

A Handbook of Unit Operations

D. A. Blackadder and R. M. Nedderman

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Preface

Prior to the Second World War, the unit operations of chemical engineering normally appeared as part of a single book covering the whole field of chemical engineering in a general way. In consequence of the rapid growth of the subject in the last thirty years, fragmentation is now commonplace, and a single volume attempting to cover all of chemical engineering could not hope to be exhaustive.

It is difficult to distinguish between unit operations and chemical engineering as a whole, but a somewhat artificial distinction is possible and is justified by teaching requirements. This distinction is achieved by a shift of emphasis, and by presupposing a slight knowledge of certain matters when dealing specifically with unit operations.

In general, a book concerned with an applied science, such as chemical engineering, contains fundamental material firmly rooted in the physical sciences, together with technical considerations which are the manifestation of science and engineering usefully applied to the service of industry. We have not attempted to write a comprehensive book, even in the limited context of unit operations. Instead we have addressed ourselves to the student who wishes to become familiar with the methods of analysing unit operations before proceeding to a study of the detailed realization of these calculations in terms of equipment. Study of this book should therefore precede the exploration of the more technical areas of performance correlations, efficiency predictions, materials of construction and economic factors. Inclusion of these matters in a basic teaching book may confuse the student by obscuring the relatively simple design calculations which provide the foundation for further study. We believe that competence in the practical sphere springs from a clear understanding of principles and their limitations. It may be felt that the old foundations of design practice (e.g. the McCabe-Thiele construction) are too inflexible and unsophisticated to justify the time spent on them by students. We do not share this view; on the contrary, we think that a shift towards more complicated or less scientific procedures would make for a bad introductory teaching book, whatever value it might have for a reader with some advance knowledge of the subject. In short, we feel that there is a need for a textbook with distinctly modest aims, based on scientific principles unclouded by technical data.

There is a heavy emphasis on worked examples throughout the book, and indeed these serve to introduce many of the minor topics besides illustrating

the major principles. SI units are used, but not without some flexibility and reservations. For example, we have adopted the bar though its general acceptance is still in doubt, and we have retained both the minute and the hour.

Grateful acknowledgements are due to The American Society of Mechanical Engineers for permission to reproduce Fig. 5.7, John Wiley and Sons, Inc. for permission to reproduce Figs. 7.3 and 7.4, Gruppo Italiano CARR for permission to reproduce Fig. 6.1, and the Gulf Publishing Company for permission to reproduce Fig. 4.2. We are greatly indebted to Mr John Bridgwater who read the whole manuscript and made a number of valuable suggestions. It is a pleasure to thank the Council of the Senate of the University of Cambridge for permission to use and adapt many problems from Tripos papers. Our students have helped by checking some of the problems and, not least, by convincing us that our aims in writing this book are realistic.

Cambridge, 1970

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List of Symbols

A	Area
C	Concentration
D	{ Diameter Diffusion Coefficient
F	{ Flow Rate of Distillate or Extract Flow Rate of Feed
G	{ Flow Rate of Gas Free Energy
H	Henry's Law Constant (see page 113)
J	Mass Fraction of Solids
K	{ Equilibrium Constant Kozeny Constant Mass Transfer Coefficient Cake Thickness
L	{ Flow Rate of Liquid or Underflow Length Quantity of Liquid
M	Molecular Weight
N	{ Mass Flux per Unit Area Number of Tubes Revolutions per Second
P	Total Pressure
Q	Heat Flux
R	{ Gas Constant Reflux Ratio
R	Cake Resistivity
S	Flow Rate of Solvent, Steam or Stream
T	Temperature
U	Volumetric Flow Rate
U	Overall Heat Transfer Coefficient
V	{ Flow Rate of Extract or Vapour Quantity of Vapour
V	Volume of Filtrate
W	Mass Flow Rate
W	Liquid Content
X	Quantity Ratio
X	Function of Temperature (see page 180)
Y	Quantity Ratio
Y	Correction Factor (see page 180)
Z	Constant
Z	Function of Temperature (see page 180)

a	Area
c	Specific Heat
d	Diameter
f	Fouling Factor
g	Acceleration due to Gravity
h	{ Enthalpy
	{ Height
h	Heat Transfer Coefficient
k	{ Mass Transfer Coefficient (see page 119)
	{ Thermal Conductivity
k	Distribution or Retention Coefficient
m	Flow Rate Ratio
p	Partial Pressure
q	{ Heat Flux per Unit Area
	{ Heat to Vaporize 1 mole of Feed divided by Latent Heat (see page 14)
r	Radius
s	Volume Fraction of Solids
s	Humid Heat
t	Time
u	{ Velocity
	{ Volume Flow Rate per Unit Area
	{ Flow Rate
v	{ Specific Volume
	{ Volume per Unit Area
x	Mass or Mole Fraction in Liquid
y	Mass or Mole Fraction in Vapour
z	{ Distance
	{ Mass or Mole Fraction in Mixed Phase
C_f	Friction Factor
Nu	Nusselt Number
Pr	Prandtl Number
Re	Reynolds Number
St	Stanton Number
HTU	Height of a Transfer Unit (see page 119)
NTU	Number of Transfer Units (see page 119)
lm	Log Mean
ln	Natural Log
\mathcal{H}	Humidity (see page 193)
\mathcal{R}	Compressible Cake Resistivity
Δ	{ Difference
	{ Nett Flow Rate
Σ	Summation
α	{ Fraction of Cylinder Immersed
	{ Relative Volatility
δ	Laminar Sub-layer Thickness
ε	Void Fraction
λ	Latent Heat

μ	Viscosity
π	3.14
ρ	Density
τ	Shear Stress
ω	Angular Velocity

SUPERSCRIPTS AND SUBSCRIPTS

The symbols listed above are modified, where necessary, by superscripts and subscripts. In general, superscripts are used to denote the nature of a stream, and subscripts to denote the section or stage under consideration. For example, T_1^A gives the temperature of stream A at section 1. On this basis it is then logical to use superscripts to denote interfacial conditions, wet bulb conditions etc:

In addition to the above convention the following are used.

Superscripts

A, B, S	In X^A , Y^S , etc:	Mass Ratio
AB	In α^{AB}	Volatility of A Relative to B
—		Average Value
*		Equilibrium Value
†, ‡		Indicate a minor modification to a previous symbol, such as a change of units. They also serve to indicate fictitious or modified streams.

Subscript

o	Datum.
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Symbols which make only a transitory appearance have not been included in the above lists because they are adequately defined in context.

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Chapter 1

DISTILLATION OF BINARY SYSTEMS

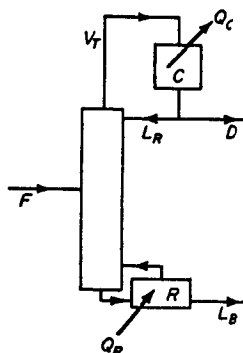
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1. INTRODUCTION

The unit operation of distillation originates from a general feature of vapour-liquid equilibrium. For a two-component vapour-liquid equilibrium a composition difference between the phases is usual, though azeotropes form an important exception to this rule. In general, however, the vapour is richer than the liquid in the more volatile component, formally identified from the fact that addition of a small amount of this component to a sample of the given liquid will increase the total vapour pressure of the liquid. If a typical binary solution is allowed to equilibrate with its own vapour in an enclosure at a fixed temperature, and if the vapour is then separated off and condensed, the result constitutes the beginning of a separation process which could be developed indefinitely, at least in theory. In a more realistic procedure each phase separation would be effected in a non-isothermal way by boiling off vapour and withdrawing it continuously. The steady boiling associated with a true distillation occurs when a vapour escapes from a liquid at a steady rate determined by the rate of heat input. In distillation the vapour contains at least two components unlike evaporation where there is only one. It is a trivial exercise to show that an elaborate sequence of simple

distillations could lead eventually to a worthwhile separation of the components. An acceptable distillation process is one which provides an efficient alternative to such a sequence of basic operations.

When a vapour boils off from a liquid at the bottom of a simple laboratory batch fractionating column it will normally contain a significant quantity of the less volatile component which must be removed to the desired extent before the stream of ascending vapour finally escapes to the condensing part of the apparatus. This removal is achieved by a kind of scrubbing action or rectification, provided by a stream of liquid, known as reflux, running down from the top of the fractionating column. Both the vapour and the liquid streams are richer in the more volatile component at the top of the column and, if the pressure is substantially constant throughout, this means that the temperature is lower at the top of the column because mixtures rich in the more volatile component have lower boiling points. The quality of the



KEY

F	Feed
D	Tops product or distillate
L_B	Bottoms product, possibly waste
V_T	Tops vapour
L_R	Reflux
Q_C	Heat removed by condenser C
Q_R	Heat supplied to reboiler R

Fig. 1.1.

encounter between the two streams, ascending vapour and descending reflux, is of crucial importance, and devices for the purpose are numerous both at laboratory level and in large-scale work.

Large-scale fractionations are usually carried out on a continuous basis and this simplifies the problem of analysing the operation. Feedstock and heat are injected continuously and product streams, or product and waste

streams, are extracted simultaneously. Figure 1.1 shows a typical unit schematically. In practice the physical disposition of the parts might well be different but the principles are general. It will be seen that formal provision is made for the supply of reflux by dividing the tops product and returning part of it to the column. In the simplest method of heat injection, steam is passed through a closed coil at the bottom of the column itself, but it is more common to inject the heat to a separate chamber called the reboiler. The feed is usually not inserted at the bottom of the column but at some intermediate point. The upper part of the column above the feed is known as the enriching or rectifying section, while the part from the feed downwards, including the feed position, is known as the exhausting or stripping section. These terms are descriptive; in the upper part of the column the quality of the tops product is being steadily improved, and in the lower part of the column the high volatility component is being recovered from the bottoms product or waste. In the upper part of the column the flow rate of the ascending vapour is naturally greater than that of the descending liquid because the condensed vapour provides both reflux and tops product. In the lower part of the column the flow rate of descending liquid exceeds that of ascending vapour for a similar reason.

2. REQUIREMENTS FOR THE MATHEMATICAL ANALYSIS OF DISTILLATION

The information necessary for a mathematical analysis of simple distillation of binary systems may be considered under three headings.

A. MATERIAL BALANCES

The feed composition is known, likewise the feed flow rate, and it is necessary to specify the compositions of both product streams, or at least to put limits on the compositions which are acceptable in the light of the desired purity and recovery. Frequently, only one of the components in a two-component mixture has a significant product value, and the specification is essentially an indication of how much impurity may be tolerated in the product stream and how much of the high-value component may be wasted in the other stream. Two equations summarize the material or mass balance requirements:

$$\text{overall} \qquad F = D + L_B \qquad (1.1)$$

$$\text{more volatile component} \quad Fz = Dx_D + L_B x_B \qquad (1.2)$$

F , D and L_B appear in Fig. 1.1; they are molal or mass flows, expressed in kmol/s or kg/s. The quantities z , x_D and x_B are mole or mass fractions. The fraction of the more volatile component is used to specify a composition and the letters x and y refer to liquid and vapour phases, respectively. The feed

may be vapour, liquid, or a mixture of the two, hence the use of z to denote its composition, again referred to the more volatile component. In this chapter flow rates enter into distillation problems merely to establish the right relationships between streams and to afford a basis for calculating unknown compositions. No attempt is made to discuss features such as column diameter and tray design which involve a technical appraisal of the proposed distillation column.

B. VAPOUR-LIQUID EQUILIBRIUM DATA

Vapour-liquid equilibrium data may take the form of diagrams, tables or even equations, though the latter are rarely suitable for wide ranges of composition. The Phase Rule indicates that a two-component system requires three degrees of freedom to account for its behaviour under all conditions, and it is instructive to consider the solid model which is the progenitor of all the plane diagrams used in actual practice.

Figure 1.2a shows a simple system where azeotropy is absent. Any flat section parallel to ABCD represents the behaviour of the system at some selected constant temperature, whereas sections parallel to ABEF show the system under conditions of constant pressure (Fig. 1.2b). The two faces of the solid model for which x and y are either both zero or both unity each indicate the dependence of the vapour pressure of a pure component on temperature.

From a diagram such as Fig. 1.2b it is an easy matter to prepare the corresponding y - x diagram at the same pressure, as shown in Fig. 1.2c, where vapour phase composition, y , is plotted against liquid composition, x . The $y = x$ diagonal is normally shown as a matter of convenience. In the experimental context y - x diagrams would probably not come into being this way, but it is a useful demonstration of the principles to consider how they may be derived from the solid model which is a complete statement of the behaviour of the system. So much confusion can result from a failure to understand these elementary diagrams properly that the student is strongly recommended to acquaint himself with the precise significance of every curve. It is a useful exercise to consider the manner in which ideal and non-ideal systems differ from one another.

From what has been said it will be clear that on a diagram such as Fig. 1.2c the bottom left-hand corner will be associated with the lower and hotter parts of a distillation column while the top right-hand corner will be concerned with the upper and cooler parts. The ordinate and abscissa of any point on the y - x curve respectively represent a vapour and a liquid in mutual equilibrium at the appropriate temperature and at the pressure applicable to the whole diagram. Using one such diagram for the analysis of a given distillation

column therefore presupposes that the pressure is sensibly constant throughout the column. The assumption is reasonable for columns operating at or near atmospheric pressure where the pressure drop through the column is small in comparison. For columns operating at pressures of the order of a few mm of mercury, allowance must be made for pressure drop, and in the

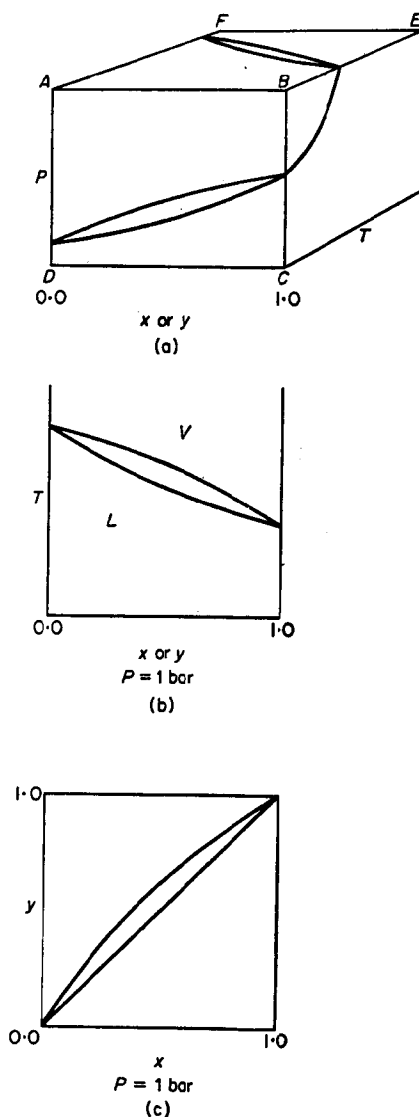


Fig. 1.2.

very high vacuum region a quite distinct technique, that of molecular distillation, comes into play.

Figures 1.3a, 1.3b and 1.3c summarize the vapour-liquid equilibria appropriate to a system showing azeotropy where, among other complications, it is not meaningful to talk about the more volatile component without some

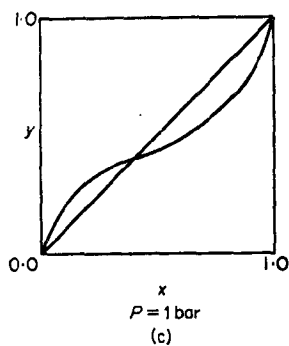
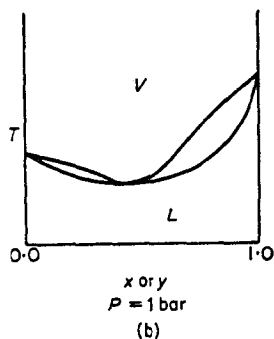
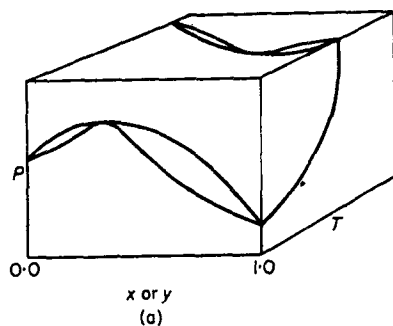


Fig. 1.3.

qualification. Minimum boiling point azeotropes, typified by Fig. 1.3, are the most common.

C. THE IDEAL STAGE CONCEPT

In Section 1, reference was made to the need for contact between the descending reflux and the ascending vapour in a distillation column. This contact must now be considered in detail. One such stage or contact unit performs its task with 100% efficiency if it accepts the streams passed to it, equilibrates them perfectly, and passes on the two new streams to adjacent stages without either stream being contaminated by traces of the other. The effect of a sequence of such units is to concentrate one component of the mixture in the vapour phase and the other in the liquid phase.

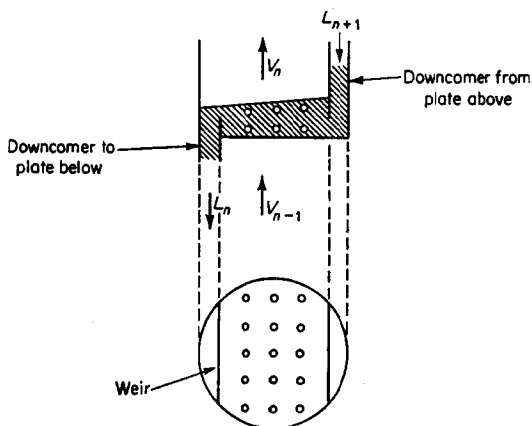


Fig. 1.4.

Many distillation columns are divided into recognizable sections by plates inserted into the column at appropriate intervals. All plates must make provision for contacting vapour and liquid streams to yield two new streams, though the actual designs vary a great deal. The plates may have elaborate bubble caps through which the ascending vapour bubbles into the liquid or there may simply be perforations on the plate. In any event, the liquid is usually passed on to a plate from a pipe or downcomer leading from the plate above, and a liquid leaves a plate by a similar downcomer after passing over a weir. Figure 1.4 shows the details of the n th stage from the bottom of a column. The mass balance for the n th plate in terms of molal flows is

$$L_{n+1} + V_{n-1} = L_n + V_n. \quad (1.3)$$

Liquid L_{n+1} from the $(n+1)$ th plate passes on to the n th plate via the downcomer. As it flows across the plate it contacts the vapour V_{n-1} passing up