UNIT OPERATIONS

Unit Operations

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Unit Operations

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Preface

This textbook is the first to carry the title *Unit Operations*, but it is not the first to treat the subject.

Modern practice and equipment are emphasized as well as mathematical interpretations, as only by properly designed, constructed, and operated equipment can mathematical treatment yield useful results. The object is to build the student's knowledge and power progressively and continuously until he has a reasonably clear concept of how to approach the problems of design and operation of processing equipment. The unit operations are grouped according to similarities in action or in methods of calculation and presented in sequence according to increasing difficulty.

By grouping similar operations and using a common nomenclature in similar theoretical discussions, we find that the student makes more rapid progress, less effort is required to master nomenclature, and a better understanding is gained of the relationships among the different unit operations. The association and comparison of similar operations from different industrial processes is the essence of unit operations and the major factor in developing chemical, metallurgical, or process engineers capable of successfully designing new plants for conducting new processes. The full advantage of the study of unit operations can be realized only if the unit operations are themselves associated and compared so the engineer may more skillfully select the most suitable operation and equipment desired for each step in the process. The tendency of the specialist to treat each unit operation as a specialty having its own peculiar result, rationalization, and nomenclature is of questionable value in any sustained educational effort and is to be resisted by all means in an undergraduate curriculum.

The arrangement in order of increasing difficulty rather than in order of assumed importance continually presents new advanced intriguing problems to the student, maintains his interest, and encourages him to continue his own development beyond the limitations of the book. The treatment of those operations covering solids in Part I requires little more preparation than is ordinarily given in high school, whereas the treatment of mass transfer in Part IV is suitable for a postgraduate course and is presented with a critical attitude tending to develop the research point of view.

The inductive method is generally followed, relying upon observations from experience rather than upon deductive rationalizations. This method is a powerful tool of the practicing engineer and has been found most satisfactory for undergraduate students. However, kinetic explanations are not neglected and receive increasing emphasis in the last part on energy and mass transfer as an important means to a thorough understanding of the mechanisms involved.

Physics, calculus, and a beginning course in material and energy balances, or thermodynamics, are assumed as prerequisites to unit operations. Even with this background the student may be confused regarding dimensions and energy balances, and these subjects are treated rather fully. It is hoped that all chapters have received sufficiently extensive treatment to meet the requirements of any undergraduate curriculum so that the desired emphasis may be obtained by omission rather than addition. About 180 recitations should be required to cover the entire material in an adequate manner with undergraduate students, allowing 8 to 10 for the first five chapters and 50 to 60 each for Parts II, III, and IV. In a postgraduate course for students who have completed an undergraduate course in unit operations, this time could be reduced by one-third or one-half. With appropriate omissions the text has been used successfully for undergraduate courses of three quarters with a total of 117 class meetings and of two semesters with a total of 105 class meetings, as well as for a single-semester short course of 60 class meetings.

References to the literature are included for the purpose of attracting the student's attention to other sources of information as well as to acknowledge sources. An effort has been made to give credit for all material used, but so many workers have contributed so much that it is impossible to recognize the contributions of everyone. Indebtedness to previous texts and handbooks and to manufacturers of equipment is freely acknowledged. The specific help and suggestions of L. F. Stutzman and George Thodos, Associate Professors, and D. A. Dahlstrom, Assistant Professor of Chemical Engineering, at Northwestern University, F. Charles Moesel and Cedomir Sliepcevich, Assistant Professors of Chemical Engineering at The University of Michigan, Dr. Joseph Allerton, of Sayville, Long Island, and Verne C. Kennedy, Jr., of Chicago, and the frank criticisms of students who have used the material as mimeographed notes have been invaluable. Tolerance and your cooperation in helping to eliminate errors and suggest improvements as they may appear are requested.

THE AUTHORS

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RULE IV OF REASONING

IN EXPERIMENTAL PHILOSOPHY WE ARE TO LOOK UPON PROPOSITIONS INFERRED BY GENERAL INDUCTION FROM PHENOMENA AS ACCURATE OR VERY NEARLY TRUE, NOTWITHSTANDING ANY CONTRARY HYPOTHESES THAT MAY BE IMAGINED, TILL SUCH TIME AS OTHER PHENOMENA OCCUR, BY WHICH THEY MAY EITHER BE MADE MORE ACCURATE, OR LIABLE TO EXCEPTIONS.

This rule we must follow, that the argument of induction may not be evaded by hypotheses.

J. ISAAC NEWTON, *Principia* (1686)

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CHAPTER I

Introduction to the Unit Operations

IN general there are two different approaches to the study of industrial processing. Each particular industry, such as the alcohol, petroleum, plastic, copper, or steel industry, including its characteristic operations, may be studied as a unit; or the different operations common to many industrial processes may be classified, each according to its function without regard to the industry using it, and each such operation studied as a unit operation. Thus heat transfer is a single or unit operation common to practically all industries, and knowledge of the principles of heat transfer is equally useful to an engineer in any industry requiring the transfer of heat.

As industrial processes have become more varied and technical, the fields open to the engineer have widened and it has become increasingly difficult, if not impossible, to cover the various industries in an adequate manner without limiting the students to a few closely related fields. By studying the unit operations themselves and their functions the engineer is trained to recognize these functions in new industrial processes; and by applying his knowledge and skill in the corresponding unit operations he is able to design, construct, and operate a plant for a new process with almost as much confidence as for a proved process. For these reasons the study of unit operations has proved to be the more efficient approach to the study of industrial processing.

Although the importance of these operations that are common to different industries was recognized as early as 1893 by Professor George Lunge,* the concept of unit operations was first crystallized by A. D. Little † in 1915.

> The arts of pulverizing, evaporating, filtering, distilling, and other operations constantly carried on in chemical works have been so thoroughly developed as to amount almost to special sciences.*
>
> Any chemical process, on whatever scale conducted, may be resolved into a coordinate series of what may be termed "Unit Operations," as pulverizing, drying, roasting, crystallizing, filtering, evaporating, electrolyzing, and so on. The number of these basic unit operations is not large and relatively few of them are involved in any particular process. The complexity of chemical engineering results from the variety of conditions as to temperature, pressure, etc., under which the unit operations must be carried out in different processes, and from the limitations as to materials of construction and design of apparatus imposed by the physical and chemical character of the reacting substances.†

A study of the unit operations is just as valuable to the operating engineer as to the designer, since all industrial operations, or plants, are composed physically of a series of unit operations in their proper sequence. The ability or capacity of a plant is no greater than that of its weakest unit. The operator analyzes his complex operations into units for individual improvement, and the designer synthesizes complex operations from a number of unit operations.

UNIT OPERATIONS CLASSIFIED

In this treatment the unit operations are classified or grouped according to their function and the phase

* Professor George Lunge of the Federal Polytechnic School of Zurich, in an address on the "Education of Industrial Chemists" presented at the Congress of Chemists at the Exposition in Chicago, 1893.

† Arthur D. Little as chairman of the Visiting Committee of the Department of Chemistry and Chemical Engineering of the Massachusetts Institute of Technology in a report to the President of the Institute in 1915.

or phases treated. A *phase* is a homogeneous and mechanically distinct or separable mass. Thus sand and water are two mechanically distinct masses, and each represents a separate phase; whether the sand is separate from or suspended in the water makes no difference. An oil phase floating upon water, or emulsified with the water, is a homogeneous mass mechanically distinct from the water whether or not it is continuous; and it is, therefore, a separate phase from the water phase. Similarly, a copper ore contains the mineral chalcopyrite as a separate solid phase from the surrounding gangue or rock, no matter how finely the mineral may be dispersed.

The phases present at any one time may be one or more solid phases, and one or more fluid phases. Sand and water represent one solid and one fluid phase, oil and water are two fluid phases, and the mineral and gangue are two (at least) solid phases. A mixture of solid salt, ice, water, and water vapor contains two solid and two fluid phases. Gases are fluids. Ordinarily there will exist only one gaseous phase.

The order of treatment begins with unit operations that treat solids alone, such as mechanical size separation, size reduction, and conveying of solids. These are followed by operations involving fluids. Since all fluids must be confined to store them or to direct their flow, a solid boundary phase is always involved, whether the solid particles are flowing through the fluid as in classification and flotation, or whether the fluid is flowing through a solid as in fluid transportation or filtration. The operations involving transfer of material from one phase to another are next treated by the method of equilibrium stages or contacts. These include leaching (solid to liquid), extraction (liquid to liquid), gas absorption and distillation (vapor to liquid), and adsorption (fluid to solid). Heat transfer and evaporation follow. Heat transfer deals with the rate of energy transfer and serves as a means of leading directly to the concept of rate of mass transfer as applied in crystallization, drying, absorption, distillation, and the more complicated operations involving catalysts and rates of reaction.

PRACTICAL OPERATIONS

In the study of unit operations, it must always be remembered that a unit operation is simply a unit of a more complex operating plant: a heat exchanger in a sugar plant, a crusher in a cement plant, a distillation column in a petroleum refinery, and that the important requirement in each case is a satisfactory workable overall operation. It makes no difference whether the result is obtained by exact mathematical calculation, by empirical approximation, or by a good guess based on the application of sound judgment, provided it is a satisfactory, workable, economical operation in its entirety.

The unit operations are the best available methods for classifying and formulating the combined experience of engineers as a guide to the operation and design of industrial plants. But these data, although of great help, are inadequate in themselves to insure successful operations. The successful engineer must develop sound judgment by his willingness to try, to recognize failures, and to keep on trying until he arrives at a satisfactory result. Seldom if ever does he have the opportunity to assemble either on paper or in physical form the ideal or perfect operation. Engineering operations require approximations and compromises. If made too nearly perfect, they may cost too much and last too long. Many plants become obsolete before they wear out.

All the information now available started with a single observation. As additional observations were made, the engineering mind began to draw conclusions which could be presented in the form of an empirical tabulation, such as the power required to operate crushing and grinding machines. Frequently these tabulated data could be presented in the form of a graph as a more satisfactory basis for extrapolating and interpolating the results. The next step was to derive an equation for the line representing the plotted data and to indicate means for estimating how the constants in the equation would be affected by different conditions. These equations might then be rationalized or sometimes "derived." However, the student and engineer should always keep in mind that these conclusions are drawn more or less soundly from a series of more or less reliable observations that have been empirically correlated; also, they should remember that the practical operator in the plant who may never have seen the equation or heard the term "unit operation" has probably made more observations himself than all those involved in deriving the equation. But it has taken the practical operator a much longer time to acquire his skill without understanding than it has the modern student of unit operations to acquire his comprehensive understanding.

FUNDAMENTAL CONCEPTS

Certain concepts or conclusions drawn from many observations are regarded as fundamental because, the more carefully the observations are made, the more closely do the data conform to the previous conclusion. Perhaps the most important of these to the engineer is the law of conservation of mass and energy.

Operations involving atomic energy have emphasized the concept that mass and energy are directly related. The quantity of energy equivalent to a unit of mass is so large, about 3×10^{16} ft-lb of energy per pound-mass, or the mass is so small, about 2.6×10^{-14} pound-mass per British thermal unit (Btu), that ordinary means of measurement are incapable of detecting any increase or decrease in mass accompanying a chemical process. In engineering operations, when nuclear changes are not involved, the mass of the products equals the mass of the reactants. This is in accord with engineering experience over many years and simplifies calculations, since material balances can then be made independently of energy balances.

The following four concepts are basic and form the foundation for the calculation of all operations. If nuclear changes are involved, the energy changes become so great that the first and second concepts are not independent and a combined energy and mass balance must be made.

1. The Material Balance

If matter may be neither created nor destroyed, the total mass for all materials entering an operation equals the total mass for all materials leaving that operation, except for any material that may be retained or accumulated in the operation. By the application of this principle, the yields of a chemical reaction or engineering operation are computed.

In continuous operations, material is usually not accumulated in the operation, and a material balance consists simply in charging (or debiting) the operation with all material entering and crediting the operation with all material leaving, in the same manner as used by any accountant. The result must be a balance. The accountant uses dollars as his unit, and the engineer uses pounds, tons, etc. In making a material balance, the engineer should not attempt to use units that may be created or destroyed during the process, such as units of volume or moles, or cubic feet, gallons, barrels, or molecules.

As long as the reaction is chemical and does not destroy or create atoms, it is proper and frequently very convenient to employ atoms as the basis for the material balance. The material balance may be made for the entire plant or for any part of it as a unit, depending upon the problem at hand. It is most conveniently made by adopting as a basis for calculation a fixed quantity of material which passes through the operation unchanged.

2. The Energy Balance

Similarly, an energy balance may be made around any plant or unit operation to determine the energy required to carry on the operation or to maintain the desired operating conditions. The principle is just as important as that of the material balance, and it is used in the same way. The important point to keep in mind is that all energy of all kinds must be included, although it may be converted to a single equivalent form such as Btu's, calories, or foot-pounds for the sake of addition. A balance cannot be made of heat or electrical energy alone, since all energy is convertible and all forms must be included in the balance.

3. The Ideal Contact

Whenever the materials being processed are in contact for any length of time under specified conditions, such as conditions of temperature, pressure, chemical composition, or electrical potential, they tend to approach a definite condition of equilibrium which is determined by the specified conditions. In many cases the rate of approach to these equilibrium conditions is so rapid or the length of time is sufficient that the equilibrium conditions are practically attained at each contact. Such a contact is known as an equilibrium or ideal contact. The calculation of the number of ideal contacts is an important step required in understanding those unit operations involving transfer of material from one phase to another, such as leaching, extraction, absorption, and distillation.

4. Rates of an Operation

In most operations equilibrium is not attained, either because of insufficient time or because it is not desired. As soon as equilibrium is attained no further change can take place and the process stops, but the engineer must keep the process going. For this reason rate operations, such as rate of energy transfer, rate of mass transfer, and rate of chemical reaction, are of the greatest importance and interest. In all such cases the rate and direction depend upon a difference in potential or driving force. The rate usually may be expressed as proportional to a potential drop divided by a resistance. An application of this principle to electrical energy is the familiar Ohm's law for steady or direct current.

$$I = \frac{E_1 - E_2}{R} = \frac{-\Delta E}{R}$$

where I = rate of electron transfer or current of electricity (coulombs/sec, or amp).
E = electrical potential, and ΔE is the increase in potential between points 1 and 2 (volts).
R = resistance (ohms).

In heat transfer under similar conditions for steady flow, the time rate of heat transfer from mass A in contact with mass B is

$$\frac{dQ}{dt} = \frac{T_A - T_B}{R} = \frac{-(T_B - T_A)}{R} = \frac{-\Delta T}{R}$$

where $\frac{dQ}{dt}$ = the instantaneous time rate of heat transfer or the quantity of heat transferred per unit of time from mass A to mass B.
T_A = temperature of mass A.
T_B = temperature of mass B.
$-\Delta T$ = the temperature drop.
R = resistance to heat transfer.

In solving rate problems as in heat transfer or mass transfer with this simple concept, the major difficulty is the evaluation of the resistance term. In practice, the values of the resistance term are generally computed from an empirical correlation of many determinations of transfer rates under different conditions.

The basic concept that rate depends directly upon a potential drop and inversely upon a resistance may be applied to any rate operation, although the rate may be expressed in different ways with particular coefficients for particular cases.

APPLICATION OF CONCEPTS

These principles, used singly or in combination, and the coordinated knowledge of the unit operations as presented in this textbook, the handbooks, and other technical literature constitute the science or theory of the unit operations. Practical engineering consists in applying the understanding of these operations and practical knowledge of the many types of equipment that may be employed to the design and operation of a commercial plant that will show not only a material balance but also a favorable dollar balance.

PART I

Solids

THIS section deals with those operations which treat material in the solid state only: screening, size reduction, and handling of solids. Before discussing these operations the properties of solids should be reviewed.