DYNAMICS AND CONTROL OF CONTINUOUS DISTILLATION UNITS

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PREFACE

For whom the book is intended

This book has been written with three types of reader in mind:

1. Those who want to know more about the subject without having to wade through too much background detail.
2. Those with a more critical approach who may wish to check the arguments put forward.
3. Those who may not be so interested in distillation units as such but are looking for ways of treating other types of countercurrent processes or are interested in ways in which studies of process dynamics can be linked to studies of control system behaviour.

These differences in interest and approach have been taken into account in the general layout, and in particular a special attempt has been made to help those in the first category, who will often be able to skip passages – providing, that is, they are willing occasionally to accept remarks they may not fully understand. The first few chapters, on the fundamentals of distillation dynamics, will probably be found the most strenuous; the basic theory presented there, however, is an essential introduction to the rest of the book.

What went before

About 1953 the Royal Dutch/Shell Group initiated an extensive programme of research into the control of distillation units. Some experience with what was then known as 'modern control theory' (mainly using the frequency response method) had been gained on a number of relatively simple processes, and the time had come to turn to more complex systems. The choice fell on distillation not only because of the intensity of its application throughout the oil industry but also because of the considerable problems known to be involved in the control of distillation units.

Over the years the project, on which numerous people worked, covered a broad field. Various theoretical methods were tried; and a wide range of laboratory experiments were conducted and quickly followed up by trials in refineries and plants. Then came a period of consolidation in which practical rules were developed, and it is this work, completed around 1959, that forms the subject of this work.

Among other things it is hoped that the discussion presented here will be of particular benefit to those engaged in similar work on other processes in the same class as distillation. No book seems to have been published yet which deals with the dynamics and control of a given class of processes in the way they are treated here, and the only book on distillation units is a Russian book, which treats the subject in an entirely different fashion and rather sketchily at that [1]. Nor do there seem to be many publications in which the development of practical control systems for complex processes is based on a thorough analysis of the dynamic behaviour. There was consequently nothing on which to model the present study, and indeed it might never have been written at all if it had been realized beforehand how complicated the task was going to be. It *has* been written, in spite of everything, but it does mean that the reader is likely to have more difficulty with it than with a book on a more conventional subject, and inevitably there is a greater chance of an occasional gap or obscurity in the argument. Any comments and criticism therefore would be most welcome.

The general layout

The discussion, like the work on which it is based, is almost entirely restricted to continuous distillation units and only touches on optimization and computer control. It is in two parts, the dynamics being handled in Chapters 1 to 7 and control aspects in Chapters 8 to 14. The literature on each subject is also discussed separately and dealt with differently in each half. This is because the treatment of the dynamics differs in many respects from the treatment in the literature up to now; hence it was decided here to develop the general argument in the first six chapters before turning to a discussion of the literature in Chapter 7. In the chapters on control, on the other hand, the discussion of the literature fits naturally into the general argument, so that the survey given in Chapter 14 is more of a supplement to what has gone before.

An effort has been made to explain in depth the premises on which the treatment of each subject is based, as well as the physical meaning of the basic equations. In particular:

Chapter 1 details the premises on which the treatment of distillation dynamics is based;

[1] Anisimov, I.V., Automatic Regulation of the Rectification Process, Gostoptekhizdat, Moscow, 1957, 2nd (revised) ed. 1961 (translation: Consultants Bureau, New York, 1959).

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Chapter 2 gives the basic equations for a distillation column and explains the physical phenomena they represent;
Chapter 4 describes the phenomena likely to be encountered in the reboiler, condenser, etc.; and
Chapter 8 introduces the premises on which the discussion of control is based.

The subsequent development of these premises and equations may follow any of three paths:

a deductive path,
a mathematical path, or
a computer path.

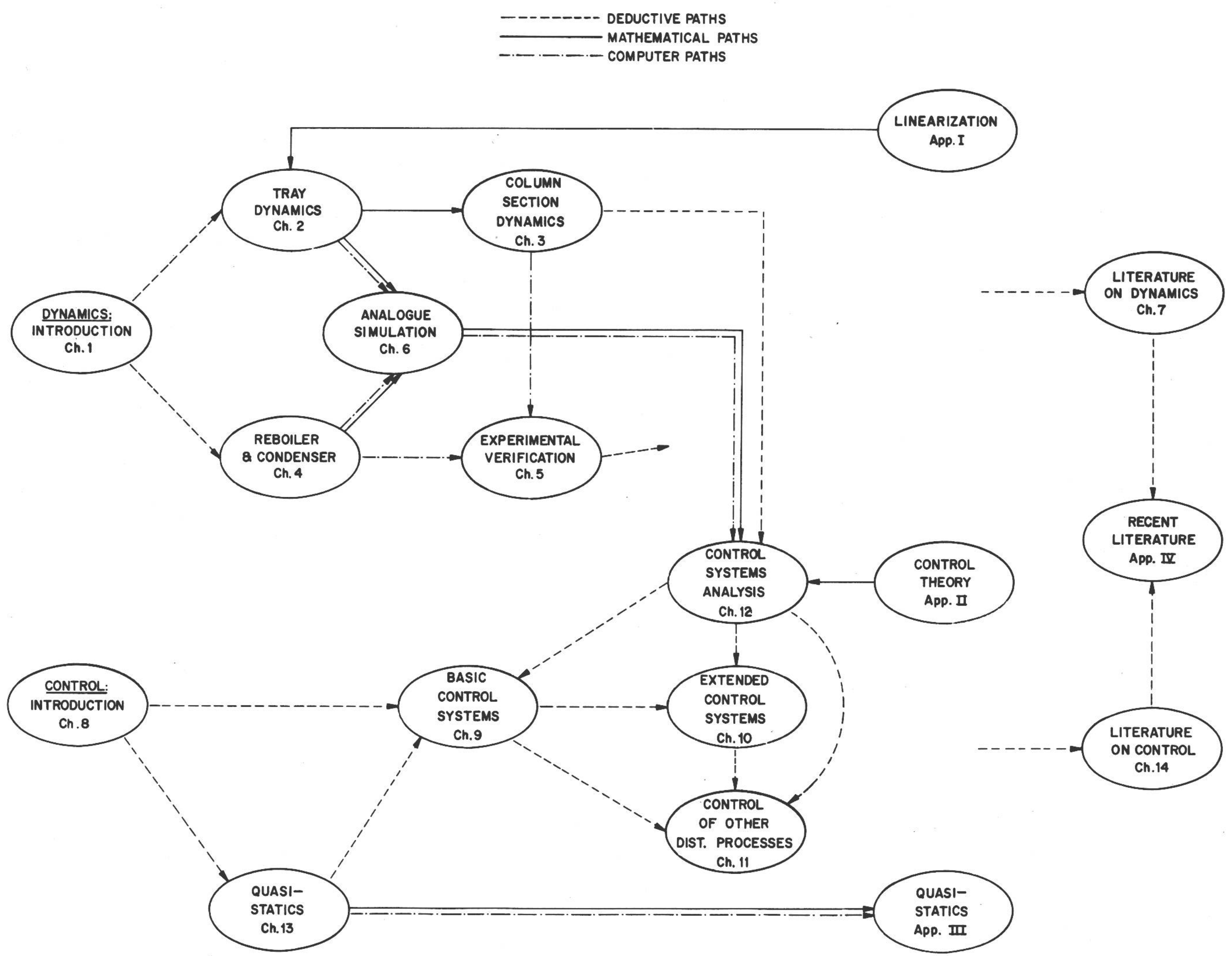
These paths are mapped out in the accompanying diagram, deductive paths being indicated by dashed lines, mathematical paths by solid lines and computer paths by dash-dot lines. In some cases computer and mathematical paths are inseparable and thus run together. Each type of path is characterized in more detail below.

There is also some development of ideas through experiment but this is limited, partly because the function of experiment as a means of verifying theory ceases to be important the moment the function is fulfilled, and partly because a comprehensive discussion of experimental work would require a book to itself – longer even than this one! As an illustration of the experimental approach, however, a whole chapter – Chapter 5 – has been devoted to a typical case.

Deductive development

The deductive development is characterized by the logical arrangement of arguments and views in an effort to detect regularities of behaviour without resorting too much to formulae. This is no armchair philosophy, however. True, the margin between sophistication and sophistry is always narrow in deduction and inference, and there can be few subjects where the risk of developing into an armchair philosopher is greater that it is in distillation dynamics and control. But it is important to stress that, in nine cases out of ten, deductions in this book are based on a close analysis of results, whether they be experimental, mathematical or computer results.

Besides the deductive development within and the paths leading from Chapter 1, the premises from which the basic equations of Chapter 2 are derived also belong to the deductive category, while Chapter 3 is an important source of material for inferences on various subjects throughout the book, including the liquid cascade, the λ_l-effect and the simplified model of the process. The best example of the deductive method in the first half, however, is probably the discussion in Chapter 5.



SIGNAL-FLOW DIAGRAM FOR THE BOOK

In the chapters on control the premises of Chapter 8 are first developed to give the basic control schemes of Chapter 9. The argument then branches to extended schemes for 'normal' distillation units (Chapter 10) or to methods of control for other types of distillation processes (Chapter 11), while Chapter 12, like Chapter 3, provides material for a number of inferences elsewhere.

Mathematical development

Mathematically, one of the most difficult steps is from a single tray to a column section with a number (possibly a large number) of similar trays. This has therefore been given a chapter to itself (Chapter 3). Mathematical methods needed in Chapters 2 and 12 but not specific to distillation dynamics or control have been outlined separately in Appendices I and II.

Computer development

Using the same basic equations the dynamics of a whole unit can also be determined with the aid of a digital or analogue computer, although of course the solutions in this case are specific to the unit in question and not generalized as in the case of mathematical analysis. Digital methods in particular are useful in calculating the dynamics of uncontrolled units and the quasi-static behaviour of controlled units (see Chapters 5 and 13, respectively), while analogues are very powerful tools for studying the dynamic behaviour of controlled units. The possibilities of analogue simulation are discussed in detail in Chapter 6, and extensive use has been made of the technique throughout, but especially in Chapter 12.

The small print, references and symbols

The small print indicates the development of side-issues, background information or detailed argumentation, all of which may be skipped on an initial reading.

References are either numeric (e.g. *7.1*) or alphameric (e.g. *M* 5, *L* 53). Numeric references are those needed in a particular chapter but not specifically relating to distillation dynamics or control; they are therefore listed at the end of the chapter in which they occur, the first number of the reference being the chapter number. Alphameric references, on the other hand, relate to publications listed in the two bibliographies, one on dynamics (Nos. 1-49) at the end of Chapter 7, and one on control (Nos. 50-99) at the end of Chapter 14, the letter in each reference being the initial letter of the first author's surname. The same publication may be listed in both bibliographies, and thus have two different numbers, in which case the alternative number is listed in the bibliography in brackets.

A complete list of symbols, with a brief explanation, is given at the end of the book.

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We are especially grateful to the Management of the Koninklijke/Shell-Laboratorium, Amsterdam, for permission to publish the material in this book and for their cooperation in its realization. We should also like to stress once more that many other people besides us were involved in the work on which the book is based and that we are therefore acting as reporters of a collective effort.

We are grateful, too, to A.M. Griffiths, who read the text in draft and suggested numerous ways in which presentation, language, and general coherence might be improved. Finally we should like to thank all our friends and all those we have met at conferences and the like, with whom we have exchanged ideas, whether we agreed or not. We have learnt a great deal from them and without the stimulus provided particularly by those with whom we begged to differ the book might never have got off the ground. Quite often, in fact, it was only while writing up our ideas that we realized we were just beginning to understand what we – and they – had been talking about.

CHAPTER 1

INTRODUCTION TO THE CHAPTERS ON DISTILLATION DYNAMICS

1.1 Reasons for studying distillation dynamics

The first seven chapters of this book deal with the dynamics of distillation units. Broadly speaking, there are four different reasons for studying the dynamics of a process.

Firstly, the dynamic behaviour may be of interest in connection with the operation of the process. Questions concerning inherent stability, startup and shutdown procedures, transitions from one operating condition to another, and the damping of pulsations belong to this category.

Secondly, knowledge of the dynamics is essential for automatic control. The importance of this reason is so obvious, that we do not have to amplify it here.

Thirdly, some processes are more effective under sustained transient conditions than under comparable steady-state conditions, typical instances of this being found in pulsed extraction and controlled-cycling distillation. Here, even if the two reasons mentioned above happen to be of secondary importance, the dynamics may still have to be studied quite thoroughly in order to advance our knowledge of these processes.

Fourthly and lastly, studies of process dynamics can be used to obtain data that are hard to come by in any other way. Under this heading come the use of tracers to measure residence-time distributions in mixing vessels, the use of frequency response techniques to determine the diffusion coefficients of packed beds, and so on. References to techniques of this kind in distillation studies will be found in Section 7.8 of the literature review.

From our point of view, these four reasons are not equally important, since it was primarily our interest in the control of continuous distillation units that led us to develop the fairly general theory of distillation dynamics which we describe in these chapters. For a better understanding of this endeavour, it may be useful to discuss its motivation in more detail.

It may be argued that the automatic control of continuous distillation units does not constitute a research challenge of very great practical value. Indeed, an overwhelming majority of the units now in operation do not appear to present any serious control problems at all, and in many of the other units the troubles are due simply to the malfunctioning of instruments or processing equipment. The remaining cases, which do present fundamental control problems, though small in percentage, are admittedly still very numerous; but these, it may be argued, mainly concern columns working under adverse conditions, or unusual systems involving split columns, side streams, azeotropic or extractive mixtures, etc., which could hardly be covered by a general theory.

Nevertheless, our principal objective has been to develop a general description of column dynamics that would be applicable to most 'normal' columns [1], in such a way that it would be possible to draw useful conclusions about the performance of the various possible control systems. How, then, are the above arguments to be countered?

In the first place, even if the overwhelming majority of distillation units do not appear to present any control problem at all, this does not necessarily guarantee that no worthwhile improvements can be made. Probably many, if not most, of the units could be operated at lower cost, or with better efficiency, higher throughput, or any attractive combination of these, by modifying their control systems. Also, it cannot be denied that the absence of control problems may already have been paid for by luxurious margins of wisdom, safety, or ignorance ('overdesign').

We reasoned that if the various possible control systems were compared with

[1] Admittedly, this definition has a tautologous streak, in that the distinction between 'normal' and 'abnormal' is partly governed by what can be conveniently handled by the theory developed.

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