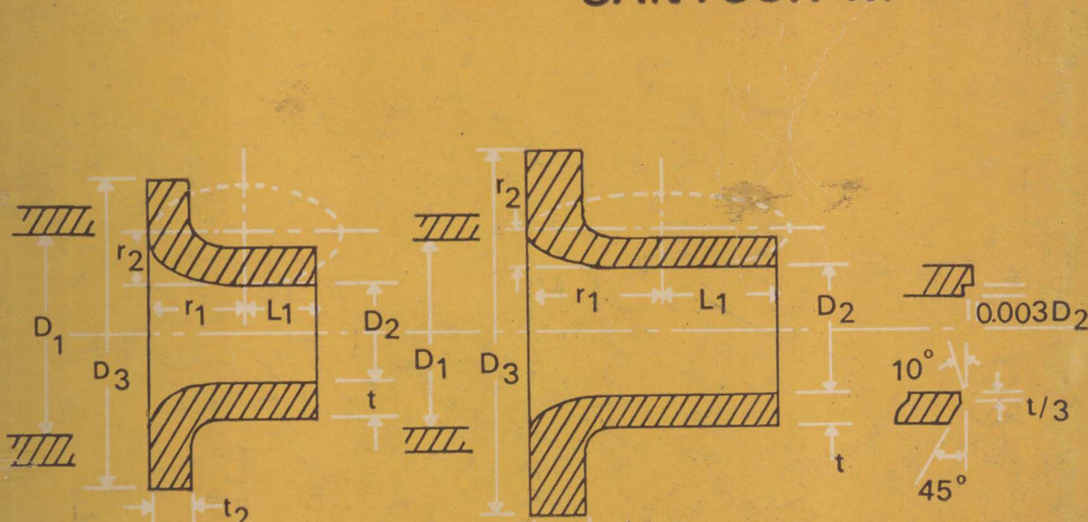
MOMENTUM TRANSFER OPERATIONS

SANTOSH K. GUPTA



Momentum Transfer Operations

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Dedicated to
R.S. Gupta
my grandfather

I wonder if I could transfer your value-systems to the next generation as effectively as you did

Preface

The undergraduate curriculum at the Indian Institute of Technology, Kanpur, has a one-semester compulsory 'core' course in transport phenomena in the third year (of a five-year programme), common to all disciplines of engineering. This is a prerequisite for a sequence of three courses in unit operations which chemical engineering students take later on. The latter are devoted to momentum, mass and heat transfer operations, respectively. It has been my experience that whereas there are several excellent books on heat and mass transfer operations, there is a dearth of books in momentum transfer operations. This text is intended to fill this void.

To keep the price and size of the book reasonable, I have had to omit the fundamentals of fluid mechanics. Several excellent texts, including low-cost editions, exist in this area and duplication is not desirable. For the same reason I have included only sketchy descriptions of commonly used equipment. Thus, use of this text has to be supplemented by a study of fluid mechanics (or preferably transport phenomena) and secondly, by a copy of Perry's *Chemical Engineers' Handbook*. I make no apologies for this.

I have focused primarily on the applications of momentum transport which are relevant to chemical engineers. An attempt has been made to *model* various types of equipment starting from fundamental equations followed by a discussion on empirical correlations and methods of design. I have thus tried to follow the engineering science approach yet attempted to give sufficient empirical information so as to make the design of equipment meaningful. At the end of each topic the design procedures usually followed are summarized, emphasizing the degrees of freedom available to the design engineer. I have found that students enjoy this because it is a welcome departure from conventional analysis-oriented courses. Experience has shown that students are better equipped for process design courses later. In the last chapter, some problems have been included to illustrate further the principles of process design. Solutions to these were used as "case studies" in a first year course "introduction to design" and some of them were given for solution to students at the end of the course on unit operations. The students found them very instructive.

Several problems have been included, some of which are complementary to the text. I believe that to appreciate this text, a student must solve several of these problems. Answers to some problems (within slide-rule accuracy) have been included.

I have converted the text into SI units but have frequently given equivalent values in the FPS system for those who find the latter more convenient. All graphs involving dimensioned variables have scales corresponding to both the FPS and SI systems.

The preface would be incomplete without the individual notes of gratitude. The students of my unit operations courses, specially in the formative years, went through a lot of hardship since the material was not as well organized and the problems probably ill defined for them. Sridhar Gopalarao painstakingly worked out several of the problems. S.R. Deo and D.S. Panesar worked on the drawings during different phases of this work and R.N. Srivastava did an excellent typing of the several drafts. T.R. Gupta, Hari Ram and Jaiballabh helped in the other activities necessary in the preparation of the manuscript. Prof. K.V.G.K. Gokhale and Prof. D.P. Rao spared their valuable time to go through the text and suggested several improvements in the language, style and content. Prof. D. Kunzru contributed substantially to the formulation of problems illustrating the principles of process design. The Educational Development Centre and the Quality Improvement Programme at IIT Kanpur provided the necessary funds for preparation of the manuscript. To all these and to several other friends and students who contributed to this text in some way or the other, I offer my humble thanks.

And, of course, the worst sufferers in book writing, other than the author (!!), are the wife and children. To Shubhra, Aatmeeyata and Akanksha, I promise less frowns and more smiles now.

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1 Unit Operations in Chemical Engineering Practice

HISTORICALLY, chemical engineering evolved from the discipline of industrial chemistry. In the early years, chemical engineers did on an industrial scale what chemists did in the laboratory. While chemists primarily dealt with chemical reactions leading to the synthesis of desired chemicals, chemical engineers emphasized not only chemical reactors but also the related problems, e.g., isolation and separation of materials, their mixing, transportation, heating and cooling, etc. Indeed, at times, these other *physical* operations assumed far greater significance than the reactors; there are several chemical plants without a single reactor, e.g., a plant separating common salt from sea water, a plant producing liquid nitrogen and liquid oxygen from air, etc.

Considerable differences existed between the professional experiences of a chemist and those of a chemical engineer even in the early years. Several problems that were not encountered in laboratory operations were of significant concern on an industrial scale. For example, in the laboratory, a chemist produced oxygen by heating a mixture of $KMnO_4$ and MnO_2 in a test tube and collecting the gas (Fig. 1.1). But a chemical

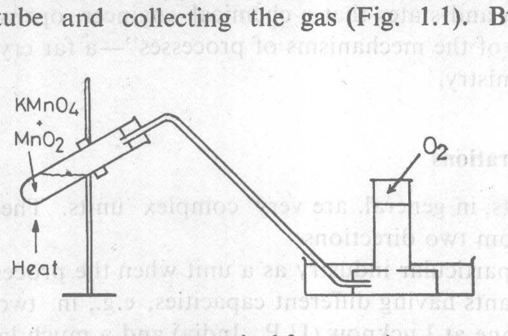

Fig. 1.1: Laboratory method for preparing oxygen.

engineer using the same process to produce oxygen faced the following problems:

(a) Crushing of $KMnO_4$ and MnO_2 into a fine powder—these chemicals are not available in powdered form in larger quantities.

(b) Mixing of large quantities of the two powders intimately—when several tonnes of material are to be mixed, special equipment has to be used.

(c) Ensuring uniform heating of the mass in the reactor and preventing gas bubbles from carrying the powders beyond the heating zone—this is easy to accomplish in the laboratory by keeping the test tube slightly tilted but far more difficult on an industrial scale.

(d) Compressing the oxygen into cylinders—the familiar gas jar inverted over water does not work when several tonnes of gas are to be collected and distributed.

(e) Removal of the solid mass from the reactor after completion of the reaction without damaging the reactor—in the laboratory, one simply discarded the test tube.

(f) Recovery of the MnO_2 and its recycling—on a small scale this is unnecessary but when large quantities are involved, reuse of the catalyst is necessary.

Further, production of oxygen from these chemicals is highly uneconomical industrially. Commercially, this gas is now produced by first liquefying air and subsequently fractionating it.[1]

It is observed from the above discussion that the actual reaction forms but a small part of the problems associated with the production of oxygen from $KMnO_4$ and MnO_2 and expertise on operations other than the reactor is also required in the design and proper maintenance of such a plant.

With the passage of time, principles of engineering relevant to chemical plants developed and chemical engineering was established as an independent discipline.[2] Today, the realm of chemical engineering is not limited to chemical plants only, but overlaps the fast growing areas of biology and energy-management. Indeed, King[3] describes chemical engineering as "energo-enviro-pharmaceutico-electro-chemico-resourco-agrico engineering" for the layman and states that a chemical engineer operates "through an understanding of the mechanisms of processes"—a far cry from the days of industrial chemistry.

1.1 Unit Operations

Chemical plants, in general, are very complex units. Their study can be approached from two directions:

(a) Each particular industry as a unit when the processes are similar in two plants having different capacities, e.g., in two paper mills, a small one at Lucknow (U.P., India) and a much larger one at Amlai

(M.P., India) may be studied. The differences in capacities, technologies, etc., are then noted. This approach was in vogue during the last century. There were specialists, say, in the paper industry, the sugar industry, the sulphuric acid plant, etc., and knowledge of any one of these was a complete secret to the others. Perhaps, such experts were looked upon with awe and wonder, and presumably, handsomely paid!

(b) Different types of equipment common to several industries may be studied. For example, crystallization of common salt from supersaturated sea water is in no way different, fundamentally, from the crystallization of ammonium sulphate from the mother liquor in a fertilizer plant. In this manner, industry lines may be crossed. George Lunge[4] was the first to realize the simplicity that results from this approach. Any chemical plant can thus be visualized as a sequence of particular operations. Fortunately, the number of such operations is relatively small and only a few of these are involved in any medium-sized chemical industry. The complexity of plants results from the multitude of variables associated with each of these operations, e.g., the temperature, pressure, flow rate and volume associated with the common salt crystallizer are so different from those encountered in the fertilizer industry that the former may be accomplished economically in shallow ditches open to the sun whereas the latter may require sophisticated machinery.

Knowledge of these operations considerably simplifies the study of large and apparently complex chemical industries. This point is specially borne out by the massive petrochemical complex at Baroda (Gujarat, India). These multimillion rupee projects are very vast but an experienced engineer can design the entire plant (of course, with a lot of time) in terms of about ten to fifteen types of operations.

Unit operations, by convention, are those operations wherein no chemical reactions are involved. In other words, unit operations involve only physical changes, in particular, the transfer of momentum, heat and mass. The study of reactors is not included in unit operations and forms another important area in chemical engineering called chemical reaction engineering. A few examples of unit operations are cited below:

mixing, e.g., in the paint and chocolate industries;

evaporation, e.g., in common salt manufacture;

crushing and grinding, e.g., in cement and phosphate fertilizer industries;

absorption, e.g., of ammonia from an air-ammonia mixture using water;

distillation, e.g., of crude oil in petroleum refineries into various fractions as kerosene, diesel, gasoline, furnace oil, etc.;

conveying of solids, e.g., of grains, plastic pellets, detergent powder, etc.;

crystallization, e.g., of common salt;
filtration, e.g., in the treatment of municipal water.

In this text, only those unit operations are discussed which involve the transfer of momentum. The reader is referred to several texts[5-7] for the study of unit operations involving mass and heat transfer. In recent years, several operations wherein both chemical reaction and physical changes are involved, have assumed importance. Such operations are also not included in this text.

1.2 Typical Breakup of a Chemical Plant

Let us study the typical sequencing of operations in a chemical process. The manufacture of common salt from sea water would involve the following unit operations in sequence:

(a) pumping of sea water to plant-site;
(b) evaporation and crystallization;
(c) filtration of the salt;
(d) drying of the salt;
(e) mixing of any additives (e.g., iodine, to prevent goitre); and
(f) screening and grading of salt.

A schematic block diagram representing these operations is referred to as a flow chart and is shown in Fig. 1.2.

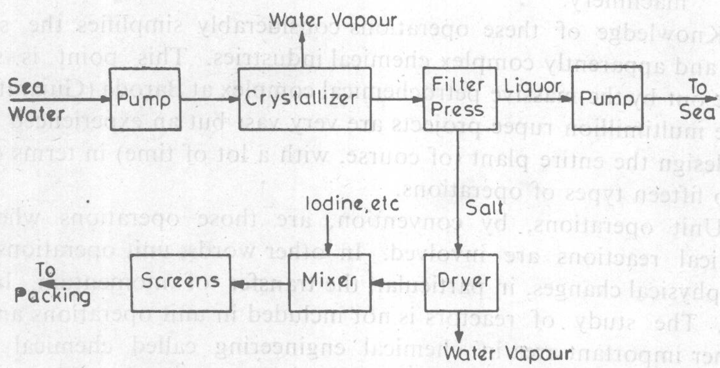

Fig. 1.2: Simple flow chart for common salt manufacture.

1.3 Empiricism in Unit Operations

It is indeed very unfortunate that chemical engineering science has not yet advanced to a level to enable one to model mathematically *all* the unit operations. There are instances, e.g., laminar flow through pipes and the separation of solid particles from liquids in a centrifuge, where fundamental knowledge is sufficiently advanced and equations relating the different variables associated with these unit operations are available. The same cannot be said of some other unit operations as in the design of setting tanks where one must perform laboratory tests on the industrial samples to get certain data before one can even attempt to design a large-scale unit. In this context, dimensional analysis[8] is of immense help in correlating relevant groups of variables. Several problems in the real plant can be attributed to the inaccuracies in the empirical methods used in design.

In this text, an attempt is made to model some chemical engineering unit operations by applying principles of transport phenomena and at times, thermodynamics, and thus arrive at some basis for their design. Where fundamental methods fail, empirical methods in practice are discussed. Attention is focussed only on obtaining fairly "coarse" information like size, temperature, pressure, power consumption, which is customarily a part of "process design". For example, a very common unit operation is centrifugation, a process to separate solid particles from a liquid using centrifugal forces. In this case, equations of motion for the liquid and the solid are used to get an idea of the length, diameter and the angular velocity of the centrifuge required for a desired separation. We shall not engage ourselves in calculating the thickness of the metal wall, of how to support the equipment, etc., since these aspects are normally carried out by specialist mechanical engineers and are part of "mechanical design".

It is commonly found while modelling these operations that there are, in general, more variables than equations. This necessitates the use of both common sense as well as optimization techniques to determine the best solution. Some of these aspects are also discussed in this text.

1.4 Importance of Unit Operations in Chemical Engineering

In the process design of any plant, the flow chart is first chosen. At times, several routes to the manufacture of any end product may exist and an

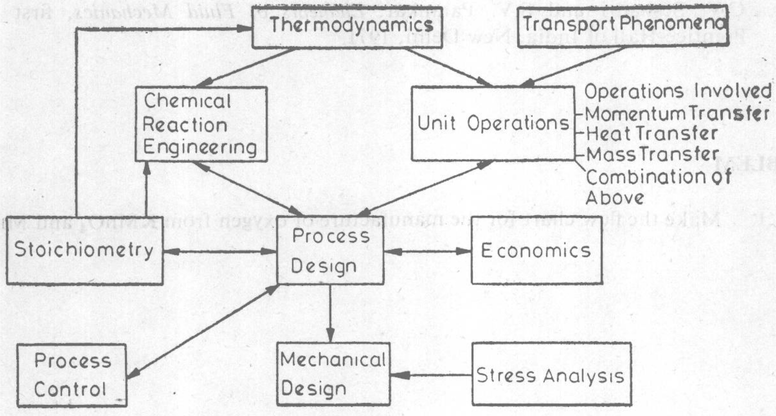

Fig 1 3: **Interrelationship of courses in the chemical engineering curricula.**

economic analysis of these processes may be necessary. A material and energy balance is then made for the process chosen. Thereafter, the various types of equipment, i.e., equipment for unit operations as well as reactors, are "sized" and an economic analysis performed to study the profitability of the plant. Several major or minor changes in the flow chart may now be made and principles of unit operations and reactor design reapplied to give the new design. An economic analysis of all these alternatives may show some designs to be better than the others. Thus, there is continuous interaction between process design, unit operations and reaction engineering (Fig. 1.3). This emphasizes the role of unit operations in the chemical engineering curricula.

Once the process design is completed, the next step would be the mechanical design of the plant.

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PROBLEM

1.1. Make the flow chart for the manufacture of oxygen from $KMnO_4$ and MnO_2.