considered to be a good method for allowing students to study additional separations without clogging the curriculum. These electives can be dual-level courses and might allow some faculty to teach in the area of their research. Unfortunately, when the details of an elective course were looked at there was considerable disagreement on the depth versus the breadth of the course. The compromise of covering a few topics in depth while other topics are only surveyed might be acceptable; but there was a strong feeling that the course had to be integrated (perhaps using Figures 1 to 3) and not be a series of unconnected topics. The coverage in an elective and a required advanced course at the authors' schools is shown in Table 1.

## SUMMARY

Like many other areas of chemical engineering, knowledge and application of new separation technologies are expanding at a rapid rate. The problem of how to introduce new separations into the curriculum is exacerbated by the neglect of particulate separations. Modest adjustments in current courses can probably be made by reducing the coverage of distillation and by adding new or neglected separations to the current course and in design and laboratory courses. One or more elective courses in separations are also highly desirable.

## ACKNOWLEDGMENT

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**ChE book review**

# CHEMICAL OSCILLATIONS AND INSTABILITIES: Non-Linear Chemical Kinetics

by Peter Gray and Stephen K. Scott

*Oxford Science Publication, Clarendon Press, Oxford; 453 pgs. $98.00 (1990)*

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Following an overview introductory chapter, this book is divided into two parts which cover a total of fifteen chapters. The first part is the broader one and is titled "The Techniques," while the second part, "Experiments," consists of only two chapters.

In the first part, the backbone kinetic scheme is the so-called Autocatalator, whose complete version consists of the following reactions: P→A; A→B; A+2B→3B; B→C. It is characterized by reaction rates following the law of mass action and by the third step which is cubic and autocatalytic. This feature of the model provides the feedback mechanism which produces instability and oscillations. In the different chapters, the autocatalator is analyzed in detail by considering some of its meaningful modifications and several reactor configurations. This kinetic scheme has been chosen because it exhibits all kinds of typical complex nonlinear behavior, while it is simple enough to allow for much exact analysis.

In Chapters 2 through 5, the closed homogeneous reactor is considered. In Chapters 2 and 3, the isothermal case is analyzed, first by determining the pseudo-stationary states of the system. These are obtained by assuming that the reactant concentration, *e.g.,* the concentration of P, is constant. Then, the concept of steady-state stability is introduced and a linear stability analysis is performed to determine stability conditions on the parameters of the model. It is shown that under the assumption of no reactant depletion, the autocatalator exhibits oscillatory behavior (*e.g.,* limit cycles) for the values of parameters where the steady-state is unstable. The importance of casting the model equations in dimensionless form is strongly emphasized and this technique is applied throughout the book. Finally, the complete model, accounting for reactant consumption, is studied, thus proving that its behavior can be understood and predicted by exploiting the previous analysis based on the pseudo-stationary states and their stability.

Chapters 4 and 5 deal with thermokinetic oscillations in a homogeneous reactor which exchanges heat with the surroundings but is closed to mass transfer. In this case the kinetic scheme simply consists of two consecutive first-order reactions: $P \rightarrow A$ and $A \rightarrow B$. Here the feedback mechanism is provided by the thermal effect due to the exothermicity of only the second reaction. Performing the same analysis (*e.g.,* first determining the pseudo-stationary states and their stability and then describing the reactant consumption) yields similar results as in the isothermal case. In order to account for the temperature dependence of the model, the following approach is used throughout the entire book. First the Arrhenius law is approximated by a simple exponential expression, allowing one to obtain several analytical results. Then the exact Arrhenius law is used and the results are compared. In Chapter 5, the Hopf bifurcation analysis and techniques for the quantitative analysis of relaxation oscillations are described and applied to the thermokinetic oscillation model.

Chapters 6 through 8 deal with CSTRs. In Chapter 6, the isothermal case is considered and steady-state multiplicity patterns for kinetic schemes of increasing complexity are determined. The effects of residence time and of the reversibility of reactions are analyzed. The non-isothermal CSTR is studied in Chapter 7 with first-order kinetics and Arrhenius temperature dependence. Both adiabatic and non-adiabatic reactors are considered. Here, the strong analogies with the cubic autocatalytic kinetics in the isothermal CSTR are illustrated. Also in the chapter, singularity theory and its applications are introduced. In order to demonstrate its power, some results about isothermal cubic antocatalysis and non-isothermal CSTR are obtained again by applying singularity theory methods.

Chapter 8 deals with the stability of stationary states in the isothermal autocatalytic CSTR. In particular, the response to transient perturbations is analyzed, illustrating the exponential relaxation to stable states and the exponential growth from unstable states. The onset of oscillations when the stationary state loses its stability is studied, with particular reference to conditions for emerging stable or unstable limit cycles.

Chapters 9 through 11 are concerned with spatially distributed systems where molecular diffusion and thermal conduction processes play a fundamental role. First, reaction-diffusion cells are introduced, and spatially distributed sta-

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glucose substrate is present at sufficiently high concentrations that growth is zero order with respect to glucose. In Eq. (6), $P_{max}$ is a semi-empirical parameter corresponding to the highest ethanol concentration which will allow growth. This value can vary significantly from one strain of yeast to another; values of 90 to 120 g/L are typical. The exponent, n, is empirical, but often a value of 0.45 is used. In Eqs. (7) and (8), $k_i$ and $K_{ix}$ are empirical parameters. For the yeast strain we used, Eq. (6) was the most satisfactory.

## CONCLUDING REMARKS

Equipment malfunctions, particularly with the dissolved oxygen electrodes, should be anticipated, and the techniques for preparing inocula should be followed consistently. Under some stress conditions, this strain of yeast can develop a pinkish pigment that can invalidate the optical density versus dry weight relationship.

We obtained generally good results for determining $k_La$, particularly with the unsteady-state method. The kinetic data are more problematic since few data points are available due to the laboratory's time constraints. Further, the requirement for a high level of precision in biomass and glucose measurements is not met by every student group. Although the actual techniques are straightforward, careful attention to detail and sample handlings are required. Groups with fewer than three students are unworkable as the students are too rushed for time to complete the assays carefully.

In summary, we believe that it is possible to introduce a meaningful, challenging but doable, bioreactor experiment to chemical engineering seniors who lack any prior exposure to biology or bioprocessing. The use of two fermenters is necessary if these goals are to be accomplished in two separate laboratory periods of three hours. The student response to the experience has been very positive.

## ACKNOWLEDGMENTS

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# REVIEW: Oscillations and Instabilities

*Continued from page 17.*

tionary states are calculated and analyzed, showing that steady-state multiplicity can occur also in this case. The effects of different kinetic mechanisms and boundary conditions on the multiplicity pattern and the stability of the steady-states are discussed.

In Chapter 10, the formation of stationary spatial patterns, the so-called Turing structures, is considered for the thermokinetic model, *e.g.,* non-isothermal first-order kinetics. First, the homogeneous steady-state is evaluated and its stability character is determined. In the case where it is stable to spatially homogeneous perturbations and the ratio of mass and thermal diffusivities is sufficiently large, it is demonstrated that stable spatial patterns can form due to spatially inhomogeneous disturbances. On the contrary, when the uniform steady-state is unstable to spatially homogeneous perturbations (*e.g.,* the corresponding well-stirred system exhibits limit cycle behavior), diffusion processes have no stabilizing effect. Spatial patterns can form and survive for a finite time, but eventually they decay to spatially homogeneous oscillations.

Chapter 11 deals with chemical traveling waves in a one-dimensional space domain. The case of constant speed of propagation is considered and its limitations are discussed. It is shown how quadratic and cubic autocatalysis produce traveling waves.

In Chapter 12, the broad issue of heterogeneous reactions is addressed. The aim of this chapter is only to show that also in this case, steady-state multiplicity and instability can occur due to non-linearities in the model equations. How these non-linearities can arise is discussed in some detail. In particular, the cases of activated adsorption, multi-site reaction mechanism and competitive chemisorption are considered. The chapter includes some examples of steady-state multiplicity and oscillations.

The last chapter of the first part of the book, Chapter 13, introduces the reader to the world of chemical chaos. After clarifying that more than two state variables are required for a continuous system to exhibit deterministic chaos, the authors turn to simple discrete mappings to illustrate the striking phenomenon of the Feigenbaum cascade. Then the periodic forcing of oscillatory systems is considered by illustrating some techniques for their analysis and some examples of their behavior. Subsequently, complex oscillations and chaos in autonomous systems are dealt with and the determination of the stability of limit cycles through the computation of Floquet multipliers is described. Examples are provided by a modified version of the autocatalator in an isothermal batch reactor and by two consecutive exothermic reactions in a CSTR.

In the first chapter of the second part of the book, Chapter 14, the widely studied Belousov-Zhabotinskii (BZ) system, as an example of a solution-phase reaction, is considered. First, background information on the BZ oscillations, its chemical mechanism and its simplified three-variable model (*e.g.,* the Oregonator) is given. Then the relaxation oscillations of the Oregonator are analyzed in some detail using the techniques developed in Chapter 5. The BZ oscillations in flow reactors are considered next, introducing the issue of bistability. The chapter is completed by the analysis of the minimal bromate oscillator, where the organic substrate is omitted.

Chapter 15 presents results for several gas-phase combustion reactions. In particular, hydrogen, carbon monoxide and acetaldehyde oxidations are considered.

Indeed, the book reaches the dual aim stated by the authors in the Preface. On one hand, it encourages more chemists "to be less afraid of mathematics" by guiding the reader through the colorful zoo of non-linear dynamics, using simple examples while avoiding the presentation and discussion of theorems in rigorous mathematical terms. On the other hand, those more familiar with the mathematical tools will find a new opportunity to appreciate the richness of "the chemical world" in terms of non-linearities.

The approach adopted throughout the book is rather pragmatic. A clear indication of this attitude is in an introduction to each chapter. It does not contain the usual list of material treated in the chapter, but rather a list of items which the reader should be able to accomplish "after a careful study of the chapter."

In presenting each new dynamic phenomenon, first a numerical example is presented in order to illustrate the physical picture, and then the mathematical tools for developing an exhaustive analysis are described. The reader is never involved in rigorous, high-level mathematical discussions, while the mathematical developments are reported in full detail. This permits smooth reading.

In the more complex area of spatially distributed reaction-diffusion systems, the emphasis is placed on the representation of the various possible dynamic behavior. The description of the mathematical tools needed for the their determination becomes inevitably more vague.

The effort expended in relating the mathematical behavior to the physico-chemical basis of the system is indeed remarkable. For this, the authors analyze in parallel two different models whose non-linearities arise from two different sources. In the autocatalator, which has been introduced and widely studied in the literature by the authors, the non-linearity is in the cubic autocatalytic step. This model has the merit, over the classical Brusselator and Oregonator, of providing probably the best compromise between simplicity and richness of dynamic behavior in an isothermal closed system. In the non-isothermal model, where two irreversible first-order reactions are considered, the exotic dynamic behavior arises from the interaction of the reaction thermal effects with the non-linear Arrhenius dependence of the kinetic constant.

On the whole, this book provides an easy and convenient entry into the difficult area of non-linear dynamics. While there are not many independent courses existing which could use this book as a text, it could certainly be used as a supplementary text for graduate-level applied mathematics and reaction engineering courses. It is most certainly a valuable reference for all who are interested in the dynamics of reaction processes. ❐

**ChE** ***book review***

## TEACHING ENGINEERING

*by Phillip C. Wankat and Frank S. Oreovicz*

*Published by McGraw-Hill, Inc., New York, NY; 370 pages, softcover $32.95 (1993)*

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*Teaching Engineering,* by Wankat and Oreovicz, covers all aspects of teaching engineering and does it in a clear and concise manner. The text evolved out of an engineering graduate course on educational methods taught at Purdue University and a project funded by the National Science Foundation. Materials from the text have been successfully used in faculty-training courses given through the American Society for Engineering Education as well as through other organizations.

Although it is oriented toward helping a new faculty member to become an excellent and efficient teacher, the text can also be quite useful for any engineering educator, and can be used as the textbook for a graduate course for students who are considering teaching as a career. The text can be used by any engineering discipline and would certainly be suitable as a resource for faculty outside of engineering.

The book is written in a pragmatic "how-to" style. This method of concept-presentation allows an instructor to easily follow the points made on any of the various subjects. Educational philosophy is incorporated when appropriate, and extensive references are given for those who want more information on a particular topic. Each chapter is effectively divided into subsections and concludes with chapter comments, summary and objectives, homework problems, and references.

The first chapter, "Introduction: Teaching Engineering,"

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