

CHE

chemical engineering education

VOLUME XXI

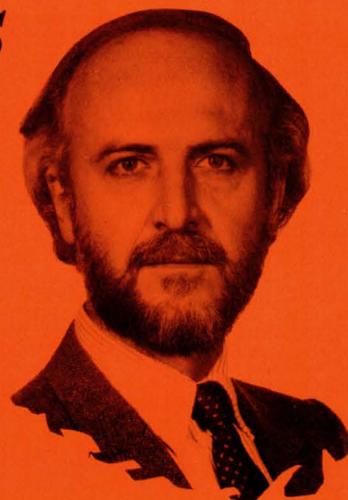
NUMBER 3

SUMMER 1987



CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

GEORGE STEPHANOPOLOUS of M.I.T.



- TIPS ON TEACHING REPORT WRITING
HUDGINS
- THE BURNING OF A LIQUID OIL DROPLET
HAYHURST/NEDDERMAN
- TEACHING HEAT EXCHANGER NETWORK SYNTHESIS
DIXON
- A FIRST CHEMICAL ENGINEERING LAB EXPERIENCE
PUNZI
- ESTIMATING RELATIVE VOLATILITY OF CLOSE-BOILING SPECIES
BARDUHN
- THE MILLIKEN/GEORGIA TECH RISING SENIOR SUMMER PROGRAM
AGRAWAL/SOMMERFELD
- UC ONLINE: BERKELEY'S MULTILoop COMPUTER CONTROL PROGRAM
FOSS
- REVERSE OSMOSIS SYSTEM FOR AN ADVANCED SEPARATION PROCESS LABORATORY
SLATER/PACCIONE

**AND ChE AT
The Johns Hopkins University**

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University of Florida
Gainesville, Florida 32611

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CHEMICAL ENGINEERING EDUCATION is published quarterly by Chemical Engineering Division, American Society for Engineering Education. The publication is edited at the Chemical Engineering Department, University of Florida. Second-class postage is paid at Gainesville, Florida, and at DeLeon Springs, Florida. Correspondence regarding editorial matter, circulation and changes of address should be addressed to the Editor at Gainesville, Florida 32611. Advertising rates and information are available from the advertising representatives. Other advertising material may be sent directly to the printer: E. O. Painter Printing Co., P. O. Box 877, DeLeon Springs, Florida 32028. Subscription rate U.S., Canada, and Mexico is \$20 per year, \$15 per year mailed to members of AIChE and of the ChE Division of ASEE. Bulk subscription rates to ChE faculty on request. Write for prices on individual back copies. Copyright © 1987 Chemical Engineering Division of American Society for Engineering Education. The statements and opinions expressed in this periodical are those of the writers and not necessarily those of the ChE Division of the ASEE which body assumes no responsibility for them. Defective copies replaced if notified within 120 days.

The International Organization for Standardization has assigned the code US ISSN 0009-2479 for the identification of this periodical.

GEORGE STEPHANOPOULOS

of MIT

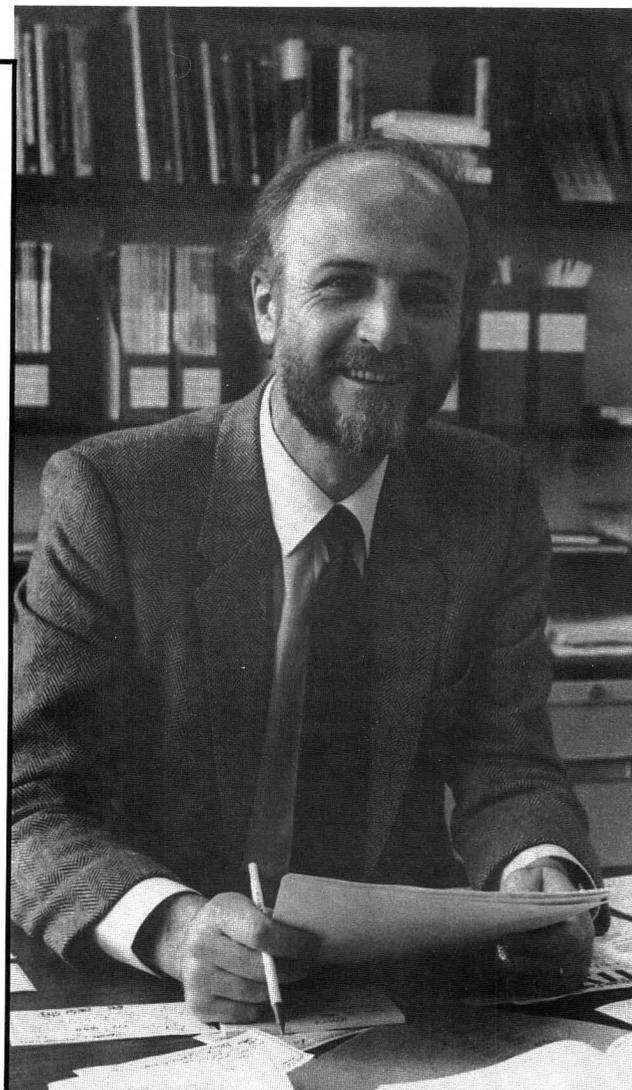
MARC J. CHELEMER

*Massachusetts Institute of Technology
Cambridge, MA 02139*

IF ONE WERE TO select current chemical engineering faculty members whose innovative research, visionary thinking, and creativity match those of the original educators in the field, George Stephanopoulos would stand high on the list. By his prodigious output of research papers, his contribution to teaching and education through textbooks and monographs, his rapport with and motivation of students, and his advancement of knowledge through a willingness to tackle new, ill-defined problems, George has distinguished himself as one of the best professors teaching today. His insight and keen intellect have made great strides in our understanding of his chosen fields of process synthesis, control systems engineering, and knowledge-based computer applications to these and other problems. Most surprising, George is only thirteen years out of the student life himself and is only forty years old. To understand his contributions, it is appropriate to examine the beginnings of George's already important career in chemical engineering.

THE STUDENT

Stephanopoulos was born on June 1, 1947, in the port city of Kalamata, Greece, near the ruins of ancient Sparta. He attended the National Technical University of Athens, receiving his diploma in chemical engineering in 1970 with the highest honors among all graduating engineering students, including the "Thomaidion" and "Chrysovergeion" Awards. From there, he moved to Hamilton, Ontario, where he began his master's studies under Cameron Crowe at McMaster University. Crowe recalls that the new arrival was "a delightful student to work with. I wish I had more like him." In his year of study, Stephanopoulos worked in "a very difficult, delicate area." The research, optimizing a tubular reactor



system with catalyst decay, contained "many traps for the unwary student," but George avoided them all, grasping concepts very quickly and integrating them into his thesis. This became George's trademark: a quick, analytical mind, the ability to understand new ideas rapidly, and a questioning nature which took him deeper into his fields of investigation.

After receiving his MS, Stephanopoulos went on to the University of Florida at Gainesville to work with Arthur Westerberg in process engineering research. His PhD effort focused on understanding how

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to analyze, synthesize, and optimize large-scale processes. The Primal-Dual Bounding problem, a computer algorithm, had just been completed, but the implications required elaboration. George took the reins of this project and forged ahead. Westerberg says that Stephanopoulos was a "joy to work with, a very strong student destined to be a great professor." Advisor and advisee argued frequently, with each side winning about half the time.

In one instance, George postulated a theorem and then, on demand, provided a complete proof three days later. Although the proof was invalid, the theory proved correct. In a similar, equally memorable event, Dr. and Mrs. Westerberg asked George if he would prepare some Greek recipes for a small dinner party if they supplied the ingredients. George informed them that the three whole bulbs of garlic supplied for his culinary work would be insufficient to prepare the food for six guests. After the necessary additions had been procured and the meal prepared, his claim again proved correct.

George finished his PhD in three years, matriculating in 1974. During that time, he wrote or co-wrote seven technical papers. This marked the beginning of Stephanopoulos' major contributions to chemical engineering research and education.

THE RESEARCHER

The now Dr. Stephanopoulos took his first teaching position at the University of Minnesota in 1974, where he followed the tenure track to full professorship by 1980. That same year, he acted as a tourguide in Greece for his colleagues. On that trip, he both met his wife-to-be, Eleni, and accepted a post at his alma mater, the National Technical University in Athens. Although he maintained his position at Minnesota, his colleagues missed his day-to-day presence on the staff. During his years in Athens, George saw the possibilities of assuming a leadership role in state science within Greece's technical community, but also felt a pull to conduct exciting and innovative research in the USA. Sometime during that same period, George first made the acquaintance of MIT's chemical engineering faculty at the Exxon suite of an AIChE meeting. "A long admiration and courtship" followed, according to MIT Department Head James Wei, which culminated in Stephanopoulos' return to the USA and MIT in 1984, where he has held the J. R. Mares Professorship in Chemical Engineering ever since.

In the thirteen years since his PhD was granted, Stephanopoulos has distinguished himself as one of the brightest and most forward-thinking faculty members

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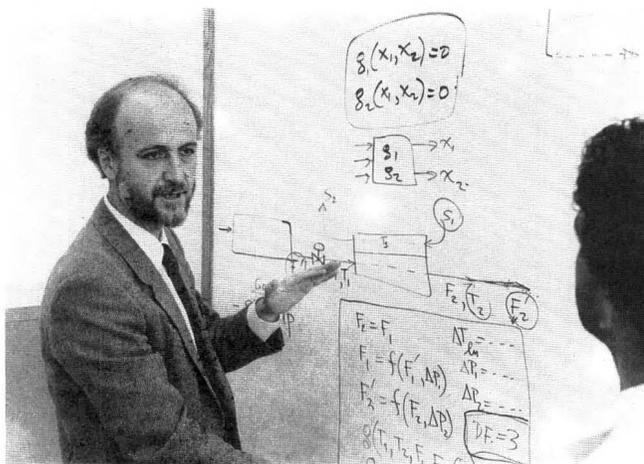
in the profession. His prodigious output of papers, monographs, and textbooks has ensured his place in chemical engineering education for many years. Colleagues describe George's work as "extremely original and inventive," "very exciting," "intellectually superb and refreshing," and "leading the way in pioneering fields." He is a methodical man: "Before he says anything," explains a colleague, "he has thought it all out—all the consequences too." He "sees things in an entirely different light, turns ideas around." "He always tackles new problems, looks into new areas. He's ahead of everybody else. He has a great vision and a long time horizon." For his research work, he was selected as a Camille and Henry Dreyfus Teacher and Scholar in 1977, and received the Allan P. Colburn Award of the AIChE for 1982. An examination of his research contributions illustrates how his work has enriched the basis for chemical engineering:

Process Synthesis: George's early work focused on branch and bound search, and evolutionary synthesis strategies for process synthesis. He developed the first rigorous techniques to solve the former, and provided the basis of logical techniques to replace *ad hoc* methods in use at the time for the latter. Later, he wrote about developing physical insights to augment the available mathematical techniques. These efforts have helped engineers adopt a more integrated approach to plant and process design. Work on chemical reaction pathways in a Gibbs' free energy versus temperature space helped understanding of the efficiency of alternative reaction pathways to desired chemical products.

In studying separations, Stephanopoulos' research in heat-integrated distillation revealed some unknown properties which allowed sequential selection of separation splits and more ideal heat integration between columns. This work justified some common industrial practices which until that time had no quantitative basis. It has also yielded better, more efficient industrial procedures.

Control Engineering: Other early professional research applied experimental ideas and techniques useful for process design to control systems. His efforts

almost single-handedly changed the field from one which studied individual unit control to understanding complete processing system control. As industrial practice follows the latter procedure, George's rigorous whole-system approach became applicable immediately. He also introduced the concepts of "constraints-based" supervisory control, and suggested that operating improvements could result from what he called "variable control structures." He also contributed to understanding the need for data reconciliation and gross error identification to ensure reliable and accurate data from which to base a control strategy. He considered not only steady-state operation,



George's patience and his ability to motivate students are the keystones of his teaching success.

but start-up, shutdown, changeover, and optimization procedures.

Model-based control systems: To ensure the effectiveness of the plant-wide strategies developed in the previously discussed research, Stephanopoulos committantly developed theoretical novel control hardware for implementing them. Two significant results of this effort are the 2-port controller and the strategy of structured control. The first concept provides a device with two control elements of different but complimentary design goals. One "port" provides command-following control within specified stability robustness levels and performance. The second port maintains current system status based on an input model, thus providing regulation against process disturbances. Depending on whether steady-state or changeover operation is desired, one port is given priority over the other. This idea is being investigated extensively; one potential use currently under study relates to in-vivo insulin control systems for diabetics.

Structured control is the application of rule- and knowledge-based computer systems to real-time, on-line responses to process disturbances. Using process measurements from the plant, the computer system responds in varying fashion depending on its instructions and "reasoning." This work, now in development, promises a new generation of control systems more powerful than any predecessor.

Artificial Intelligence: Since arriving at MIT, George has pursued applications of powerful AI computers using the LISP programming language. He has established an industry-sponsored research laboratory to study the impact of these "intelligent systems" on process engineering. In this new area of study, George is leading both MIT's effort and the profession as a whole.

Some of the ongoing projects are amplifications of earlier work. Having studied heat exchanger networks, separation processes, whole chemical plants, and control engineering, he is looking at some of the basic science involved. For example, he is attempting to design solvent molecules with characteristics useful for extractive separations, heat-pump fluids with efficient economics, and polymer molecules with desired mechanical, chemical, and other properties. This effort relies on the use of factor analysis and additive group contributions, relationships so complex and intertwined that rule-based computer systems are needed to assist engineers in devising likely molecular candidates. He is also attempting to use AI and knowledge-based systems to screen alternative production routes and develop process flowsheets, plantwide control schemes, and operating strategies for problems ranging from individual process units to entire chemical plants.

Biotechnology: George's research looks at three areas in this new field: modeling of bacterial biochemical pathways, design and development of mammalian cell bioreactors, and synthesis of separation and recovery schemes for bioproducts, notably proteins. The first effort helps scientists understand genetic modifications necessary to obtain certain desirable products and to identify those bacteria most amenable to that genetic engineering. The work in the second area aims at the development of an "intelligent" system which coordinates the knowledge from three different areas—molecular biology and genetics, reactor engineering, and operational analysis and control—to design a bioreactor system with optimum characteristics. George's brother Greg, who is collaborating on these projects, played a pivotal role in stimulating interest in this research area. As MIT has established

At Minnesota he was awarded the G. Taylor Teaching Award for his efforts in the classroom, yet was playfully chided for his pronunciation of certain words and kidded about his habit of not wearing a tie. The latter joke involved the presentation of a hair-covered undershirt for colder days in Minneapolis.

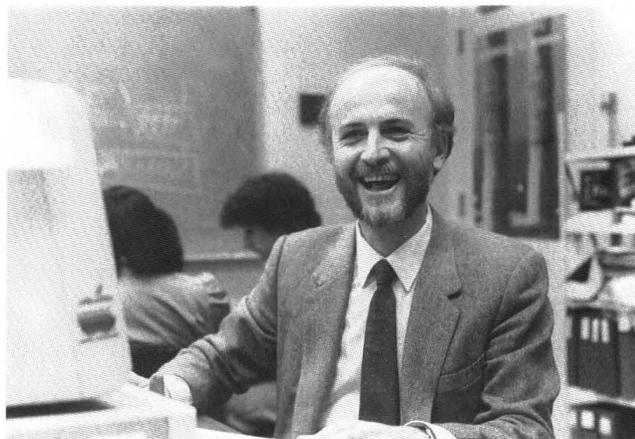
a new research center for biotechnology processing, George plays a vital role in both fields—AI and cell biology—new and perhaps unfamiliar to many other engineers. True to form, Stephanopoulos and his students are already producing paper after paper demonstrating high-quality research and understanding.

THE EDUCATOR

Stephanopoulos' written contributions to chemical engineering education includes books, monographs, and course notes. His best-known opus, *Chemical Process Control: An Introduction to Theory and Practice*, is used by more than 50% of the chemical engineering departments in the US, only two years after publication. His review papers on process synthesis, on control systems for complete chemical plants, and on AI in process engineering are unique in their respective fields. In addition to his writing, George is a leader in developing MIT's chemical engineering curriculum. James Wei describes George's role: "He thinks about what the meaning of education and research really is. He wonders how we should be teaching our students, and what changes should be made." George has strengthened the MIT department by helping to attract his brother Gregory and his sister-in-law Maria to MIT, where they have assumed important roles in the areas of biotechnology and pollution control science, both traditional MIT strengths.

Stephanopoulos has contributed to new course development in all of his teaching positions, and many of his PhD students have gone on to take faculty positions in other universities. These professors are themselves among the most important control system/process design faculty working today. Altogether, he has supervised thirty graduate students at the three universities.

George enjoys the same popularity with his students at all levels as he does with his peers. He is described as being very patient, understanding, and slow to anger. At Minnesota he was awarded the G. Taylor Teaching Award for his efforts in the classroom, yet was playfully chided for his pronunciation of certain words and kidded about his habit of not wearing a necktie. The latter joke involved the presentation of a hair-covered undershirt for colder days in Minneapolis. When one irate student expressed his dissatisfaction with a particular exam by placing a



Stephanopoulos sharing a relaxed moment with his students.

"Nuke Stephanopoulos" ad in the school paper, other students rallied. The culprit was waiting for a lecture soon after the ad appeared when four "gangsters" marched into the room in zoot suits and wing-tips, carrying violin cases. They promptly dispatched the culprit with vanilla cream pies.

According to some of his current students, he "does a tremendous job of getting people motivated." In the area of AI, the original student skepticism has been replaced by a positive, team attitude. Meetings in the Lab for Intelligent Systems in Process Engineering (LISPE) often last twice as long as scheduled, with computer code, ideas, and camaraderie shared within the group. George is particularly approachable, his students say. Perhaps that explains why he is the most sought-after professor in MIT's free-market advisor selection system. George is also a participant in soccer, volleyball, and outdoor recreational activities with his students. "He's just as aggressive on the field as off, and a fine athlete, too," says one.

THE PRIVATE MAN

In the midst of this hectic and intensively dedicated professional life, George commits himself to many private, philosophical, and artistic pursuits. "He is a deep thinker and has more cultural interests than many of his colleagues." "George is a true renaissance man, particularly in music and in art." "He keeps a

healthy attitude about leading a balanced life." He is a friend and confidant to many, and is a dedicated family man. George and Eleni visit their families in Greece annually, and are the parents of two small children, Nikos and Elvie. George enjoys working with his family members in the department, although his suite-mates indicate that he shows a kindred spirit with all of them.

Chess occupies George's technically creative time. A computer program which might teach novices opening moves, standard defenses, and some basic strategies is one ongoing project.

Many colleagues mention his deep and profound interests in literature and philosophy. George explains that his Greek poetry and short stories are a very private creative outlet for him. He always gave public talks and poetry readings of other authors at Minnesota's annual AIChE spring banquet, much to the delight of the audiences. Stephanopoulos has read ex-

tensively from 20th Century American writers, the Russian literature, and German philosophy. He follows Greek poetry, notably Nobel laureates George Seferis and Odysseus Elytis. Lately, the South American writers, notably Garcia-Marquez (a strong influence, he says), Ernest Sabato, Jorge Luis Borges, and Vargas Llosa are his favorites.

Commenting on his recent winning of the Curtis McGraw Award for Research from ASEE, George notes, jokingly, that engineering is rarely a route to the Nobel Prize, and that he personally would try to win it only for literature or peace. Considering that he ably handles his commitments to MIT, his editorship on two journals, and his membership in eleven technical and professional societies, while still maintaining strong ties to family, friends and students, the Nobel seems an appropriate long-term goal for this man of vision, technical excellence, and commitment to learning. □

ChE book reviews

PRINCIPLES OF UNIT OPERATIONS, 2nd Edition

*by Foust, Wenzel, Clump, Maus, and Anderson
John Wiley & Sons, 1980, 768 pages*

**Reviewed by
Davis W. Hubbard
Michigan Technological University**

This is a revision of the first edition published in 1960 and retains the same large-page format, arrangement of subject matter, and emphasis on engineering practice and design. The type size has been increased and two chapters have been added, increasing the number of pages from 578 to 768. The new edition bears a 1980 copyright and quite a number of references have been added to most chapters since the first edition. The book is intended to be an undergraduate textbook. It is quite easy to read, yet the material is covered in such a way that the reader has the feeling of progressing beyond the simplest basic material. There are extensive equipment diagrams and an excellent emphasis on practical design. One of the attributes of the book is the treatment of the common features of the various topics in a unified way. This is applied both to separations processes and to transport phenomena topics. British engineering system units are used mostly, but there are scattered examples in which SI units are used. There is a good selection of

design data, eliminating the need for searching for data in other sources and making the book easy to use for beginning students.

The first section of the book deals with continuous stagewise processes. The emphasis is on the similarities among the different processes discussed. This works well for distillation and absorption, but it is a little strained for leaching and adsorption. The Ponchon-Savarit graphical method of analyzing distillation processes and other related graphical methods are the focal point of this section. The material is written in a straightforward manner and is easy to understand and apply. The ideas of minimum solvent flow rate and minimum reflux ratio are handled well. People who believe that using the Ponchon-Savarit method or graphical methods in general is outmoded and should be discontinued in favor of using numerical methods will not like this section. People who believe that the Ponchon-Savarit method helps provide insight related to energy balances and changes in molar flow rates between stages will be pleased with this section.

At the end of the section about stagewise processing there is a new chapter on multicomponent calculation methods. This chapter replaces one about unsteady distillation processes in the first edition. The discussion focuses on distillation processes and emphasizes fundamentals. Computer codes are not emphasized though computer methods are apparently

used in solving the example problems. A very clear example dealing with a five-component mixture is solved using the Fenske-Underwood-Gilliland shortcut method.

The second section of the book treats transport phenomena. There are chapters about transport coefficients, molecular transport, and turbulent transport. The discussion of the various concepts seems quite straightforward and easy to understand. The treatment of unsteady conduction has been changed quite a bit from the first edition. The discussion is somewhat confusing, but empirical equations which could be used for computer calculations are supplied. There is a good discussion about the limitations of semi-empirical turbulence models.

A chapter on heat transfer comes next. This chapter uses British engineering units. The detailed example calculations emphasizing assumptions are good, and there is good coverage of practical aspects of shell-tube heat exchanger design. Condenser design methods are restricted to pure vapors. Mixed vapor condensation is not discussed. The references cited are quite old.

The next chapter treats mass transfer with emphasis on continuous contactors. The differences between gas-liquid and liquid-liquid operations is blurred sufficiently so that the similarities can be seen. The mass transfer coefficient correlations presented are easy to use. There is a clear development of design equations with good explanations of the assumptions involved and the methods of integrating the equations. Some good numerical examples are given. Stage efficiency is mentioned in this chapter, but the treatment is not extensive.

The next section is devoted to simultaneous energy and mass transfer with chapters on humidification and water cooling, drying, and evaporation and crystallization. There is good coverage of water cooling—a topic sometimes treated in a superficial way in textbooks. The discussion includes methods for determining the gas phase temperature and evaluating heat and mass transfer coefficient data from experimental data. The discussion of drying is quite standard. There is an extensive discussion of spray drying, but other types of continuous drying are not mentioned. The chapter on evaporation is written using SI units, and evaporator calculations are described clearly. There is a good review of mass and energy balances and an introductory discussion of mass transfer considerations in crystallization.

The final chapters are devoted to fluid mechanics and fluid mechanical separations processes. The discussion of the Bernoulli equation seems somewhat

ponderous, and the notation for friction loss is not the same as used by other writers. The discussion of friction factors for straight pipe is good, but fitting losses are discussed exclusively in terms of equivalent length. This is a time-honored method, but for smooth-walled pipe it introduces a small Reynolds number dependence which is not supported by data. The discussion of flow meters is good. It includes examples of meters suitable for remote reading as well as the traditional types.

The chapter about pumps contains excellent pictures of pump assemblies and excellent discussions of NPSH and specific speed. There is not much discussion of pump efficiency, though the examples of pump characteristic curves which are given include efficiency.

The chapter about fluid-solid separation begins with a discussion of drag coefficients which includes the effect of particle shape. Many topics are covered in this chapter, and there is a certain lack of continuity. It might have been better to make separate chapters focusing on moving solids and fixed solids. The example of thickener design calculations is complete, detailed, and easy to follow. The filtration calculations based upon using an equivalent volume of filtrate to represent the filter medium resistance are fairly easy to understand, but the method has always seemed artificial. The filter analysis calculations are presented in terms of the filtration rate even though this requires graphical or numerical differentiation. The integrated equations are presented but are not used in the analysis. Applications to continuous filtration are ignored.

The appendices are well written and useful. There is a lucid discussion of g_c and J putting these factors into their proper perspective as unit conversion proportionality constants. The dimensional analysis discussion focuses on the Buckingham Pi method, hitting the high points without excessive mathematical development. The unit system which includes force as a fundamental dimension is used exclusively. The appendix in which screen analysis and the characteristics of particles are discussed is well written and easy to understand. There is also an appendix containing most data needed for solving the problems. The sources are sometimes not cited fully.

This book is a gold mine for problems designed to be challenging but easy enough so that students beginning their study of unit operations can be expected to complete them. Between ten and sixty problems are included with each chapter, and only a few chapters have fewer than twenty-five. This is a major strong point of the book. □

THE JOHNS HOPKINS UNIVERSITY

CAROL HYMAN

*The John Hopkins University
Baltimore, MD 21218*

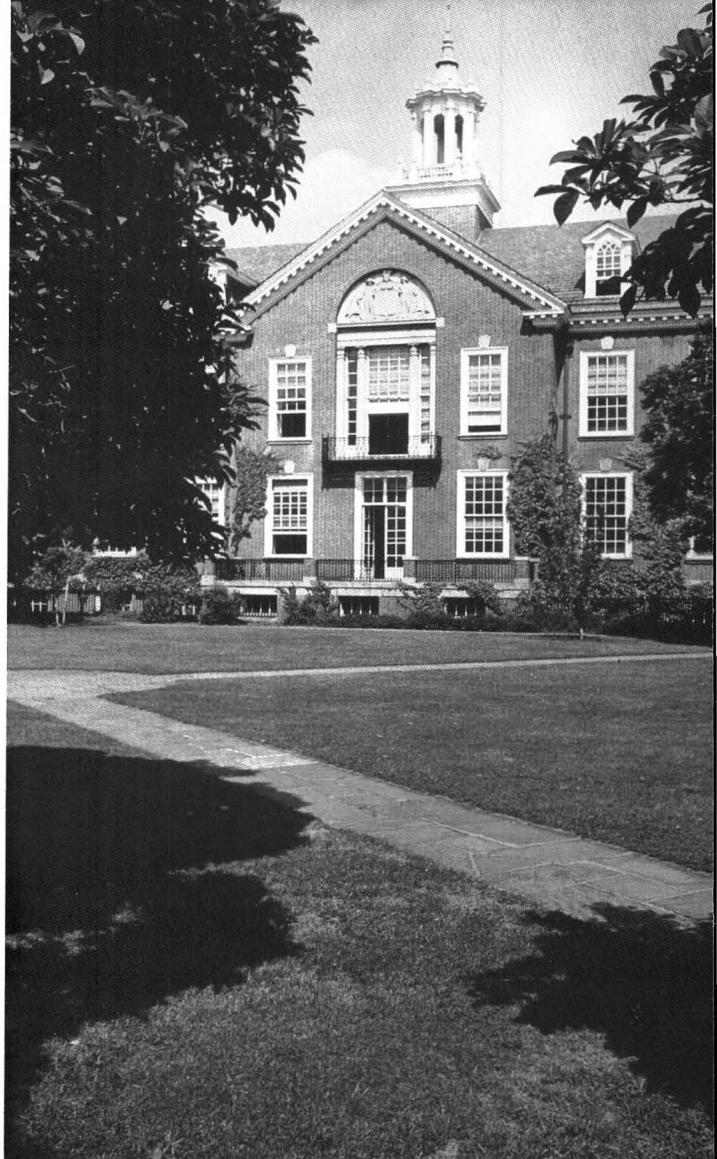
JOHNS HOPKIN UNIVERSITY, John Hopkins University, John's Hopkins University, The Johns Hopkins University. Never has a university's name produced so many variations. In brief, Johns was the founder's mother's maiden name, and unfortunately for him, he inherited a last name for a first name.

Despite the frequent misspellings and confusion, The Johns Hopkins University has a long and prestigious history. Founded in 1876, Hopkins established itself as the first true American university on the European model; a graduate institution in which knowledge would be created as well as taught. As early as 1913 engineering became an integral part of this university, creating the foundation for what would later become the G.W.C. Whiting School of Engineering.

The Schools of Engineering, Continuing Studies, and Arts and Sciences, and the Space Telescope Institute are located on the Homewood campus in north Baltimore on a 140-acre wooded campus in a residential area. The campus was originally the Homewood estate, built for Charles Carroll, Jr., son of a signer of the Declaration of Independence. The university was given the estate in 1902.

In addition to the facilities at the Homewood campus, The Johns Hopkins University's academic divisions and research institutions include the world-renowned schools of medicine, public health, and nursing, all located at the East Baltimore campus; the

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Maryland Hall

photo by Alan Bearden

School of Advanced International Studies in Washington, DC, with centers for foreign studies in Bologna, Italy, and Nanjing, China; the Peabody Institute, one of the leading music schools in the United States, located in downtown Baltimore; and the Applied Physics Laboratory in Columbia, Maryland, a scientific and engineering research facility.

BALTIMORE

The Hopkins community shares in the exciting, nationally recognized, urban renaissance of Baltimore. Baltimore is no longer just a place to drive around on the way to New York from Washington. The city now boasts the "Inner Harbor," a waterfront area that includes the National Aquarium, the Maryland Science Center, and shops and restaurants in two glass pavilions. The Baltimore Museum of Art, adjacent to the Hopkins campus, houses excellent permanent collections and attracts important traveling exhibitions.

The Baltimore Symphony Orchestra, which has a superb new symphony hall, the Morris Mechanic Theatre, which presents Broadway touring companies and pre-Broadway tryouts, Center Stage, and the Baltimore City Opera are just a few of the many institutions providing entertainment for Baltimoreans.

And who could pass up watching the Baltimore Orioles play at Memorial Stadium, just a short walk from the Homewood campus. A good bet for seeing a home team win would be watching the University's own championship lacrosse team, the Blue Jays. Since their first season in 1888, the Blue Jays have had 73 winning seasons and have won 41 national championships.

Festivals abound in Baltimore. Its many ethnic communities stage weekend galas throughout the spring and summer, and the city sponsors the annual City Fair and the Artscape Festival. Not to be left out, Hopkins holds its own Spring Fair, "3400 On Stage." The fair is organized and run by students, with revenues benefitting student organizations. The Hopkins Fair draws Baltimoreans from every corner of the city.

ENGINEERING AND CHE

Perhaps it is appropriate that just about the time the Baltimore urban renaissance began in 1979 the G.W.C. Whiting School of Engineering was founded. Today a full complement of undergraduate and graduate-level programs exist, including the largest part-time graduate engineering program in the country. Along with chemical engineering, the Whiting School departments include biomedical engineering, civil engineering, electrical engineering and computer science, geography and environmental engineering, and materials science and engineering.

Renaissance is also an applicable term to use when discussing chemical engineering at The Johns Hopkins University. After existing in some form or another from the 1930s until 1967, the department was reestablished in 1979 with the rest of the engineering school. The full-time faculty now numbers seven, but plans are underway to increase the size of the department. The department also has ten part-time members, including several who are on the staff of the Applied Physics Laboratory. In 1988 the department will occupy part of a new engineering building, adding to its existing facilities. Chemical engineering's facilities now include laboratories for research in fluid mechanics, heat and mass transfer, nucleation, rheology, acoustics, phase-equilibria, electrochemical engineering, separation processes, and biochemical engineering.

The department places a great deal of emphasis on

the use of computers; both graduate and undergraduate students have access to the department's computers which include four Micro-VAX computers, a PDP 11/45, a PDP 11/40, and a PDP 11/34, several PC's and the School of Engineering's VAX 8600 and AT&T 3B20.

Despite its apparent youth, the department has a history of distinguished alumni, including several now teaching at a variety of colleges and universities in this country and abroad. These include Simon Goren (Berkeley), Robert Anderson (McMaster University), Robert Sparks (Washington University), George Frazier (University of Tennessee), Gerald Esterson

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(Hebrew University), Eric Bauer (Case-Western Reserve), Irvin Glassman (Princeton), Kenneth Keller (President, University of Minnesota), John Falconer (University of Colorado), Ralph Kummeler (Chairman, Wayne State) Stanley Middleman (University of California, San Diego), James Douglas (University of Massachusetts), Robert Edwards (Chairman, Case-Western Reserve), and Edward Fisher (Chairman, Michigan Technological University).

THE FACULTY

Marc Donohue, chairman of the department since 1984, came to Hopkins in 1979. He saw the potential for a stimulating environment that would allow close interaction with the students. "An outstanding feature of Hopkins is the intimate atmosphere," he says. The university runs on a system much like the British system in which students receive considerable individual attention (almost comparable to private tutoring) from the faculty. This is possible because of the small student/faculty ratio in the department. It is common to find Donohue in his office with one of his advisees, hashing out a problem.

Donohue teaches a popular undergraduate course, "Ethical Questions in Engineering," and he stresses its importance. "Engineering is the discipline that translates scientific advances into products for society. As such, an engineering education must include attention to the adverse effects of that technology," he says. "We strive therefore to both provide the technical foundations necessary for students to function as engineers and to instill a sense of sensitivity to social, political, and environmental issues that the future leaders of the engineering profession will face."

He is particularly proud of the undergraduate research program, funded by a grant from the Exxon Foundation. The program enables a dozen undergraduates each year to participate in meaningful research while earning salaries competitive with industry. Last year several students published papers that resulted from their work in the program, and all of the participants continued studies in graduate schools. In fact, since the program began three years ago, only one participant has not gone on for further study.

Donohue, his wife, and his two small children like to spend their free time hiking, camping, and bicycle riding. Many weekends find them riding the trail that leads from Washington, DC, to Mt. Vernon, Virginia.

William Schwarz has the longest association with Hopkins. He received his BS, MS, and DrEngr degrees at Hopkins. His areas of research include non-Newtonian fluid dynamics, rheology, physical acoustics of fluids, turbulence, and biotechnology; He is currently collaborating with physicians and speech pathologists from Hopkins and Good Samaritan Hospitals on the study of dysphagia, or swallowing disorders.

The research of **Joseph Katz** involves nucleation processes (*e.g.*, condensation of supersaturated vapors, boiling of superheated liquids, condensation in flames, void formation in solids) and equations of state. He has also worked at the nearby National Bureau of Standards, studying combustion-generated ceramic materials. Katz, like Donohue, came to Hopkins in 1979 from Clarkson with the expectation of "high-quality students and shorter winters." His expectations were met. And, like Donohue, he appreciates the intimacy that "comes with a class of fifteen instead of ninety students." At Clarkson, Katz began his teaching career after a number of years in industry. "I prefer teaching students how to do research," he says. "You can't do that in industry." Katz initiated the participation of undergraduates in research projects at Clarkson. In fact, Donohue did undergraduate research there with Katz.

Robert Kelly specializes in separation processes (chemical absorption and stripping, in particular) and biochemical engineering. After spending some time with DuPont at Marshall Lab in Philadelphia, he returned to school at North Carolina State University



Lower quad on a crisp winter's day.

photo by Carol Hyman

where he worked with Ron Rousseau and Jim Ferrell on a project involving the removal of acid gases from coal gasification streams. Since coming to Hopkins he has returned to earlier research interests in biochemical engineering, an area particularly appropriate given Hopkins' strengths in the biological sciences. Here the primary emphasis is on engineering problems related to bacteria from extreme environments, especially extremely thermophilic archaeobacteria. "One of the great things about Hopkins is the opportunities for collaboration," he says. "Not only have we been able to work with faculty in the biology department, but with scientists at NIH, NBS, and other government laboratories."

Kelly's other interests include sports; he often can be found involved in lunchtime basketball games ("I may be slow, but I can't jump.") or on the jogging circuit around campus. He and his wife spend most of their spare time trying to keep track of their two young daughters, who are living proof of the second law of thermodynamics.

Geoffrey Prentice traces his interest in chemical engineering back to his early teens. "In the post-Sputnik era, do-it-yourself rocket construction was a popular activity among the junior high school set," he says. His interest in rocket fuels led naturally to an investigation of optimum mixtures (stoichiometry) as well as combustion processes (thermodynamic and kinetics). After completing his bachelor's and master's at Ohio State, Prentice went to work as a staff engineer in Sweden with Goodyear International. This was a wonderful opportunity for both professional responsibility and extensive travel throughout Europe. His second assignment took him to the Republic of Zaire (formerly the Belgian Congo). Returning to the States, Prentice completed his PhD at Berkeley, where he worked with Charles Tobias on the modeling of current distribution in electrochemical systems. Among several projects he is currently working on, he and fellow faculty member Mark McHugh are investigating the feasibility of performing electro-organic syntheses in supercritical fluids.

Prentice spends his spare time with his family, waiting for the kids to be old enough to "get away to places we haven't visited yet." He and his son just completed a scuba diving course, and they "hope to get under a few new places as well."

Mark McHugh came to the department in 1985 from Notre Dame. His areas of expertise include high-pressure phase equilibria, polymer solution thermodynamics, and supercritical solvent extraction. While he admits he was originally interested in coming to Hopkins because of family ties, it was not long be-



photo by Carol Hyman

Prof. Robert Kelly with Loy Wilkinson, Chairman of the Chemical Engineering Department Visiting Committee.

fore he discovered the benefits of being associated with a small but well-known university. He enjoys telling a story which illustrates the camaraderie among faculty here. A short time after he arrived, Bob Kelly introduced him to a colleague in the biology department. They chatted about their work, and McHugh was impressed with his friendliness. It wasn't until some time later that he discovered that the colleague was a Nobel Laureate. "This attitude and friendliness is typical of Hopkins," says McHugh. "You rub shoulders with some of the best people in the world." McHugh believes this ability to interact with faculty in other departments makes the university much more than the sum of its parts. "Each part is strong on its own," he says, "but working together makes us formidable." McHugh is impressed with the strides the department has made in the last few years. At an AIChE meeting in Miami, all of the faculty gave papers and three faculty chaired sessions. "Our impact is being felt," he says.

McHugh likes to spend his lunch hour in the gym, shooting baskets with Bob Kelly or lifting weights. His free time away from Hopkins is spent discovering Baltimore. "We go downtown as much as we can," he says. "The geographical location is fabulous."

Chemical engineering's newest faculty member came on board last November. **Timothy Barbari's** areas of research include diffusion in polymers, membrane science, and separation processes. He was attracted to Hopkins because "there is a sense of creativity and innovation here that is hard to find at other universities. The opportunities for collaboration within the department and across departmental lines

appear limitless." Still discovering much about Baltimore, Barbari has been spending much of his free time exploring the area and "getting lost in museums in Washington."

Two more faculty members will be joining the department this year. Michael Betenbaugh, whose specialty is biochemical engineering, and Mark Saltzman, who works in transport phenomena and controlled release, are welcome additions to the department.

THE GRADUATE PROGRAM

The program currently has about thirty graduate students, most of whom are PhD candidates. At Hopkins, the PhD degree is an individualized research de-



photo by Carol Hyman

Grad student Galen Suppes injecting a sample into a high-pressure equilibrium cell.

gree with few formal requirements. Each candidate chooses courses with the help of an adviser in an effort to obtain the depth of knowledge necessary to carry out successful research in a specific subject while obtaining the breadth and flexibility of skills needed to expand into new areas of research. The number and type of courses depend upon the student's academic background and areas of interest.

This individualized approach has attracted top students to the program. Many of the grad students agree that a drawing factor of Hopkins is the opportunity for research experience coupled with classwork related to this research. John Walsh, a PhD candidate who came to Hopkins with a master's degree, says that what attracted him to Hopkins was the size of the department. He appreciates the chance to use his initiative and to have a say in the direction of his research. Due to the small student to faculty ratio, initiative is encouraged and supported by faculty input.

The department also offers a Master of Science degree. The course requirements are more well-defined in this program, although specific programs are chosen based on consultation with the student's research adviser. In addition to coursework, the student performs research culminating in a master's thesis.

Because of the diversity of expertise of the faculty, students at Hopkins may choose from a wide variety of areas of specialization.

THE UNDERGRADUATE PROGRAM

Undergrads in chemical engineering at Hopkins also reap benefits of individualized attention from faculty. Beside the Exxon program, many juniors and seniors participate in research with faculty members. They also have access to an array of computers, and coursework involving computer applications is introduced early in the program. The undergraduate curriculum emphasizes chemistry as well as engineering, mathematics and physics. Students with a degree from Hopkins are well-prepared to continue to an advanced degree or to go right into a professional career. And although many students pursue further studies in chemical engineering, a number of students have gone on to study business, law, and medicine.

CONCLUSION

And so, though it has only been eight years, "The Hopkins" has returned. The chemical engineering department, beginning in 1979 with a few faculty members but with a solid history to build upon, has seen tremendous growth and change.

Since Marc Donohue has been with the department from its inception, he has a clear picture of the growth and changes that have occurred. He feels the department is over those inevitable initial struggles. "The department has finally gotten to the point where we have an identity; we have stability; we have strength."

DEDICATION

This article is respectfully dedicated to the memory of Stanley Corrsin, Theophilus Halley Smoot Professor of Fluid Mechanics at Hopkins until his death June 2, 1986. Prof. Corrsin, at Hopkins since 1947, set an example of style and tone for his many graduate students and associates. His availability to workers in all fields was an invaluable gift to Hopkins. Though Stan Corrsin's legacy may well be his contributions to fluid mechanics, he will be remembered by his friends for his sense of humor, strength of convictions, untiring pursuit of knowledge, and love of academic life. □

CHEMICAL PROCESS COMPUTATIONS*by Raghu Raman**Elsevier Applied Science Publishers, 1985,
592 pages, \$90***Reviewed by****Ihab Farag****University of New Hampshire**

This is a very nice reference book which contains a wealth of algorithms and computer program listings (in FORTRAN) for solving a wide range of chemical engineering problems. The author set out to show how to develop algorithms and obtain solutions for a number of practical problems. In addition, it has a wealth of references and literature citations. I think the book would be useful for those seeking to solve modeling and simulation problems, but who do not have access to well-developed process simulators, *e.g.*, ASPEN PLUS (trademark of Aspen Technology, Cambridge, MA).

The seven chapters in the book are: Introduction, Estimation of Gas and Liquid Properties, Mass Transfer Operations, Flow of Fluids in Pipes, Heat Trans-

fer, Chemical Reaction Engineering, and Chemical Process Simulation. The appendix has several useful sections on: Matrix Methods, Solution of Equations, Polynomial Approximation, Numerical Integration, Ordinary Differential Equations, Function Extermination, and Computation Errors. Within each chapter a number of models of varying degree of complexity are described. A sample list of examples given include: Application of UNIQUAC equation to obtain bubble point of a four-component mixture, four-component hydrocarbon mixture distillation, sizing of pipes for non-Newtonian flow, shell-and-tube heat exchanger calculation with phase change, process furnace analysis using Hottel's zone method, residence time distribution in a CSTR, three-phase fluidized bed countercurrent backmixing model, and aniline manufacture. The 100 computer programs are well-documented and have been tested to insure correctness.

The author, correctly so, assumes a basic understanding of unit operations and formulation of mathematical models. I believe this book should be a very useful reference for those interested in process simulation. I only wish it was possible to get the programs in the book on an IBM compatible floppy diskette. □

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TEACHING HEAT EXCHANGER NETWORK SYNTHESIS USING INTERACTIVE MICROCOMPUTER GRAPHICS

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A MAJOR GOAL of the senior year process design course at Worcester Polytechnic Institute (WPI) is to expose chemical engineering students to the appropriate application of a variety of computer tools within the design task. These range from material and energy balance calculations using a flowsheeting package (such as FLOWTRAN) on a mainframe machine, to interactive uses of computer graphics and input screens on a microcomputer. One area where interactive computing can be particularly helpful is in the teaching of process synthesis topics such as heat exchanger network and separation train design.

Process synthesis involves the partial or complete invention of the flowsheet to achieve specified ends. In the early stages many alternatives can be generated for evaluation, and computer graphics can allow a student to screen (in both senses of the word) competing flowsheet designs rapidly and easily. This paper describes the HENS (Heat Exchanger Network Synthesis) program used at WPI as an aid to performing the energy integration step in process design.

HEAT EXCHANGER NETWORK SYNTHESIS

The problem of heat exchanger network specification, or energy integration, arises for a partially completed flowsheet in which major equipment items and process streams are known. Streams are identified which have heating or cooling needs, and the task is to meet these needs at minimum cost. Other objectives may also be considered, such as flexibility in the

One area where interactive computing can be particularly helpful is in the teaching of process synthesis topics such as heat exchanger network and separation train design.



Anthony G. Dixon is an associate professor in the Department of Chemical Engineering at Worcester Polytechnic Institute. He received his BSc in mathematics and his PhD in chemical engineering from the University of Edinburgh, and was a post-doctoral fellow at the University of Wisconsin from 1978-1980, when he joined WPI. He teaches process design, mathematical modelling and transport phenomena, and his research interests include fixed bed reactor modelling, zeolite technology and semiconductor technology.

face of process disturbances, and constraints of plant layout and process safety.

The extent to which the heating and cooling needs may be met by heat transfer between process streams is limited by both the enthalpy contents of the streams and the minimum approach temperature (ΔT_{\min}) of two streams in a heat exchanger. This minimum temperature driving force is usually fixed by rule of thumb before the synthesis task is begun and is taken as constant for all exchangers. Utility heating and cooling are used to bring streams to temperature when further process heat exchange is not possible.

This problem is a relatively mature one, and one method, the pinch design method, has been extensively developed [1, 2, 3] and applied to real-life problems [4]. It is particularly suitable for undergraduate instruction, as it is simple to apply, has a high graphical component, and requires active participation and decision-making by the designer at all stages. The key elements of the method are 1) preanalysis of the prob-

lem data to give minimum possible utility requirements, minimum number of units (both process and utility), and identification of the location of a temperature "pinch point" (if one exists); 2) specification of process stream matches beginning at the pinch point, as the design is most constrained there, to give a "minimum utility" network; 3) evolution of the minimum utility network to examine trade-offs of energy recovery versus units, *i.e.*, operating versus capital costs. The preanalysis step involves repetitive calculations and can easily be relegated to a computer. The two design steps (2 and 3) involve drawing and re-drawing the exchanger network for graphical manipulations. The HENS program allows this to be done interactively, saving time and allowing students to investigate a wider range of design alternatives.

Several other computer packages for heat exchanger network synthesis exist, although none serve the function of the HENS package. The HEXTRAN [5] simulation package allows for design of the network by repetitive calculation of heat and mass balances and economic evaluation of modified networks. It provides an alternative approach to the use of pinch technology. Both Chemcalc 5 [6] and the recently-described program by Govind *et al* [7] design the network for the user, which is not the objective of instructional use.

SuperTarget™ presents a comprehensive framework for preanalysis and investigating the effects of process modifications for both grassroots and retrofit design [8]. Its graphical displays include composite curves on the temperature-enthalpy diagram, and an annotated design grid. SuperTarget™ does not present the entire network design on the grid, but as a design aid gives the user a full analysis of the consequences of any process stream match.

RESHEX [9, 10] allows preanalysis of data, interactive synthesis of a new network or modification of an existing one, or automatic synthesis of a network by the program. In addition, considerable emphasis is given to post-analysis of a network for optimization, feasibility and resilience testing. RESHEX is a comprehensive program of great utility, but appears to be limited in its use of graphics and user-friendliness. As an instructional aid, it may be more suitable for advanced classes and as a research tool.

A more mathematically rigorous approach than the pinch method to the synthesis of optimal heat exchanger networks has been developed [11] and embodied in the MAGNETS program [12]. This is another very powerful package, able to handle stream splits, multiple pinch points and restricted matches, and to automatically synthesize the network struc-

This problem is a relatively mature one, and one method, the pinch design method, has been extensively developed and applied to real-life problems. It is particularly suitable for undergraduate instruction . . .

ture. Again, this may be a more advanced tool than is suitable for beginning students.

STUDENT BACKGROUND

The fundamentals of the pinch design method are covered in class before the students are given the HENS program. The minimum utilities are derived for an example problem both on the temperature-enthalpy diagram using composite curves, and algebraically by the "problem table" [1, 2]. This introductory material is limited to constant heat capacity-flow rate (CpW) streams, although linearization of the temperature-enthalpy relationship is mentioned. The simple minimum units formulas [1, 2, 3] are also presented during this target-setting stage.

Particular attention is paid to the physical interpretation of the pinch point and the rules regarding decomposition of the problem at the pinch [3]. The grid representation of the network is introduced and an example worked by hand in class. Stream splitting and feasibility criteria at the pinch are discussed.

The final part of the lecture material explores the incompatibility of minimum units and minimum utilities, and the generation of a small number of near-minimum-utility networks by a utilities/units trade-off. Depending on time, unpinched problems, resiliency and multiple utilities pinches may also be included.

WPI has recently endorsed the AT&T 6300® microcomputer for undergraduate instruction, and almost all seniors have experience on this machine. As the computer is integrated into the curriculum most students will own one. There is thus no need for special instruction on the microcomputer use itself.

PROGRAM OPERATION

The HENS program is written in Turbo Pascal™ for the AT&T 6300 microcomputer. The main program and associated files take up 70K of memory. The interactive input procedures are modified versions of the general-purpose code described by Wood [13]. The graphical part of the program was developed with the aid of the Turbo Graphix Toolbox™.

The program is distributed to the students in a compiled form; the source code is not made available nor can they abstract parts of the package for future use. This protects the interests of the commercial

software vendors. Students may either use the distribution disks in any one of several computer labs on campus, or copy a disk for home use on their own machine.

The HENS program operates in two parts: data entry and analysis, and graphical network design. The design part is nested within the data entry part, so that students can abandon (<ESC> Exit) a design to change the problem data without returning to system level.

DATA ENTRY AND ANALYSIS

The students enter data to the program by filling in blanks on an input screen. The initial screen with some default values is shown in Figure 1a. Prompts appear at the bottom of the screen, and menu options are selected by keying in the initial letter of the option. All input is user-friendly and controlled, so that if inappropriate characters are entered they are trapped, an error message is issued and the prompt for the required input is repeated.

The Compute and Design options are not active

```

Number of Streams...: 0
Minimum approach temperature...: 10.0

STREAM NO.      TEMP.(SOURCE)    TEMP.(TARGET)    CPW
-----
Pinch point location...: None
Minimum hot utility...: 0.00    Minimum cold utility...: 0.00

-----
INP: Press a CMD: key to enter selection ==>
CMD: Compute / Modify / Design / F1 HELP / <Esc> Exit

```

(a)

```

Number of Streams...: 4
Minimum approach temperature...: -----

STREAM NO.      TEMP.(SOURCE)    TEMP.(TARGET)    CPW
-----
1              150.0            60.0             2.00
2              90.0             60.0             8.00
3              20.0            125.0            2.50
4              25.0            100.0            3.00

Pinch point location...: 90/70
Minimum hot utility...: 107.50    Minimum cold utility...: 40.00

-----
← : 20.0
MSG: Enter minimum delta-T. Up to 6 digits inc. decimal.
CMD: ↑ Prev Fld / → Clear Fld / <Esc> Exit

```

(b)

FIGURE 1

until the Modify option has been selected at least once. Pressing "M" causes a cursor to appear at the first entry, the number of streams (between two and ten). The cursor is moved to the next entry by pressing Enter, or can be made to go back to the previous entry by the Up arrow. In Figure 1b the input screen is shown for a four-stream design [3] in which the cursor has been placed at the second entry, the approach temperature. The current value of the entry appears at the bottom of the screen, along with a suitable prompt and cursor control options. If Enter is pressed the current value is accepted, otherwise a new value should be typed in. Again all input is controlled, and only a positive real number will be accepted in this case. Pressing <Esc> at this point causes a return to the data entry and analysis menu.

The Compute option causes a calculation of minimum utilities and the pinch point location to be performed. This just follows the Problem Table algorithm [1, 2] and is restricted, like the HENS program, to streams of constant CpW with no phase change. Figure 1b shows the results of this option for the four-stream problem. If a pinch point does not exist, the algorithm recognizes this and reports "None."

"Help" screens are available by pressing the F1 special key when this appears as a menu option. A new Help Menu appears, from which the students can select a Help screen on each data entry menu option. These screens consist of explanations of program operation, warnings and occasionally a reminder from the lecture material. An exit from the Help menu restores the data input screen.

DESIGN STAGE

Selecting the Design option on the data entry and analysis menu passes the user to the design stage. The input screen is replaced by an initial stream grid and design menu (Figure 2). The student can return to the input screen by pressing <Esc> during the design stage. On the initial grid the problem data are shown associated with hot (upper) or cold (lower) streams. The minimum utilities targets are displayed as a convenient reminder.

A design according to the pinch decomposition principle is not forced upon the students, therefore the pinch is not shown at first. It can be turned on by selecting the Pinch option, upon which a cursor is provided at the top of the screen that can be moved horizontally, to position the pinch lines (see Figures 3 and 5). The pinch can be removed by selecting the Pinch option again, and can be turned on and off and repositioned as often as desired.

UC ONLINE*

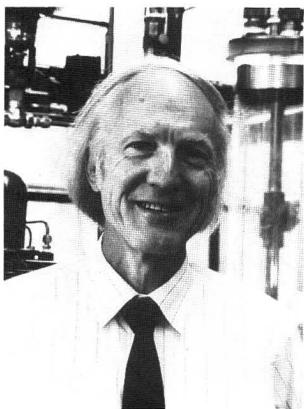
Berkeley's Multiloop Computer Control Program

ALAN S. FOSS
 University of California
 Berkeley, CA 94720

MULTILOOPS AROUND. They are all around us. We invent these intricate control systems and apply them to distillation columns, fired heaters, reactors, steam systems. They are the "brains" and "nervous system" of chemical processes. Processes need them to operate and to operate safely.

That's news? Not at all. Everyone has known it for generations. Everyone, that is, except the students in our process control courses here in the States.**

That's got to change! And the change has to be made in the first course in process control—the *first*



Author **Alan Foss** writes that "after a quarter of a century of searching for ways to tell Californians about process control, I am still searching. The article published here reports one of the 'finds' along the way. Richer veins assuredly lie somewhere farther along the tunnel." Professor Foss came to the academic world after five years of industrial practice with the DuPont Company and studies at Worcester Polytechnic Institute and the University of Delaware.

*©Copyright 1986 by P. H. Gusciora, C-H Mak, L. Poslavsky, and A. S. Foss

**There is probably a handful of departments to which this statement does not apply, and I know colleagues there will forgive this slight overstatement in the recognition that it is very close to the truth.

course, my colleagues, because there is seldom a second. Not everyone will agree with that of course, and those that do will ask, "How?"

HERE'S HOW

Imagine that you have a computer program that permits the user to configure any multiloop control system he desires for a particular process, say the system shown in Figure 1 for a distillation column. And suppose such a control system accepts process "measurements" from a dynamic simulation of the column and delivers its "commands" to that same simulation. With the keyboard command

$$YC, KP = 10, KI = 20, FREQ = 5$$

the user sets the proportional- and integral-gain pa-

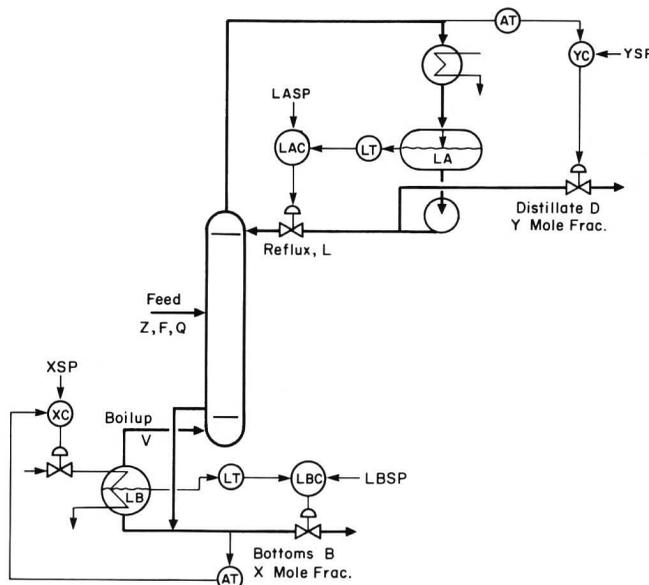


FIGURE 1. Control system for regulation of top and bottom product concentrations by manipulation of distillate and boilup flow rates. The relative gain for this control configuration is 0.68.

Imagine that you have a computer program that permits the user to configure any multiloop control system he desires for a particular process, say the system shown in Figure 1 for a distillation column. And suppose such a control system accepts process "measurements" from a dynamic simulation of the column . . .

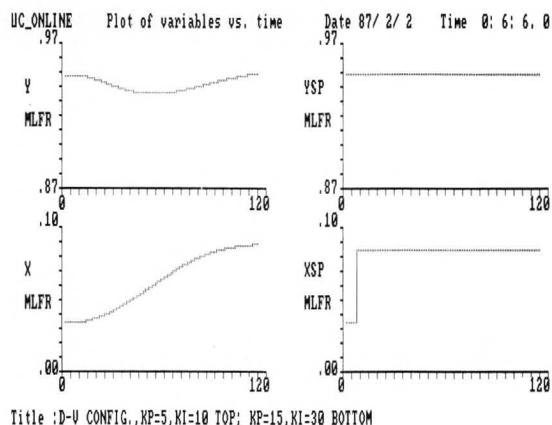


FIGURE 2. A page of the screen display of trends in top and bottom product concentrations. Response to a step increase in setpoint of bottom product concentration with control system of Figure 1.

parameters of the top-product concentration controller YC and the sample time to 5 seconds.

The command

YC, CD = ON

turns the controller to ON status and the user now has an operating process running in a real-time mode under the action of a simple control loop. He may commission the bottom-product concentration controller XC in the same way with the command

XC, KP = 10, KI = 20, FREQ = 5, CD = ON

at which time he will find himself in the land of multiloop control, control loop interactions, active input constraints, reset windup, and multiple alarms. Getting such a system to work when the column feed rate is varying will likely require a little tuning, all of which can be done "online" while the process and control system is running by simply typing commands for setting KP and KI similar to those above. The user knows how his system is shaping up by viewing periodically updated tabular data about the measured and manipulated variables and controller states or graphical displays of trends in any set of selected system variables, such as the group in Figure 2. The graphs shown there come from a full tray-by-tray calculation of a 39-tray column.

Now suppose the user is dissatisfied with the best performance he can squeeze out of this particular control system configuration and is curious about the

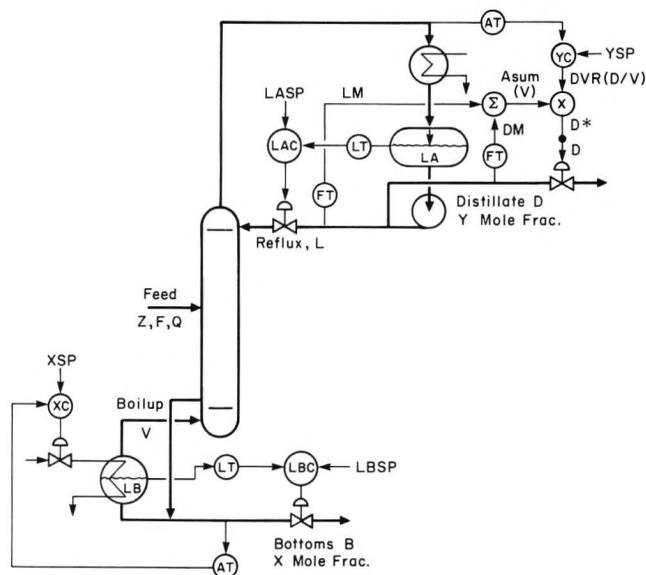


FIGURE 3. Control system using the ratio D/V and V as manipulated inputs. The relative gain is 1.92.

claims found in Shinskey's book [4] for the superiority of the configuration shown in Figure 3. He is curious because the argument about the reduction in loop interaction given by Shinskey seems to be just what he is looking for, but he will have to see the performance improvement to believe it; Shinskey does not show performance. Some reconfiguration obviously needs to be done to convert the control system of Figure 1 to Figure 3.

No problem, as we say. Turn off both controllers, define a new variable as the product of D/V and V in the overhead system, and redirect the output of controller YC to the multiplier. The sequence of commands for these changes, which can be made in a few minutes at the keyboard once one has decided what to try, are shown in Table 1. Turn both controllers to

TABLE 1
Keyboard Input to Convert the (D/V) configuration to $(D/V, V)$

```
VD,DVR,ASUM,D*
ASUM,AL=+,V1=DM,V2=LM,A0=1.0,A1=1.0,ML=0.0,MH=1200,UN=MPH,VA=600
DVR,MH=1.0,ML=0.0,SF=2,VA=.132
D*,AL=*,IO=24,V1=ASUM,V2=DVR,A0=1,A1=0,MH=300,ML=0,UN=MPH,VA=100.0
VREM,D
VD,D=24
D,IO=2,A0=0.0,A1=1.0,MH=300,ML=0.0,SF=2,AL=DA,UN=MPH,VA=100.0
YC,OD=DVR,OH=1.0,KP=.0083,KI=.0167,CD=ON
XC,CD=ON
```

Now, things are a little more involved than I have made out. I am sure that that is no news. There are a lot of details about maximum and minimum values of variables everywhere in the control system that need specification . . .

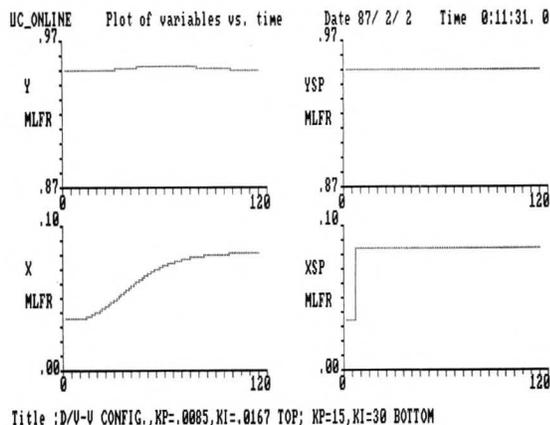


FIGURE 4. Top and bottom concentration responses to a step increase in setpoint of bottom product concentration. Control system of Figure 3.

ON and retune. Sure enough; performance is indeed better. The top product concentration is barely influenced by a change in the set point of the bottoms controller (see Figure 2 and 4).

“Professor, just a moment,” you interject. “What about the need to recompile the control system program and to relink it to the process simulation?” That’s not necessary these days. Everything about the control system is stored in tables. The program simply moves data from here to there when asked. All of that was worked out years ago by the computer scientists; we simply adopt the technique.

EASY CONFIGURATION

Now, things are a little more involved than I have made out. I am sure that that is no news either. There are a lot of details about maximum and minimum values of variables everywhere in the control system that need specification, else alarms announcing over-ranging would never reach the operator’s eyes or ears. The declaration of such maximum and minimum values for all variables is an added chore for the user, to be sure, but is not the consideration of process limits important to safe process operation? It is, and we should expose students at least once to this component of the process control task.

The input of such information is easy. The screen display of the set of process variables for Shinskey’s

control configuration is shown in Figure 5. The variables named in the list are identified by the labels shown on the process diagram in Figure 3. All variables are free to be named by any 4-character symbol the user desires. So also may controllers be named. The command structure of ONLINE is designed so that the user need only type the name of the variable or controller followed by the attributes to effect whatever setting or change he desires to make in those attributes. Important information for the top product concentration y , for example, is that its input channel (IO) is 1, that the type of algorithm (AL) is an analog-to-digital conversion (AD), and that the linear conversion of the concentration transducer signal to mole fraction has a slope of 1.0 (AI) and an intercept of zero (AO).

To set this information, the user simply types

$$y, IO = 1, AL = AD, AI = 1, AO = 0$$

This information appears immediately on the screen upon completion of typing this line. Error messages appear should there be any miskeying. Other variables in this example are seen to be identified as multipliers, summers, and digital-to-analog (DA) conversions. The use of input-output A/D and D/A data channels is a carry-over from a version of this program used with experimental apparatus. Their retention here serves two purposes: a decoupling of the simulation and control program is achieved, and students are made aware early that input and output channels must be specified when communicating with physical processes. Variables such as summers and multipliers have their inputs named under the VI and V2 columns. With such declarations, the user specifies that part of the control system configuration. The maximum and minimum values mentioned earlier are

Page 4 PROCESS VARIABLES										Date	2/ 2/87	Time	0: 6:47. 0
Ln	Name	AL	IO	V1	V2	RO	AO	AI	ML	MH	VA	Unit	
1	Y	AD	1			.949	.00	1.0	.000	1.000	.949	MLFR	
2	X	AD	2			.034	.00	1.0	.000	1.000	.034	MLFR	
3	LA	AD	3			300.000	.00	1.0	0.	600.	300.	MOLE	
4	LB	AD	4			300.000	.00	1.0	0.	600.	300.	MOLE	
5	DM	AD	6			79.831	.00	1.0	0.	239.	80.	MPH	
6	LM	AD	7			514.378	.00	1.0	0.	1534.	514.	MPH	
7	BM	AD	5			120.169	.00	1.0	0.	361.	120.	MPH	
8	VM	AD	8			594.208	.00	1.0	0.	1183.	594.	MPH	
9	DP	AD	9			5.251	.00	1.0	.000	10.000	5.251	PSI	
11	L	DA	3			514.378	.00	1.0	0.	1534.	514.	MPH	
12	B	DA	1			120.169	.00	1.0	0.	361.	120.	MPH	
13	V	DA	4			594.174	.00	1.0	0.	1183.	594.	MPH	
14	Z	DA	5			.400	.00	1.0	.000	1.000	.400	MLFR	
15	F	DA	6			200.000	.00	1.0	0.	400.	200.	MPH	
16	Q	DA	7			.000	.00	1.0	-.2	1.2	.0	NONE	
17	YSP	0				.000	.00	1.0	.600	.999	.950	MLFR	
18	XSP	0				.000	.00	1.0	.001	.400	.035	MLFR	
19	DVR	0				.000	.00	1.0	.00	1.00	.13	none	
20	ASUM	+	0	DM	LM	.000	1.0	1.0	.0	1200.0	594.2	MPH	
21	D*	*	24	ASUM	DVR	.000	1.0	.00	.0	300.0	100.0	MPH	
24	D	DA	2			79.763	.00	1.0	.00	300.00	79.76	MPH	

FIGURE 5. Screen display of process variables for control system of Figure 3.

listed under the columns labeled MH (measurement high) and ML (measurement low). These limits represent the operable range of the measurement transducer.

The remaining part of the system configuration is established by naming the inputs and outputs of all the controllers. Figure 6 displays the video screen "page" that provides that information for each controller. The measurement source (MS), setpoint source (SS), and output destination (OD) for each controller is declared by variable name. These "connections" can be altered easily by the user through a few key strokes like those just mentioned. Such ease of reconfiguration is a feature indispensable to the efficient use of ONLINE in coursework. Students need to implement their conceptions in a matter of minutes, not days. Figure 6 also displays maximum and minimum declarations for the setpoint, the measured variable, and the controller output. The significance of these limits differs from those of the process variables just described. The limits on the measured variable, for example, are considered alarm limits, which when transgressed trigger an H or L message to the operator. The setpoint limits, normally set "inside" the limits on the measured variable, constrain the desired range of the controlled variable. Output limits

Page 1	LOOPS				Date	2/ 2/87	Time	0: 8: 3. 0		
Ln	CmmD	CScd	NAmE	SetPt	MeaS	Unit	Output	KP	KI	KD
1	ON	YC	.950	.950	MLFR	.13		8.30E-03	1.67E-02	.00
2	ON	XC	.035	.035	MLFR	594.		15.	30.	.00
3	ON	ALC	514.	514.	MPH	514.		1.0	.00	.00
4	ON	BLC	120.	120.	MPH	120.		1.0	.00	.00

FIGURE 6. Screen display of controller page for system of Figure 3.

reflect the rangeability of the process manipulatable variable driven by the controller. The ON-OFF-COND-FAIL status of the controller and the PID parameters are also displayed. All of the information for the process variables and controllers just described is "dynamic" and is updated in the data base and on the video display at intervals selectable by the user.

Suppose the exercise for the day concerns the tuning of a multiloop system already configured. The complete slate of information just described about system variables and controllers (excluding the PID parameters) can be prepared by the instructor ahead of time in a disk file. The user merely types

READ, SETUP

to load the entire configuration. Keyboard work is then necessary only for setting controller parameters. Portions of such a SETUP file are shown in Table 2. These files also serve as a permanent record and documentation of each control system.

TABLE 2

Key Portions of the File Used to Set Up the (D,V) Configuration for the Example of this paper

```

C,SETUP FILE FOR UCONLINE
C,BINARY DISTILLATION COLUMN - CONCENTRATION DYNAMICS ONLY
C
C,THIS FILE DEFINES PROCESS VARIABLES AND PROVIDES
C,THEIR FULL CHARACTERIZATION.
C,MAXIMUM FLOW RATES OF
C,
C,DEFINITION OF MEASURED TOP & BOTTOM CONCENTRATIONS
C,AND HOLDUPS (A/D)
C
VD,Y,X,LA,LB
Y ,IO=1,AO=0.0,A1=1.0,MH= 1.0,ML=0.0,SF=3,AL=AD,UN=MLFR
X ,IO=2,AO=0.0,A1=1.0,MH= 1.0,ML=0.0,SF=3,AL=AD,UN=MLFR
LA,IO=3,AO=0.0,A1=1.0,MH= 600.,ML=0.0,SF=
LB,IO=4,AO=0.0,A1=1.0,MH= 400.,ML=0.0,SF=
C
C,DEFINITION OF MANIPULATED PROCESS VARIABLES (D/A)
C
VD,D,L,B,V,Z,F,Q
D ,IO=2,AO=0.0,A1=1.0,MH= 239.,ML=0.0,SF=0,AL=DA,UN=MPH ,VA= 80.
L ,IO=3,AO=0.0,A1=1.0,MH=1534.,ML=0.0,SF=0,AL=DA,UN=MPH ,VA= 511.
B ,IO=1,AO=0.0,A1=1.0,MH= 361.,ML=0.0,SF=0,AL=DA,UN=MPH ,VA=
V ,IO=4,AO=0.0,A1=1.0,MH=1183.,ML=0.0,SF=0,AL=DA,UN=MPH ,VA=
Z ,IO=5,AO=0.0,A1=1.0,MH=
F ,IO=
C
C,LOOP DEFINITIONS
C
LD,YC,0,XC,0,ALC,0,BLC,0
YC ,CD=OFF,AL=PIDM,MS= Y,SS=YSP,OD=D
YC ,ST=1.0,MH= 1.,ML=0,SH=0.999,SL=0.001,OH=300.,OL=0
XC ,CD=OFF,AL=PIDM,MS= X,SS=XSP,OD=V
XC ,ST=1.0,MH=1.,ML=0,SH= .999,SL=0.001,OH=
ALC,CD=OFF,AL=PIDM,MS=L,SS=LSP,OD=L
ALC,ST=1.0,MH=1.,ML=0,SH=

```

If the exercise asks the user to invent his own control system, then the instructor merely lops off that segment of the SETUP file defining the control links, leaving only the process variables for loading. In Table 2, everything from the entry LD (loop definition) and below would be omitted in such a SETUP file. Creating that slate of information would constitute the exercise for the day. Alternatively, two SETUP files could have been prepared, one defining process variables only, the other the control links; the instructor supplies whichever file combination is appropriate.

Or "preanalysis" programs can be developed that prepare a complete SETUP file defining process variables. We have such a "front-end" program for binary distillation columns that calculates and displays the relative gains and steady-state operating conditions. A full set of information for the distillation simulation and the SETUP file for process variables, like that in Table 2, is written to disk upon user command and is read into ONLINE's data structure during the initialization phase. Such "front-end" programs, particularly for distillation columns, make it practical for students

Continued on page 154.

THE BURNING OF A LIQUID OIL DROPLET

A SIMPLE MATHEMATICAL ANALYSIS FOR TEACHING PURPOSES

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THE QUASI-STEADY STATE combustion of a single isolated liquid oil droplet has been considered by several authors [1-5]. We have found it necessary in our teaching to seek a simpler treatment than those usually presented. Below we consider such a single drop, burning in stagnant air without any effects from natural convection or radiative heat transfer. Of course, once this, the simplest situation, has been described mathematically, it is possible to treat more realistic and complicated cases. The experimental observations are clear, and excellent reviews are available [1]. The fundamental empirical fact is that the radius, a , of a liquid oil droplet decreases with time, t , according to

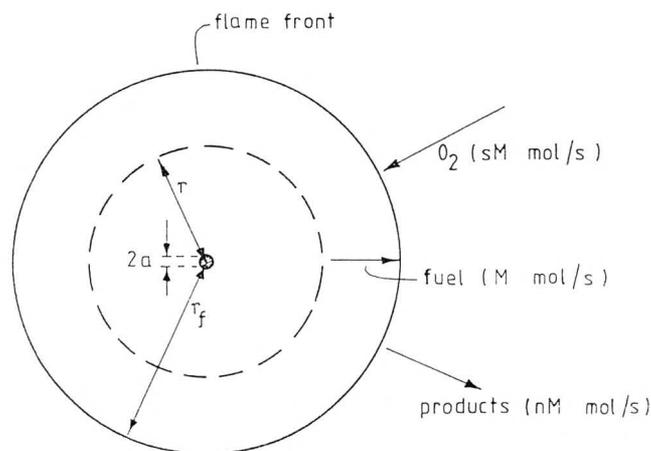
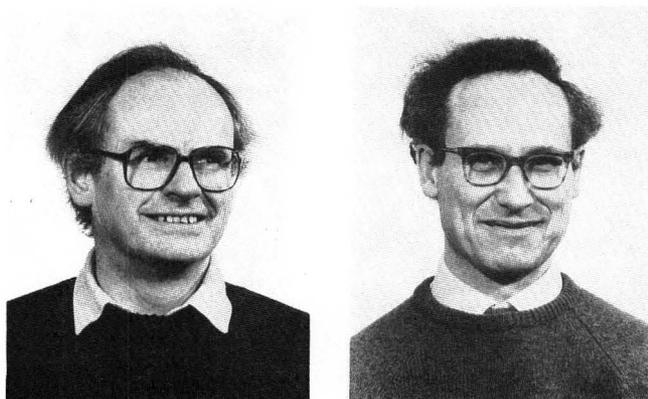


FIGURE 1. Sketch of burning oil droplet surrounded by spherical flame front and sphere of general radius r . The total radial flow rates of fuel, O_2 and products are as shown.



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$$-\frac{d(a^2)}{dt} = \text{constant}, k_b \quad (1)$$

during its burning. This paper gives a rigorous derivation of k_b . Unlike the standard textbooks [2, 3], the approach below uses entirely molar, rather than mass, units because of the much simpler description of diffusion which results. Like Long's analysis [4], but in contrast with Spalding's [2], this treatment takes the products of combustion into account. However, unlike Long, we calculate, from first principles, the temperature of the flame front surrounding the burning droplet. All these approaches rely on Godsave's early experimental and theoretical work [5].

DIFFUSION

To formulate the equations for diffusion we first consider a binary mixture of two gases A and B moving together in a one-dimensional situation. The molar flux of A in the x -direction (for a stationary observer) is given by

The oil droplet, depicted in Figure 1, is assumed to be at a constant temperature which is just less than, but close to, the boiling-point of the liquid fuel. While the droplet evaporates, vapour of the fuel diffuses outward; oxygen from the surrounding air diffuses inward.

$$N_A = N \frac{c_A}{c} - D \frac{dc_A}{dx} = N y_A - D \frac{dc_A}{dx} \quad (2)$$

where c_A and c_B are the molar concentrations of A and B, $c (= c_A + c_B)$ is the total molar concentration, N is the total molar flux, *i.e.*, $N_A + N_B$, and y_A is the mole fraction of A. Eq. (2) derives from the fact that the flux of A consists of a convective term, $N y_A$, and a diffusive term, $-D dc_A/dx$. If A is in a multicomponent mixture of gases (temperature T and total pressure P) and confined to a one-dimensional situation, then Eq. (2) becomes

$$N_A = N y_A - \frac{D_A P}{RT} \cdot \frac{dy_A}{dx} \quad (3)$$

This assumes that multicomponent diffusion can be simplified to a pseudobinary description with a constant effective diffusivity, D_A . Eq. (2) is identical with the possibly more familiar [6] form:

$$N_A c_B - N_B c_A = -cD \cdot \frac{dc_A}{dx}$$

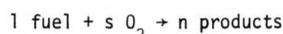
By analogy with Eq. (2) the equation for the enthalpy flux, Q , is

$$Q = Nh - k \frac{dT}{dx} \quad (4)$$

where k is the thermal conductivity and h is the molar enthalpy of the particular gas mixture.

THE MODEL

The oil droplet, depicted in Figure 1, is assumed to be at a constant temperature, T_o , which is just less than, but close to, the boiling-point of the liquid fuel. While the droplet evaporates, vapour of the fuel diffuses outward; oxygen from the surrounding air diffuses inward. Fuel and oxygen meet in stoichiometric amounts and react very rapidly in a thin reaction zone, or flame front, at a distance r_f from the centre of the droplet. Here the oxidation reaction is assumed to be



and is taken to occur almost instantaneously. Consequently, the ratio of the molar fluxes of O_2 and fuel into the flame front is s . No distinction will be made at this stage between the products CO_2 and H_2O , although this is a straightforward thing to do, if it were considered necessary. Thus a total of n moles of prod-

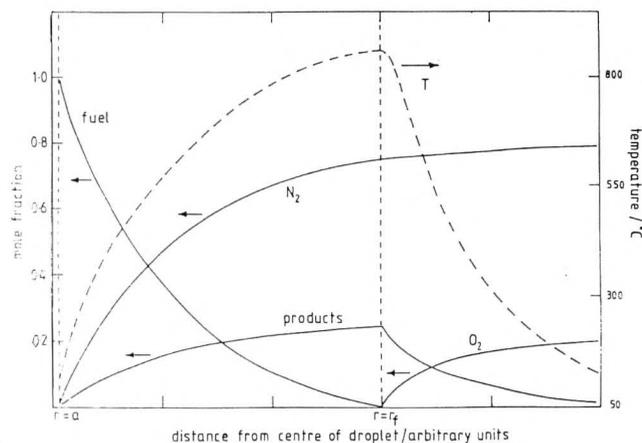


FIGURE 2. Approximate sketch of mole fractions of fuel vapour, O_2 , N_2 and combustion products around liquid droplet, together with gas temperature.

ucts diffuses radially outwards for each mole of fuel consumed. The situation in Figure 1 has spherical symmetry.

Figure 2 sketches the expected concentration profiles of fuel, O_2 , N_2 and products. It will be noticed that for a radius $r < r_f$ there is no oxygen, and for $r > r_f$ there is no fuel. The concentrations of both oxygen and fuel in the reaction zone are taken to be in effect zero, *i.e.*, reaction is rapid. As the droplet contracts, both N_2 and products diffuse inward to fill part of the space formerly occupied by the liquid fuel. The fluxes of N_2 and products toward the shrinking droplet's surface must be small, since the upper limit of their sum is (ρ_{gas}/ρ_{liq}) times the flux of fuel outwards away from the drop. Here (ρ_{gas}/ρ_{liq}) is the ratio of the molar density of the gas around the drop to that of the liquid fuel; its value will be roughly 1.5×10^{-3} . These considerations of the limiting case, when all the evaporating liquid is replaced by N_2 and products, establish that the flux of, *e.g.*, N_2 is everywhere negligible, as also is the flux of products in the region $a < r < r_f$.

Of the heat liberated in the reaction zone, some is conducted back to the droplet and provides the latent heat of vaporisation. The rest is convected or conducted outward from the flame front. Radiative effects are ignored here. A rough sketch of the temperature of the gases around the droplet is also given in

Figure 2. The temperature is assumed to have a maximum value of T_f in the reaction zone, which is well above T_∞ , the temperature of the surrounding air. A calculation given below indicates that T_f can be as high as 900 °C.

The above model is one controlled by diffusion and heat transfer, with chemical kinetics being relatively fast. Suppose that M mol/s of fuel evaporate from the drop. The steady state rate of heat production in the flame front, where the temperature is a maximum, is accordingly $-M\Delta H^\circ$ (*N.B.* the molar heat of combustion of the fuel, $\Delta H^\circ < 0$). Of this heat an amount $M\lambda$ is conducted inward to the droplet surface, λ being the molar latent heat of evaporation. Thus for $r > r_f$, the total net outflow of heat past any spherical surface is

$$-(\Delta H^\circ + \lambda) M$$

In addition, the total inflow of oxygen toward the reaction zone is sM mol/s and the total outflow of products is nM mol/s (see Figure 1).

In principle, there are five basic unknowns in this problem: the temperature of the drop, T_o , and the corresponding vapour pressure, P_v , of the fuel; the evaporation rate, M ; the radius, r_f ; and temperature, T_f , of the flame front. These can be evaluated by considering

1. Heat transfer from the flame front to the drop
2. Heat transfer outward from the flame front
3. Mass transfer of fuel from the droplet to the flame front
4. Mass transfer of oxygen inward to the flame front
5. The dependence of vapour pressure of the fuel on temperature.

In fact, it turns out that the drop is close to its boiling point, so that P_v is approximately atmospheric pressure. Consideration of 1, 2 and 4 is now sufficient to predict M , r_f and T_f and the remaining two relationships can be used to confirm the starting assumption that the drop is very close to its boiling point.

DIFFUSION OF OXYGEN OUTSIDE THE FLAME FRONT

Here we consider oxygen diffusing from the surrounding air to the reaction zone. The flux of O_2 past a sphere of radius r is

$$-(sM)/(4\pi r^2)$$

with the negative sign denoting an inward flux. Substitution into Eq. (3) gives

$$-\frac{sM}{4\pi r^2} = \frac{(n-s)My_{O_2}}{4\pi r^2} - \frac{D_{O_2}P}{RT} \cdot \frac{dy_{O_2}}{dr}$$

This equation assumes the total flux of all species to be

$$(n-s)M/4\pi r^2$$

i.e., the difference between the fluxes of products outward and O_2 inward. That the flux of N_2 in this region of space is negligible was demonstrated above. The above equation gives

$$\frac{M}{4\pi} \int_{r_f}^{\infty} \frac{dr}{r^2} = \frac{D_{O_2}P}{RT} \int_0^{y_\infty} \frac{dy_{O_2}}{(n-s)y_{O_2} + s}$$

for a mole fraction, y_∞ , of O_2 far away from the droplet. Integration yields

$$\frac{M}{4\pi r_f} = \frac{D_{O_2}P}{RT(n-s)} \ln \left(1 + \frac{(n-s)y_\infty}{s} \right) \quad (5)$$

In deriving Eq. (5) it has been assumed that D_{O_2}/T is independent of temperature, so that D_{O_2} is a mean value for the range $T_\infty < T < T_f$. In fact, $D_{O_2} \propto T^{5/3}$ would have been a better approximation [7], but the need for simplicity is paramount and a careful averaging is not attempted at this stage.

ENTHALPY BALANCE FOR $r < r_f$

There is only fuel (M mol/s) diffusing outward in the region $a < r < r_f$, with heat being conducted inward to the droplet at a rate $M\lambda$. In the steady state the total enthalpy flow rate past an arbitrary surface of radius r is given by Eq. (4) as

$$4\pi r^2 Q = 4\pi r^2 \left(-k_f \frac{dT}{dr} \right) + M(H_f^\circ + c_f T)$$

Here k_f is the thermal conductivity of the fuel-rich gases for $r < r_f$, c_f is the molar specific heat of the fuel and $h = H_f^\circ + c_f T$ is the molar enthalpy of the fuel at temperature T . If T is in °C, then H_f° is the fuel's standard molar enthalpy referred to 0°C as the datum for enthalpy. It is convenient to use 0°C as the reference temperature for enthalpy, as it avoids an explicit statement of where the enthalpy datum lies. The above expression for the net energy flow rate past any sphere of general radius r can be calculated at the droplet's surface. Here the rate of heat conduction inward to the droplet from the surrounding gases is $M\lambda$ (see above) and the molar enthalpy of the vapour leaving the droplet is $(H_f^\circ + c_f T_o)$, where T_o can be

taken to be the boiling point of the fuel in °C. Equating the enthalpy flow rates past spheres at $r = r$ and $r = a$ gives

$$4\pi r^2 \left(-k_f \frac{dT}{dr} \right) + M(H_f^\circ + c_f T) = -M\lambda + M(H_f^\circ + c_f T_o)$$

This simplifies to

$$4\pi r^2 k_f \frac{dT}{dr} = M \{ \lambda + c_f (T - T_o) \}$$

or

$$\frac{M}{4\pi} \int_a^{r_f} \frac{dr}{r^2} = \int_{T_o}^{T_f} \frac{k_f dT}{\lambda + c_f (T - T_o)}$$

i.e.,

$$\frac{M}{4\pi} \left(\frac{1}{a} - \frac{1}{r_f} \right) = \frac{k_f}{c_f} \ln \left(1 + \frac{c_f (T_f - T_o)}{\lambda} \right) \quad (6)$$

Eq. (6) assumes mean values of k_f and c_f for the interval T_o to T_f .

ENTHALPY BALANCE FOR $r > r_f$

If combustion in the flame front is adiabatic, so that, e.g., there are no gains or losses of energy by radiation, then the rate of energy flow past any surface $r = r$ equals the rate of flow across the droplet's surface at $r = a$. In the steady state this can be expressed as

$$-M\lambda + M(H_f^\circ + c_f T_o) = -4\pi r^2 k_o \frac{dT}{dr} + M \{ n(H_p^\circ + c_p T) - s(H_{O_2}^\circ + c_{O_2} T) \} \quad (7)$$

In Eq. (7) positive signs represent outward radial flows. Again, $H_{O_2}^\circ$ and H_p° are, respectively, the standard molar enthalpies of oxygen and products (lumped together, with no distinction between the triatomic species CO_2 and H_2O), but referred to 0°C. The thermal conductivity of this oxygen-rich mixture is k_o . By definition ΔH° , the heat of combustion at 0°C, equals

$$nH_p^\circ - sH_{O_2}^\circ - H_f^\circ$$

so that Eq. (7) simplifies to

$$-M(\Delta H^\circ + \lambda) = M \{ T(nc_p - sc_{O_2}) - c_f T_o \} - 4\pi r^2 k_o \frac{dT}{dr}$$

The left-hand side of this equation corresponds to there being an outward flow rate of heat equal to $-M(\Delta H^\circ + \lambda)$ past a surface of given $r (> r_f)$, as discussed above. Rearrangement yields

$$\frac{M}{4\pi} \int_{r_f}^{\infty} \frac{dr}{r^2} = \int_{T_f}^{\infty} \frac{k_o dT}{(nc_p - sc_{O_2})T + \Delta H^\circ + \lambda - c_f T_o}$$

i.e.,

$$\frac{M}{4\pi r_f} = \frac{k_o}{(nc_p - sc_{O_2})} \ln \left(\frac{(nc_p - sc_{O_2})T_\infty + \Delta H^\circ + \lambda - c_f T_o}{(nc_p - sc_{O_2})T_f + \Delta H^\circ + \lambda - c_f T_o} \right) \quad (8)$$

This assumes that specific heats and k_o do not vary with temperature. Addition of Eqs.(6) and (8) gives

$$\frac{M}{4\pi a} = \frac{k_f}{c_f} \ln \left(1 + \frac{c_f (T_f - T_o)}{\lambda} \right) + \frac{k_o}{(nc_p - sc_{O_2})} \ln \left(\frac{(nc_p - sc_{O_2})T_\infty + \Delta H^\circ + \lambda - c_f T_o}{(nc_p - sc_{O_2})T_f + \Delta H^\circ + \lambda - c_f T_o} \right) \quad (9)$$

The subsequent calculation can be simplified by assuming that

$$|\Delta H^\circ| \gg (\lambda - c_f T_o)$$

as is borne out in reality. Also, if a mean specific heat, c_o , for the fuel-lean gases at $r > r_f$ is defined, so that

$$(n-s)c_o = nc_p - sc_{O_2}$$

then Eqs. (8) and (9), respectively, become

$$\frac{M}{4\pi r_f} = \frac{k_o}{c_o(n-s)} \ln \left(\frac{(n-s)c_o T_\infty + \Delta H^\circ}{(n-s)c_o T_f + \Delta H^\circ} \right) \quad (10)$$

and

$$\frac{M}{4\pi a} = \frac{k_f}{c_f} \ln \left(1 + \frac{c_f (T_f - T_o)}{\lambda} \right) + \frac{k_o}{(n-s)c_o} \ln \left(\frac{(n-s)c_o T_\infty + \Delta H^\circ}{(n-s)c_o T_f + \Delta H^\circ} \right) \quad (11)$$

Eqs.(5) and (10) can now be equated to eliminate $(M/4\pi r_f)$ and give

$$\frac{PD_{O_2}}{RT} \ln \left(1 + \frac{(n-s)y_\infty}{s} \right) = \frac{k_o}{c_o} \ln \left(\frac{(n-s)c_o T_\infty + \Delta H^\circ}{(n-s)c_o T_f + \Delta H^\circ} \right)$$

which gives the value of T_f . The last, but strictly-speaking unnecessary, assumption can now be made to simplify the algebra. This is to recognise the dimensionless group

$$(k_o RT / PD_{O_2} c_o)$$

as the Lewis number, or the ratio of the Schmidt and Prandtl numbers for the oxygen-rich gases at $r > r_f$. Simple versions of the kinetic theory of gases give a value of unity for the Lewis number. This is often a

Continued on page 149.

TIPS ON TEACHING REPORT WRITING

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MANY PEOPLE IGNORE their bodies until they start to pain. Similarly, many engineers ignore report writing skills until their bosses complain.

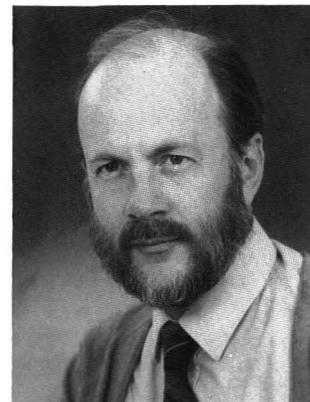
Normally, such feedback produces a strong response. Indeed, among recent alumni, I have come across many born-again report writers. Most of them favour greater emphasis on report writing in the undergraduate curriculum. Listening to them, I marvel that they look so much like the people who only a short time ago condemned the very thing they now praise. St. Paul would certainly understand.

And so we address that perennial problem: how to make instruction in report writing efficient and palatable for both students and instructors. In this article, I would like to offer a few tips that I have found helpful. Among them will *not* be found the suggestion to simply write more reports. Instead, the focus will be on a more considered approach to writing and evaluating the reports already assigned.

STYLE MANUALS

Whenever I open a style manual, I feel smothered by detail. As for those earnest, homemade style guides that professors sometimes grind out . . . no comment; by reflex, students cheerfully ignore the lot. As an alternative, I have opted for brevity. Table 1 is a one-page crib sheet on which I have organized the key points of style in an attention-getting but boiled down form [1]. Evidence suggests it does get read. Those who want more detail are referred to a recent research journal. This confers the added benefit of introducing the student to some current literature.

Whenever I open a style manual, I feel smothered by detail. As for those earnest, homemade style guides that professors sometimes grind out . . . no comment; by reflex, students cheerfully ignore the lot. As an alternative, I have opted for brevity.



Bob Hudgins is a professor of chemical engineering at University of Waterloo, Canada, and holds degrees from University of Toronto and Princeton University. He teaches reaction engineering, staged operations, and laboratories that go with them. His research interests lie in periodic operation of catalytic reactors and in the improvement of gravity clarifiers.

MEASURING STYLE: THE FOG INDEX

One trick that amuses as it teaches is the "Fog Index," a term coined by Robert Gunning [2]. The Fog Index for a particular sample of prose is given by the relation

$$F = 0.4 (W/S + 100P/W)$$

where F = Fog Index, a number representing approximately the years of schooling needed for a reader to readily understand the written passage

W = number of words in a passage composed of several consecutive sentences. W must be at least 100 words.

S = number of sentences in the sample.

P = number of polysyllabic words (three syllables or more) in the word sample. Capitalized words, simple fusions such as "manpower," and verbs containing three syllables by virtue of a suffix "es" or "ed," must be omitted from P .

To survive in the marketplace, popular magazines

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have evolved Fog Indices between 8 and 12. Furthermore, according to Gunning, passages in which $F > 17$ cannot be fathomed by a general reader.

Clearly, the Fog Index can nudge a writer into using short sentences and small words. However, it does not encourage the higher elements of style such as clarity, imagery, or diction. Even so, chopping the ratios W/S and P/W may represent an improvement for many.

Someone calculating an F for the first time may be shocked to find it well above the 8 to 12 range. A little experience will show it is easier to keep F small in descriptive passages (e.g., experimental details) than in more convoluted discussions. On the other hand, students often observe that an unavoidable repetition

of technical terms quickly inflates the P/W ratio. In fairness to them, Gunning's suggested range ($8 < F < 12$) may be a few points too low for technical writing. (Incidentally, F is about 10 for this article.)

GRADING THE REPORT

Marking reports is a highly individualistic task. Even so, a legitimate concern of the student author is how consistently the reports have been graded. For example, did the marker use a set of objective standards for judging each report? In an effort to achieve consistency in grading, I have worked up a checklist of the type shown in Table 2. Its use assures that the same minimum number of questions is asked of each

TABLE 1
Style Cribsheet for Formal Reports

STYLE CRIBSHEET FOR FORMAL REPORTS

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TITLE PAGE

- title in caps, centred; institution, author, co-authors, group number, signature, ID No., date; pleasing spacing

ABSTRACT

"An experiment was performed to study... by means of... in the range... Results showed... and compared (un)favourably with (un)published values. It was concluded... recommended..."

- cite no references except by authors' names and only if essential to the abstract.
- less than 100 words.

TABLE OF CONTENTS

- major headings, page numbers

INTRODUCTION

- purpose (objectives)
- approach taken (general remarks)
- utility of such measurements
- general background

THEORETICAL PRINCIPLES

- equations and supporting references
- use Appendix for necessary derivations.
- results expected.

EXPERIMENTAL METHOD

- use schematic of apparatus; procedure should refer to it.
- for detailed procedure, refer to lab. manual.
- give criteria for steady state or equilibrium.

RESULTS

- explain what results were obtained; how obtained from raw data.
- graphical data preferable to tabular data.
- SI units preferred; watch abbreviations.
- follow suggestions for Figures & Tables.
- place raw data & tabular data (if extensive) in Appendix.

VISUAL TIPS

- rule tables and axes of graphs.
- margins surrounding pages.
- underline headings
- print neatly

CLEAR ENGLISH

"... 10 per cent of the articles submitted to the Journal of Experimental Psychology are so unintelligible that it is not possible to decide what experiment has been carried out."
Times Higher Education Supplement, 1980.

DISCUSSION OF RESULTS

- are results internally consistent? results vs. theory?
- compare results with others' values (published or private).
- error analysis: evaluate the relative importance of error
- anticipate conclusions and recommendations. sources

CONCLUSIONS & RECOMMENDATIONS

- summaries of the main ones.
- no discussion of them here.
- address the objectives (see Intro.)

REFERENCES

- make each one complete: see format such as in Treybal's text.
- cite each reference at least once.
- cite by number or use author-year system.

NOTATION

- collect symbols here, define them, and give units.

APPENDICES

- entitle each one; cite each one at least once in main text.
- use for material your successor (not a normal reader) will likely need to repeat, verify, or continue your work.
- sample calculations section; show all units.

SPELLING ANYONE?

accommodate, eighth, comparative, consistent, gauge, its (possessive), (in)dependent, occur(red), order(ed), refer(red), parallel, maintenance, negligible, principle(rule), separate, exaggerate.

WEED OUT JARGON

"in-depth, triaxial, hopefully, costwise, (and other "-wises"), debottlenecked," etc.

FIGURES & TABLES

indicate datum for each axis

- identify which curve is the model and cite its equation
- show units on axes
- avoid calculations on figures.
- beware of hiding information in report binding.

No!	Yes!
$\Delta H \times 10^{-3}$ (cal/mol)	ΔH (kcal/mol)
12.3	12.3

- give units in column headings.
- number each Figure & Table; entitle each.
- cite each Fig. & Table in report text.
- give conditions for runs on each Figure, Table.

report and that none is overlooked. It also serves as a quick, written record of the report's strong and weak points.

Once a checklist has been completed for a given report, how is a grade to be assigned? My preference is to give separate grades for form and for content. This assures that both of these vital aspects of good

TABLE 2
Checklist for Report Writing

AUTHOR
EXPERIMENT
GENERAL APPEARANCE
ABSTRACT:
(Y N) Describes essential results, conclusions, recommendations?
(Y N) <i>Informative</i> rather than <i>descriptive</i> ?
INTRODUCTION: I suggest developing this section from the general to the particular.
(Y N) Objective <i>stated</i> rather than just <i>implied</i> ? Objectives are guides to content.
THEORY:
(Y N) Essential assumptions of model presented?
(Y N) Relevant equations identified? (No need to develop.)
(Y N) References cited?
METHOD / RESULTS:
(Y N) Complete criterion given for determining the onset of steady state?
DISCUSSION:
(Y N n/a) Justification needed that data were taken at steady state?
(Y N) Adequate discussion of relative importance of errors?
(Y N n/a) Mass/Energy balances presented?
(N Y) Needs reorganizing into smaller segments using sub-heading?
(N Y) Tortured English / logic?
Comment on style (optional)
CONCLUSION / RECOMMENDATIONS: (As the word implies, imperatives should be avoided.)
(Y N) Are they appropriate, <i>i.e.</i> , do they complement the objectives?
(N Y) Is new material introduced? (Should only summarize.)
REFERENCES:
(Y N) Reference cited at least once in the text?
(Y N) Referencing given in proper form?
APPENDICES: Appendix should be used to hold . . .
(Y N) Spot-checked sample calculation OK?
TABLES & FIGURES (Schematic rather than pictorial drawings of apparatus are preferred.)
() Tables . . . that duplicate data in Figures should be placed in Appendix.
(Y N) Appearance OK?
(Y N) Informative independently of the text?
(N Y) Information obscured in binding?
(Y N n/a) Theoretical lines properly referenced?
INACCURACIES of statement or analysis?

report writing are evaluated. The over-all grade is simply the mean.

INTERVIEWS

Finally, if the teaching of report writing is to be taken seriously, one-on-one discussions between the student and the instructor should be encouraged. Marking a report in the style of a final examination paper produces a grade, but no feedback, so an interview with the student is useful for reviewing the report's content and structure. The checklist can serve as a helpful focus for this purpose. In my experience, most students welcome such meetings in proportion to their need to improve.

REFERENCES

- ChE 410 Undergraduate Laboratory Manual, Dept. Chemical Engineering, University of Waterloo.
- R. Gunning, *How to Take the Fog Out of Writing*, Dartnell Corp., Chicago, Ill., 1964. (My thanks to Dr. B.M.E. van der Hoff for this reference). □

ChE book reviews

FUNDAMENTALS OF MOMENTUM, HEAT, AND MASS TRANSFER

by Welty, Wicks and Wilson

Wiley & Sons, Somerset, NJ 08873 (1984) \$36.95

Reviewed by

Hugo S. Caram

Lehigh University

This is the third edition of a popular undergraduate textbook and comes some twenty-three years after the publication of the book that started it all; Bird, Stewart and Lighfoot's *Transport Phenomena*. A new edition of that book is expected to reflect what we have learned since then about transport phenomena and the teaching of it.

As done in BSL, the three transfers are treated in series with the option of covering them in parallel for the integrated approach where similarities between the processes are emphasized. This seems to be the current trend with the exception of the unique book of R. Fahien where the three processes are initially treated simultaneously. Where is the book different from the original BSL?

First, this is a finite undergraduate textbook and this means that one can essentially cover all of the book in two semesters without leaving out a paragraph. This is in opposition to "open" survey books where all the material in the book cannot possibly be covered in any reasonable amount of time. Our stand-

ard BSL is closer to an open text of which a leading example would be Batchelor's *Introduction to Fluid Mechanics*. This closed-end approach also, unfortunately, means that a number of things are left out. They include, for example, non-Newtonian fluids, multicomponent diffusion and simultaneous heat and mass transfer when discussing the traditional material and diffusion through membranes and in ionic solutions, turbulent diffusion and mixing in jets and plumes and multiphase flows when thinking of newer material of technical relevance.

Second, the authors begin with macroscopic balances that are the natural extension of the first chemical engineering course on material and energy balances and are the everyday tool used by the engineer. They are then used to derive the microscopic equations (although I find it unfortunate that after the conceptual effort involved in the derivation of the macroscopic equations, the authors were not willing to introduce the divergence theorem). Traditional books, like BSL, will derive them independently and lack some internal unity. The book also treats some of the approximations like boundary layer theory and ideal flow with great clarity while, again, leaving out completely the low Reynolds number hydrodynamics as applied, for example, to flow about a sphere. It should also be pointed out that in recent years a well-developed body of theory has appeared that allows the engineer to recognize the order of magnitude of the terms in an equation and make the approximations described above in a more or less scientific way. These techniques are, however, barely mentioned in association with the boundary layer discussion.

Finally, the book covers a number of applications to the design of equipment of industrial interest like flow in pipes, heat exchangers, and packed absorption columns. Comparison with a common book in unit operations would show, with the exception of the discussion of staged operations and distillation, a wide overlap with those texts. The missing parts correspond mostly to equipment description but not to fundamental concepts since the book provides enough tools to solve a large fraction of the problems found in unit operations textbooks.

End of the chapter problems are one of the strong points of the book. There are many short, numerically simple, attractive exercises that, while lacking overwhelming industrial flavor, will be of great help in the teaching of the subject. Missing, however, are problems discussing non-traditional chemical engineering applications of the methods to biochemical-biomedical, product engineering, or environmental situations. They would be desirable to broaden the outlook of the chemical engineering student. In summary, this is a

very good junior-level textbook that adds to the teaching of the subject as is traditionally known, but does not bring in any of either the new problems that are starting to fascinate chemical engineers or new techniques developed to deal with the old problems. It must, in that area, be supplemented from other sources to cover more advanced topics or to find the description of specific industrial equipment. □

WORKSHOP ON BIOTECHNOLOGY FOR THE MINING, METAL-REFINING AND FOSSIL FUEL PROCESSING INDUSTRIES

*by L. Ehrlich and David S. Holmes
John Wiley and Sons*

**Reviewed by
George T. Tsao
Purdue University**

Biotechnology is an old field which has taken on a great deal of new excitement since the 1970's due to the advances made in molecular genetics. There are those who consider biotechnology involves nothing else but genetic engineering and production of proteins for pharmaceutical uses. There are also those who prefer a broad definition of biotechnology to mean technology based upon biological activities of one type or another. Biotechnology and Bioengineering Symposium No. 16 is the proceedings volume of the workshop on "Biotechnology for the Mining, Metal-Refining and Fossil Fuel Processing Industries," held in May 1985 on the campus of Rensselaer Polytechnic Institute in Troy, New York. The workshop brought together many top experts in this field from different parts of the world to review biotechnological application in the metal-mining industry, the current state of the technology, the industry's and the government's view on the subject and the latest advances in molecular biology and the application of genetics and genetic engineering in the metal-mining industry. The volume should be a useful reference to those who have been working in this field; it should also serve as an informative introductory volume for technical managers, policy makers, life scientists, process engineers, and others who wish to quickly become somewhat knowledgeable on the subject.

While the volume may be an excellent review of biotechnology in the metal-mining industry, it does not address specifically what work may be important for the future advancement of this subject. This reviewer believes that a logical follow-up event could be a workshop on the identification of general and specific research needs in biotechnology for the metal-mining industry. □

THE MILLIKEN/GEORGIA TECH RISING SENIOR SUMMER PROGRAM

PRADEEP K. AGRAWAL,
JUDE T. SOMMERFELD
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MILLIKEN AND COMPANY is one of the leading textile manufacturers in the country. The company, which produces a wide range of fabric materials, is headquartered in Spartanburg, South Carolina, and has approximately sixty manufacturing locations in the Carolinas and Georgia. Its Interior Furnishings Division, for example, produces carpeting, drapery and upholstery materials. Apparel products include athletic uniform and tennis shoe materials in addition to conventional clothing fabrics (polyester, nylon, polycotton). It also manufactures a wide variety of automotive upholstery materials. Specialty industrial fabrics include materials for tires and conveyor belts. The company also has a small chemicals manufacturing facility located in Inman, South Carolina (near Spartanburg); products of this facility include specialty chemicals for a variety of applications in addition to textile chemicals for both internal consumption and external marketing.

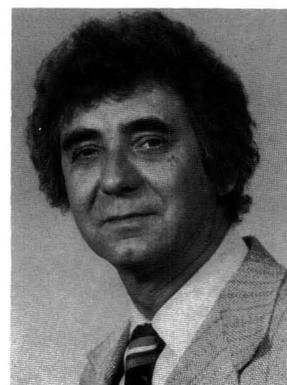
With its extensive manufacturing capabilities and its exceptionally strong emphasis on research and development, Milliken is a large employer of engineers and scientists. The company has been responsible for a number of revolutionary developments within the domestic textile industry. Chief among these is its computer-controlled system for continuous dyeing (of carpeting and upholstery), developed in the 1970's and known as the Millitron system, which completely changed this industry. The company also developed

Georgia Tech was instrumental in helping to set up the company's cooperative work-study program in the 1970's. Shortly thereafter, the School of Chemical Engineering at Georgia Tech inaugurated its graduate residency program.

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Jude T. Sommerfeld is professor and associate director of the School of Chemical Engineering at Georgia Tech. He received his BChE degree from the University of Detroit and his MSE and PhD degrees from the University of Michigan. His 25 years of industrial and academic experience have been primarily in the area of computer-aided design, and he has published over 70 articles in this and other areas. (R)

the well-known VISA fabric treating process to enhance washability, and the CAPTURE dry-process carpet cleaning technology.

Georgia Tech has a long history of synergistic cooperation with Milliken and Company. Georgia Tech was instrumental in helping to set up the company's cooperative work-study program in the 1970's. Shortly thereafter, the School of Chemical Engineering at Georgia Tech inaugurated its graduate residency program (a form of cooperative program at the master's level), with Milliken as the prototype participating company and which has since been extended to a number of other companies (including Tennessee-Eastman, 3M, Phillips Petroleum, Philip-Morris, and the Institute of Paper Chemistry). The president of Milliken and Company—Thomas J. Malone, a Georgia Tech chemical engineering graduate—served as the

This program is specifically oriented to rising senior engineering students, *i.e.*, students who have completed their junior year. Occasional exceptions have been made for outstanding underclassmen or recent BS graduates bound for graduate school . . . Applicants are required to be U.S. citizens, in the top 10% of their class or with a grade-point average of 3.5 and with demonstrated interpersonal skills.

first chairman of the School's Industrial Advisory Board. A number of the institute's faculty members have also been engaged in summer employment and/or served as consultants to the company in the past fifteen years.

ORIGIN

As indicated above, Milliken and Company has had an extensive cooperative education program for some time, as well as a summer employment program for both students and faculty. The unique feature of the program described in this article, however, relates to direct faculty involvement in the summer projects of undergraduate student interns. The idea for this specific program originated in discussions between Malone and Gary W. Poehlein—then Director of Georgia Tech's School of Chemical Engineering—in late 1984. Known as the Rising Senior Program, it is designed to provide student interns with an opportunity to apply engineering principles to real problems related to the broad scope of Milliken business interests. Students in this program benefit from the guidance of both Milliken professionals and Georgia Tech engineering faculty.

STRUCTURE

This summer work program is specifically oriented to rising senior engineering students, *i.e.*, students who have completed their junior year. Occasional exceptions have been made for outstanding underclassmen or recent BS graduates bound for graduate school. Student applicants to this program are required to be U.S. citizens, in the top 10% of their class or with a grade-point average of 3.5 (out of 4.0), and with demonstrated interpersonal skills.

The chemical engineering component of this program operates with the equivalent of one full-time faculty member supported by the company for the summer. During the first two years (1985 and 1986) of operation of this program, the actual Georgia Tech chemical engineering faculty contribution has been two faculty members—the authors of this present article—each on a 50% time basis. Included among the students they have advised have been a few textile engineering students. A program of comparable mag-

nitude also operates in the mechanical engineering sector, again with a similar contribution from Georgia Tech faculty members. This latter program has also included a small number of industrial engineering students. Milliken supports summer programs of smaller scope in the electrical engineering (including computer engineering) and textile technology areas. Students who participate in this program are recruited from the major engineering schools in the Southeast, plus a few other targeted schools. Thus, in comparison with conventional cooperative and summer work programs, the only additional costs for this Rising Senior Summer Program are faculty salary, travel expenses, and associated overhead. These additional costs constitute a small fraction (approximately 20%) of the total program cost.

IMPLEMENTATION

As presently implemented, planning for the summer program begins in the preceding fall quarter or semester. At this time (around Thanksgiving), brochures and letters are sent to the department heads at the selected schools, asking them to invite qualified students to apply. Depending upon recruiter schedules, some interested students are interviewed on campus by Milliken representatives while others are invited directly to company facilities for interviews. All prospective summer employees are eventually interviewed at their proposed work location. The candidate selection process is finalized near the end of the winter quarter, at which time offers of summer positions are made. The summer work terms are typically of ten to twelve weeks duration. Students from semester schools usually begin their work in May and finish in August, while those from quarter schools start in June and conclude in September.

Concurrently with the candidate selection process, suggestions for appropriate summer projects are being solicited and received from the various company manufacturing and technical locations. These projects are also reviewed for suitability by the contributing Georgia Tech faculty members. Summer interns are matched with projects at a specific location and are assigned to a Milliken professional who acts as his/her supervisor (or sponsor). This entire activity is coordinated by Milliken's Director of College Relations.

TABLE 1
ChE Students in
Milliken's Rising Senior Summer Program
(Q = quarter; S = semester)

School	Type of Term	Year	
		1985	1986
Auburn	Q	3	2
Clemson	S	2	1
Florida	S	2	3
Georgia Tech	Q	1	1
Mass. Inst. Tech.	S	0	2
N.C. State	S	2	1
South Carolina	S	1	0
Tennessee	Q	2	2
Yale	S	1	1
TOTALS		14	13

The schools and number of students participating in the chemical engineering component of this program during the summers of 1985 and 1986 are listed in Table 1. The total number of student interns (all disciplines) engaged in the summer 1986 program was approximately forty. This was in addition to a half dozen or so faculty members (not advising students *per se*) from different schools, including Georgia Tech, who participated as faculty summer interns on various independent projects.

In operation, a faculty advisor meets with each student intern on the average of once a week. Given the widespread locations of Milliken's various operations, a considerable amount of travel by the contributing faculty members is required. This travel time is considered in the determination of a faculty member's contribution to the program.

Some of the chemical engineering projects from this summer program are summarized in Table 2. Chemical engineering students are typically placed in textile finishing plants, wherein the operations of washing, dyeing, drying, *etc.* are more akin to chemical engineering unit operations. Mechanical engineering students, on the other hand, are usually engaged in projects in the upstream areas of cloth knitting and weaving.

Milliken Research Corporation (also located in Spartanburg), in addition to its research and development functions, is also strongly oriented to customer technical service and manufacturing support activities. Thus, many of the summer interns have direct (sometimes hands-on) experience with advanced analytical methods, *e.g.*, differential scanning

calorimetry (DSC), infrared (IR) analysis, and sophisticated colorimetric techniques, not to mention a myriad of computer applications.

Milliken, like the automotive and other industries, is a state-of-the-art practitioner of statistical quality control (SQC) procedures; thus, most of the summer interns experience, during their term, considerable exposure to statistics—an important topic virtually absent in most undergraduate chemical engineering curricula. These various work experiences are clearly quite valuable to engineering students returning to their senior year who are about to embark on professional careers.

In their weekly meetings, of typical duration of an hour or so, the student intern and faculty advisor (and sometimes the student's sponsor) review progress on the project and discuss future plans, experiments, any problems, *etc.* The faculty advisor is quite available to all of the student interns, and may be contacted at his Georgia Tech office in Atlanta at any time by the students. In addition to providing professional guidance and technical support, the faculty advisor functions as a resource person. The student interns are often directed to certain textbooks and articles relevant to their project(s). Copies of the latter are often directly supplied to the student interns from the faculty member's personal files or from the Georgia Tech library although, depending upon the timing and the student's specific location, his/her needs may be served more readily by Milliken's excellent technical library in Spartanburg. In some cases, the faculty advisor has served as a communications link between two or more different plants wherein students were working with a newly introduced technique. The faculty advisor is also in a unique position to suggest advanced technical solutions which the student intern (and company sponsor) may be unaware of. Specific examples from our two years of experience have included applications of linear programming, cascade control, queuing theory, and sophisticated numerical integration techniques.

Certainly, a highlight of the past two years has been the two-day sharing meeting. This meeting, at company headquarters in Spartanburg, is held in July—the only month in which the summer interns from both semester and quarter schools are all employed. The student interns, faculty advisors and faculty interns are all assembled for this meeting. On the first day, they are given a general overview of the company's business and operations by representatives of senior corporate management, followed by tours of the company's central facilities (research center, cus-

tomer center, *etc.*). On that evening, social events include a picnic and a volleyball tournament (dominated to date, by the way, by the chemical engineering team). On the second day, the student and faculty interns all make brief (five-minute) presentations on their summer projects. Again, senior corporate managers attend these presentations. The planning and scheduling for this event is quite complex, but all participants have felt it to be a very valuable experience.

Thus, the unique aspects of this Rising Senior

TABLE 2
Sample of ChE Projects in Milliken's
Rising Senior Summer Program

- Energy conservation in batch textile dyeing operations
 - Design of a heat transfer system for a batch chemical reactor
 - Interfacing of laboratory colorimeters with personal computers
 - Determination of kinetic parameters in batch textile dyeing operations
 - Extraction of oils from knitted or woven greige fabrics
 - Computer control of a batch chemical reactor
 - Development of chemical process for manufacture of a de-foaming agent
 - Determination of the time-temperature histories of finished fabrics
 - Viscosity studies of various gum blends as admixtures with dyestuffs
 - Analysis of oxidation/reduction processes in the post-dyeing treatment
 - Effect of oxygen as an impurity in steam on the dye-fixing process
 - Study of process variables in the wick-proofing (air diffusion resistance) of chafer fabrics
-

Summer Program, in comparison with conventional Summer or cooperative work programs, can be summarized as follows:

- *The weekly meetings between the student and faculty member can be best described as brainstorming sessions. The thought process developed during these sessions can often be quite different from that employed by someone who has worked closely in the area for a long time. It thus permits a student to critically examine the various approaches available to define and solve a problem.*
- *This interaction provides an opportunity and encouragement for the student to relate the project to science and engineering fundamentals. Many young engineers become disillusioned with the academic learning process when they first encounter an industrial problem. The presence of a faculty member facilitates a smoother transition from an academic to an industrial environment.*

RESULTS

Startup problems associated with the Rising Senior Summer Program have been minimal. Certainly, not all of the various projects have yielded quantifiable results. On the other hand, savings of several hundred thousand dollars per year can be clearly identified with a good number of these projects. In any event, the informational value resulting from most of these projects has been substantial.

Company and student response to this program has been enthusiastic. Critiques are solicited from both the company sponsors and student summer interns at the end of their terms. Following are some selected comments from these critiques:

- *It is good to be able to discuss your project with someone knowledgeable from outside the plant [the faculty advisor] in order to get different viewpoints.*
- *I applaud Milliken and Company for designing and organizing both the summer intern and summer professor programs.*
- *I feel the strengths of the intern program are the challenging projects that the interns face and the help of the professor advisors. . . . The two days at the Milliken Research Center were the highlights of the internship.*
- *My preferential pickup project required me to learn about heterogeneous surfaces and mass transport.*
- *I wish other companies would follow your example so more students could benefit from this type of experience. . . . Having someone from outside the plant to explain my project to was very helpful in organizing my thoughts.*
- *I have friends [at my school] that would love to have a chance to do the kind of work I did this summer. . . . It was extremely helpful to have a professor from Georgia Tech come to visit and give technical advice.*
- *I feel that the summer professors added to the program, supplying additional technical insight.*
- *I have worked internships with two other large companies and I feel the Milliken program is a step above the rest.*

Cooperative and summer work programs have long been recognized by companies as important adjuncts to their overall corporate recruiting programs. Thus, for example, at Georgia Tech approximately 55% of our co-op program graduates have traditionally accepted their initial employment after graduation with their co-op employer. In 1986, Milliken and Company hired about half of the chemical engineering student participants in the 1985 Summer program after their graduation (recall the qualifications for participation in this program). Clearly, this Rising Senior Summer Program has redounded favorably to both the company and the student participants. □

A REVERSE OSMOSIS SYSTEM FOR AN ADVANCED SEPARATION PROCESS LABORATORY*

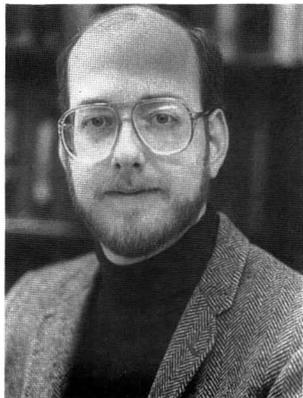
C. S. SLATER, J. D. PACCIONE
Manhattan College
Riverdale, NY 10471

MEMBRANE PROCESSES are one of the new technologies being introduced in today's engineering curriculum. The membrane process reverse osmosis (RO) is being utilized by a broad spectrum of industries for a variety of uses. Applications are found in the agricultural, biochemical, chemical, electrochemical, food and beverage, metal finishing, petrochemical, pharmaceutical, pulp and paper, and textile industries [1]. Reverse osmosis membrane processes are competing with the more traditional separation techniques such as distillation, evaporation, and filtration.

Reverse osmosis is considered a mass transfer unit operation and as such, theory relating to membrane transport should be presented in a mass transfer oriented course. System design and operation can be discussed briefly in a process or plant design course. Most engineering curricula present membrane technology in graduate courses, but some knowledge of the theory and operation should also be presented

C. Stewart Slater is an assistant professor of chemical engineering at Manhattan College. He has held the position since 1983 and had prior industrial experience with Procter & Gamble Co. and Arthur W. Ponzio Co. He received his PhD, MPh, MS and BS degrees in chemical engineering from Rutgers University. His research and teaching interests are in separation and recovery technology, membrane processes and biotechnology. (R)

John D. Paccione is currently a graduate student in chemical engineering at Rensselaer Polytechnic Institute. His involvement in this project was part of a Senior Honors Project at Manhattan College. He was active in the department's laboratory development activities for two years. He has industrial experience as a research technician with the Union Carbide Corporation. (Not pictured)



to undergraduates. The demonstration of reverse osmosis should occur in a senior level chemical engineering or "unit operations" laboratory. In such an experimental setting the student can understand the theory, operation and design of these systems and see the applications to industry. This could be in the form of a half-day experiment or a full semester project.

This paper focuses on the development of a small pilot unit for use in an advanced separations process laboratory. The end goal is to develop experiments with advanced separation processes such as reverse osmosis, ultrafiltration, adsorption, chromatography, etc. This paper presents one step in that direction.

REVERSE OSMOSIS PRINCIPLES

In simplest terms, RO uses a thin semipermeable membrane that allows the transport of certain species while retaining others. A feed stream is introduced, and the membrane separates it into a purer stream, the permeate, and a more concentrated stream, the retentate or concentrate. The permeate is the stream that permeates the membrane barrier. Mass transfer through an RO membrane can occur by several mechanisms for which many models have been proposed [2, 3]. The solution-diffusion model describing water and solute transport through the membrane is utilized here [4]. In this model each species in solution dissolves and diffuses through the membrane at a rate corresponding to the applied transmembrane pressure, ΔP , and the concentration gradient ΔC_s , across the membrane.

The permeate flux, J_w , which in most applications is water, is directly related to the transmembrane or hydraulic pressure driving force, ΔP , minus the difference in osmotic pressure, $\Delta\pi$, on both sides of the membrane.

$$J_w = A_w (\Delta P - \Delta\pi) \quad (1)$$

The flux and pressure gradients are related by the water permeability coefficient, A_w .

The solute flux, J_s , is related to the concentration

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*This paper is based on a paper previously published in the ASEE 1986 Annual Conference Proceedings.

gradient on both sides of the membrane, ΔC_s , by a solute permeability coefficient, B_s

$$J_s = (B_s)(\Delta C_s) \quad (2)$$

Recovery is the ratio of permeate production, Q_p , to feed rate, Q_f .

$$\text{Recovery, } Y = \frac{Q_p}{Q_f} \quad (3)$$

Solute rejection, R , can be measured in several ways. It can be denoted as a relationship between feed and permeate solute concentrations

$$R = 1 - \frac{C_p}{C_f} \quad (4)$$

Other ways to express rejection compare permeate to retentate concentrations or to an average of the feed and retentate concentrations. The recovery can also be incorporated into the expression [5]. It can be demonstrated from the solute and permeate flux equations that rejection is a function of pressure and concentration gradients. Water flux is dependent on pressure; therefore, an increase in pressure will increase water flux at constant solute flux, *i.e.*, decrease permeate solute concentration and increase solute rejection.

EXPERIMENTAL SYSTEM DESIGN

Since the membrane is the critical element in the RO system, proper understanding of structure and configuration is necessary before system design can commence. Reverse osmosis membranes are characterized by a high degree of semipermeability, high water flux, mechanical strength, chemical stability and economically acceptable cost. The early RO membranes were made out of cellulose acetate, but restrictions on process stream pH and temperature, including low rejection of some organics, spurred the development of non-cellulosic and composite materials. Polysulfones, polyamides, among others, and composite structures are popular alternatives because they do not have the draw-back of cellulose acetate [6]. The conventional composite membranes, normally called thin film composite membranes, do have a drawback in their ability to tolerate chlorine.

The membranes are configured into certain geometries for system operation. The four basic configurations are plate and frame, tubular, spiral wound, and hollow fiber. Since the studies employed in this paper use the spiral wound module, emphasis will be given to its characteristics with the reader referred to Leeper *et al* [7] for more design details. The spiral

This paper focuses on the development of a small pilot unit for use in an advanced separations process laboratory. The end goal is to develop experiments with advanced separation processes such as reverse osmosis, ultrafiltration, adsorption, chromatography, etc.

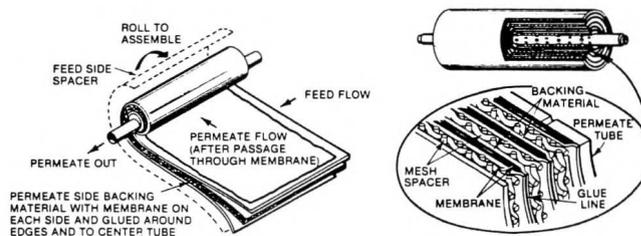


FIGURE 1. Spiral wound membrane configuration (from McNulty, K. J. and P. R. Hoover, EPA-600/2-80-084, U.S. Environmental Protection Agency, Cincinnati, OH, 1980, page 5).

wound configuration consists of two membrane sheets forming an envelope for a permeate channel with feed channels on the outside of the envelope wrapped in a “jelly-roll” pattern around a perforated tube (Figure 1). The feed flows axially through the unit, exiting as retentate. The permeate enters the membrane envelope and travels spirally to the perforated center tube where it exits the membrane at the retentate end. The plate and frame and tubular membrane modules employ far more simple geometries, as their names imply. The hollow fiber membrane configuration utilizes thousands of “hair-like” hollow fibers in a fiber bundle.

The aforementioned membrane modules can be arranged in series and parallel to design a commercial scale unit. In most large-scale commercial systems, this is needed to accommodate the higher feed rates and produce a high recovery. The functioning of one module is the basis for commercial system design and scale-up. Therefore, experiments on one membrane element can be utilized by a student to develop a system for a process or plant design course.

A simple laboratory RO system was designed to be as versatile as possible. It can be operated in such a way that different process parameters can be evaluated. A single (or small multiple) membrane system was chosen. It has the capability to independently vary the following process parameters: membrane feed rate, operating pressure and temperature. It is designed so that modifications can be easily done and membrane replacement can be quickly accomplished. Use of other membrane configurations is also a design consideration. Since spiral wound RO membrane sys-

tems are the most prevalent in the industry the system was designed on this basis. The system can be easily retrofitted for hollow fiber and tubular configurations.

System design rationale and a detailed discussion of the system's components are presented in Slater and Paccione [8]. A list of manufacturers of spiral wound membrane modules can be acquired by writing the author. Table 1 and the accompanying Figure 2 present the components and layout of the system. Some key features of the system are

- Stainless steel construction to allow for durability and for the processing of a broad range of fluids
- Sizing to accommodate all 2.5 inch diameter spiral wound membranes and most of the 4 inch diameter modules
- Independent setting of feed rate (0-10 gpm) and pressure (0-1000 psi) to obtain desired recoveries
- Construction with tubing and standard compression fittings to allow for easy alterations
- Layout which permits easy control of system and direct observation of flow patterns

System cost is always a consideration in a laboratory development project. It is encouraging to note that many membrane vendors and equipment suppliers give educational institutions discounts ranging up to 20% and some will even supply membranes. The system described in this paper, including a variety of membrane types, costs approximately \$12,000. Obviously this figure does not include the labor involved in design and fabrication. It is important to note that this cost could be reduced by not using stainless steel construction, by using a modest pump and drive, and by using house water for temperature regulation. A simple system on the order of \$5000 can be constructed for basic experiments if the future use and utility of the system is not important. Regardless of the complexity of the system involved, it is always cheaper to build your own system, and the involvement of students in the design, fabrication, and start-up activities broadens the scope of the project.

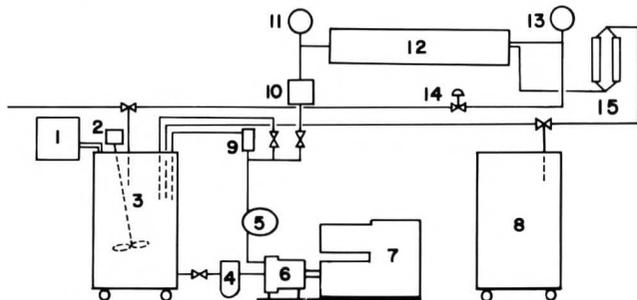


FIGURE 2. Reverse osmosis system (numbering refers to Table 1).

Several modes of operation are possible with the RO system and are shown in Figure 3. The steady-state recycle pattern of operation was used in the detailed experiments that follow. The critical process stream characteristics are flow rate and solute concentration. Permeate flux is obtained by dividing the permeate flow rate by the respective membrane surface area. Typical units are m^3/m^2d , cm^3/cm^2s and gal/

**TABLE 1
Reverse Osmosis System Component Listing**

Component	Model	Manufacturer-Distributor
1. Temperature Control Unit	2095	Forma Scientific Marietta, OH
2. Agitator	T-Line Lab Model 104	Talboys Engineering Corp. Emerson, NJ
3. Feed Tank	Model SSD-55	Utensco, Inc. Port Washington, NY
4. Prefilter	Big Blue Model T-1508-70 w/1508-78	Cole-Parmer Instrument Co., Chicago, IL
5. Pulsation Dampener	850990	Greer Products, Los Angeles, CA
6. Pump	Hydra-Cell D 10S	Wanner Engineering, Mahwah, NJ
7. Drive	Reeves Vari-Speed 5 Hp—Size 331	Reliance Electric Co., Columbus, IN
8. Permeate Tank	Model CC-55	Utensco, Inc. Port Washington, NY
9. Pressure Relief Valve	R3A	Nupro Co., Willingboro, OH
10. Feed Rotameter	10A 2227A	Fischer & Porter Warminster, PA
11. Feed Pressure Gauge	Master Series E 9672B	Marsh Instrument Co., Skokie, IL
12a. Membrane Pressure Vessel*	2S-1-2521	Advanced Structures, San Marcos, CA
12b. Membrane Module*	SW 30-2521	FilmTec Corp. Minneapolis, MN
13. Retentate Pressure Gauge	see component 11	
14. Back Pressure Regulator	26-1723-28-035	Tescom Corp. Elk River, MN
15. Permeate Rotameters	3202,3,4-20	Gilmont Instruments, Great Neck, NY

*Used in the specific experiments described in the paper. Other suppliers and specifications listed in ref. [8]

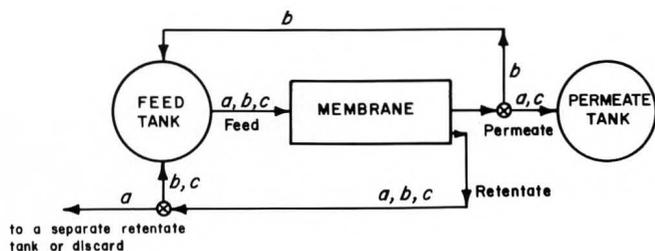


FIGURE 3. System operational schematic. Flow options: a) single pass, b) recycle steady state, c) recycle unsteady state.

dayft², also written as gfd. Solute concentration for a simple solute system is determined by measuring process stream conductivity and correlating the value to solute concentration.

EXPERIMENTAL STUDIES

Several simple experimental studies can be conducted to examine process parameters and membrane mass transfer characteristics. Data can be analyzed quickly to determine if the experiment was carried out correctly. In most of these experiments certain process parameters are kept constant and others varied. Process feed rate, concentration, temperature, pH, recovery, and pressure can be adjusted within certain operating limits.

The two major characteristics to be observed in a reverse osmosis experiment are separation efficiency and permeate production. The effect of process variables on these, and the verification of membrane mass transfer models, can be accomplished with simple experiments. A summary of some typical experiments is presented below. Specific details are omitted so that instructors can construct the proper experiment for the appropriate student audience and time frame.

Pressure Study

The effect of pressure on permeate production and solute rejection can be easily demonstrated. A particular membrane module should be chosen for this study—particularly one that will allow for a wide range of operating pressures. A simple solute, *e.g.*, NaCl, can be utilized as the feed at a certain concentration, *e.g.*, 5000 mg/L. Process parameters such as temperature and pH are maintained at certain values. The recovery for each run can be held constant by regulating the feed flow rate. It is important to remember to operate within the appropriate feed flow and/or recovery limits established by the manufacturer to lessen the problems associated with concentration polarization. Runs are conducted at various pressures, at 25 or 50 psi increments, depending on

the amount of data to be collected. Membrane manufacturers give a maximum operating pressure for each membrane along with a normal or recommended operating range. This range is usually 10 to 25% less than the maximum. The system's safety relief valve can be set at the upper end of the pressure range to protect the membrane from excessive pressures resulting from operator error or mechanical malfunction.

In the experiment the student first observes the minimum pressure needed to produce permeate. As the pressure increases, the permeate flow will increase and the permeate concentration will decrease. The effect of increased pressure on permeate production can be explained by the permeate flux model (Eq. 1). By plotting permeate flux *vs* pressure the relationship is observed. At each of the pressures a sample of the permeate is analyzed using the conductivity meter, and its salt concentration is determined. The permeate concentration will decrease exponentially

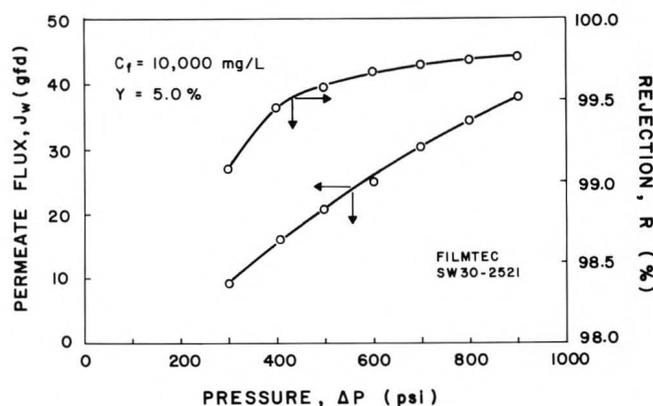


FIGURE 4. Results of a typical experimental study examining the effect of pressure on permeate flux and solute rejection.

with increasing pressure. This phenomena is a result of solute flux being independent of applied pressure (Eq. 2). The membrane's solute rejection can be calculated by one of the expressions given earlier (Eq. 4). The rejection will increase and appear to approach a maximum as pressure is increased.

An example of typical experimental output is shown in Figure 4. This study utilized a FilmTec SW30-2521 (2.5 in. diameter × 21 in. length) thin film composite spiral wound membrane. A 10,000 mg/L solution of NaCl was used as the feed at a temperature of 20°C and pH of 6. The study was run at a recovery of 5.0% at pressures ranging from 300 to 900 psi.

Feed Concentration Study

The effect of feed solute concentration on permeate

The two major characteristics to be observed . . . are separation efficiency and permeate production. The effect of process variables on these, and the verification of membrane mass transfer models, can be accomplished . . .

flux and concentration can be readily observed. In this experiment the only parameter varied is the solute concentration. The feed and standard processing conditions utilized in the previous study can be employed here. A particular operating pressure is selected for all runs. The recovery can also be maintained.

Runs are conducted at various concentrations from a low value to a high value, e.g., 1000 mg/L to 35,000 mg/L. Increments are chosen depending on time; five to ten different concentrations are usually sufficient. At each different concentration the permeate production and its concentration are determined. As concentration increases, permeate flux decreases because of the increased osmotic pressure of the feed (Eq. 1). The solute flux is dependent on the concentration (Eq. 2) so it will increase as the feed concentration is increased. Therefore an increase in the permeate concentration and a decrease in solute rejection with increased feed concentration will be demonstrated.

Experimental output from a series of runs with a FilmTec SW30-2521 membrane at increasing NaCl feed concentrations can be seen in Figure 5. The plot illustrates the decrease in permeate flux and the increase in permeate concentration as the concentration of the NaCl feed solution is increased. The runs were performed at an applied pressure of 600 psi at 20°C with a feed rate of 3.0 gpm.

An extension of this and the initial study would be to examine different membrane models from each manufacturer. This comparison would show the differ-

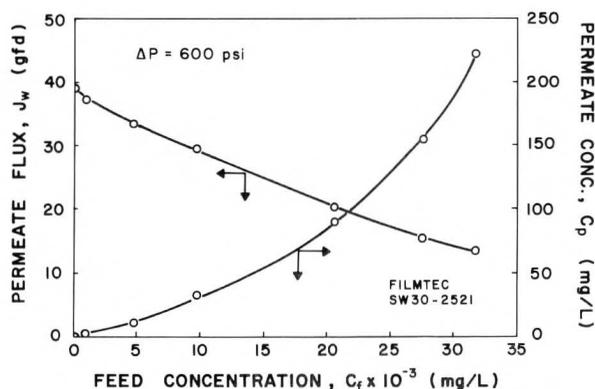


FIGURE 5. Results of a typical experimental study examining the effect of feed concentration on permeate flux and concentration.

ent membrane characteristics within a particular membrane product line.

Additional Studies

Many other studies can be performed utilizing the RO system. Publication of a thorough description of each study is planned for some later date and will include

- The effect of temperature on permeate production and separation efficiency
- Determination of mass transfer coefficients
- Analysis of concentration polarization and related models
- The effects of fouling on permeate production and separation efficiency
- Operational characteristics of other membrane configurations, e.g., tubular and hollow fiber
- The effect of different membrane materials on organic solute rejection
- The effect of recovery and feed rate on permeate production and separation efficiency
- The effect of pH on separation efficiency and membrane life

CONCLUSIONS

Reverse osmosis theory and system operation can be demonstrated with a series of experiments on a small pilot-scale unit. The system design is simple and yet quite versatile. The system is made with an "open-end" design and can be easily changed to incorporate future design modifications and be used with different types of membranes. The system that was developed for an advanced separations laboratory was based on using small spiral wound membranes and can operate at feed rates to 10 gpm and pressures to 1000 psi. Feed flow, solute concentration, temperature, pressure, and recovery can all be independently varied. The system can operate in various flow schemes. Experiments investigate simple operational parameters and mass transfer characteristics. Permeate production and solute rejection are studied. More detailed experiments involving organic separation, concentration polarization and fouling and other membrane configurations can be performed.

ACKNOWLEDGEMENTS

Partial support for this work was provided by the National Science Foundation's College Science Instrumentation Program through grant #CSI-8551851. The authors would like to thank Paul Carney for his outstanding technical assistance in system design and fabrication. The authors would also like to thank Richard Ide of Desal Desalination Systems and David

McGovern of FilmTec for their assistance with this project.

NOMENCLATURE

A_w	Water permeability coefficient [$L^{-1}t$]
B_s	Solute permeability coefficient [Lt^{-1}]
C_f	Feed solute concentration [ML^{-3}]
C_p	Permeate solute concentration [ML^{-3}]
C_r	Retentate solute concentration [ML^{-3}]
C_s	Solute concentration [ML^{-3}]
J_s	Solute flux [$L^3L^{-2}t^{-1}$], [$ML^{-2}t^{-1}$]
J_w	Water or permeate flux [$L^3L^{-2}t^{-1}$], [$ML^{-2}t^{-1}$]
ΔP	Applied pressure gradient [$ML^{-1}t^{-2}$]
Q_f	Volumetric flow rate of feed [L^3t^{-1}]
Q_p	Volumetric flow rate of permeate [L^3t^{-1}]
Y	Recovery, single-pass operation [unitless]
$\Delta\pi$	Osmotic pressure gradient [$ML^{-1}t^{-2}$]

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1. Slater, C. S., R. C. Ahlert, and C. G. Uchirin, *Desalination*,

ChE book reviews

FUNDAMENTALS AND APPLICATIONS OF ION EXCHANGE

Edited by L. Liberti and J. R. Millar
Martinus Nijhoff Publishers, Dordrecht,
The Netherlands, 1985. 484 pgs, \$65.50

Reviewed by
Friedrich G. Helfferich
Pennsylvania State University

Fundamentals and Applications of Ion Exchange is a collection of thirty contributions to a NATO Advanced Study Institute held in Maratea, Italy. A wide range of topics is covered, from a crystal-ball perspective "Ion Exchange Towards the Twenty-First Century" by the unforgettable Calvin Calmon, to highly specialized industrial problems such as reduction of regenerant acid use in water desalination (Hendry), start-up of a RIM-NUT plant for recovery of nutrients from eutrophic aqueous discharges (Liberti *et al*), and copper and nickel recovery from plating plant effluents (Stortini), and to complex theoretical studies *e.g.* of the microscopic basis and limits of the Nernst-Planck-Poisson system (Buck) and use of the Stefan-Maxwell flux equations in multicomponent ion exchange (Graham).

The attractively produced volume constitutes the third crop harvested from the Maratea NATO Ad-

vanced Study Institute. The thirteen main lectures were published in a previous volume of the NATO ASI Series (*Mass Transfer and Kinetics of Ion Exchange*, No. 71, Nijhoff, The Hague, 1983) and a selection of fifteen other contributions of general interest appeared in *Reactive Polymers* (Vol. 2, Nos. 1, 2, January 1984). The residue collected here is of mostly high, if uneven, quality. Perhaps the harshest criticism that can be voiced on this score is that the volume has no cohesion, no common denominator other than a loose relation to ion exchange. The seemingly unorganized side-by-side of specialized pragmatic, abstract complex theoretical, and review-style papers is a little disconcerting.

Perhaps more disturbing is that at least five of the thirty papers of the book have been published previously [Hogfeldt *et al* on a method of summarizing equilibria data, and Meagher *et al* on Mossbauer and electron microprobe studies of precipitation in Nafion membranes, in *Reactive Polymers*, 2 (1984) 19 and 51, respectively; Bolto *et al* on recycling of waste water constituents, in *Effluent Water Treat. J.*, (1983) 23; Buck on the Nernst-Planck-Poisson system, in *J. Membrane Sci.*, 17 (1984) 1; Drummond *et al* on kinetics in Zeolite A in *J. Phys. Chem.*, 87 (1983) 1967]. No references to such prior publications are given in the book.

The ion exchange expert will welcome this volume as a reasonably priced collection of specialized information. No other reader is likely to be interested, and the didactic value for course work is nil. □

The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested as well as those that are more traditional in nature, which elucidate difficult concepts. Please submit them to Professor H. Scott Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

ESTIMATING RELATIVE VOLATILITY OF CLOSE-BOILING SPECIES

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PROBLEM STATEMENT

IN ORDER TO separate two close-boiling species by distillation, it is most useful to know their relative volatility (α) since one can calculate from only this the approximate number of stages to get any given degree of separation, *e.g.* by the methods of McCabe and Thiele or Fenske's equation for total reflux. On the other hand, the α may not be readily available and the data in handbooks are usually limited to only the boiling points of the two species.

You are to derive an equation for the relative volatility of two species knowing *only* the two normal boiling points. It may be assumed that:

- They boil only a few degrees apart, say no more than 10°C *e.g.*, ortho vs para-xylene.
- They are similar chemically and thus conform to Raoult's Law.
- They thus do not form an azeotrope.
- For simplicity, the ideal gas law may be assumed if needed.

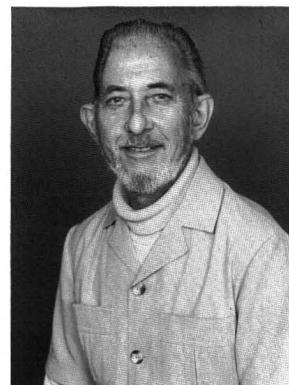
You should know the exact definition of relative volatility. Also, state any further assumptions you need to make.

SOLUTION

The relative volatility (α) of a pair of substances is defined as the ratio of their volatilities (v_i), *i.e.*

$$\alpha_{12} = \frac{v_1}{v_2} \quad (1)$$

and the volatility, v_i is defined as the partial pressure of i , p_i , above a liquid solution divided by its mole



Allen J. Barduhn received his MS from the University of Washington in 1941 and worked for several years at a California oil refinery before re-entering college at the University of Texas, Austin, where he received his PhD in 1955. He was a professor of chemical engineering at Syracuse University from that date until last year when he retired. He is presently involved in writing a book and articles.

fraction in the liquid, *i.e.*

$$v_i = \frac{p_i}{x_i} \quad (2)$$

For solutions which follow Raoult's Law, the volatility is thus equal to its vapor pressure.

In this case then, the relative volatility is just the ratio of vapor pressures, or

$$\alpha_{12} = \frac{P_1^*}{P_2^*} \quad (3)$$

Also for this case we may estimate the relative volatility knowing only the normal boiling points of the two substances, especially when they boil within a few degrees of one another, say no more than 10°C apart. The derivation of this relation follows.

Accepting Eq. (3) above with all its special requirements, *i.e.*, (a) ideal solution in the liquid, (b) Raoult's Law followed, (c) n.b.p. not far apart but known, we proceed

$$\alpha_{12} = \frac{P_1^*}{P_2^*} = 1 + \frac{P_1^* - P_2^*}{P_2^*} \quad (4)$$

We may estimate the change in vapor pressure with temperature from the Clapeyron Equation

$$\frac{dP}{dT} = \frac{\Delta H}{T\Delta V} = \frac{\Delta H}{T(V_{\text{gas}} - V_{\text{liq}})} \quad (5)$$

and making the usual assumption that $V_{\text{gas}} \gg V_{\text{liq}}$ and that the ideal gas law applies to the vapor,

$$\Delta V = V_{\text{gas}} = \frac{RT}{P} \quad (6)$$

applying Eq. (6) to Eq. (5) we get

$$\frac{dP}{dT} = \frac{\Delta H}{T} \cdot \frac{P}{RT} \quad (7)$$

and if we may approximate dP/dT with $\Delta P/\Delta T$ over the small temperature range involved

$$\frac{dP}{dT} = \frac{\Delta P}{\Delta T} = \frac{\Delta H \cdot P}{RT^2} \quad (8)$$

and further that

$$\Delta P = \frac{\Delta T}{T} \cdot \frac{P\Delta H}{RT} \quad (9)$$

Now the ΔP is the change in vapor pressure with a change in temperature of ΔT and may be applied to either component in Eq. (4) above in which the $P_1^* - P_2^*$ may be identified with the ΔP in Eq. (9). Thus combining Eq. (4) with Eq. (9)

$$\alpha_{12} = 1 + \frac{\Delta P}{P_2^*} = 1 + \frac{\Delta T}{T} \cdot \frac{\Delta H}{RT} \frac{P}{P_2} = 1 + \frac{\Delta T}{T} \frac{\Delta H}{RT} \quad (10)$$

since P_1 and P_2 are the same as P from *normal* boiling points, or for boiling points known at any other fixed pressure.

The ratio $\Delta H/T$ is Trouton's constant which is often taken as 21 cal/(gmole)(K) at 1 atmosphere. Also since $R = 1.987$ cal/gmole(K) we arrive at

$$\alpha_{12} = 1 + \frac{\Delta T}{T} \cdot \frac{21}{1.987} = \boxed{1 + \frac{10.6 \Delta T}{T} = \alpha_{12}} \quad (11)$$

In Eq. (11) the temperatures must all be on the same absolute scale, Kelvin or Rankine.

The constant 10.6 is subject to experimental confirmation since Trouton's constant is not a fixed number but depends on the substances and the temperature level at which they boil.

The constant appears to lie between 10 and 13 for many of the close boiling pairs I have checked it on. For the isomeric xylenes it is 12.

Also it is 17 to 20 for the system ($O_2 + N_2$) at 1 atm. The temperature range is probably too large (ΔT

= 13°C), or the temperature is too low (77 and 90K) for Trouton's constant to hold. The α range is 3.7 to 4.2 at 1 atm and at 5 atm the mean $\alpha = 2.6$.

NOMENCLATURE

- α_{ij} = relative volatility of i with respect to j
- p_i = partial pressure of i
- P^* = vapor pressure of i
- P = total pressure
- R = gas constant
- T = absolute temperature °R or K
- ΔT = difference in boiling points at a fixed P
- v_i = volatility of i (Eq. 2)
- x_i = mole fraction of i in the liquid \square

ChE book reviews

TWO PHASE FLOW AND HEAT TRANSFER: CHINA-US PROGRESS

by Xue-jun Chen, and T. Nehat Veziroglu
Hemisphere Press, 785 pgs, \$175 (1985)

Reviewed by

A. E. Dukler

University of Houston

In 1984, a small conference in Xian China on two phase flow and heat transfer was attended by about forty Chinese researchers, ten US researchers, and four researchers from other countries. The conference was organized to stimulate interaction between the Chinese and US community working on this subject, as has been the purpose of many other such conferences. This volume contains the 49 papers presented at that meeting.

Of the thirteen papers presented by US participants, ten were essentially review papers (pressure drop, burnout, critical flow, heat exchanger design, etc). These vary greatly in quality and completeness. In many cases more complete reviews can be found elsewhere, in some cases by the same authors.

The papers presented by Chinese investigators were, in the most part, reports on work in progress which was largely experimental and which were concerned with global characteristics of the flow (pressure gradient, Nusselt number, flow patterns, burnout conditions, etc.). These papers contribute little to a knowledge of the basic mechanisms underlying these processes, although in some cases the new data are of interest.

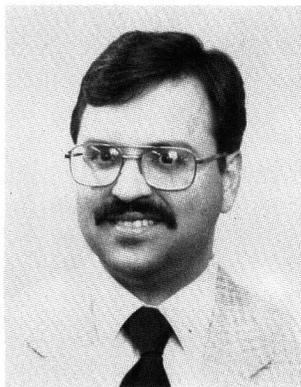
The individual papers appear to be unedited and the book consists of direct reproduction of each paper as prepared by the author. Thus the type and graphics differ in each paper. There is a very complete index. \square

A FIRST CHEMICAL ENGINEERING LAB EXPERIENCE

VITO L. PUNZI
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ONE OF THE major challenges for faculty involved in a first chemical engineering lab course which emphasizes technical report writing is the development of appropriate experiments. Because the students have limited chemical engineering experience at the start of such a course, the first few experiments must be simple and should be based on chemical engineering courses completed in the sophomore year.

This paper describes a simple thermodynamics experiment currently in use at Villanova University. The specific heat of a liquid is determined using an easily and inexpensively constructed, operated, and maintained apparatus. The students use the results of the experiments to formulate recommendations on how the performance of the apparatus can be improved so that it could be used in a wider range of



Vito L. Punzi joined the chemical engineering faculty at Villanova University in 1980 after previous experience in industry. He received his BS degree from Polytechnic Institute of Brooklyn in 1972 and his MS and PhD from Polytechnic Institute of New York in 1974 and 1979, respectively. His teaching interests are in chemical process calculations, chemical engineering thermodynamics, and fluid dynamics, and he is currently performing research on the solute rejection mechanism in reverse osmosis and on the removal of heavy metals from industrial waste water via adsorption.

This paper describes a simple thermodynamics experiment currently in use at Villanova University. The specific heat of a liquid is determined using an easily and inexpensively constructed, operated, and maintained apparatus.

applications than those specifically tested through experimentation.

Since the experiment produces accurate results and stimulates the development of "engineering judgment," a satisfying technical report writing experience usually results.

APPARATUS

The principal components used in this experiment are shown in Figure 1. A wide-mouthed 700 ml Dewar flask vacuum bottle is fitted with a styrofoam insulated lid which supports a 300 watt immersion heater and a mercury-in-glass thermometer. The flask is mounted on a magnetic stirrer to ensure proper mixing and a uniform liquid temperature. The immersion heater is connected to a variable power transformer and wattmeter (accurate to $\pm 5\%$) so that the energy input rate to the liquid can be controlled and determined. A 500 ml graduated cylinder and hydrometers are used for the volume and specific gravity measurements needed to determine the mass of the liquid samples. A digital stopwatch is used along with the thermometer to collect elapsed time and liquid temperature data.

THEORY

The unsteady state energy balance for a nonflow process with negligible kinetic and potential energy effects can be expressed as

$$Q_{\text{net}} - W_{\text{net}} = [dU/dt] \quad (1)$$

where Q_{net} is the net rate of heat transfer into the system from the surroundings, W_{net} is the net rate of work performed by the system on the surroundings,

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and U is the internal energy of the system, which varies with time, t . If the system undergoes changes at constant pressure and if shaft work effects are negligible, the thermodynamic definitions of work and enthalpy (H) can be used to obtain

$$Q_{\text{net}} = [dH/dt] \quad (2)$$

For the calorimeter used in the experiment (a Dewar flask vacuum bottle), the thermodynamic system is the liquid contents of the calorimeter, the solid components of the immersion heater and the inner wall of the Dewar flask. In this system, Q_{net} is the sum of the heat added to the system through the immersion heater (Q), and the heat added to the system through the inner wall of the Dewar flask due to the temperature difference between the surrounding environment and the system. Since the heat added to the system through the inner wall of the Dewar flask is negligible when compared to the heat added to the system through the immersion heater, Eq. 2 simplifies to

$$Q = c_p [dT/dt] \quad (3)$$

where c_p is the total heat capacity of the system considered, and T is the temperature of the system, assumed uniform throughout the system.

The total heat capacity of the system consists of the heat capacity of the liquid contents, c_{pl} , and the heat capacity of the solid components of the immersion heater and the inner wall of the Dewar flask which are lumped into a single parameter, the calorimeter constant c_{pc} . If the heat capacity of the liquid is expressed in terms of the specific heat of the liquid (c_{pl}') and the mass of the liquid (m_l), then Eq. 3 can be rewritten as

$$Q = (m_l c_{pl}' + c_{pc}) [dT/dt] \quad (4)$$

Thus, a well-insulated batch calorimeter can be used to determine the specific heat of a liquid from the rate of temperature change which results when energy is added at a known rate to a known liquid mass.

EXPERIMENTAL PROCEDURE

First, the students perform three repetitions of a calibration experiment to determine the calorimeter constant c_{pc} . A constant energy input rate between 100 and 200 watts is used to heat 500 ml of water. Since the specific heat of water is known and is relatively constant, rate of temperature change data can be used to determine c_{pc} using the following rearrangement of Eq. 4

$$c_{pc} = (Q/[dT/dt]) - m_l c_{pl}' \quad (5)$$

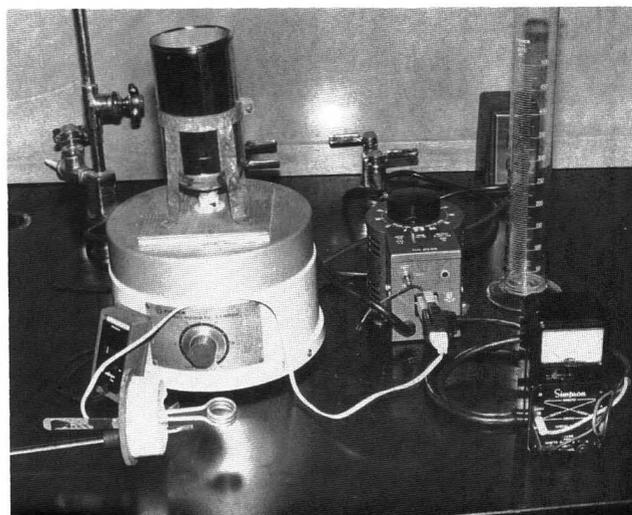


FIGURE 1. Experimental Apparatus

Next, a series of experimental runs is performed to determine the specific heat of the test solution, c_{pl}' , at several concentrations. The same procedure is used as in the calibration experiments, except that a test solution is used instead of water. Using the value of c_{pc} determined above, the value of c_{pl}' can be calculated from

$$c_{pl}' = \{(Q/[dT/dt]) - c_{pc}\} / m_l \quad (6)$$

Ethanol-water solutions and glycerol-water solutions have been used successfully as test solutions. These solutions have been used primarily because minimal evaporative losses occur, and because extensive specific heat data are available in the literature.

The test solutions are heated over a narrow temperature range chosen so that the middle of the range coincides with a temperature at which literature values of the specific heat are available. For example, glycerol-water solutions are usually heated from 5°C to 25°C, since literature data are available at 15°C (1). If calibration runs are performed over the same temperature range, the final results of the experiment are usually quite accurate.

The experiment can be performed either using standard solutions of known composition or using solution compositions chosen at random by the students. The advantage of the former approach is that it allows a direct comparison between experimental and literature values.

RESULTS

The heat capacity of the solid components of the calorimeter (c_{pc}) is approximately 10% of the total heat capacity of the system. Thus, neglecting this

parameter in an energy balance would result in a significant deterioration in the quality of the final results. However, the magnitude of this parameter is small enough so that more accurate estimates would not significantly improve the final results.

During the 1984-85 academic year, ethanol-water solutions were used, with solution compositions chosen at random by the students. All experimentally determined values of specific heat were within 10% of an interpolated literature value, at all concentrations.

During the 1985-86 academic year, standard glycerol-water solutions containing 10 wt% glycerol and 40 wt% glycerol were used; a limited number of additional experiments were performed using a 20 wt% glycerol solution. As shown in Table 1, the experimentally determined values of the specific heat of the 10 wt% solution were, on the average, within 2% of the literature value at 15°C. All but one of the 38 individual values determined in the experiments using the 10 wt% solution were within 7.5% of the literature value at 15°C, with 32 of the 38 individual values within 5% of the literature value at 15°C.

TABLE 1
Results of Experiments Using
Glycerol-Water Solutions at 15°C

Composition (weight % glycerol)	Specific Heat, cal/g·°C			Number of Samples
	Range of Individual Values	Average Experimental Value	Literature Value ⁽¹⁾	
10	0.866-1.002	0.941	0.961	38
20	0.859-0.893	0.881	0.929	3
40	0.752-0.849	0.791	0.851	37

The experimentally determined values of the specific heat of the 40 wt% solution were, on the average, within 7% of the literature value at 15°C. All of the individual values determined in the experiments using the 40 wt% solution were within 11.5% of the literature value at 15°C, with 33 of the 37 individual values within 10% of the literature value at 15°C.

DISCUSSION

The exercise described above is structured so that the student is required to do more than collect data and tabulate results. For many students, this experiment provides them with their first opportunity to develop "engineering judgment" in the chemical engineering laboratory environment. The students must use knowledge obtained in lecture courses, and the results of experimentation, to make logical conclusions and meaningful recommendations. Further, the stu-

This . . . experiment involves basic thermodynamics, uses easily operated experimental equipments, produces accurate final results . . . and encourages students to use engineering judgment . . .

dents are required to organize and present their findings in a technical report written in accordance with the classroom instruction they are given.

The experiment is not intended to produce handbook-quality physical property data, nor to duplicate industrial research methods. Indeed, more accurate results could easily be obtained, for example, by using a more accurate wattmeter or by using a direct measurement of sample mass. However, despite these and a few other built-in flaws in the equipment and procedures used, reproducible results which are within $\pm 10\%$ of handbook data are consistently achieved. The flaws do not significantly deteriorate the quality of the results produced by the apparatus, but are obvious enough so that the students can usually make several worthwhile recommendations, rather than the contrived recommendations which are quite prevalent in undergraduate reports.

CONCLUSIONS

This paper describes an experiment which involves basic thermodynamics, uses easily operated experimental equipment, produces accurate final results from a rather straightforward analysis and encourages students to use engineering judgment to formulate worthwhile conclusions and recommendations on how to improve the apparatus. All of these features combine to produce a favorable first experience in technical report writing.

In addition, the experiment requires only a small expenditure of funds: since breakable parts are relatively inexpensive, annual operating costs are usually minimal and most of the equipment involved in the experiment need not be committed solely to this experiment since it can be used in other teaching, laboratory, and research applications.

ACKNOWLEDGEMENTS

The author thanks the members of the Villanova University Department of Chemical Engineering classes of 1986 and 1987 for providing the experimental results discussed above.

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LIQUID OIL DROPLET

Continued from page 129.

good approximation, as discussed below, in which case the above equation becomes

$$1 + \frac{(n-s)y_\infty}{s} = \frac{(n-s)c_o T_\infty + \Delta H^\circ}{(n-s)c_o T_f + \Delta H^\circ} \quad (12)$$

or

$$T_f = \frac{s T_\infty}{[s + (n-s)y_\infty]} - \frac{\Delta H^\circ y_\infty}{c_o [s + (n-s)y_\infty]} \quad (13)$$

This is the simplest expression for T_f , the temperature of the flame front and, in fact, on detailed examination shows that T_f is not equal to the adiabatic flame temperature, as assumed by Long [4]. Eqs. (12) and (13) can now be substituted into Eq. (11), giving

$$\frac{M}{4\pi a} = \frac{k_f}{c_f} \ln \left[1 + \frac{c_f [c_o T_\infty - \Delta H^\circ y_\infty / s - c_o T_o (1 + (n-s)y_\infty / s)]}{c_o \lambda \left(1 + (n-s) \frac{y_\infty}{s} \right)} \right] + \frac{k_o}{c_o (n-s)} \ln \left(1 + (n-s) \frac{y_\infty}{s} \right) \quad (14)$$

This now enables a simple expression to be calculated for the burning constant k_b (see Eq. (1)) using

$$M = - \frac{d}{dt} \left(\frac{4}{3} \pi a^3 \rho_{liq} \right) = - 4\pi a^2 \rho_{liq} \frac{da}{dt}$$

or

$$- \frac{d}{dt} (a^2) = k_b = \frac{M}{2\pi a \rho_{liq}}$$

giving

$$k_b = \frac{2k_f}{c_f \rho_{liq}} \ln \left[1 + \frac{c_f [c_o T_\infty - \Delta H^\circ y_\infty / s - c_o T_o (1 + (n-s)y_\infty / s)]}{c_o \lambda \left(1 + (n-s) \frac{y_\infty}{s} \right)} \right] + \frac{2k_o}{c_o (n-s) \rho_{liq}} \ln \left(1 + \frac{(n-s)y_\infty}{s} \right) \quad (15)$$

Of course, a somewhat more cumbersome form of Eq. (15) can be derived by not using the above approximations of an averaged specific heat, c_o , for O_2 and the products of combustion or of unit Lewis number, etc. In fact, Eqs. (5), (8), and (9) without these assumptions lead to the general expression

$$k_b = \frac{2k_f}{c_f \rho_{liq}} \ln \left[1 + \frac{c_f T_\infty + \frac{c_f (\Delta H^\circ + \lambda - c_f T_o)}{(nc_p - sc_{O_2})} \left(1 - \left(1 + \frac{(n-s)y_\infty}{s} \right)^\alpha \right) - c_f T_o \left(1 + \frac{(n-s)y_\infty}{s} \right)^\alpha}{\lambda \left(1 + \frac{(n-s)y_\infty}{s} \right)^\alpha} \right] + \frac{2k_o \alpha}{\rho_{liq} (nc_p - sc_{O_2})} \ln \left(1 + \frac{(n-s)y_\infty}{s} \right) \quad (16)$$

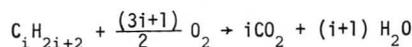
Here the dimensionless group α is given by

$$\alpha = PD_{O_2} c_o / RTk_o$$

and is the reciprocal of a Lewis number. Of course, Eq. (15) is preferred over Eq. (16) for teaching purposes.

DISCUSSION

Eqs. (15) and (16) each contain two terms, and in that sense are similar to Long's result [4]. However, our second term is different from Long's, which we conclude to be in error. Substitution of numerical values into either Eq. (15) or (16) indicates that the second term is 1-2% of the first term. In this case k_b can be taken to be the first term of either Eq. (15) or (16), depending on the precision required. Fixing attention on Eq. (15) for a fairly heavy paraffin being burnt according to



we have

$$n/s = 2(2i+1)/(3i+1) \approx 4/3$$

provided $i > 5$. As a result

$$(1 + (n-s)y_\infty/s) \approx 1 + y_\infty/3 \approx 1.07$$

which can be taken as unity. Consequently, the first term in Eq. (15) can be simplified to

$$k_b = \frac{2k_f}{c_f \rho_{liq}} \ln \left[1 + \frac{c_f [(T_\infty - T_o) - \Delta H^\circ y_\infty / c_o s]}{\lambda} \right] \quad (17)$$

which is similar to Spalding's result [2]. In fact, it is identical to Spalding's result, when $c_f = c_o$. Spalding's derivation [2] is interestingly different from that given above; in particular, it requires the possibly unpalatable assumption that diffusion for both $r < r_f$ and $r > r_f$ can be modelled by one composite substance of fuel and "negative" oxygen, with complete neglect of the products of combustion. As discussed below, Spalding's assumption that $c_f = c_o$ is often not a good one.

Some insight can be gained into the above conclusion that the ratio of the second term to the first in both Eqs. (15) and (16) is small. Comparison of Eqs. (6), (11), and (14) reveals that the ratio of the first and second terms in both Eqs. (15) and (16) is r_f/a . Substitution of the values of physical properties (see below) shows that r_f/a is roughly in the range 50-100. Thus neglect of the second term in Eqs. (15) or (16) generates an uncertainty of less than 2%. Perhaps the best expression for k_b from Eq. (16) neglects the second term and assumes

$$1 \gg (n-s)y_\infty/s$$

but does not assume unit Lewis number. The result is

$$k_b = \frac{2k_f}{c_f \rho_{liq}} \ln \left(1 + \frac{c_f(T_\infty - T_o) - c_f \Delta H^\circ \alpha y_\infty / s c_o}{\lambda} \right) \quad (18)$$

NUMERICAL CONSIDERATIONS

1. First we estimate T_f by substituting values into Eq. (13). Consider toluene burning in $C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$, for which $\Delta H^\circ = -3.9 \times 10^6$ J/mol, $\lambda = 3.2 \times 10^4$ J/mol, $s = 9$, $y_\infty = 0.21$ and $n = 11$. At the quite arbitrary temperature of 700 K, the molar heat capacities of O_2 , H_2O and CO_2 are [8], respectively, 33.0, 37.5 and 49.6 J/(mol K). This gives $2c_o = 7 \times 49.6 + 4 \times 37.5 - 9 \times 33.0$ or $c_o = 100$ J/(mol K). Also, these data give $T_f = 1149$ K for an ambient air temperature $T_\infty = 20^\circ C$. This value of T_f is less than the adiabatic temperature of around 2300 K, in contrast with Long's assumption [4] that the two are identical. This discrepancy arises partly because c_o is much greater than the heat capacities of O_2 , H_2O or CO_2 . Even so, c_o is not as large as the specific heat of the fuel, with [8] *e.g.*, $c_f = 173, 208$ and 358 J/(mol K), respectively, for benzene, toluene and n-octane. Spalding's simplification [2] that $c_f = c_o$ accordingly should be treated with great care.

2. The above data also give $r_f/a = 49$ (again for toluene burning in air at $20^\circ C$), from a comparison of the two terms in Eq. (15). However, if the more precise Eq. (16) is used, then $r_f/a = 72$ is obtained. For these calculations values of k_f and k_o were taken [8] to be 0.065 and 0.050 J/(K s m), respectively, and $T_o = 383$ K (boiling point of toluene = $110.6^\circ C$) was assumed. Such a magnitude for r_f/a justifies the earlier neglect of the second term in Eqs. (15) and (16).

3. The previous assumption of unit Lewis number is worthy of comment. In fact, the value [9] for single gases at atmospheric pressure is close to unity at $0^\circ C$, but can rise to around 1.3 at 700 K. The magnitude of

α (the reciprocal of a Lewis number) used in Eqs. (16) and (18) turns out to be 2.6 at 700 K, but this is due to the unexpectedly large value of c_o .

4. We are now in a position to calculate the burning constant, k_b . Eq. (16) is expected to yield the most precise value of it, and Eq. (17) the crudest. Eq. (18) is relatively simple and unlike Eq. (17), does not take the Lewis number to be unity. The resulting values of k_b are 1.7×10^{-7} , 1.2×10^{-7} and 1.8×10^{-7} m²/s, as calculated from Eqs. (16)-(18), respectively. The second term in Eq. (16) was ignored in this calculation, which assumed $\rho_{liq} = 9.6$ kmol/m³. The experimental value [3, 4, 5] of k_b is around 1.8×10^{-7} m²/s, which suggests that Eqs. (16) and (18) both provide satisfactory estimates. However, it will be noted that in each case the calculated k_b is proportional to the ratio k_f/c_f , which for pure toluene increases by a factor of 3.1 from its boiling point ($110.6^\circ C$) to $1000^\circ C$. Hence, by a *judicious* choice of mean temperature for estimating k_f/c_f , a match between theory and experiment can always be obtained. Long [4] used 1300 K (*i.e.*, greater than T_f as calculated here for toluene), whereas 700 K was arbitrarily used above. Clearly, for any greater precision, the above theory has to be re-worked to cope with k_f and c_f varying with temperature and also composition, because traces of H_2 from pyrolysis of the fuel will have a significant effect on k_f . Otherwise, it is worth noting that Eq. (18) is a useful and more precise simplification of Eq. (16) than Eq. (17).

5. It was assumed above that T_o , the droplet's temperature, was in effect the normal boiling point of the liquid concerned. This assumption can be checked by first considering mass transfer of fuel from the droplet (at $r = a$) to the flame front at $r = r_f$. Here the total outward flow of fuel vapour is M mol/s and Eq. (3) becomes

$$\frac{M}{4\pi r^2} = \frac{M}{4\pi r^2} y_f - \frac{D_f P}{RT} \cdot \frac{dy_f}{dr}$$

where y_f and D_f are, respectively, the mole fraction and diffusivity of the fuel. Hence

$$\frac{M}{4\pi} \int_a^{r_f} \frac{dr}{r^2} = - \frac{D_f P}{RT} \int_{y_{fo}}^0 \frac{dy_f}{(1 - y_f)}$$

where $y_f = y_{fo}$ at the droplet's surface ($r = a$). The left hand side of this equation is given by Eq. (6), so that after integration, assuming D_f/T to be constant

$$\frac{k_f}{c_f} \ln \left(1 + \frac{c_f(T_f - T_o)}{\lambda} \right) = \frac{D_f P}{RT} \ln \left(\frac{1}{1 - y_{fo}} \right)$$

As a good approximation the Lewis number for the fuel ($k_f RT / PD_f c_f$) can be taken to be unity, leading to

$$y_{f_0} = \frac{c_f (T_f - T_0)}{\lambda + c_f (T_f - T_0)} \quad (20)$$

Also the Clausius-Clapeyron equation gives the variation of y_{f_0} with T_0 as

$$\ln y_{f_0} = - \frac{\lambda}{R} \left(\frac{1}{T_0} - \frac{1}{T_{bp}} \right) \quad (21)$$

where T_{bp} is the normal boiling point of the liquid fuel. Eqs. (20) and (21) are two simultaneous equations in T_0 and y_{f_0} . Using the above data for a toluene droplet burning in atmospheric pressure air, the solution is that $y_{f_0} = 0.898$ and $T_0 = 380$ K for $T_{bp} = 384$ K. This confirms the previous assumption that $T_0 = T_{bp}$.

6. Finally, as noted by Spalding [2] and Long [4], the above treatment can be used to calculate the diffusion-controlled burning rate and burn-out time for an involatile solid, such as carbon. In this case O_2 diffuses right up to the surface of the solid, and Eq. (5) has to be modified to make $a = r_f$, giving

$$\frac{M}{4\pi a} = \frac{D_{O_2} P}{RT(n-s)} \ln \left(1 + \frac{(n-s)y_\infty}{s} \right) \quad (22)$$

which simplifies, for $1 \gg (n-s) y_\infty/s$, to

$$\frac{M}{4\pi a} = \frac{D_{O_2} P y_\infty}{sRT} \quad (23)$$

Eq. (23) is exactly true (see the derivation of Eq. (5) for $n = s$) if the combustion reaction is $C_s + O_2 \rightarrow CO_2$, when in fact, $n = s$. Alternatively, if the surface reaction is $C_s + \frac{1}{2}O_2 \rightarrow CO$, then $(n-s) y_\infty/s = 0.21$, in which case Eq. (23) is true to within 10%. Eq. (23) is the Nusselt relationship [10] for the diffusion-controlled burning of a solid particle, such as coal char.

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NOMENCLATURE

a	radius of burning droplet
c_A, c_B	concentration of gaseous species A and B (mol/m ³)
c	$c_A + c_B$
c_f, c_{O_2}, c_p	molar heat capacity of fuel, oxygen and products
c_o	mean molar heat capacity defined by $(n-s)c_o = (nc_p - sc_{O_2})$
D	binary diffusion coefficient
D_A, D_{O_2}	diffusion coefficient of a species in a multicomponent mixture
$H_f^0, H_{O_2}^0, H_p^0$	standard molar reference enthalpies for fuel, oxygen and combustion products
k_b	burning constant (see Eq. (1))
k_f, k_o	thermal conductivity for fuel-rich ($r < r_f$) and fuel-lean gases ($r > r_f$), respectively
k	thermal conductivity
M	number of moles evaporating from fuel droplet per sec.
N_A, N_B	molar fluxes of species A and B (mol/(m ² s))
N	total of all molar fluxes
n	number of moles of products formed by complete combustion of one mole of fuel
P	total pressure
P_v	saturated vapour pressure of fuel at temperature T_0
Q	enthalpy flux (per unit area)
R	universal gas constant
r	distance from centre of burning oil droplet
r_f	distance of flame front from centre of oil droplet
s	number of moles of O_2 required to burn completely one mole of fuel

T	temperature of gases around droplet at distance r
T_{bp}	normal boiling point of liquid fuel
T_o	temperature of oil droplet's surface
T_∞	temperature of surrounding air well away from droplet
T_f	temperature of gases in flame front
t	time
x	distance in one-dimensional situation
y_A, y_{O_2}	mole fractions of A and O_2
y_∞	mole fraction of O_2 in air = 0.21
α	dimensionless group = $D_{O_2} P(nc_p - sc_{O_2}) / RTk_o(n-s)$
ΔH°	heat of combustion per mole fuel at $0^\circ C$
λ	latent heat of vaporisation per mole fuel
ρ_{gas}	density of gas adjacent to droplet (mol/m^3)
ρ_{liq}	density of liquid fuel (mol/m^3) <input type="checkbox"/>

ChE book reviews

COAL SCIENCE: AN INTRODUCTION TO CHEMISTRY, TECHNOLOGY, AND UTILIZATION

by Rita K. Hessley, John W. Reasoner, and John T. Riley
John Wiley & Sons, New York, 1986. \$35.00

Reviewed by
T. D. Wheelock
Iowa State University

This concise and easily read book provides a useful and basic introduction to the field of coal science and technology. The introductory chapter provides an overview of the coal mining/utilization industry and coal resources of the United States. Subsequent chapters deal with a series of varied and important topics. A description of the complex processes which form peat and convert peat into coal provides a basis for the physical and petrographic characterization of coal. A picture of the organic structure and chemical reactions of coal is built up through a review of coal treatments involving pyrolysis, solvent extraction, hydrogenation, and oxidation, and through a review of coal characterization by instrumental analysis. The book treats the chemistry and technology of a number of methods which have been proposed and sometimes used for converting coal into liquid and gaseous fuels. The final chapter is devoted to a review of standard methods (mainly ASTM) for determining the chemical and physical properties of coal. By seeing how such

properties are measured, the reader is left with a greater appreciation for a number of empirical properties such as the proximate analysis, free-swelling index, and grindability. This appreciation justifies the greater coverage given to methods of analysis than to any other topic.

The book should serve as a useful reference for those seeking a broad rather than a penetrating introduction to coal science and technology. However, it could also serve those with more specialized interests by providing an entry into the technical literature. Frequent references are made to the literature throughout the text, and each chapter is furnished with a lengthy list of references.

The book has been used as a college text for coal chemistry courses taught by the authors. Students and others using this book would benefit from a prior knowledge of general chemistry and organic chemistry.

ChE letters

THE "AYES" OF TEXAS . . .

Editor:

I want to express my appreciation and that of my colleagues for the very generous editorial entitled, "A Department That Serves," that appeared in the Spring 1987 issue of *Chemical Engineering Education*. It is most gratifying to us that you have so eloquently expressed our actual motives for developing the study on "Chemical Engineering for the Future" and disseminating its findings.

Howard F. Rase
The University of Texas, Austin

ChE books received

Adsorption Technology: A Step-By-Step Approach to Process Evaluation and Application, edited by Frank L. Slejko; Marcel Dekker, 270 Madison Ave., New York 10016; 240 pages, \$55 (1985).

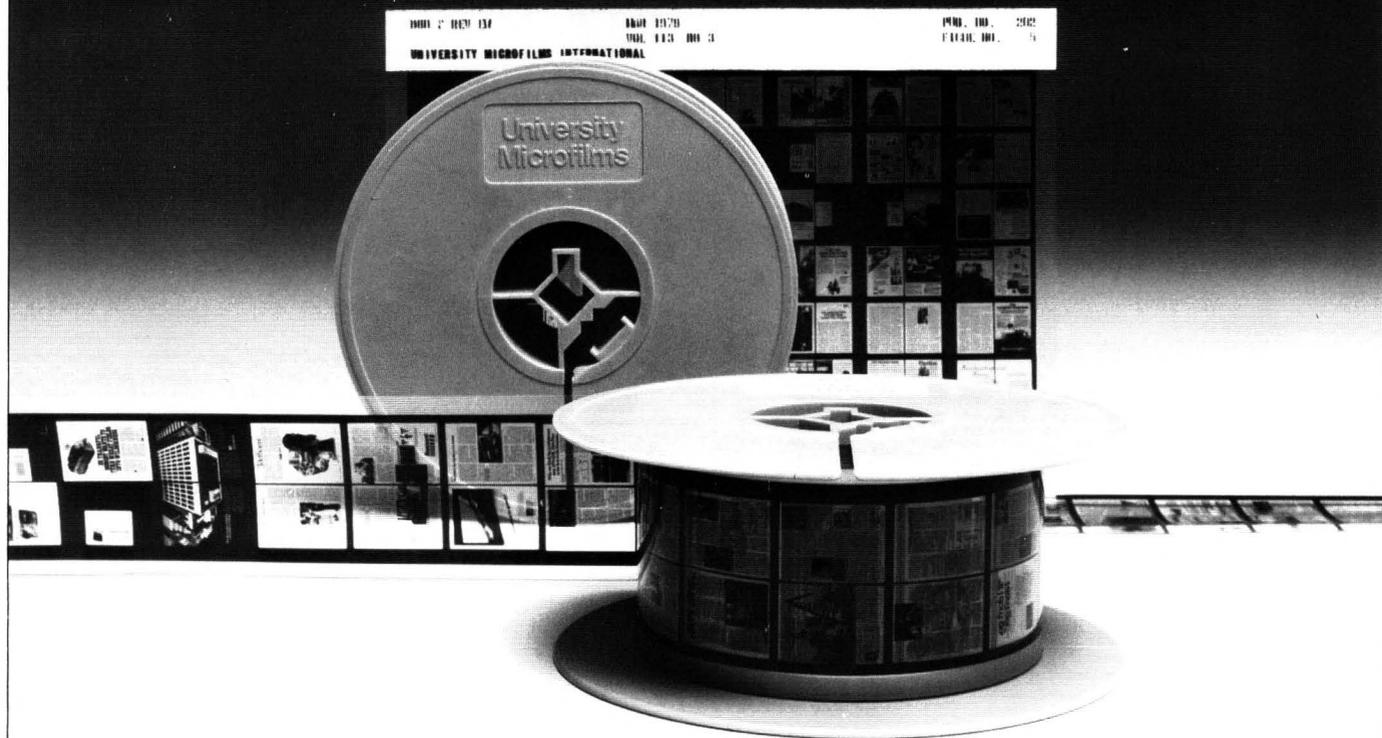
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Continued from page 125.

to investigate control systems for a spectrum of situations.

SOPHISTICATED PID CONTROLLERS

The controllers implemented in ONLINE are sophisticated even though they execute only a PID algorithm. Here are examples of what they can do.

Suppose in the cascade system shown in Figure 7, the operator decides to switch the flow controller to OFF. That action leaves the level controller ineffective because the link between the measured and manipulated variable has been "broken." It is essential that the level controller (and the process operator) be informed of any such break in the loop linkage whatever its genesis and that the level controller properly accommodate to the new situation. In ONLINE, information about the status of controllers and control system variables is communicated through the signal network in the direction opposite to that of the control signal propagation. In this particular circumstance, the receipt of information by the level controller about the OFF status of the flow controller will trigger an automatic switch in the level controller status from ON to CONDITIONAL. In the CONDITIONAL mode the level controller discontinues execution of its algorithm until the flow controller status returns to ON. When the "downstream" link of a master controller is fully reestablished all the way to a valve or other process actuator, the controller status is switched automatically from CONDITIONAL to ON. This process of information transmission and status changes occurs no matter how deep the cascade or how branched the signal network [3]. We view these features as essential and are surprised to find them lacking in some commercially marketed packages.

A closely analogous situation arises when the valve driven by the flow controller is forced full open yet the level in the accumulator is still rising. In the event that integral action is used in the level controller, the integration should be suspended as soon as the valve saturation condition is known. That is accomplished by a digital counterpart of the feedback signal used in electronic controllers to achieve integral action. The controllers in ONLINE are equipped with a "TRACK" input variable (shown in Figure 7), which can be named as any control system variable previously defined. In the cascade system of Figure 7, the track variable is the output signal of the flow controller. As the controller module is processed, the value of the tracked variable is compared with high and low limits (such as the maximum and minimum flow

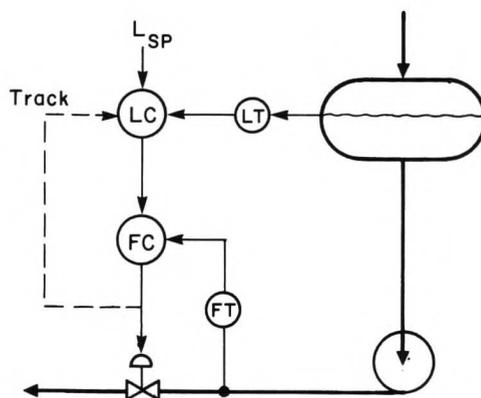


FIGURE 7. Cascade level control system with Track variable communicated to the master controller.

through the valve in this example). If a transgression is detected, the integrating action is suspended as long as the saturated condition exists. Actually, the tracked variable is used to change the gains of all three modes to any values the user desires. Such a feature can also be used to fashion a 3-segment non-linear controller. We use it in this way for gain scheduling in the temperature control of a laboratory heat exchanger over a range of flow rates. It adds a bit of spice to the life of students as they discover the interesting and useful embellishments that can be made to simple loops.

The use of a track variable is essential when high- or low-select operators are placed on the output of PI controllers because the integral calculation must be suspended for that controller that has been excluded from the active control link. Shinskey [6] gives several examples of this type. The track variable proves to be an extremely useful auxiliary input.

The user also has a choice of three different PID-controller configurations. The "classical" configuration employs the error between setpoint and measured signal in all three modes. Another uses the error in the integral mode only; the measured signal is used directly in the P and D modes. Such a configuration avoids "setpoint kick." A third uses error on P and I and measurement on D. All versions are implemented by the incremental algorithm and all employ a first-order filter on the derivative mode. The calculated output is checked against the maximum and minimum declared by the user and is not allowed to exceed those limits.

Other "signal transformations" available in ONLINE are: a lead-lag, addition, multiplication, and division of two signals, high and low selection of two signals, and square root evaluation. These operations permit the implementation of just about any multiloop

The availability of ONLINE has "shaken the earth" out here in Berkeley. Systems with similar capability are also causing a stir elsewhere. The possibilities for the treatment of process control problems beyond a stirred tank or a dead time are now without bound.

control system imaginable. Indeed, the limiting link in the control system configuration process seems to be one's imagination.

The number of controllers placed by designers on even simple and modest-sized processes can escalate to the point where tuning becomes a noisome chore, particularly when loops interact strongly. The incorporation of an automatic tuning procedure as one of the controller status states is an obvious way to relieve the user of such a task. We are working on it. The program structure of ONLINE permits the addition of such new features, new control algorithms, and new commands.

It is also obvious that "umbrella" procedures such as process optimization procedures and knowledge-based systems that monitor process operability could be interfaced with ONLINE. Those matters are also of pressing interest to chemical engineers, and our students could benefit from some practice on these topics.

UC ONLINE AT BERKELEY

Why use this "real-time" coupling of control system and process simulation to practice multiloop system operation? Why not instead use the "once-through" type of simulation starting from prescribed initial conditions and disturbances? The principal merit of a "real-time" system such as ONLINE is its interactive capabilities. The immediate observation of the cause-effect relation in complex processes as changes are made is a very effective teacher. Further, the interactive capability gives the student experience in running an operating process, which contrasts with the experience in calculating a "once-through" type of simulation. Making judgements about what should be done to halt a reactor runaway, for example, with information up to the moment, is distinctly different from making those judgements after the complete "once-through" response is available. "Once-through" calculations historically have been the unvaried fare of this subject. We now have a challenging new capability.

Why not use commercially available software packages for the teaching of multiloop control? Several are now available that run on microcomputer systems. Some of these systems, however, require special hardware. And some require "special" money. These commercial programs have been developed to meet

the demands of the industrial workplace and understandably are much more sophisticated and complex than UC ONLINE. Those two attributes can be a liability for a university instructional environment, however, because there is more to master (by both student and instructor) and more time has to be invested in gaining that mastery. User manuals for commercial programs are very thick. That can easily deflect the focus of a course from one of learning principles and their application to one of searching for a route through the labyrinth of multiple screens, data files, and system conventions. UC ONLINE is not without these, but they were built keeping in mind the special needs of the chemical engineering student and the constraints imposed by the university instructional environment. Ten pages of description are all that's needed to inform students about UC ONLINE. They pick it up very fast.

The availability of ONLINE has "shaken the earth" out here in Berkeley. Systems with similar capability are also causing a stir elsewhere [1, 2]. The possibilities for the treatment of process control problems beyond a stirred tank or a dead time are now without bound. One can now ask students to invent those control systems that we have heretofore only talked about, to implement them, and to make them work. Attention can be focused on the synthesis of control systems addressing production rate control, control under constraints, local optimization, and variable structures. Interesting examples of problems in these areas are found in Shinsky's books [4, 5, 6], and UC ONLINE is up to handling all of them. With such capability we can now engage our students in an activity that, in the author's opinion, is the activity in which chemical engineers make their most significant contribution to process control systems: the invention and development of the control system configuration.

ACKNOWLEDGMENT

UC ONLINE was conceived and developed in 1984 by Paul H. Gusciora and Chi-Ho Mak, graduate and undergraduate students respectively. Their implementation was made in Fortran in the multitasking environment of the Data General RDOS and RTOS operating systems. Leonid Poslavsky, an undergraduate student, converted their version to the single-task version also in Fortran, described here; it runs on the IBM PC/XT and AT. The work of these

young men holds my respect and admiration. The distillation simulation used as the example in this paper was developed by Professor Babu Joseph of Washington University while on sabbatical leave at Berkeley. Financial support for a portion of the conversion was provided by the chemical engineering department at Berkeley. The computing equipment used was donated by the IBM Corporation through the UC Berkeley/IBM joint project on distributed academic computing.

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MICROCOMPUTER GRAPHICS

Continued from page 121.

Subcooling and overheating of streams is allowed, but the user has the responsibility of ensuring the correct overall heat load.

A Help menu is brought up by special key F1, and gives information on the design menu options. It operates similarly to the data entry Help screens.

A minimum utility network for the four-stream problem of Figure 1b is shown in Figure 3. Seven units are used, which is two more than the absolute minimum. In Figure 4 the network has been evolved into a six-unit design with slightly increased utilities. The pinch lines have been removed, as the design violates the pinch decomposition.

In a design with more process streams and hence more units, the screen can become very busy. It may be necessary to do only part of the design at a time, as shown in Figure 5. For this nine-stream problem [14] only the hot end is shown, and the pinch lines moved far to the right.

A print-out of the network can be obtained at any time by pressing the <PrtSc> key.

SUMMARY

The HENS program relieves the student of a tedious target-setting hand calculation and allows rapid

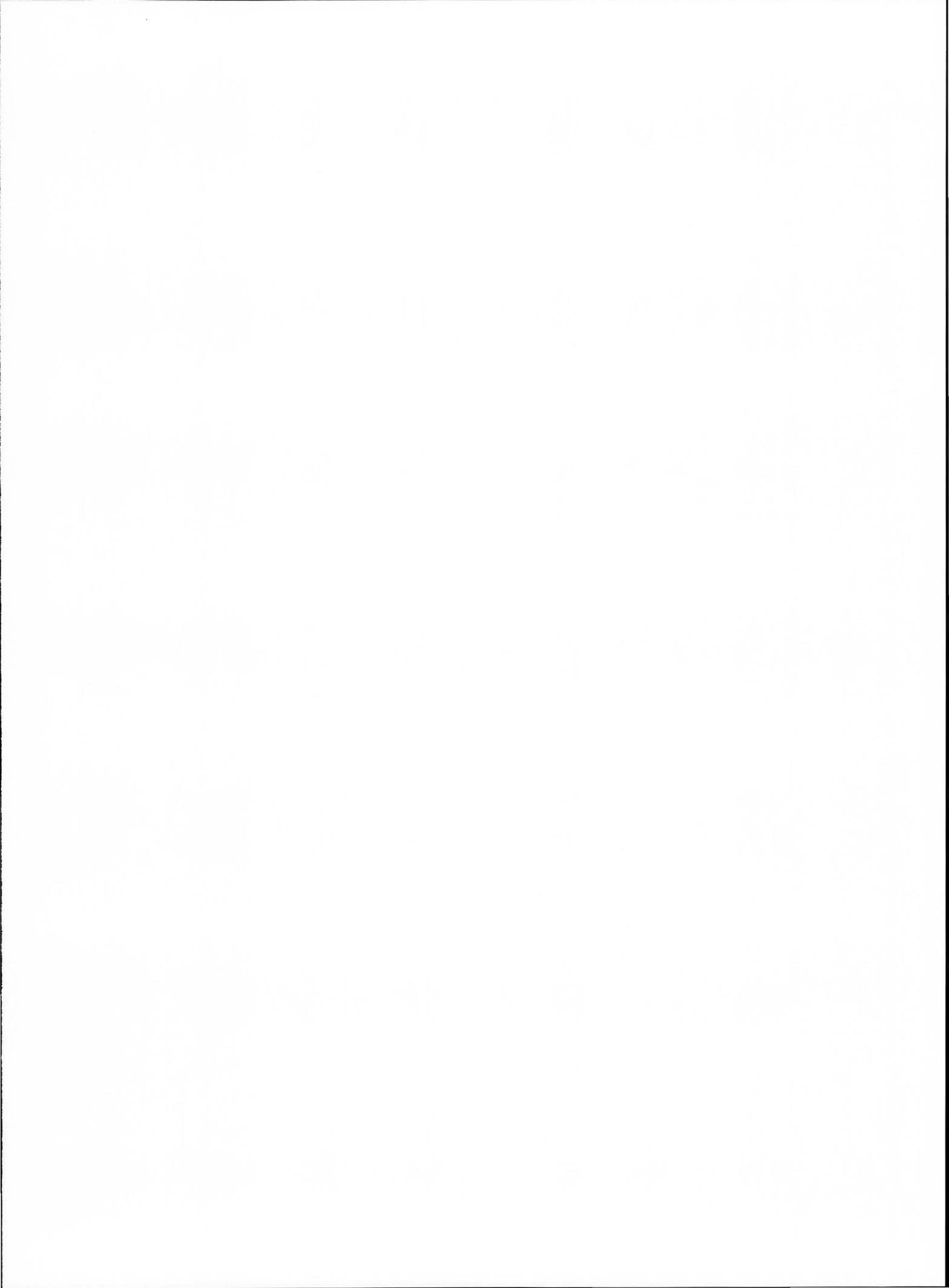
generation and change of networks in the graphical design stage. A major guideline during program development was that the program should allow the students to make the same mistakes as they could with pencil and paper. The objective of the program is to help students think about heat exchanger networks, not to think for them.

Student reception of the program has been good on limited exposure to fairly simple designs. Despite the on-line help material, several students had difficulty using the program efficiently. An in-class demonstration is planned for future classes that should alleviate this problem. Some improvements for the future might include allowing a split stream to be erased and allowing a design to be saved to disk, along with the problem data.

The program is available on disk at nominal cost from the author. Please indicate whether the AT&T version (640x400 screen) or the IBM version (640x200 screen) is wanted.

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