Committee).

A paraphrase of this carefully worded statement is inadvisable, but it is convenient to examine certain aspects of the definition separately and at greater length in the development which follows, thereby providing some amplification of this basic definition of engineering. In the meantime it is suggested that the definition itself be reread carefully and thoughtfully.

It is helpful to identify more specifically the sciences referred to in the above definition. Mathematics, physics, and chemistry head the list of *basic* sciences. Less obvious (in terms of their importance to engineering) are such fields as geology, astronomy, and biology, but they are also included. Indeed, a knowledge of one or more of these secondary sciences is of critical importance in many specialized areas of engineering activity.

Attendant on the basic sciences is the field of *engineering* science, considered to be of fundamental importance even though it generally involves the *application* of basic concepts. An evaluation of engineering education by a committee of the American Society for Engineering Education resulted in a suggested breakdown of engineering science into six rather broad areas of subject matter:*

1) Mechanics of solids (statics, dynamics, and strength of materials).
2) Fluid mechanics.
3) Thermodynamics.
4) Transfer and rate mechanisms or processes (heat, mass, and momentum transfer).
5) Electrical theory (fields, circuits, electronics).
6) Nature and properties of materials (relating atomic, particle, and aggregate structure to properties).

It is patently impossible for any one person to assimilate a depth of knowledge in all areas of basic and engineering science. The obvious alternative is to specialize, and it is this practice which accounts for the existence of the various branches of engineering. Thus the electrical engineer is primarily concerned with electrical theory; the mechanical engineer with mechanics, thermodynamics, and heat transfer; the aeronautical engineer with fluid mechanics and thermodynamics; and so on.

The utilization of engineers in industry follows the same pattern, for the birth and growth of each of the major branches of engineering is a direct consequence of industry's need for a particular type of engineering specialist. In summary, then, each branch of engineering can be identified by those areas of science with which it is primarily concerned, and also by the corresponding areas of industry in which this specialized knowledge is applied.

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* American Society for Engineering Education, "Report on Evaluation of Engineering Education," June 15, 1955.

1.2 The Chemical Branch of Engineering

Chemical change in industrial processes has increased prodigiously in importance since the turn of the century. This development is perhaps most readily associated with the so-called chemical process industries; but the petroleum, food, paper, rubber, drug, and primary metals industries are typical examples of major industries which have also been affected. Even the automotive industry, generally considered to be the domain of mechanical and automotive engineers, depends on chemical processes for: tires, glass, lightweight metals, plastic materials, fuels and lubricants, paints and lacquers, and chemical specialties such as rust inhibitors and permanent anti-freeze.

Although all branches of engineering are firmly based on the underlying sciences of mathematics and physics, chemical engineering is unique because of its equally strong dependence on the science of chemistry. In the areas of engineering science, the chemical engineer gives special attention to fluid mechanics, thermodynamics, transfer processes, and the nature and properties of materials. This broad background makes him particularly well suited to handle not only those engineering problems specifically pertaining to chemistry, but all related non-chemical problems as well.

To substantiate this assertion, we need only note the dependence upon chemical engineering characterizing all industrial manufacturing processes in which chemical changes are involved: the development and operation of all phases, physical as well as chemical, of such processes are for the most part the responsibility of the chemical engineer. Since chemical change is involved in the manufacture of almost all products of importance, the tremendous potential of chemical engineering is clearly indicated.

1.3 The Realm of the Chemist

Sketchy though it be, the foregoing development should suffice to give an adequate understanding, for the present at least, of what chemical engineering is and how it differs from its sister branches of engineering. Let us now examine the other side of the family tree, i.e., the relationship between chemical engineering and chemistry. It will then be possible to present a more detailed job description for the chemical engineer.

At first glance, the definition of engineering presented earlier would seem to include chemistry as well. Careful scrutiny discloses ample grounds for excluding it, but it is indeed true that there is a close kinship between chemistry and chemical engineering. As a matter of fact, chemical engineers were originally known as industrial chemists, and this term still persists to some extent outside the United States.

The implication that chemical engineering is merely a specialty within the field of chemistry—as are physical and organic chemistry, for example—is most unfortunate. The chemical engineer is first and foremost an engineer and only secondarily a chemical specialist. The chemist, on the other hand, is not an engineer at all. The distinction can best be emphasized by means of a hypothetical example.

Consider a chemist carrying out a typical organic synthesis in an industrial laboratory: He pours liquid *A* into a flask and sets the flask over a burner to heat it. When conditions are right, he bubbles gas *B* through the liquid until the resulting reaction stops and then sets the flask aside to cool. His next step is to add a second liquid, *C*, while vigorously agitating the contents of the flask, thereupon obtaining a precipitate. The contents of the flask are next emptied into a filtering funnel, after which the wet solid residue is scraped off the filter paper onto a watch glass and evaporated to dryness. The yield is approximately one gram of final product *D*.*

When the chemist makes tests to determine the properties of compound *D*, his findings indicate that the compound has potential applications as a pharmaceutical. After a market study, the company decides to put the compound into commercial production at a rate of one ton per day. (This rate, while not unrealistic for a pharmaceutical, is actually quite low when compared to typical rates of production in other industries. Rates upwards of 50 tons per day are typical for many chemical intermediates, and plants which turn out hundreds of tons per day of heavy inorganic chemicals are not uncommon.)

A simple calculation will show that the proposed rate represents the scale-up of the chemist's original one-gram batch by a factor of more than 900,000. Even assuming that the chemist and his colleagues might turn out as many as 1,000 batches in a 24-hour day, it would be necessary for them to increase the size of their flasks, burners, filtering funnels, etc., by a factor of more than 900. The conclusion is inescapable: the bench-scale techniques of the chemist, however effective they may be in making original and exploratory investigations, are entirely unsuited for large-scale production.

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* The process described is for the most part coincident with that used to prepare 2,4,6-tripropyl-*s*-trithiane-trisulfone from butyraldehyde, hydrogen sulfide, and aqueous hydrogen peroxide. The specific identification of these compounds is not essential, and could actually detract from clarity and simplicity to the extent that it would require the repeated use of complex and unfamiliar organic nomenclature. Hypothetical reactions are used freely in this text because they can be carefully tailored to illustrate specific points. Equivalent reactions do almost invariably exist in fact.

1.4 Chemical Engineering vs. Chemistry

The foregoing correctly implies that the problems involved in producing a chemical compound on a commercial scale lie beyond the knowledge and skill of the laboratory chemist. The engineering background of the chemical engineer, on the other hand, is a significant additional qualification. It therefore falls to him to convert the chemist's laboratory-scale synthesis into full-scale production.

Mere scale-up is not the only challenge to be faced, however. The company's—and hence the engineer's—ultimate objective is not to make compound *D* but rather to make a profit. This motive is hardly as materialistic as it may sound, for it is a basic tenet in our system of free enterprise. In any event the chemical engineer must devise a process which will produce large quantities of compound *D* *economically*. Recall that this word appears in the definition of engineering, and that it automatically excludes the chemist: his sole objective is to make compound *D*, not money.

The difference between laboratory-scale and plant-scale production, even when coupled with the fact that the chemical engineer must satisfy economic restrictions not imposed on the chemist, may appear to be a trivial distinction between the fields of chemistry and chemical engineering. Actually, the detailed process ultimately specified by the chemical engineer may differ radically from that originally used by the chemist. Each point of departure introduces problems which are, for the most part, totally different from those faced by the chemist. It is this difference which justifies the existence of chemical engineering as a separate profession.

1.5 Design of a Production Process

By way of preparation for an analysis of the chemical engineering problems involved in the design of a plant for the large-scale, economical production of compound *D*, let us summarize the procedure followed by the chemist. The *schematic flow diagram* shown in Fig. 1.1 serves this purpose.

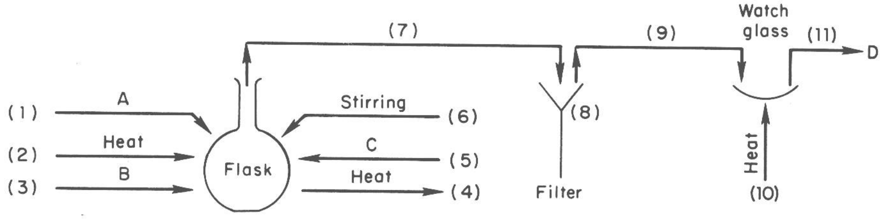

Fig. 1.1 Schematic flow diagram for the laboratory synthesis of product *D* from reactants *A*, *B*, and *C*.