

SPECIAL LABORATORY ISSUE

Diffusion and Surface Reaction - BAIKER, RICHARZ

Traveling Circus - WOODS, DUNN, NEWTON, WEBSTER

Thermo Lab with Lecture - McNEIL

Gas Chromatography - GILOT, GUIRAUD

Heat Transfer - ECONOMIDES, MALONEY

ALSO

Modular Instruction - COHEN, ALONSO, HENLEY

Engineering in Algeria - SHAHEEN, KNEIBES

Superheated Liquids: Part II - R. C. REID

***CHE AT
CARNEGIE-
MELLON***

***MCMASTER'S
DON WOODS***



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SUMMER 1978

Chemical Engineering Education

VOLUME XII

NUMBER 3

SUMMER 1978

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CHEMICAL ENGINEERING EDUCATION is published quarterly by the 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. Plates and 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 \$10 per year, \$7 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 © 1978 Chemical Engineering Division of American Society for Engineering Education, Ray Fahien, Editor. 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.

Don Woods

of McMaster

PREPARED BY

C. M. CROWE

McMaster University

Hamilton, Ontario, Canada L8S 4L7

DON WOODS HAS RECENTLY graduated in chemical engineering—for the second time! Explaining why Don, a Professor of Chemical Engineering, attended undergraduate courses in chemical engineering for four years will highlight what makes Don such an unusual and stimulating teacher and colleague.

This all began in 1974 when several of us expressed concern about whether we were really doing a good enough job of teaching our students how to solve problems. Stimulated by this challenge, and aided by a grant for teaching relief, Don initiated a program to find out how our students now solve problems, what skills they are taught and ultimately how to help them develop their skills.

He led a group of volunteer ChE students through four years of weekly workshops and discussions—attending their classes, exploring many different approaches and stimulating the students to select and develop their own preferred techniques. The students who undertook this program have clearly become very adept at solving engineering problems and at analysing their own

Don organizes what he calls a "traveling circus" of chemical process hardware. This consists of a collection of pieces of equipment associated with a particular unit operation. The students have two weeks to find out what each piece is called, what it is used for and how it works.



The Woods family relaxing at home with Cynthia, recorder; Russell, organ; Suzi, melodica; Don, banjo-uke and wife Diane, guitar.

methods of attack. They were very impressive in running a workshop on problem solving for second year physics students. We have also seen the effectiveness of this program in comparing students who worked with Don to those who did not.

In addition to trying to break down the process of solving a problem into steps (Define, Think About It, Plan, Do It, and Look Back) Don has tried to encourage creative thinking. An example which the current graduating students recount with relish was a brainstorming session on how to crack seeds.

Words and phrases, outlandish or not, were recorded and the craziest was used to generate ideas for the process. The word "No", which arose in response to Don's invitation to share a student's private joke, was chosen. This led one student to "Yes-No" which suggested a reciprocating mechanical device. Another student thought of "Nein" which suggested numbers and a sequential staged operation. A third student took "NON" and was led to a rotary drum (the "O" with blades) fed by a belt (the right "N") and crushed and collected in a hopper (the left "N").

The objective of such sessions is not to achieve detailed or even feasible processes but to liberate thinking from conventional patterns so that unusual proposals may arise.

The result of Don's problem solving program will result, we hope, in a manual which we can all use in our own courses. An added benefit is that we have, through Don, a unique view of our entire undergraduate program, from the receiving end

but with the eye of experience. This should be most valuable in future curriculum revisions.

BACKGROUND

DON IS A PRODUCT of a small town in eastern Ontario, where his father's hardware store stimulated his interest in working with his hands. His house in Waterdown, a nearby town, has been largely remodeled by Don and his wife Diane, and decorated with his paintings and her weaving.

Don graduated from Queen's University, Kingston in 1957 and then went to Wisconsin to study with Warren Stewart. After his Ph.D. in 1961, he went to Britain on a two-year Athlone Fellowship to study and work with three different chemical process industries. These two years involved several case studies which Don has since used in his teaching. In 1964, we were very fortunate to attract Don to join our department and the wisdom of our choice has since been continually reconfirmed.

While Don has taught several different courses over the years, there are two which he pioneered and which demonstrate his concern that students learn not only the conventional ChE science but also skills which are essential to a practising engineer, although peripheral to the classical academic core.

The first is a second year course on Information Management, an important subject but one which is not everyone's first choice to teach. While



Senior undergraduate students, Suzanne Norman and Sue Tyne discuss how to solve a problem with Don Woods.

all of us worry about our students' ability to communicate, Don saw the problem in the wider context of handling, storing and transmitting information. The students learn how to search for information in the library including a few obscure sources that were even unfamiliar to some of the librarians.

Technical report writing, important and much criticized as it is, is also a major component of this

In his fourth-year course on Process Design and Cost Estimation, he initiated the trouble-shooting problems. These are drawn from his and others practical experience and each student is required to diagnose a problem by asking questions. The penalty for each question depends on the estimated cost of obtaining the answer. This has been so exciting for the students that our graduates frequently send in new examples from their industrial experience.

course. According to Don's plan, topics are offered to students which both interest the faculty member and should stimulate the student's excitement about ChE. Much effort is devoted to advising a student during the writing and to constructively criticizing the finished report. We all share Don's enthusiasm that the effort is worthwhile.

He originated the television taping of two student speeches and the private playback with each student alone with the instructor. This used to be done on a 20-ft screen, which exaggerated each student's shortcomings so much that we now use normal-sized monitors. The assurance which this develops in our students is evident in their oral presentations of design projects in following years and in their critical comments about some speakers at ChE conferences. It is a tribute to Don's original concept that this course is run on the same model even when Don is not involved.

In his fourth-year course on Process Design and Cost Estimation, he initiated the trouble-shooting problems. These are drawn from his and others' practical experience and each student is required to diagnose a problem by asking questions. The penalty for each question depends on the estimated cost of obtaining the answer. This has been so exciting for students that our graduates frequently send in new examples from their industrial experience.

As a preparation for the job market, the students in that class had to apply for a job with one

of several fictional companies in different fields of chemical operations. Don designed letterheads for each company and treated each application as a real employer would. Subsequently the problem assignments given to the students were related to the company they had joined. In fact, one problem was a real question about tar distillation drawn from a local firm.

Don also gave every student experience in the stock market by giving each one an (imaginary) credit of \$20,000 at the beginning of the year and allowing them to buy and sell stocks through orders placed in his mailbox. The market report was eagerly sought every morning and at the end of the course, the students' remaining assets varied from \$18,000 to \$22,000.

METHOD OF TEACHING

DON ORGANIZES WHAT HE calls a "traveling circus" of chemical process hardware. This consists of a collection of pieces of equipment associated with a particular unit operation. The students have two weeks to find out what each piece is called, what it is used for and how it works.

In order to teach senior students about plant layout, Don has used a piping layout model as a laboratory project. The students are required to locate the piping, valves and pumps so as to conform to practical requirements.

In his approach to teaching, Don has explored, more than most of us, the voluminous literature on the psychology of learning, and on teaching methodology. He is open to any new and different ideas and is eager to try them out with his students.

He is also a showman, especially with overhead transparencies. He always uses two projectors, so that the previous slide is still visible while he discusses the current one. He makes liberal use of overlays to allow the story to unfold gradually. His experience in painting contributes to his use of colors for highlights and to his amusing drawings.

He originated the television taping of two student speeches and the private playback with each student alone with the instructor. . . . It is a tribute to Don's original concept that this course is run on the same model even when Don is not involved.

His showmanship also comes to the fore at the annual welcoming party for new graduate students. He always leads the singing while playing his banjo-ukulele and students newly arrived from abroad are persuaded to join in "She'll be comin' "

Don initiated a program to find out how our students now solve problems, what skills they are taught and ultimately how to help them develop their skills. . . . He led a group of volunteer ChE students through four years of weekly workshops and discussions—attending their classes, exploring many different approaches and stimulating the students to select and develop their own preferred techniques.

Round the Mountain When She Comes' " with all the appropriate noises and gestures.

Another quality which distinguishes Don from many of the rest of us is his extraordinary ability to organize masses of detail. This is seen in his massive collection of cost data for various types of process equipment, which he has been publishing as a series in the *Can. J. Chem. Eng.* He has also compiled an excellent set of course notes on surface chemistry in an attempt to bridge the gap between the different approaches of chemists and engineers. This activity has been noted widely, as shown by an invitation to present a course on surface chemistry with John Berg of the University of Washington at the ASEE Summer School in Snowmass, Colorado in 1977. Don also was invited to contribute to a course on cost estimation to the AIChE local section in Odessa, Texas. He is much in demand for courses and seminars in these and his other areas of interest and experience.

In his research, Don selected the field of two-phase liquid phenomena including mechanical separation and coalescence, as his main interest. He and his students have done some fascinating work, particularly in techniques for producing clean interfaces between two liquids and in filming the Newton's rings during the coalescence of a rising droplet with a liquid layer of the same substance.

DIVERSITY OF INTERESTS

THE DIVERSITY OF DON'S interests and of his publications is impressive, even overwhelming. He has produced books on Communication, Putting Chemistry to Work, Problem Solving, Surface Chemistry, and the Use of the Library through McMaster's Printing Dept. He was one of

six co-authors of "Chemical Plant Simulation" and wrote "Financial Decision Making in the Process Industry", which has been well received. When he and his family went to the Netherlands on sabbatical leave a few years ago, he and his wife were concerned at the quality of first readers available in English. They produced a charming book, "L is for Lucky", with their own illustrations, which was a hit with their children.

For the Canadian centennial year of 1967, Don grew a beard (which was not then a common occurrence) and edited, with his wife and four others, a history of Waterdown and East Flamborough—his home township. He is and has been active in numerous community activities as a leader in Cub Scouts, as a founder and director of the Waterdown and East Flamborough Heritage Society, as a Sunday school teacher and in various other church activities and as member and chairman of the Flamborough Committee of Adjustment (to decide on permits for building and alterations).

We asked the 1978 graduating students for

their evaluation of Don, since many of them had worked and studied with him for four years on the problem-solving project. Their response, put together by Stevan Cosic from talk during a camping weekend, emphasized Don's enthusiasm for sharing his past industrial and educational experiences—both good and bad. They cited his continual efforts to achieve maximum participation of the class such as when he puts a problem on the screen, then goes to the rear of the room and sits down. According to the students, Don makes learning fun and he manages to make the students confident that they can solve their problems on their own.

It is difficult to describe in words what Don Woods is and how he teaches. Those who have not been fortunate enough to see him in action will, we hope, have found here some idea of his many qualities. Those who have met him may have found here some new facets of his character. At McMaster University, we count ourselves very fortunate indeed to have Don Woods as a ChE colleague. □

ChE book reviews

SMOKE, DUST AND HAZE: FUNDAMENTALS OF AEROSOL BEHAVIOR

By S. K. Friedlander, Wiley Interscience, 1977. 317 pp. \$16.95.

Reviewed by Benjamin Y. H. Liu,
University of Minnesota.

This book, by a well-known author in the field of aerosol science, provides a much-needed text on the subject of aerosol behavior. The word "aerosol," according to contemporary scientific usage, refers to a system of particles, either solid or liquid, suspended in a gas. "Smoke, dust and haze," consequently, are all specific examples of aerosols.

The book is divided into eleven chapters, with Chapters 1 through 5 covering the fundamental aerosol properties, including the basic transport and light scattering properties, size distribution functions and particle deposition by convective diffusion and inertial impaction. Chapter 6, on experimental methods, provides a concise but adequate description of the modern aerosol generation, measuring, sampling, and analysis techniques. Chapters 7 through 11 deal with the

general dynamic processes of coagulation, nucleation, gas-to-particle conversion, and source-ambient relationships for particulate air pollutants. Problems at the end of each chapter provide the needed exercise for students. The references given, though not extensive, are well-chosen. They provide a convenient source for further literature studies on the respective topics.

One of the outstanding features of the book is its clarity of presentation. The topics are developed clearly and rigorously from an elementary to an advanced level. Mathematical methods are used to make the theoretical development rigorous, but reference to the actual physical process taking place makes the meaning of the mathematical development clear. The chapter on Collision and Coagulation is particularly well-done, reflecting the author's own original contribution to the field.

Interest in aerosols has mushroomed in the last few years. Many specialized treatises and books have appeared, but none has dealt with the subject in a sufficiently comprehensive manner to be used as an introductory text. *Smoke, Dust and Haze* will provide such an introductory text. It is suitable for the engineering curriculum at the advanced undergraduate or beginning graduate level. It should also serve as a valuable reference book for those working in the field. □



An aerial photo showing Carnegie-Mellon University and Schenley Park.

ChE department

CARNEGIE - MELLON

DENNIS C. PRIEVE

*Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213*

IN JUNE OF 1974, I was headed for Pittsburgh to attend a national AIChE meeting. On my only previous trip, I flew to Pittsburgh at night to interview for a position as Assistant Professor with the Department of Chemical Engineering at Carnegie-Mellon University (CMU). But this was my first trip by car and I did some exploring. I found that the absence of any regular pattern of streets and the scarcity of signs made driving in Pittsburgh an adventure. The hills of the city create such a turmoil in the network of roads that Fifth Avenue intersects Sixth Avenue.

Once I found it, Carnegie-Mellon's 100-acre campus turned out to be remarkably spacious for an urban university with only 4500 students and 450 faculty. That commodious feeling is enhanced by neighboring Schenley Park whose 500 acres in-

clude hiking trails, a golf course, tennis courts and a skating rink. On the academic side, I was pleasantly surprised to discover an outstanding College of Fine Arts here. Drama has been quite successful, with two student productions—"Godspell" and "Pippin"—becoming well known on Broadway. Other major strengths of Carnegie-Mellon University are the Graduate School of Industrial Administration (GSIA), the Computer Science Program, and the Engineering College. All are nationally recognized. Herb Toor, a former Head of Chemical Engineering, ably leads the Engineering College as its current Dean.

GSIA gained its reputation by emphasizing the use of modern mathematics, behavior sciences, and orderly analytical problem-solving in managerial decision-making. President Richard M. Cyert, a former dean of GSIA, has successfully applied these concepts to transform the University's financial state into one of fiscal health: the University is run without deficits. In this era of a nation-

wide decline in college enrollments, it is important for a university to have good fiscal management.

GENERAL ATMOSPHERE

BUT I BECAME MOST enthusiastic about that segment of the university with which I am most familiar: the Department of Chemical Engineering. It is a dynamic place, with continuous and productive activity. Such activity is possible both because of superior people, and because of good relations among the faculty and between faculty and students.

Tom Fort, as Head of the Department, deserves much of the credit for generating and maintaining that atmosphere. In spite of many time-consuming administrative chores, he maintains an open-door policy in his relations with both faculty and students: he will listen to any and all problems. Knowing the talents of each of the faculty, Tom applies his administrative influence to help each of us to make the most of our talent. Finally, the Department is run in a democratic manner: each of the faculty is polled before a decision is made on a matter of substance. Such policies permit good relations among faculty and promote productivity.

Good relations are also enhanced by the Friday happy-hours organized by the graduate students. The proceeds from a soft-drink machine operated by the students are used to buy beer which is then made available, free, to all. These well-attended weekly events are held in the department's graduate student lounge (ignored by the University) which contains a pool table, a foosball table, a TV-Pong game, and the daily *New York Times*, all obtained from vending machine proceeds.

Prof. Cussler answered a knock at the door of his office only to be greeted by a shaving cream pie in the face, which was prepared by a group of students to celebrate his birthday.

Besides the formal weekly departmental seminars at which researchers from outside the University are invited to speak, several internal seminar programs have been organized. One of these is the biweekly "zoo meeting," in which graduate students and postdoctoral researchers in the programs directed by Ed Cussler or Fennell Evans get together to discuss recent findings. On alternate weeks, another informal seminar meets. The

latter program, organized by John Anderson, involves more than half the faculty in the Department and their graduate students as well as a few from other departments. Topics generally pertain to interfacial phenomena or preparation and be-



Simultaneous collisions in many-body systems are possible. This photo records one such event in which all the faculty of the ChE Department were recently found in the same place at the same time. Seated (left to right): Kun Li, Bob Rothfus, Tom Fort, Steve Rosen, and Ed Cussler. Standing are Gary Powers, Rosemary Frollini, Clarence Miller, Ethel Casassa, John Zondlo, Dennis Prieve, Fennell Evans, Eric Suuberg, Tony Dent, Mike Massey, John Anderson, Howard Gerhart, and Art Westerberg.

havior of hydrosols. Some of the talks are reviews or tutorials, but the main purpose of these seminars is to convey freshly obtained information and to gather criticism regarding the proposed interpretation. A third group, organized by Art Westerberg and Gary Powers, meets regularly to discuss problems related to computer-aided design. These informal seminars provide a means for broadening perspectives on problems which are incompletely solved. The resulting interplay of ideas has a synergistic effect, causing the total research output of the Department to be greater than the sum of contributions possible from isolated individuals.

It is, sir, as I have said,

a small college, and yet
there are those who love it.

—Daniel Webster
(1818)

All Souls College, Oxford, planned
better than it knew when it limited
the number of its undergraduates to
four; four is exactly the right
number for any college which is
really intent on getting results.

—Albert Jay Nock
(1943)

While these words were written about other schools, they echo a sentiment which has always been held at Carnegie-Mellon University. Although a university must be large enough to accommodate the diversity of its students' interests, it should remain small enough to be personal. Close personal relations between faculty and students have existed since the beginning, as illustrated in the following recollections by Mr. Frederick L. Koethen, who enrolled in the first class at (then) Carnegie Tech in 1905:

After things at Tech had become organized, Director and Mrs. Hamerschlag took a trip to Europe. We knew about this trip and, when we learned they were due back in Pittsburgh, some of the boys went to the station, removed the two horses from an open passenger rig, and attached two ropes to the vehicle. A crowd of students provided ample motor power for a triumphal tour of Oakland. It was a sincere expression of the respect and admiration they had for their leader. They did not have a mass meeting to build up enthusiasm for the stunt. It was not necessary.

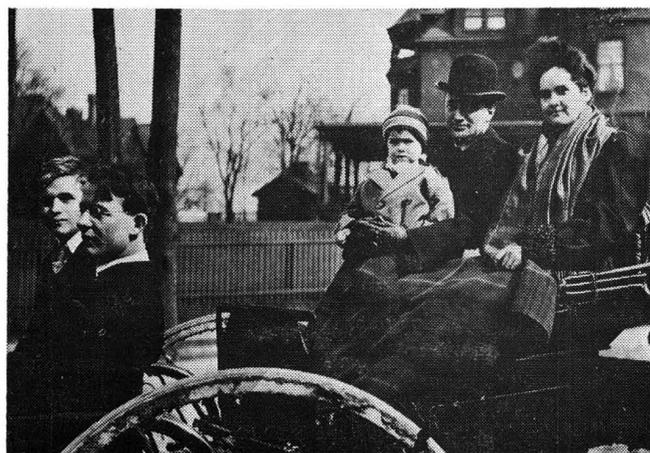
Dr. Herbert F. Sills was frequently late to give his chemistry lectures at one o'clock. We finally told him that the next time he was late, we were going to the baseball game. It was a temptation to us because Forbes Field was very close. It was new and the Pirates in the National League were playing championship ball. The next time he was late came very soon. We were walking over the Panther Hollow bridge toward Forbes Field when we met Dr. Sills. We told him to turn around, which he did, then bought his own ticket and enjoyed the game with us. That was not the approved way to "run a railroad" or any other organization but the later lectures of Dr. Sills did seem to come across better, being given by a friend.

Since that first class of 200 students in 1905, enrollment at CMU has climbed to the current 4500. Now the Department of Chemical Engineering alone has more undergraduates (a total of about 300) than the entire school had in Mr. Koethen's time. There are also 80 full-time and 45 part-time graduate students, together with seven postdoctoral fellows.

PERSONAL TOUCH CONTINUES

YET THE PERSONAL touch has not been forgotten. Episodes like those quoted above still occur. For example, last year Kun Li and Steve Rosen each taught one section of a course entitled

Another recent educational development in the Department is the New Alternatives Program, which was designed to give master's-level training in ChE to technically oriented students whose bachelor's degree is not in ChE



Director and Mrs. Hamerschlag are welcomed back from an European trip (1905) by students who pulled their carriage on a tour through Oakland as a stunt.

"Analysis, Synthesis, and Evaluation," which is required of all engineering sophomores and emphasizes creative engineering. One part of the course involved a project on how to make use of the rubber in worn-out automobile tires. One morning, near the end of that part of the course, Profs. Li and Rosen each found awards for their efforts outside their office doors. They were halves of a worn-out tire, cut diagonally, each of which bore an inscription. Kun's read

Good year, Dr. Li,
We're tired of your course,
We shed a tear* for the souls next year.

while Steve's said

Don't tread on us, Dr. Rosen,
We never promised you a Rosen garden,
Spare us.

The students had come up with a solution to the problem that had never occurred to their teachers.

On another occasion, Ed Cussler returned to his office to find a large part of it occupied by a fully inflated weather balloon. Then there was the time when Prof. Cussler answered a knock at the door of his office only to be greeted by a shaving-cream pie in the face, which was prepared by a group of graduate students to celebrate his birthday. Considerable speculation followed about what would have happened if a visiting professor, who was in the office at the time, had answered the door instead.

To cope with the increasing numbers of stu-

*An allusion to University Professor Dick Teare, who also taught part of the course.

dents, we have increased the number of faculty members by three since I arrived, and have broken core courses into multiple sections. However, none of the lecture or recitation sections is taught by a graduate student. One of the new faculty members is John Zondlo, who is a full-time instructor in charge of the three undergraduate lab courses. Prof. Zondlo takes care of the daily operation of the lab, including a total refurbishment of the facilities during last summer, daily maintenance of the equipment, and setting up the schedule of experiments. The rest of the faculty equally share the responsibility of explaining experiments to students, deciding on any modifications to existing apparatus, and grading the lab reports, with about two or three experiments assigned to each faculty member.

An educational development, which occurred here several years ago, was the organization of the Colloids, Polymers, and Surfaces Program (CPS). It grew out of an expression of need by local industries for graduate-level training of some of

An educational development, which occurred here several years ago, was the organization of the Colloids, Polymers, and Surfaces Program (CPS).

their employees in these specialized areas. Since there were several faculty members here who had research interests in these subjects, Fennell Evans took on the task of organizing a joint program with the Chemistry Department which leads to a nonthesis Master's degree in CPS. Besides a core of lecture courses, students are required to complete eight credits of a special laboratory course taught by Ethel Casassa. Students get individual instruction on a variety of research-oriented instruments. All these instruments are also available to other students in chemistry or chemical engineering who may need them for their thesis research. While the CPS program was designed for students who hold full-time jobs in local industry, a number of regular graduate students have elected either some of the lecture courses or a joint ChE-CPS Master's degree, which requires a thesis

Because of the interest and favorable reaction from industry, plans are underway to teach some of the material in the CPS program to undergraduates in ChE. Fundamentals of colloids, polymers and surfaces will be taught in new lecture courses with applications to conventional unit op-

erations such as polymer processing and solid/liquid separations. Again, a laboratory course will be included in the curriculum to illustrate the principles.

Another recent educational development in the Department is the New Alternatives Program, which was designed to give master's-level training in ChE to technically oriented students whose bachelor's degree is not in ChE. Students in the program are given an intensive course during the summer, complete with laboratory experiments, which covers undergraduate ChE principles. Upon successful completion of the summer program, they are admitted to the regular master's degree program, where they compete with other ChE students in both courses and the comprehensive written exam given to all graduate students. Details of this program have been previously published (CEE 11, 176 (1977)).

DEPARTMENTAL RESEARCH

ALL FACULTY IN the Department are actively involved in research. Topics are generally related to energy, biochemical engineering, colloids, polymers, surfaces, or computer-aided design. Some of the projects involve the development of large-scale equipment, such as the coal-gasification work by Mike Massey or the development of heat exchangers for the ocean-thermal energy conversion (OTEC) plant by Bob Rothfus. Both of these industrial-scale projects involve a number of



Ethel Casassa, giving instructions to students in the CPS lab on the technique for operating a pressure-filter to remove dust from solutions used in light-scattering experiments.

These informal seminars provide a means for broadening perspectives on problems which are incompletely solved. The resulting interplay of ideas has a synergistic effect, causing the total research output of the department to be greater than the sum of contributions possible from isolated individuals.

faculty from several departments. Eric Suuberg also conducts energy-related research in coal pyrolysis.

Clarence Miller and Tom Fort are currently studying systems where surfactants lower interfacial tensions between oil and water. One major application is in tertiary oil-recovery, where surfactant flooding is used to increase the amount of oil obtained from wells. Prof. Miller is also interested in spreading of liquids on rough surfaces and other interfacial phenomena. Gas adsorption and surface chemistry are also of interest to Prof. Miller and, separately, to Tony Dent, whose research focuses on heterogeneous catalysis. Other studies of kinetics of gas-solid reactions are performed by Kun Li, who worked for a local steel manufacturer before joining CMU. As a result, his particular subject is iron-ore reduction, where he has some fascinating electronmicrographs showing reduced-iron whiskers growing out of the oxide. Why, he asks, does reduction occur in this manner?

Kun Li and Bob Rothfus also have an interest in fine particle technology. Their most recent joint venture was to study the coagulation of iron-oxide particles in water by the addition of alum. Thus, Prof. Li provides a link between the gas/solid interface people and the liquid/solid interface people.

John Anderson's research concerns hindered diffusion of hydrosols and macromolecules in pores, together with electrokinetic effects which result from the charge on all solid/aqueous interfaces. Examples of hydrosols (a phase which is finely dispersed in water) include latex paints, waste-water sludge, milk and most other foodstuffs, as well as blood cells and globular proteins. Prof. Anderson's work overlaps with mine, which is the transport of hydrosols. Because of their finite size and electrostatic charge, colloidal particles behave differently from molecular solutes. I am currently applying my approach to the deposition of latex films on steel surfaces. On the other hand, Prof. Anderson's work is applicable to the transport of large solutes through porous membranes as well as the catalyzed reaction of macromolecules in liquid-filled pores.

Additional studies on transport of molecular or ionic solutes through biological membranes are conducted by Ed Cussler and Fennell Evans. They attempt to explain such anomalous behavior as transport of a solute in the direction of increasing concentration, or transport at a rate which is nonlinearly related to the difference in concentration across the membrane. Prof. Cussler is also concerned with solubilization kinetics and the psychophysics of texture—that is, relating what people perceive as the feel of foods to chemical and physical properties. He likes to introduce the latter subject as the "Funny Feelies" (maybe that's why some people jokingly call him Crazy Ed).

Fennell Evans is also involved with surfactants, with applications to detergency. He recently developed a surfactant-selective electrode for measuring the concentration of free surfactant molecules in the presence of aggregates of surfactant molecules known as micelles. This and other work on the behavior of electrolytes complements much of the research here on aqueous systems.

Both John Anderson and I use latex polymers as sols in our work. The mechanism for synthesizing these sols by emulsion polymerization is one of the topics of Steve Rosen's research. He is also developing an *in situ* polymerization process for stabilizing soil on which emergency shelters could be built and is studying ways to separate polymer mixtures in order to recycle the huge masses of petroleum-based polymers which are discarded as solid municipal wastes. A third project, in cooperation with Tom Fort, focuses on improved interfacial bonding in polymer-based composites.

As a Vice President of PPG Industries, Howard Gerhart was instrumental in the inception of the CPS program. After retiring from PPG in 1974, Dr. Gerhart joined CMU and organized the National Coatings Center (NCC). As a branch of Carnegie-Mellon Institute of Research (CMIR), NCC provides a national focus for both fundamental and applied research related to coatings and corrosion. Besides a full-time staff of postdoctoral researchers, who cooperate with faculty in chemistry and ChE, the NCC has access to the analytical-instrument resources of CMIR, the present counterpart of the pre-merger Mellon Institute. Dr. Gerhart and I have cooperated in several projects, including the electrophoretic and chemiphoretic (electroless) deposition of latex films on metal surfaces, and the sacrificial protection of steel against corrosion. At the NCC, Dr. Gerhart has also succeeded in developing a new polymeric material with a high refractive index for optical use.

Much of the research described above lies on an interface between ChE and some other discipline (often chemistry). However, Gary Powers and Art Westerberg are studying the use of the computer in the very traditional area of chemical process design. They cooperate, through the Design Research Center (DRC), with people in all the other engineering departments on campus, as

Continued on page 135.



CHEMICAL ENGINEERING DIVISION ACTIVITIES

SIXTEENTH ANNUAL LECTURESHIP AWARD TO THEODORE VERMEULEN

The 1978 ASEE Chemical Engineering Division Lecturer was Theodore Vermeulen of the University of California at Berkeley. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this annual lecture award.

Bestowed annually upon a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of \$1,000 and an engraved certificate. These were presented to this year's Lecturer at the Annual Chemical Engineering Division banquet, held at the University of British Columbia on June 20, 1978. Dr. Vermeulen spoke on "Dynamics of Runaway Systems".

RECENT PREVIOUS LECTURES

- 1970 Joe M. Smith, University of California at Davis, "Photochemical Processing-Photo-Decomposition of Pollutants in Water"
- 1971 William R. Schowalter, Princeton University, "The Art and Science of Rheology"
- 1972 Dale F. Rudd, University of Wisconsin, "Synthesis and Analysis in Engineering"
- 1973 Rutherford Aris, University of Minnesota, "Diffusion and Reaction in Porous Catalysts—a Chemical Engineering Symphony"
- 1974 Elmer L. Gaden, Jr., Columbia University, "Biotechnology—an Old Solution to a New Problem."
- 1975 John M. Prausnitz, University of California at Berkeley, "Molecular Thermodynamics for Chemical Process Design"
- 1976 Abraham E. Dukler, University of Houston, "The Role of Waves in Two-Phase Flow: Some New Understandings"
- 1977 Robert C. Reid, Massachusetts Institute of Technology, "Superheated Liquids: A Laboratory Curiosity and An Industrial Curse"

Ted Vermeulen, born in Los Angeles, completed his B.S. and M.S. in chemical engineering at CalTech and later a Ph.D. in physical chemistry at UCLA. He did catalytic process research for Union Oil Company for two years, and later worked six years in process development and research planning for Shell Development Company. He then joined the University of California at Berkeley, serving as founding chairman for chemical engineering from 1947 to 1953. He has been a Fulbright Professor at

Liege and Ghent in Belgium, and at the French Petroleum Institute; a Guggenheim Fellow for research at Cambridge University; and a visiting lecturer at Syracuse and Notre Dame Universities, and the National University of Mexico.

Vermeulen's research has been aimed at strengthening the ties between engineering science and engineering practice, and has centered on the combined action of chemical kinetics and transport effects in multiphase systems. In the kinetics area, he has worked on non-isothermal-reactor calculation methods, multireaction analysis, homogeneous catalysis, polymerization, and combustion. In the separations area, he has contributed to a unified design theory for adsorption and ion exchange, and also to liquid-liquid extraction design based on both axial dispersion and multiphase agitation. Currently he is applying these collective interests to research on the liquefaction and desulfurization of coal.

He serves as co-editor of "Advances in Chemical Engineering." He is a Fellow of AIChE, has chaired the Northern California Section and has been a member of national committees. He received the William H. Walker Award in 1971.

OTHER CHEM.E.'S RECEIVE AWARDS

Several other chemical engineers were recipients of special awards and recognition at the recent ASEE Annual Conference in Vancouver. Those so honored are as follows:

C. JUDSON KING, professor and Chairman of ChE at the University of California, Berkeley, received the 33rd annual George Westinghouse Award. Sponsored by the Westinghouse Education Foundation, the award is designed to encourage young educators who show evidence of excellence and innovation in engineering teaching.

The 22nd Curtis W. McGraw Award for outstanding early achievements by a young engineering college researcher was presented to GERALD L. KULCINSKI, professor of nuclear engineering and associate director of the Wisconsin Fusion Technology Program at the University of Wisconsin, Madison. ASEE's Engineering Research Council, with the McGraw-Hill Book Company, sponsors this award.

ROBERT P. MORGAN will receive the Chester F. Carlson Award for Innovation in Engineering Education. He is a professor and chairman of

Continued on page 121.

SUPERHEATED LIQUIDS A LABORATORY CURIOSITY AND, POSSIBLY, AN INDUSTRIAL CURSE

Part 2: Industrial Vapor Explosions

ROBERT C. REID

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VAPOR EXPLOSIONS—A REVIEW

IN PART 1, WE EMPHASIZED the concept of a superheated liquid and the fact that there is a superheat-limit temperature (SLT). Kinetic theory described, approximately, the rates and probabilities of vapor formation in superheated liquids—while thermodynamics placed an upper value on the SLT. We saw that experimental measurements of the superheat-limit temperature were in good agreement with predictions from kinetic theory and, correctly, less than limiting values estimated from thermodynamics.

Nevertheless, the experiments were carried out under laboratory conditions with great care taken to minimize heterogeneous nucleation. Only a very small fraction of all bubble-column tests are successful wherein a drop is indeed heated to the SLT. Most drops begin to vaporize before this limit is attained.

Can we, therefore, ever expect, in real world operations to superheat a liquid sufficiently high to induce true homogeneous nucleation where there is very rapid (even explosive) formation of vapor? We examine a number of case histories—drawn from research studies or plant accidents. In all instances, two liquids come into contact; one is significantly more volatile and at a lower initial temperature than the other. Modes of contact vary greatly and as will be suggested, the type of contact may be very important in determining the outcome.

MOLTEN TITANIUM-WATER VAPOR EXPLOSIONS

THROUGH THE KINDNESS of Dr. Robert A. Beall I have been allowed access to a number of

unpublished accident reports, several of which have recently been declassified. These deal with water-molten metal explosions in the cold-mold arc-melting and casting process. In this industrial operation, large ingots of titanium, zirconium, tantalum, columbium, molybdenum, tungsten, alloyed steels, etc., are prepared. To minimize contamination, crucibles are constructed of copper and kept cool by an external water jacket. The metal to be cast is prepared as a consumable electrode by compressing and welding "sponge" metal into a vertical cylinder. A high amperage-high voltage arc causes melting. (See Figure 12)

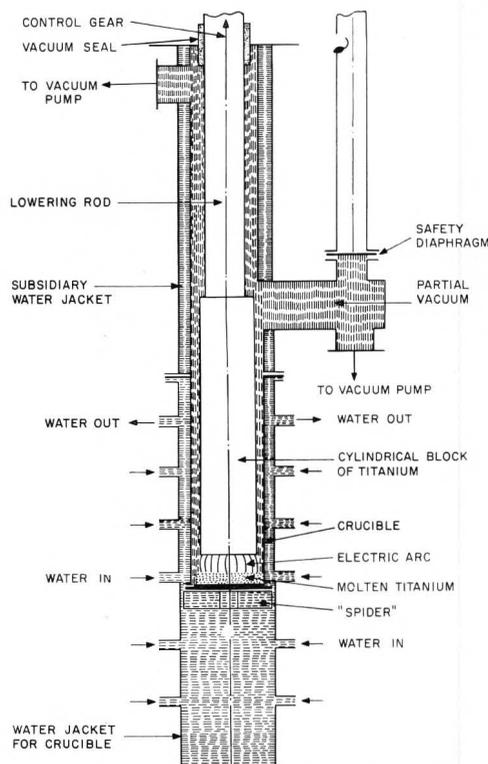


FIGURE 12 DIAGRAM OF TITANIUM MELTING FURNACE

A review of this process is available in a Bureau of Mines report (Beall et al., 1968).

In the past twenty-five years, a number of accidents have been reported. Essentially, all have resulted when, for various reasons, there was a failure of the copper mold with subsequent contact between molten metal and water. Fortunately, most led only to mild steam explosions, but a few were very different. These, in a Spockian sense were "most interesting," but in a humanoid view make for depressing reading.

As an example, quoting from a letter from Dr. Beall, "In one case, a hole was burned in the crucible, water intruded, and the arc was extinguished. Interlocks on this particular furnace called for the electrode to be drawn up (out of the water). However, the limit switches on the withdrawal mechanism

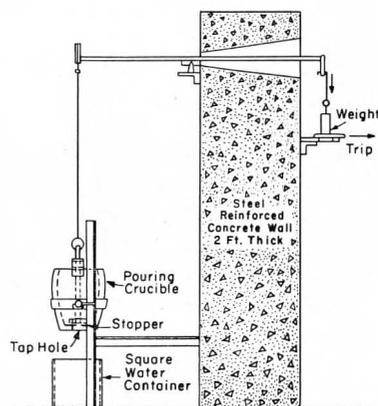


FIGURE 13 SKETCH OF DEVICE FOR INDUCING EXPLOSIONS WHEN DUMPING HOT ALUMINUM INTO WATER. FROM LONG, 1957.

We turn next to accidents which occur all too frequently in paper pulping operations. . . . Severe explosions have occurred in the step where the molten salt (smelt) from the furnace is dissolved in water.

ism failed to function, and when the electrode reached the top of the furnace, the cable broke, and the electrode fell, driving the water standing in the crucible into the molten pool of metal. A very severe explosion resulted, scattering furnace components like shrapnel."

With a good deal of insight, Dr. Beall concludes "Of important consideration is the fact that water leaks in arc furnaces of this type have occurred occasionally in the various melting establishments without any serious explosion resulting therefrom. In a few reported instances, steam buildups have been noted but not of serious consequence. It must be pointed out that the affair here reported required the coincidental occurrence of a water injection, intimate mixing with molten metal, and very possibly, tamping of the mixture by the falling electrode. Such a chain of circumstances can lead to a powerful explosion rather than the customary quiet extinguishing of the arc."

We cannot conclude with any certainty that explosions in cold-mold arc-melting furnaces are due to superheated liquid water. It does appear to us, however, that it is less than coincidental that two elements appear necessary to achieve an explosion: molten metal contacts water, and there is some impact event, i.e., the falling of a heavy electrode into the metal-water, the shock-wave due to

failure of a rupture disc, etc. It is easy to hypothesize—but more difficult to prove—that the impact event forced water and metal into intimate contact for a brief period to develop a highly superheated water layer that nucleated violently and efficiently mixed the metal-water together to enhance rapid steam (or hydrogen) production on a large scale.

MATTE-WATER EXPLOSIONS

A NEW DIMENSION was introduced to me by letter from Roland S. Young of Victoria, B. C. who told of several harrowing experiences when molten matte contacted water. In fact, he indicates that the problem is so serious that before transferring molten matte with cast iron ladles, the ladles must first be dried over an open fire to insure no moisture is present. He writes, "I recall a distressing incident in a large copper-cobalt smelter in Northern Rhodesia. Here too, careful attention was given to the drying of matte ladles, but on this occasion a small leak in the roof must have allowed water from a tropical downpour to fall unobserved into a ladle. The resulting explosion ejected matte 40 feet into the air, killing the craneman in his cab. Can you offer an explanation for the high activity of metallic sulphides, when molten, with water?"

Unfortunately, I have no firm answer for Mr. Young. Molten metallic sulfides appear to be par-

. . . .vapor explosions can also occur when cryogenic liquids contact water. . . . in two instances, vapor explosions resulted when liquified natural gas (LNG) spilled upon a water surface.

ticularly sensitive when contacted with water.

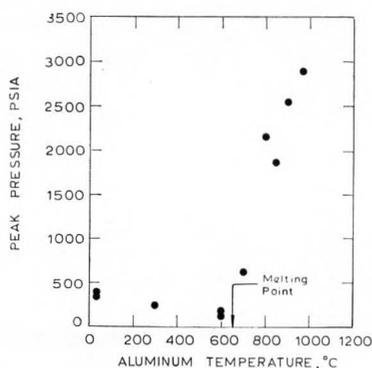
MOLTEN ALUMINUM-WATER EXPLOSIONS

EXPLOSIONS RESULTING from the contact between molten aluminum and water are often most impressive as documented by two research teams at Alcoa Research Laboratories (Long, 1957; Hess and Brondyke, 1969). Most tests consisted of tapping a molten aluminum crucible suspended above a small water tank (see Figure 13). Although the water containers were constructed of 3/16 to 1/4 inch welded steel plate (or were concrete), an explosion was readily detected since, as noted by Long, "all but the mildest . . . broke the steel water containers . . . and frequently hurled pieces several hundred feet."

The salient results show that below some minimum flow rate of metal, no explosions resulted. Also, a long fall through air reduced explosions as did deep water depth. Apparently, some molten metal had to reach the container bottom to obtain an explosion; any modification which fragmented the falling molten aluminum or allowed it to solidify before touching the bottom would reduce or eliminate explosions. Organic coatings or grease on the bottom of the water vessel were effective in eliminating explosions. The severity of the interaction was also reduced by dissolving oils or wetting agents in the water or by increasing the lateral dimensions (for the same quantity of aluminum poured—usually 22.6 kg).

On the other hand, the explosions became more violent if the water contained dissolved salt or if there were lime, rust, or gypsum coatings on the *bottom* (the condition of the sides was of little importance).

The negative effect of the hydrophobic coatings



Temperature Dependence of the Peak Pressure Resulting from Water Impact Upon Aluminum.
From Wright and Humberstone, 1966

FIGURE 14

certainly suggests that the initiating step occurs on the bottom of the water container between (still) molten aluminum and water. Superheating a thin water film could form the initiating steps, but recent experiments by Briggs (Board and Caldarola, 1977) have shown that when molten

We examine a number of case histories—drawn from research studies or plant accidents. In all instances, two liquids come into contact; one is significantly more volatile and at a lower initial temperature than the other.

aluminum is poured into a tank of water, a coarse dispersion (~1 cm scale) is formed in the lower half of the tank. The vapor explosion seems to be initiated at the base of the tank and propagates at a velocity of about 200 m/s. Clearly, additional research is warranted.

As opposed to these studies, simply contacting the surface of a molten aluminum pool with water leads to little but film boiling. However, Wright and Humberstone (1966) impacted water on a 6 mm-deep molten pool of aluminum in a vacuum; the impact pressure was estimated as about 14 bar (200 psi). A violent disruption occurred and the highest observed pressure was about 200 bar (2900 psi). This pressure was achieved in about 40 μ s after contact and decayed in about 3 ms. Figure 14 shows low peak pressures were obtained when the aluminum was below the melting point but they increased with temperatures above 650°C. In another test, the impact of water on molten aluminum saturated the pressure transducer at 5800 psi.

SMELT-WATER EXPLOSIONS

WE TURN NEXT TO accidents which occur all too frequently in paper pulping operations. In the "Kraft" process, wood chips are "digested" with a cooking liquor consisting primarily of sodium sulfide, caustic soda and sodium carbonate. Hydrolysis of the lignins occurs. The spent cooking solution (black liquor) is concentrated in evaporators, salt cake (sodium sulfate) is added and the strong solution fed to a furnace. Organic compounds burn, much of the sodium sulfate is reduced to sodium sulfide and the molten salt residue is discharged and dissolved in water to form "green liquor".

Severe explosions have occurred in the step

where the molten salt (smelt) from the furnace is dissolved in water. At this stage, the principal salts are sodium carbonate and sodium sulfide with lesser amounts of other sodium (and potassium) salts; the furnace discharge temperature varies from about 870-1050°C. Other explosions have resulted when the water-tube wall of the furnace failed and leaks developed.

Studies over the past 10 years have attempted to clarify the mechanism of these smelt-water explosions. Although several theories are now available, there still remain a host of unanswered questions.

Let us review briefly some of the experimental research results which seem most relevant; these have been abstracted primarily from a report by Battelle—Columbus (Krause et al., 1973) and from development studies at Combustion Engineering (Nelson and Kennedy, 1951, 1956). In these studies, small quantities of water (or green liquor) were injected into a pool of smelt held in a cone and heated by an induction furnace.

The smelt composition was found to be critically important in establishing whether an explosion is probable. Pure molten Na_2CO_3 could never be made to explode when contacted with water. Addition of Na_2S (or NaCl , NaOH , etc.) sensitized the smelt and led to a higher likelihood of explosion (Sallack, 1955). Also, use of green liquor (water with dissolved Na_2CO_3 and Na_2S) led to more frequent (and more violent) explosions. Time lags after injection, before an explosion, were in the order of 2 ms. Higher injection velocities also increased the probability of an explosion and extended the temperature range of the smelt over which explosions occurred. This latter fact is quite interesting. For example, with a 70% Na_2CO_3 - 30% Na_2S smelt, the maximum temperature of the smelt leading to an explosion was about 850°C with a water injection pressure of 6.9 bar but increased to 925°C when the injection pressure was raised to 10.3 bar. One must conclude that the mode of contacting is also an important variable in these cases. Finally, very

hot water (>65°C) led to almost no explosions irrespective of smelt composition.

Most studies have discounted any significant effects of chemical reaction in the explosion mechanism. It seems clear that some physical initiating step is required to cause intense fragmentation of the water (and smelt?) to produce very large volumes of steam in a short time scale. Superheating of thin films of water with subsequent homogeneous nucleation has been proposed by Nelson (1972) and not rejected by Krause et al. (1973). In some manner, there is assumed to be local liquid-liquid contact between the smelt and water for a brief period of time. A thin film of water superheats (theoretical limit $\sim 300^\circ\text{C}$)

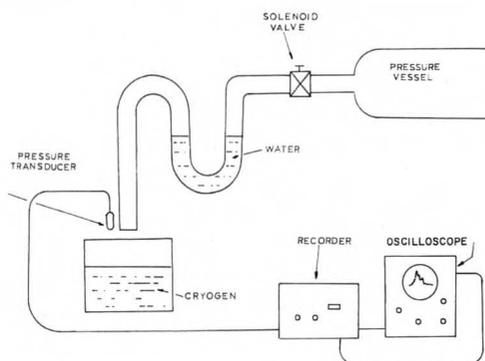


FIGURE 15 IMPACT APPARATUS

and nucleates. This generates local, but very strong, pressure and shock waves. These both fragment the water and smelt in the near vicinity, but may also cause collapse of other vapor films separating water and smelt to produce secondary superheat explosions, and these, in turn, etc.

Does this mechanism agree with the experimental facts? In most instances, yes, but there remain critical experiments to be done.

Molten sodium carbonate will not explode with water; presumably there is CO_2 generated at the boundary and this inhibits liquid-liquid contact. Sodium sulfide sensitizes the smelt. Why should this molten salt enhance liquid-liquid contact? There is a definite time lag, after injection, before

Continued on page 127.

... I have been allowed access to a number of unpublished accident reports. . . . These deal with water-molten metal explosions in the cold-mold arc-melting and casting process. . . . Fortunately, most led only to mild steam explosions, but a few were very different. These, in a Spockian sense were "most interesting", but in a humanoid view make for depressing reading.

DIFFUSION AND SURFACE REACTION IN HETEROGENEOUS CATALYSIS

A. BAIKER and
W. RICHARZ

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THE INTERACTIONS between mass transfer and chemical reaction in heterogeneous catalysis are described in many textbooks on chemical reaction engineering. However, few laboratory experiments are known that permit the student to apply his theoretical knowledge [1]. This is certainly due to the fact that it is difficult to find suitable easy-to-handle heterogeneous reaction systems. Furthermore, a rigorous quantitative determination of the chemical reaction rate on the catalyst surface is not possible in most cases since boundary conditions that permit a solution of the differential equations describing mass transfer are too complicated.

Now, the ethylene hydrogenation on a platinum catalyst, electrolytically applied to a tube wall, proved to be a good system for the study of the interactions between diffusion and surface reaction in heterogeneous catalysis. Boundary conditions are well defined and by varying the temperature from room temperature to 180°C, the transition between surface reaction control and mass transfer control can be well observed. Since the differential mass balance can be integrated numerically for this laminar flow system, an exact value of the surface reaction rate constant may be obtained.

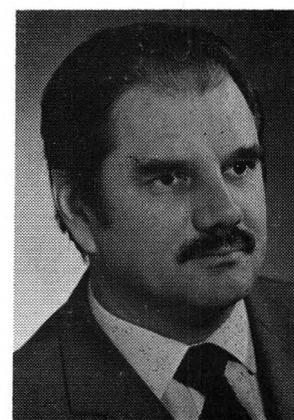
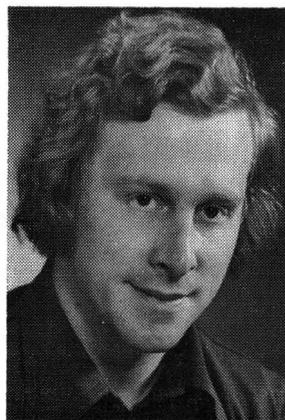
In a previous publication [2], some aspects of the 4th year ChE laboratory program at the Swiss Federal Institute of Technology (ETH) have been described. This experiment is part of that course and has been developed in recent years in order to combine transport phenomena and heterogeneous catalysis and to bring at the same time the FORSIM computer simulation program [3] into

ChE laboratory. Its application permits the student to integrate the differential mass balance and helps to take away some of the magic still associated with partial differential equations.

In fact, the laminar flow system used has a simple geometry (tube) so that the differential mass balance is easily established and boundary conditions can be precisely stated. After transformation of the partial differential equations to dimensionless form as described by Bräuer [4], the numerical integration by the FORSIM program is straightforward and rapid.

Werner Richarz studied chemistry at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland (PhD, 1954) and is Associate Professor for Chemical Engineering at ETH Zurich since 1972. Presently he teaches Chemical Reaction Engineering for Chemical Engineers and Heat and Mass Transfer for chemists. His research interests are in the fundamentals of heterogeneous reactions (catalytic and non-catalytic) at normal and high pressure and in reactor modelling. (R)

Alfons Baiker studied Chemical Engineering at Swiss Federal Institute of Technology (ETH) Zurich, where he received his Ph.D. degree in 1974. His principal research interests are heterogeneous catalysis and surface chemistry. Since 1975 he has been leading a research group at ETH. Current research includes development of catalytic amination processes, behaviour of non-stationary operated catalytic reactors, diffusion in porous solids, catalyst preparation and characterization of catalyst structure. (L)



... for some of their experiments the students have to calculate axial and radial concentration profiles in the reactor.

THEORETICAL BACKGROUND

IT HAS BEEN SHOWN that the ethylene hydrogenation is 1st order with respect to ethylene (gas mixture: 98% H₂, 2% C₂H₄). Thus the global reaction rate can be defined as:

$$r_G = -k_{\text{eff}} \bar{c}(x) \quad (1)$$

The average ethylene concentration at the exit of the reactor is therefore:

$$\bar{c}(L) = c_0 \exp(-k_{\text{eff}} \tau) \quad (2)$$

The surface reaction rate is given by:

$$r_s = -k_s c(R, x) \quad (3)$$

The influence of diffusion can be seen by comparing the global and surface reaction rates. However, for this comparison k_{eff} has to be multiplied by V_R/S . The surface reaction rate is determined by integrating the differential mass balance over the cross section and length of the reactor.

We assume that

- we have a constant volume reaction (in fact, $\epsilon \leq .02$)
- the reaction is conducted isothermally
- the flow is steady-state and the laminar velocity profile is fully developed
- axial diffusion is negligible as compared to the transport by bulk flow.

Therefore we have the following mass balance:

$$D \left[\frac{\partial^2 c}{\partial r^2} + \frac{1}{r} \frac{\partial c}{\partial r} \right] - 2\bar{v}_x \left[1 - \left(\frac{r}{R} \right)^2 \right] \frac{\partial c}{\partial x} = 0 \quad (4)$$

For the system described in Figure 1 the boundary conditions are:

$$c(r, 0) = c_0 \quad (5)$$

$$\frac{\partial c(0, x)}{\partial r} = 0 \quad (6)$$

$$D \frac{\partial c(R, x)}{\partial r} = -k_s c(R, x) \quad (7)$$

Bräuer [4] integrated equation (4) numerically after transformation to dimensionless form by introducing the numbers given in Table 1.

Thus equations (4) to (7) become:

$$\frac{\partial^2 f}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial f}{\partial \rho} - 2[1 - \rho^2] \frac{\partial f}{\partial \theta} = 0 \quad (8)$$

$$f(\rho, 0) = 1 \quad (9)$$

$$\frac{\partial f(0, \theta)}{\partial \rho} = 0 \quad (10)$$

$$\frac{\partial f(1, \theta)}{\partial \rho} = -Da f(1, \theta) \quad (11)$$

The mean concentration $\bar{f}(\theta)$ at the exit of the reactor is calculated by integrating $f(\rho, \theta)$ over the cross section:

$$\bar{f}(\theta) = \frac{\int_0^1 \rho(1 - \rho^2) f(\rho, \theta) d\rho}{\int_0^1 \rho(1 - \rho^2) d\rho} \quad (12)$$

The results of the numerical integration by the FORSIM-program are given in Figure 2. For all important parameters the programs default values

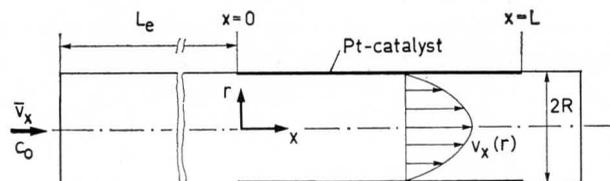


FIGURE 1. Notations for the ethylene hydrogenation system

can be used (Runge-Kutta-integration, eleven spatial points, three-point difference formulae). Equation (12) is integrated by the Simpson-method. For the evaluation of the experimental

As a whole, this experiment proved to be a very helpful tool for a better understanding of the influence of diffusion on heterogeneous chemical reactions.

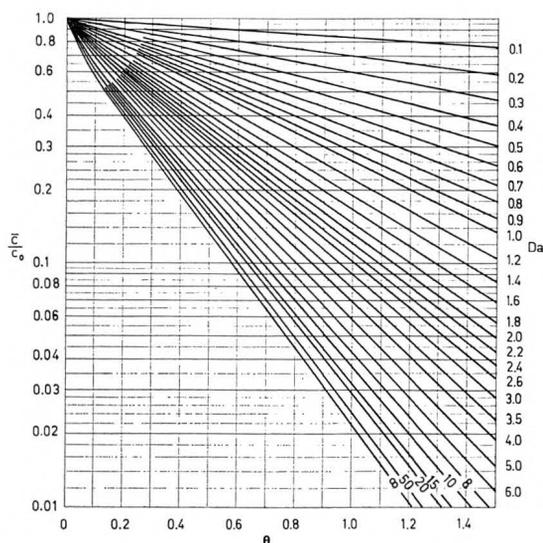


FIGURE 2. \bar{c}/c_0 as a function of Da and θ

results i.e. the determination of the surface reaction constant, the graph as given in Figure 2 is most useful. The diffusion coefficients needed can be estimated e.g. by the Wilke-Lee-method [5].

APPARATUS

A SCHEMATIC DIAGRAM of the experimental system is given in Figure 3. It consists essentially of two gas cylinders containing pure H_2 and the premixed 98% $H_2/2\%$ C_2H_4 , a gas metering valve, the thermostated reactor tube, a gas meter and a gas chromatograph.

In our setup we use an automatic sampling valve, but sample taking with a gas syringe is equally good, only a bit more tiresome.

A simple gas chromatograph is sufficient; we

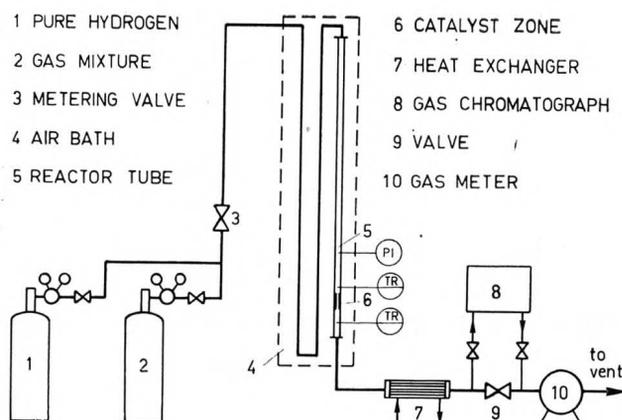


FIGURE 3. Flow diagram of experimental reactor system

use a GowMac 69-552. Column: Poropak s, length 1.7 m, inner diameter 0.005 m. Column temperature: $55^\circ C$. Detector: HW. Analysis time: 4 min.

Reactor and piping are made of stainless steel. The reactor tube is heated in an air bath and has the following dimensions: inner diameter 0.02 m, length 1.4 m. Gas temperature is measured before and after the reaction zone with NiCr/Ni thermoelements enabling one to verify that the reaction is conducted isothermally. The platinum catalyst is not directly applied to the tube wall but to a thin tubular nickel support consisting of two separate halves, put together by means of two O-rings (see Fig. 4).

After electrolysis, the support is put together and introduced into the reactor. The catalyst zone length is 0.1 m. If the zone is longer, the reaction

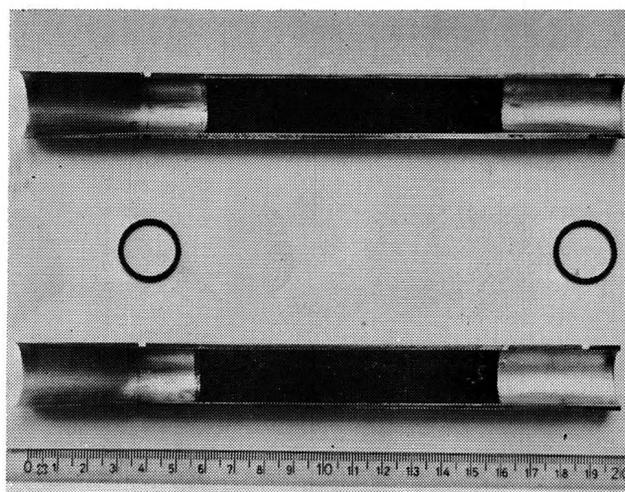


FIGURE 4. Catalyst support

can not be conducted isothermally. The entrance length is 1.2 m.

PROCEDURE

IN ORDER TO HAVE high and constant activity, fresh catalyst is prepared for each series of measurements (old catalyst is easily wiped off the nickel support). For the electrolysis, each half of the nickel support is treated separately in a 3% aqueous solution of $H_2(Pt_6Cl_6) \cdot 6H_2O$. At a current of 0.4 A ($750 A/m^2$) electrolysis time is 3 minutes. The catalytic surface is then rinsed with distilled water. The catalyst is introduced into the reactor tube and heated to the highest desired temperature in a pure hydrogen atmosphere in order to avoid catalyst poisoning. At a given temperature, measurements are made at several gas flow rates vary-

... the ethylene hydrogenation on a platinum catalyst, electrolytically applied to a tube wall, proved to be a good system for the study of the interactions between diffusion and surface reaction in heterogeneous catalysis.

ing from 0.001 to 0.006 m³/min. Steady state is always quickly achieved (less than the time necessary for product gas analysis). Usually the measurements are carried out going from the lowest to the highest temperature.

STUDENT PERFORMANCE

THIRTY HOURS LABORATORY TIME during 3 weeks are provided for this experiment. The students usually need about a day for the theoretical preparation of the experiment and to get acquainted with the apparatus. Some difficulty arises from the fact that a change of flow rate in the reactor has to be made with valves 3 and 9 simultaneously in order to maintain the pressure at a given value. The experiments should be run in one day in order to have constant catalytic activity. Invariably, good results are obtained. Evaluation of the measurements are rapid, k_{eff} is calculated from equation (2), k_s is determined from the Damköhler group by means of the graph given in Figure 2. Some typical results are given in Figure 5.

In addition, for some of their experiments the students have to calculate axial and radial concentration profiles in the reactor by means of the FORSIM-program. Previously we discuss the physical situation with the students. Their uncertainty clearly shows the need for this exercise. As a whole, this experiment proved to be a very helpful tool for a better understanding of the influence of diffusion on heterogeneous chemical reactions.

TABLE 1. Dimensionless groups

DEFINITION	SIGNIFICANCE
$Da = \frac{k_s R}{D}$	$\frac{\text{chemical reaction rate}}{\text{diffusion rate}}$
$\theta = \frac{D L}{R^2 v_x}$	$\frac{\text{mean residence time}}{\text{diffusion time from tube center to wall}}$
$\rho = \frac{r}{R}$	$\frac{\text{radius (variable)}}{\text{tube radius}}$
$f = \frac{c}{c_0}$	$\frac{\text{concentration (variable)}}{\text{concentration at reactor entrance}}$

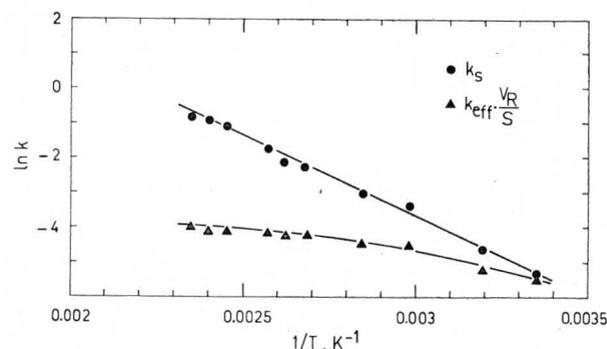


FIGURE 5. Arrhenius plot of reaction rate constants

ACKNOWLEDGMENT

THE AUTHORS THANK THE graduate student W. Caprez for his help in preparing the experiment. □

NOMENCLATURE

c	concentration, mole/m ³
c_0	initial concentration, mole/m ³
\bar{c}	mean concentration, mole/m ³
D	diffusion coefficient, m ² /s
Da	Damköhler
k_{eff}	effective reaction rate constant, s ⁻¹
k_s	surface reaction rate constant, m/s
L	catalyst zone length, m
r	radius (variable), m
R	tube radius, m
r_G	global reaction rate, mole/m ³ ·s
r_s	surface reaction rate, mole/m ² ·s
S	catalyst surface, m ²
\bar{v}_x	mean flow rate, m/s
V_R	volume of catalyst zone, m ³
ϵ	fractional volume change
τ	mean residence time, s

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THE TRAVELING CIRCUS AS A MEANS OF INTRODUCING PRACTICAL HARDWARE

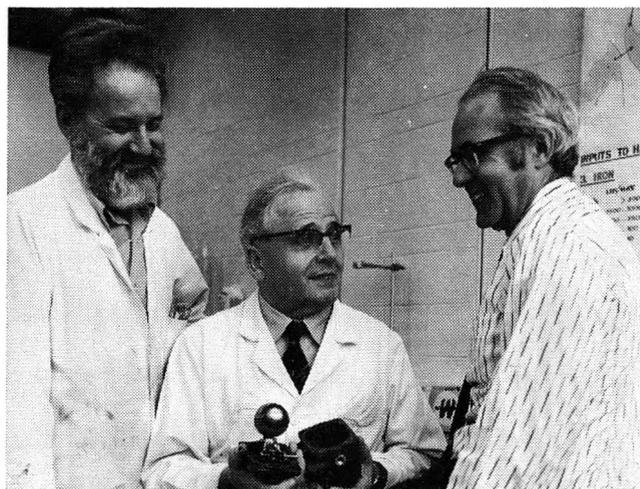
DONALD R. WOODS, ROBERT W. DUNN,
JOSEPH J. NEWTON AND
DONALD J. WEBSTER
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AT THE AICHE NEW YORK Meeting, 1967, Dr. Charles Littlejohn of Clemson described a procedure for introducing his students to hardware. He had a sectioned display box and each week he put some piece of hardware into each pigeon hole and asked his students to familiarize themselves with each during the week.

We, at McMaster, found this idea to be attractive and have used it since then to complement our fourth (and to a limited extent our third) year's activity. The particular hardware about which we feel all engineers should have some knowledge is shown in Table 1. The mechanics of the approach follows. About every two weeks we display some of the hardware given in Table 1 in one of the fume hoods in our laboratory. About 20 items are displayed at a time. Each item is numbered as in Table 1 and each student is given a copy of Table 1. A slide-tape show providing details of some of the hardware is available in a nearby resource center. The students are expected to handle the hardware, take it apart, and together with the help of the slide tape show and selected books [1-4] to give themselves a working knowledge of the specifications, the principles of operation and the application of each piece of hardware. At the end of each two week period the students' knowledge is tested.

Some example questions are:

- For the pitot probe, draw a diagram and clearly identify the parts. Two pressures are measured; show the location of the leads from these two measurements and indicate which pressure is the higher. Differentiate between a pitot probe and an impact probe. How would



Authors Bob Dunn, Joe Newton and Don Woods (left to right) select items for the travelling circus.

Robert Dunn was Senior Technician at the Welsh College of Advanced Technology, Cardiff, Wales, where he was part time lecturer and technician. He has been Chief Technician in the Chemical Engineering Department at McMaster University since 1965. His special concerns are to develop laboratory experiments and experiences that acquaint students with the practical side of engineering and provide insight into the fundamental principles. He is an avid wilderness hiker, fisherman and outdoorsman.

Joe Newton was "on the job" training instructor for adults during World War II, then transferred to Craft apprentice basic workshop instructing. He developed and implemented Basic Technician Training courses and later was appointed Craft Apprentice Training Officer, supervising all craft apprentice training at the Associated Electrical Industries, Rugby, England. He has been technician in the Chemical Engineering Department at McMaster University since 1968, assisting in the design and production of research and undergraduate projects and furthering the practical knowledge of students. He is a gardener, a furniture maker and a keen model engineering enthusiast.

Don Woods worked in industry for two years before joining the Department of Chemical Engineering in 1964. One of his teaching responsibilities is process analysis and design. He has tried to integrate practical knowhow into these courses. His other interests include square dancing, community activities and home renovation.

Don Webster graduated from McMaster University in 1977. As part of a course in communications skills, Don developed a slide-tape show of the hardware associated with piping and pumps.

TABLE 1
The Traveling Circus

TRANSPORTATION:

- Valves:** 1. gate; 2. globe; 3. ball; 4. butterfly; 5. diaphragm; 6. needle; 7. check; 8. back pressure; 9. safety relief; 10. solenoid; 11. pneumatic; 12. control; 13. regulating.
- Fittings:** 14. nipple; 15. union; 16. bushing; 17. tee; elbow (18. 90°; 19. 45°; 20. street); 21. reducer; 22. cross; 23. male connector; 24. female connector; 25. swagelok fittings for tubing.
- Pumps:** 26. centrifugal; 27. screw; 28. Moyno^R; 29. magnetic; 30. vacuum; 31. reciprocating piston; 32. diaphragm.

MEASURING INSTRUMENTS:

- Flow velocity:** 33. pilot tube; 34. impact tube; 35. velometer; 36. anemometer; 37. rotameter.
- Pressure:** 38. Bourdon pressure gauge; 39. compound gauge; 40. McCloud gauge; 41. pressure controller; 42. orifice plate; 43. sonic orifice; 44. manometers (44. micro; 45. slant; 46. vertical).
- Particles:** 47. coulter counter; 48. microscopic; 49. Zeta meter.
- Shop:** 50. dividers; 51. inside/out calipers; 52. odd leggs (hermofrodites); 53. scribe; 54. square; 55. spirit level; 56. center punch.
- Energy flow** 57. thermocouple; 58. heat flux meter;
Temperature: 59. potentiometer.

TOOLS AND CONNECTORS:

- Wrenches:** 60. open; 61. socket; 62. box.
- Cutters:** 63. tubing cutters; 64. hacksaw; 65. tin snips.
- Screw drivers:** 66. Robertson; 67. Philips; 68. slot; 69. files; 70. tube benders.
- Bolts:** 71. coach or carriage; 72. lag, machine; (73. hex head; 74. allenhead; 75. flat head); 76. stove bolt; 77. rawlugs or expanders.

UNIT OPERATIONS:

- Heat exchanger:** 78. shell and tube; 79. bubble plate; 80. sieve and 81. floater plate; 82. intalox packing.
- Steam traps:** 83. strainer; 84. centrifix separator; 85. bucket; 86. thermostatic; 87. ball; 88. thermodynamics traps.
- Miscellaneous:** 89. rupture disc; 90. hydrocyclone.

you calculate the local velocity from the data output, namely from the pressure differential? What correction factors would you make in your calculations or what precautions would you take in the experimental use of a pitot probe?

- For a pitot probe, how might one use a pitot probe or the principles thereof to measure the gas velocity in a dust laden stream?
- For valves, draw a diagram and clearly identify the parts to distinguish between a globe, gate, butterfly, needle and ball valve.
- If the "arrow" showing the direction of flow is not marked on a globe valve, how would you tell which way the flow should go through the valve?
- If one is pressure testing a system by spraying soap solution on the joints and looking for bubbling, what often overlooked part of a gate valve-pipe network is likely to be the source of the leak?
- If a globe valve is to be used for the inlet and outlet pipes to a batch vacuum receiver, why might the globe valve be installed "backwards" on the inlet lines?
- For thermocouples, draw a diagram of a measuring copper—constantan thermocouple system and clearly identify the location of the potentiometer and all the parts necessary to make the system work. Where would you look up the "best" choice of materials to use in a thermocouple to measure the following temperatures:
—100°C; 5°C; 200°C; 500°C; 800°C; 1000°C;
What criterion does one use in choosing a thermocouple? A colleague of yours plans to use boiling water as the reference temperature. What do you think about his idea?
- For fasteners, draw a diagram of a machine bolt, stove bolt, lag bolt, and carriage bolt that clearly differentiates among this? In each of the foregoing, mark on the distance that is meant when we identify a bolt as 3/8" x 3". If your girlfriend's Dad is building a wooden deck, what type of bolt would you recommend he use to fasten the 2 x 6 joists to the 4 x 4 posts?

This procedure relieves the necessity of spending classroom time discussing these features and gives the students flexibility in becoming acquainted with these hardware details. The approach is popular with the students and has been nicknamed by them "the travelling circus" because of the variety and changeability of the display. □

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TRAINING AND GAS ENGINEERING AT THE ALGERIAN PETROLEUM INSTITUTE

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ALGERIA IS A LAND of beautiful nature located on the Northern tip of Africa, it stretches along the Mediterranean sea for 640 miles, where the sun-bathed beaches are among the most beautiful in the world. It has large fertile plains, beautiful mountains, and a desert rich with oil, gas, and minerals. Many civilizations crossed this magnificent land, and left a spectrum of impacts; from the Romans, to the Arabs, Turks and French. The Arabs left an everlasting effect of Arabization. The Algerians fought courageously for their independence, which they gained from the French on July 5, 1962. In the defense of their motherland, they lost nearly one and a half million martyrs. Algeria is known nowadays as the "land of the million shahid and millions of moujahidine".

Throughout Algeria massive industrialization and development is taking place. Algerians have called on technologists and top scientists and engineers from across all political boundaries. This breathtaking pace for development was luckily blessed with oil and gas reserves which helped in bringing about the necessary cash for taking such gigantic steps. Thus, the creation of an Algerian Petroleum Institute to fulfill the needs of the oil and gas industry was a must.

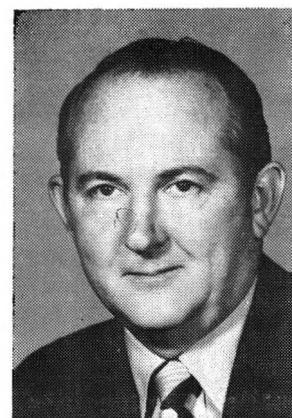
Created November 29, 1965, the Algerian Petroleum Institute expanded its mission of February 28, 1973 and thus became the Algerian Petroleum Institute of Gas, Chemistry, Petro-Chemistry, Plastic Materials, and Motors. Or, as is called in French, "Institut Algérien du Pétrole", abbreviation as IAP. It functions under the ministry of industry and energy, and works very closely with the major and only oil company in Algeria, namely SONATRACH (Societe Nationale de Transport et de Commercialisation des Hydrocarbures). In essence it is this oil company that makes the cash available for IAP's operations.

The three major objectives of the Algerian Institute of Petroleum are to provide: technician's training, engineering education, scientific and technical research.

The administration offices are mainly located at Dar El-Beida near the airport, about twelve miles from the city of Algiers. In this location, the technical training of engineers in the short cycle program takes place. This is a specialization for graduate students who have degrees in physics,

Dr. Esber I. Shaheen is Director of Education Services with the Institute of Gas Technology (IGT) in Chicago. He is also Director of International Education Programs with Gas Developments Corporation (GDC), a wholly-owned subsidiary of IGT. Dr. Shaheen has experience in both industry and the academic field, having taught at six different universities. Dr. Shaheen received his BS from Oklahoma State University, his MS from the University of Arizona, and his PhD from the University of Tennessee, all in chemical engineering. He is the author of many articles and four books: "Environmental Pollution Awareness and Control"; "Basic Practice of Chemical Engineering with Solutions Manual"; "Energy/Pollution Illustrated Glossary"; and "Arabic-English with a Petroleum Accent." He is listed in American Men of Science and in Outstanding Educators of America. (L)

Mr. Duane V. Kniebes, Assistant Vice President of Education and Research Services; BS in chemistry, MS in physics. Joining IGT's staff in 1949, Mr. Kniebes has served as head of the Analytical Division and as Director of Operations. His current administrative responsibilities include chemical analysis, technical information, and educational services, including management of specially-designed engineering and technician education programs. (R)





Industrial and Educational boom in Algeria.

chemistry, and engineering and who wish to specialize in the gas or oil disciplines. These students normally spend a preparatory year and another year for specialization.

The Ecole d'Ingenieurs at Boumerdes was opened in 1971. Here, most of the students take a normal engineering program, called the long cycle, where they will study for nearly five years before receiving their engineering degree. A special short cycle lasting about a year and a half is given to students in the specialty of gas transmission and distribution.

Technical schools are located near industrial centers. Thus, the specialized technicians while gaining their industrial education become accustomed to the industrial atmosphere. These centers are at Hassi Messaoud, Oran-Es-Senia, Arzew, Skikda, Annaba and Setif.

The students admitted to the technicians' program have already finished the first or second baccalaureate which is approximately equivalent to the high school diploma. These students study for a year or two depending on the speciality involved. At the end of their program, they become "technicians supérieurs". The various specialities for technicians are: geology, geophysics, production, refining, petro-chemistry, chemistry, gas and plastics, regulation, mechanical drawing, and safety. The general academic program includes the revision of basic principles of mathematics, physics and chemistry, and then some specific theoretical courses in the technology of materials, along with laboratory work, and a certain period of work in a plant to gain industrial experience.

RESEARCH AND ENGINEERING

SCIENTIFIC RESEARCH and measurements are made at Dar El-Beida's laboratories. This type of work touches on the various branches of the petroleum industry, and covers geology, geophysics, production, refining and petrochemistry. Thus, in geology, IAP arranges missions to various terrains for establishing geological charts and geochemical works. In the production area, the research is directed toward harnessing of petroleum. It comprises the study of fluid flow in porous media, the mechanics of reservoirs, and the stimulus of reservoirs by chemical methods or through fracturing. The laboratories in the area of refining constitute distillation, chromatography, spectrophotometry by atomic absorption and flame emission, and solvents extraction.

As previously mentioned, the two major engineering programs offered at IAP are: short cycle (cycle court) and the long cycle (cycle long). A number of review courses are given in the short cycle program. After that the students specialize in any of these chosen disciplines:

- Petroleum Exploration, (Geology and Geophysics)
- Refinery and Petrochemistry
- Petroleum Production
- Motors and Applications
- Natural Gas.

Aside from the courses received at the institute, some practical experience is gained by working in the petroleum industry. For the short cycle the duration of the practical experience lasts about one month. Certain seminars are also given by specialists who visit the institute from time to time. This helps in rounding up the education given to the students prior to their full engagement in industrial work.

In the long cycle program, the first four years are spent in formal education, where students take the necessary courses along with various plant visitations that may last from a few days to five or six weeks. Each engineering student spends the fifth year at a plant, for gaining practical experience. Certain remedial courses are given from time to time. This is due to the temporary unavailability of professors in a given line of specialty.

Algeria leads the world in building two huge plants for the liquefaction of natural gas: the Skikda plant and the CAMAL plant at Arzew.



Vacation in the countryside away from oil and the pressures of the job.

The detailed program for gas engineering, which includes liquefied natural gas (LNG), and gas transmission and distribution, will be discussed to give the reader a good example of the long cycle type academic program at IAP.

GAS ENGINEERING

ALGERIA LEADS THE WORLD in building two huge plants for the liquefaction of natural gas: the Skikda plant, and the CAMEL plant of Arzew.

With basic plans for earning hard currency for industrialization, and a major goal for improving the standard of living, and bringing gas to all sectors of industry and all residential areas, the obvious need was for the development of LNG operations, transmission and distribution of gas. At IAP, the two major disciplines in the gas engineering program are: liquefied natural gas (LNG), and transmission and distribution. One major objective of this program is to train engineers for the natural gas industry of Algeria. Graduates of the program are badly needed, and jobs are waiting for them.

Currently, the long cycle discipline for liquefied natural gas is being taught. However, the short cycle was taught during the academic year 1973-1974. The discussion here will deal with the long cycle program because it will be used in the future.

Students choose their option after the second academic year.

This program is being modified so that students will receive instruction in the English language rather than French. Students will be receiving about a 6-month intensive course in English prior to receiving their classical engineering instruction.

TRANSMISSION AND DISTRIBUTION ENGINEERING

THE SHORT CYCLE program for Engineering and Distribution Engineering is described here. Its duration is nearly three semesters. It has been especially designed to train competent engineers for the SONELGAZ company (Société Nationale d'Electricité et de Gaz).

Although very few engineers come from the Algerian Technical University (Ecole Nationale Polytechnique d'Alger), most of the students are chemists and physicists with B.S. degrees (license es-sciences). They have a strong theoretical background, but are extremely lacking in applications. Their laboratory experience is limited; and they are totally unfamiliar with engineering and operating practices.

These students have obtained the second baccalaureate (Baccalaureat Deuxième Partie). The second baccalaureate is essentially equivalent to our first semester of the sophomore year. After the second baccalaureate, and depending on performance, these students attend a University. The chemists and physicists take the first year in common. In the first year, they will have mathematics (integral, Taylor, matrices, differential equations), chemistry (general, organic), and physics (electronics, magnetism, optics). They do not take physical chemistry. In order to graduate with a B.S. from the university, the student must earn six certificates in the following 2 or 3 years.

- **Program for Chemists at the University:**

In the second, third, and fourth years, the chemists will take organic and general chemistry, thermodynamics, mineral chemistry, physics, experimental physics, and then may choose among the options of analytical chemistry, applied organic, applied mineral chemistry, or biochemistry.

This breathtaking pace for development was luckily blessed with gas and oil reserves which helped in bringing about the necessary cash for taking such gigantic steps. Thus the creation of an Algerian Petroleum Institute to fulfill the needs of the oil and gas industry was a must.

• **Physicists Program at the University:**

The subjects studied by the physicists are as follows: mathematical techniques of physics, triple integrations, differential equations, electricity, thermodynamics, optics, and the general theory of mechanics (trajectories). Finally they can choose among electronics, modern physics, fluid mechanics, and atmospheric physics.

A review of basic fundamentals is essential prior to dwelling into the basic topics of gas transmission and distribution. When a chemist or a physicist is enrolled in such a program, and the majority of the students have obtained degrees in physics and chemistry, basic fundamentals such as those encountered in material and energy balances, heat transfer, fluid flow, mass transfer and thermodynamics, must all be covered to bring such candidates into applied engineering. The difference between the thought process of the scientist, and that of an engineer is a basic and a real one. Review courses are aimed to give the students basic tools for developing good engineering judgement, and to approach and think of their problems as good engineers do.



Developing modern cities in the developing countries.

After this review, other basic courses such as energy conversion and resources, gas piping systems, natural gas properties, pressure regulation and measurements, corrosion control of underground piping systems, transmission and distribution systems, and gas utilization are presented to give the spectrum needed for formulating this specialty in gas transmission and distribution.

CONCLUSION

AT BOUMERDES a huge and attractive building is about to be finished. It is destined to be the major headquarters for the Algerian Petroleum Institute. This large building will house administrative offices whether for the engineering or technicians' programs. It will also have classrooms and laboratories for the engineers and for research and development. This future home of IAP, which will be finished in less than two years, is in the midst of a scientific and technical complex

which contains various institutes. Among these are the National Institute of Hydrocarbons (INH), the National Institute of Light Industries (INIL), the National Institute of Productivity and Industrial Development (INPED), along with the central laboratories for Sonatrach, Sonarem and the National Society for Materials of Construction.

Fine talents from throughout the world and Algeria have been chosen to bring about an Algerian Petroleum Institute which will train the brain-trusts who will develop the petroleum and gas industry and bring more progress to their homeland. The students that IAP recruits are dedicated and hard working. They will be a fine asset to the future of Algeria. Many of these students rank among the top ten percent found in American engineering schools.

In the years to come, IAP should play a great role in the training of engineers and technicians, not only for Algeria, but some of the oil producing countries and the third world as a whole. Its accomplishments are impressive and its future is a bright one indeed. □

ACKNOWLEDGMENTS

The authors kindly acknowledge the help of M. Baghli, Directeur Général of the Algerian Petroleum Institute; M. Benammar, Directeur Technique; M. Bouzertini, Directeur d'Engineering; and M. Souidi, former Chef de Département.

ASEE AWARDS

Continued from page 107.

the Department of Technology and Human Affairs, and director of the Center for Development Technology at Washington University. The award is sponsored by the Xerox Corporation.

DR. GEORGE BURNET, Anson Marston Distinguished Professor and Head of the Department of Chemical and Nuclear Engineering at Iowa State, has been elected to Honorary Membership in ASEE. Nominations are made to the Committee on Honorary Membership and the Committee in turn recommends candidates to the Board of Directors, which elects not more than two Honorary Members each year. They are chosen for eminent service to mankind in engineering education or other engineering fields.

The Western Electric Fund Awards were presented to the following: **ROBERT G. SQUIRES** in the Illinois-Indiana Section and **GORDON R. YOUNGQUIST** in the St. Lawrence Section.

TWO EXPERIMENTS FOR ESTIMATING FREE CONVECTION AND RADIATION HEAT TRANSFER COEFFICIENTS

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THIS ARTICLE DESCRIBES two simple undergraduate heat transfer experiments which, when properly understood, may reinforce a student's understanding of free convection and radiation.

The purposes of the experiments are:

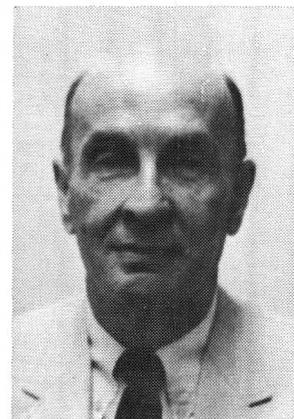
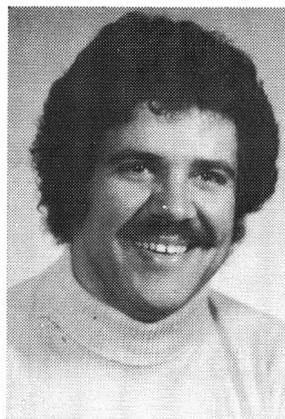
- To demonstrate how the combined individual coefficients for free convection and radiation may be extracted from an experimentally determined overall heat transfer coefficient by arranging experimental conditions in such a way that the major resistances to heat transfer are the two of interest and all other resistances are so small as to be negligible.
- To illustrate a technique for reducing the radiation heat transfer coefficient to such a small value that a close estimation of the free convection coefficient is possible.

In designing experiments for our undergraduates, we have attempted to keep them as simple as possible, and we wish to have the principle or principles they demonstrate to be so obvious that they are difficult to overlook. Also, we wish to have the results agree fairly closely with those values reported in the standard texts or with those values which would be calculated from standard correlations. Finally, we believe that students should either do or see done experiments which demonstrate the major phenomena we cover in our lecture courses. Although both free convection and radiation are covered in most lecture courses on heat transfer, few simple laboratory experiments seem to be available. We hope that the two

experiments about to be described will be of some interest and use to instructors and students concerned with this subject.

APPARATUS

THE FUNCTION OF the apparatus is to provide data from which one may calculate an overall heat transfer coefficient. It consists, in its basic form, of a vertical glass tube exposed to the air, into the bottom of which is passed a stream of saturated vapor. As the vapor rises up through the tube and passes out the top of it, a portion



Michael Economides has attended the University of Kansas where he obtained both B.S. and M.S. degrees in chemical engineering. Between degrees he has worked as a process engineer for Celanese Chem. Co. He is currently pursuing a Ph.D. at the University of California, Berkeley. His main interests are process design and economics. (L)

James O. Maloney is professor of Chemical Engineering at the University of Kansas. He received his B.S. Degree from the University of Illinois and his M.S. and Ph.D. Degrees from the Pennsylvania State University. He has been employed by the Dupont Company and has held Fulbright posts at Naples, Italy; Cairo, Egypt; and Athens, Greece. (R)

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of the vapor condenses on the walls and runs down to the bottom of the tube. This condensate is drawn off and its rate of production measured. Knowing this, the latent heat of condensation, the area and the temperature difference, one may calculate the heat loss from the tube and the overall heat transfer coefficient.

Thus:

$$(\dot{m}) (h_v) = Q/\theta = U(\pi D_o L) (T_v - T_A)$$

where

- \dot{m} = lb. condensate per hour
- h_v = latent heat of condensation, Btu/lb.
- Q/θ = heat loss from the tube, Btu/hr.
- D_o = outside diameter of the tube, ft.
- L = length of the tube on which condensation occurs, ft.
- T_v = temperature of the saturated vapor, °F.
- T_A = temperature of the air, °F.
- U = overall heat transfer coefficient, Btu/(hr. ft² °F)

When this overall coefficient is determined experimentally, it is found to range from 2.2 to 3.4.

A consideration of this heat transfer process shows that there are three resistances in series to heat transfer: that resulting from the condensing vapor, that from the glass tube, and that of the combined resistance of free convection and radiation from the outside surface of the tube. That is:

$$\begin{aligned} R_{\text{total}} &= R_{(\text{cond. vapor})} + R_{\text{tube}} + R_{(\text{conv.} + \text{rad.})} \\ &= \frac{1}{(hA)_{\text{cond. vapor}}} + \left(\frac{L}{kA}\right)_{\text{tube}} + \\ &\quad \left[\frac{1}{(h_{\text{conv.}} + h_{\text{rad.}})A} \right]_{\text{outside surface}} \end{aligned}$$

The resistance of the condensing vapor is in the range of 0.005 to 0.0005 reciprocal Btu/(hr. ft.² °F), i.e., coefficients of 200 to 2,000. The resistance of the glass tube is about 0.013 [2.5 mm. thick, borosilica glass and a k of 0.63 Btu/(hr. ft. °F)]. Free convection coefficients on the outside of the tube are in the range of 1 to 2 Btu/hr. ft.² °F, and the radiation coefficients are in the same range or less. One can thus draw the preliminary conclusion that the overall coefficient will be essentially composed of the combination of a convection and a radiation coefficient from the outside of the tube.

Glass has an emissivity of about 0.9, but if it is wrapped tightly with polished aluminum foil,

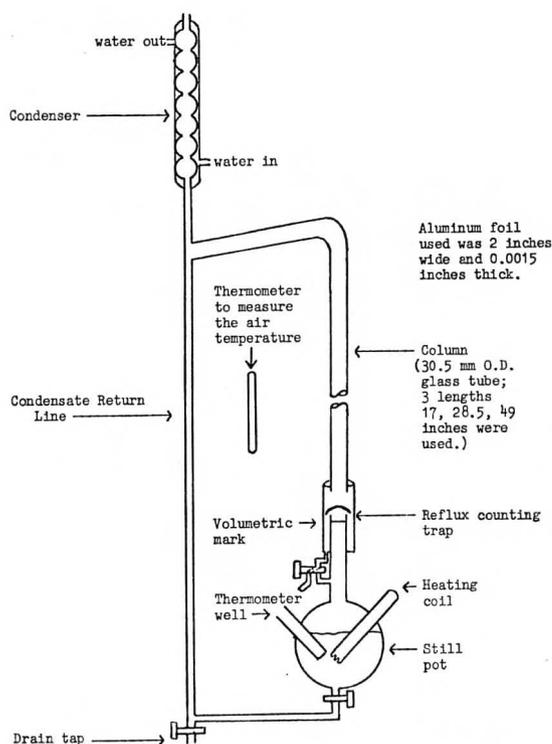


FIGURE 1. Vertical Column for Heat Transfer Coefficient Measurements

the emissivity of the vertical tube would be reduced from about 0.9 to about 0.05. Thus by wrapping the tube with aluminum foil the radiation coefficient can be so markedly reduced that the overall coefficient essentially equals the free convection coefficient.

The apparatus actually used in the experiment is shown in schematic form in Figure 1. The only unusual feature was the reflux counting trap [1] which was a vacuum jacketed device that allowed measurement of a known volume of liquid condensate and separated the condensate stream from the rising vapor stream. Any device which will accomplish this purpose would be satisfactory. The excess vapor, which is necessary in order to be certain that the entire length of the column is at a constant temperature, does not need to be recycled provided the still pot contains enough liquid for several runs. The boil-up rate had no significant effect on the overall heat transfer coefficient as long as excess vapor left the top of the tube. The liquid in the still pot was vaporized by an immersion-type heater, but an exterior heater would, of course, work satisfactorily. A certain amount of care probably should be used to minimize the effects of any forced convection around the column. In our experiments, the air condition-

TABLE 1. Effect of the Tube Height and Surface Condition on Overall Heat Transfer Coefficients

System: n-Butanol						
Tube Height in.	Column Surface Condition	Temperature, °F.		Condensate Rate grams/hr.	Q Btu/hr.	U Btu/(hr.)(sq.ft.)(°F.)
		n-Butanol	Air			
17	Bare Glass	242.6	82.4	383.9	215.3	3.02
28.5	Bare Glass	242.6	75.2	680.8	381.7	3.05
49	Bare Glass	242.6	82.4	1149.0	644.2	3.13
17	Aluminum Wrapped	241.7	76.1	227.4	127.5	1.73
28.5	Aluminum Wrapped	242.6	75.2	380.7	213.5	1.71
49	Aluminum Wrapped	242.6	82.4	624.0	349.9	1.70
System: Water						
28.5	Bare Glass	211.1	73.4	129.0	276	2.69
28.5	Aluminum Wrapped	211.1	73.4	76.3	163	1.57

Example: First Run

$$\text{Area} = \pi D_o L = (\pi) \left(\frac{30.5}{12} \times \frac{1}{2.54} \right) \left(\frac{17.0}{12} \times \frac{1}{1.27} \right) = 0.445 \text{ sq. ft.}$$

$$U = (215.3) / ((242.6 - 82.4)(0.445)) = 3.02 \text{ Btu/(hr.)(sq.ft.)(°F.)}$$

ing vents were covered, and the windows were closed. In several runs, the entire assembly was surrounded with a vertical cardboard shield about two feet away from the column, but no significant difference in results was found. The columns we used were fitted with TS joints for ease of assembly.

EXPERIMENTAL PROCEDURE

Two main types of runs were done: (1) those in which the glass tube was left bare, and (2) those in which the glass tube was covered with aluminum foil. During either type of run a reasonably pure liquid was placed in the still pot where it was boiled. Vapor ascended through the reflux trap into the tube. A certain amount condensed on the sides of the column, and the remaining vapor passed through the opening on the top of the column and off into the adjoining condenser. The condensate from it was then recycled via a condensate return and back into the still pot.

Whenever a measurement was desired, the

TABLE 2. Effect of Temperature Difference or the Overall Heat Transfer Coefficient

Compound	Difference in Temperature Between Boiling Liquid and Air °F.	Condensate Rate grams/hr.	Q Btu/hr.	U Btu/(hr.)(sq.ft.)(°F.)
Acetone	59.9	132.2	63.5	1.42
Methanol	66.6	71.1	80.2	1.61
Benzene	95.5	308.2	115.2	1.57
Water	137.7	73.4	163.0	1.57
Toluene	155.3	596.7	201.5	1.74
n-Butanol	161.8	390.8	219.4	1.82
n-Octanol	307.6	1549.7	599.6	2.61

Example: First Run

$$\text{Area} = \pi DL = (\pi) \left(\frac{30.5}{12} \times \frac{1}{2.54} \right) \left(\frac{28.5}{12} \times \frac{1}{1.27} \right) = 0.747 \text{ sq. ft.}$$

$$U = \frac{(Q/\theta)}{(A)(\Delta T)} = \frac{63.5}{(0.747)(59.9)} = 1.42 \text{ Btu/(hr.)(sq.ft.)(°F.)}$$

three-way valve attached to the reflux trap was closed. The time required for the reflux trap to fill up to a marked level was recorded. Then the condensate was allowed to flow back into the still pot. This measuring procedure was repeated several times. After the last timing, the condensate in the reflux trap (up to the marked level) was collected and weighed.

During the run the temperature of the boiling liquid was measured by a thermometer immersed in a well in the still pot. In some later runs a thermometer was placed in the top of the tube to measure the vapor temperature there. The still pot temperature and this temperature were essentially identical. The ambient temperature was also measured.

A brief study was made of the effect of tube length on the overall heat transfer coefficients. Tubes of 17, 28.5 and 49 in. in length were used.

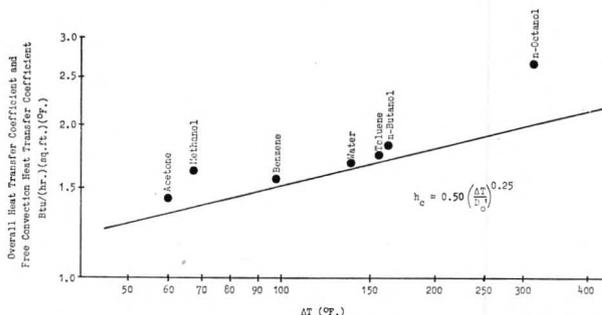


FIGURE 2. Measured Overall Heat Transfer Coefficients Together with a Plot of the Perry, Third Edition Formula for Free Convection Coefficients

In order to have a variety of temperature driving forces, a number of liquids of various boiling points were used, including: acetone, benzene, toluene, water, methanol, n-butanol, n-amyl alcohol, and n-octanol (BP, range 56-195°C.).

TYPICAL RESULTS

SOME TYPICAL RESULTS are shown in Tables 1 and 2. Table 1 shows two things. It shows that the overall coefficient is essentially independent of tube heights from 17 to 49 inches and that wrapping the tube tightly with aluminum foil results in a marked decrease in the overall coefficient from 3.1 to 1.7. Table 2 and Figure 2 show that the overall coefficient generally increases as the temperature difference between the boiling points of the compound and the air increases.

DISCUSSION

IT IS CUSTOMARY to have students compare their results calculated from experimental data with values found in the literature. The procedure used here is to compare the experimental value with ones calculated using the methods found in the five consecutive editions of Perry's Chemical Engineers' Handbook. The particular comparison shown here is for the case of water condensing at 735 mm. Hg and 99.5°C. inside a 28.5 inch long vertical tube 1.2 inches in outside diameter. The tube was carefully wrapped with shiny aluminum foil. The air temperature was 23°C. The measured overall U was 1.57 Btu/(hr. ft.² °F.).

The principal reason for selecting the procedures found in Perry is that it is a reference more widely available to undergraduates than any particular text on heat transfer.

While all of the details of calculating the values by each method will not be gone through, the values used in the calculation will be shown.

First Edition [2]:

$$h_{\text{vert. cylinder}} = h_{\text{hor. cylinder}} \times \text{shape factor}$$

$$h_{\text{hor. cylinder}} = f(\text{film temp.}, \frac{P^2 \Delta T_m}{D})$$

$$\text{film temp.} = \frac{(99.5 + 23)}{2} = 61.3^\circ\text{C}$$

$$\frac{P^2 \Delta T_m}{D} = \frac{(0.97)^2 (99.5 - 23)}{1.2} = 60$$

$$h_{\text{hor. cylinder}} = 1.2 \text{ Btu}/(\text{hr. ft.}^2 \text{ }^\circ\text{F.})$$

$$\text{shape factor} = 1.22$$

$$h_{\text{vert. cylinder}} = (1.2)(1.22) = 1.46 \text{ Btu}/(\text{hr. ft.}^2 \text{ }^\circ\text{F.})$$

Second Edition [3]:

For long vertical pipes:

$$h_c = 0.4 \left(\frac{\Delta t_s}{D_o'} \right)^{0.25}$$

$$\Delta t_s = 211.1 - 73.4 = 137.7$$

$$h_c = 0.4 \left(\frac{137.7}{1.2} \right)^{0.25} = 1.31 \text{ Btu}/(\text{hr. ft.}^2 \text{ }^\circ\text{F.})$$

Third Edition [4]:

For long vertical pipes:

$$h_c = 0.5 \left(\frac{\Delta t_s}{D_o'} \right)^{0.25}$$

$$= 0.5 \left(\frac{137.7}{1.2} \right)^{0.25} = 1.64 \text{ Btu}/(\text{hr. ft.}^2 \text{ }^\circ\text{F.})$$

Fourth Edition [5]:

For vertical surfaces:

$$\frac{h_c L}{k} = a(x)^m$$

$$\text{for } x > 10^9; a = 0.13, m = 1/3$$

$$x = \left[\frac{L^3 \rho^2 g \beta \Delta t}{\mu^2} \frac{c \mu}{k} \right]_{\text{film temperature}}$$

$$x = \frac{(2.38)^3 (0.0636)^2 (4.18 \times 10^8)}{(0.001673) (137.7) (0.70)}$$

$$= \frac{1.7 \times 10^9}{(0.0465)^2}$$

$$h_c = (0.13) (1.7 \times 10^9)^{1/3} \left(\frac{0.0166}{2.38} \right)$$

$$= 1.08 \text{ Btu}/(\text{hr. ft.}^2 \text{ }^\circ\text{F.})$$

Fifth Edition [6]:

For vertical surfaces:

$$N_{Nu} = a(N_{Gr} N_{Pr})^m$$

$$\text{for } x > 10^9; a = 0.13, m = 1/3$$

This is the same procedure as found in the fourth edition, so:

$$h_c = 1.08 \text{ Btu}/(\text{hr. ft.}^2 \text{ }^\circ\text{F.})$$

The results of these calculations are summarized in Table 3. One sees considerable variation among the results. Two comments may be made about the five procedures. Nothing is stated about how well these calculated values agree with experimental values. Furthermore, as the calculational procedures change from edition to edition, no reasons are stated for making the changes. A

TABLE 3
Natural Convection Coefficients for Air
As Calculated from Procedures Found in
Five Consecutive Editions of
Perry's *Chemical Engineers' Handbook*

Edition	Date	h_c , Btu/(hr. ft. ² °F.)
First	1934	1.46
Second	1941	1.31
Third	1950	1.67
Fourth	1963	1.08
Fifth	1973	1.08

student looking at the wide range of these values might be somewhat confused or not know exactly how to proceed; without access to the actual data upon which the methods in Perry are based, (s)he is probably at an impasse.

Table 4 and Figure 2 have been prepared using experimental results and the correlation

TABLE 4. Comparison of Overall Measured U with the Calculated Free Convection Coefficients for the Aluminum Wrapped Tube

Substance	U Measured Btu/(hr.)(sq.ft.)(°F.)	h _c Calculated Btu/(hr.)(sq.ft.)(°F.)
Acetone	1.42	1.34
Methanol	1.61	1.37
Benzene	1.57	1.51
Water	1.57	1.67
Toluene	1.74	1.70
n-Butanol	1.82	1.71
n-Octanol	2.61	2.01

equation from the third edition of Perry:

$$h_c = 0.5 \left(\frac{\Delta t_s}{D_o'} \right)^{0.25}$$

- h_c = free convection coefficient, Btu/(hr. ft.² °F.)
 Δt_s = temperature difference between the hot surface and the ambient air, °F.
 D_o' = diameter of the tube, in.

One observes that the trend of the values is similar to that predicted by the equation and that h_c is usually lower than the overall heat transfer coefficient, as would be expected.

Another calculation can be made to take the radiation heat loss into account. The radiation heat loss can be estimated from Stefan's Law:

$$\dot{Q}_r = \sigma \epsilon A (T_s^4 - T_a^4)$$

where

- Q_r = heat transfer rate, Btu/hr.
 σ = 0.1717 x 10⁻⁸
 ε = tube surface emissivity
 A = the area of heat transfer, sq. ft.
 T_s = surface temperature of the tube, °R.
 T_a = air temperature, °R.

Table 5 shows the results of two calculations in which the amount of heat transferred by radiation is estimated from the 28.5 in. long tube, using n-butanol as the boiling material. In the first case,

TABLE 5. Estimated Heat Loss by Radiation and the Radiation Heat Transfer Coefficient

Tube Condition	Emissivity, ε	Q̇ _{total} Btu/hr.	Q̇ _r Btu/hr.	Q̇ _{free convection} Btu/hr.	h _r
Bare Glass	0.9	381.7	185.9	195.8	1.47
Aluminum Covered	0.05	213.5	10.3	203.2	0.08

the tube is bare and the glass emissivity is taken as 0.9. In the second case, the aluminum emissivity is taken as 0.05. The two emissivity values are taken from Kreith [7]. From the heat lost by radiation, the two radiation heat transfer coefficients were calculated. One sees from the calculation that an aluminum covering should markedly reduce the coefficient, which is exactly what happened experimentally.

The two values of h_r calculated may be used together with the measured overall U for the bare tube to estimate the overall coefficient for the aluminum foil wrapped tube as follows:

overall U with bare tube	3.05 Btu/(hr. ft. ² °F.)
reduction by radiation coefficient of bare tube	1.47 Btu/(hr. ft. ² °F.)
net h _c	1.58 Btu/(hr. ft. ² °F.)
add back radiation coefficient of Al-foil surface	0.08 Btu/(hr. ft. ² °F.)
estimated overall U, Al-wrapped tube	1.66 Btu/(hr. ft. ² °F.)
measured overall U, Al-wrapped tube	1.71 Btu/(hr. ft. ² °F.)

One sees that the estimated and measured overall U for this case are very close.

CONCLUSIONS

- These experiments provide a means for measuring overall heat transfer coefficients under conditions where free convection and radiation are controlling the transfer.
- The experiments show how the radiation coefficient may be reduced so much that free convection is controlling the heat transfer.
- Application of procedures found in successive editions of Perry's *Chemical Engineers' Handbook* to estimate free convection coefficients give significantly different answers.
- A closer inspection of the data on which the correlating procedures found in Perry are based seems warranted. □

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3. *Ibid*, 2nd Ed., 1941, pp. 985-987.
4. *Ibid*, 3rd Ed., 1950, pp. 474-476.
5. *Ibid*, 4th Ed., 1965, pp. 10-10 — 10-13.
6. *Ibid*, 5th Ed., 1973, pp. 10-10 — 10-12.
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REID: Award Lecture

Continued from page 111.

an explosion; is this the time to superheat water or does it represent an interval of time to place water below the smelt surface so that the later injection force can collapse the vapor film? Higher injection velocities enhanced explosion probabilities—for the same reason? Hot water explodes with difficulty: is the steam vapor film now too thick to be collapsed? Why should “green liquor” lead to more violent explosions?

Studies are critically needed to determine *if* there is a minimum force or shock necessary to establish initial liquid-liquid contact—and, if so, what is the effect of the independent system variables on this force.

CRYOGEN-WATER EXPLOSIONS

IN ALL CASES DESCRIBED earlier, water was contacted with a hot liquid. But vapor explosions can also occur when cryogenic liquids contact water. The system R-12 or R-22/water has been studied in several laboratories (Holt and Muenker, 1972; Rausch and Levine, 1973; Henry et al., 1974; Anderson and Armstrong, 1977).

We have been interested in vapor explosions involving light hydrocarbons. The impetus for this study began in 1970 when the U. S. Bureau of Mines reported that, in two instances, vapor explosions resulted when liquefied natural gas (LNG) spilled upon a water surface (Burgess et al., 1970). The explosions did not lead to ignition, but they were sufficiently severe to cause concern to the burgeoning LNG industry.

Extensive research programs were initiated by the Shell Pipe Line Corp. (Enger and Hart-

... a small leak in the roof must have allowed water from a tropical downpour to fall unobserved into a ladle. The resulting explosion ejected matte 40 feet into the air, killing the craneman in his cab.

man, 1972) and in our own laboratories (Nakanishi and Reid, 1971; Porteous and Reid, 1976). (See also, Katz and Sliepcevic, 1971; Katz, 1972; Burgess et al., 1972.)

Light hydrocarbon-water vapor explosions almost certainly result when a portion of the liquid hydrocarbon is heated to a temperature where it may undergo homogeneous nucleation. Usually, in simple spills, only a thin film is involved and the

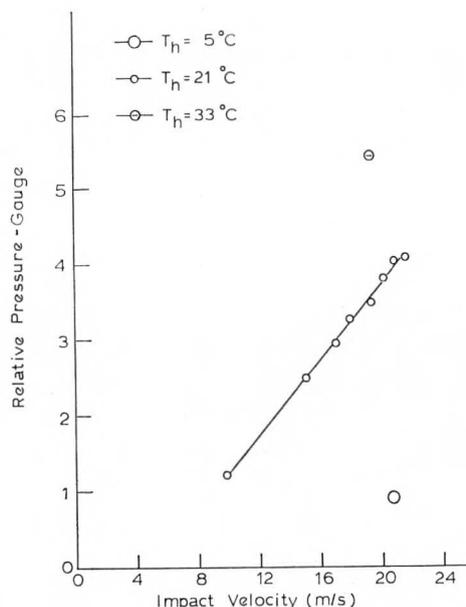


FIGURE 16 EFFECT OF IMPACT VELOCITY AND WATER TEMPERATURE ON PEAK PRESSURE, ETHANE AND WATER

resulting explosion, while impressive, is not particularly energetic nor damaging.

Based on the proposed theory, there then exists a clear definition of interactions which cannot produce vapor explosions. If T_w is the bulk water temperature and T_{SL} the homogeneous nucleation temperature of the light hydrocarbon (pure or mixture), then, for a true vapor explosion, $T_w \geq T_{SL}$. In literally hundreds of different experiments with various water temperatures and cryogenes, this criterion is rarely violated.* There now is general agreement that one can predict if a vapor explosion is possible knowing only the initial water temperature and the value of T_{SL} for the hydrocarbon. (It is important to note that if $T_{SL} > T_w$, and the two liquids are rapidly mixed, rather violent boiling may still ensue, but no shock waves characteristic of an explosion are noted.)

For simple spills of hydrocarbons into water (or vice versa), the probability of an explosion is the highest when T_w only slightly exceeds T_{SL} . That is,

$$T_w/T_{SL} \geq 1, \text{ criterion for a vapor explosion}$$

$$T_w/T_{SL} = 1.04 - 1.06, \text{ criterion for maximum probability for a vapor explosion in simple spills of light hydrocarbons on water.}$$

*Porteous and Reid (1976) show data which indicate a vapor explosion resulted in the propene-water system when $T_w/T_{SL} \sim 0.97$ to 1.06 and for n-butane-water at $T_w/T_{SL} = 0.98$. In all other cases $T_w/T_{SL} \geq 1$.

These criteria are in excellent agreement with experimental data; the first is general and independent of the fluids, the second must be modified if the hot liquid has thermal properties different from water. For example, if methanol is used, the T_w/T_{SL} range for maximum probability increases to about 1.14 - 1.20.

Such a variation of the limiting T_{hot}/T_{SL} criteria follows the hypothesis of Henry et al. (1974) that one should employ the interface temperature rather than the bulk hot liquid temperature to develop a criterion for vapor explosions. That is, the interface temperature upon contact of the two liquids must be greater than the homogeneous nucleation temperature of the volatile one before a large-scale vapor explosion can occur. To estimate this interface temperature, a simple one-dimensional heat transfer model is proposed wherein the two liquids are contacted at time zero. Assuming constant thermal properties and no phase changes, the interfacial temperature, T_i , is invariant with time and depends only on the original temperatures of the hot liquid (T_h) and cold liquid (T_c) and their thermal properties, i.e.,

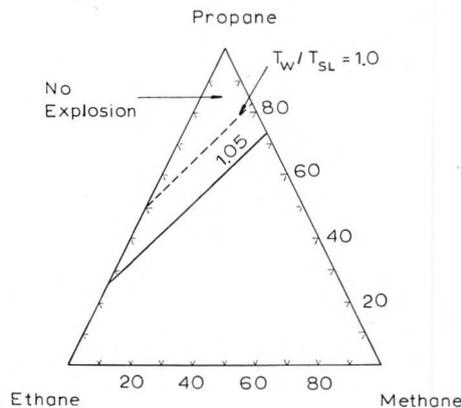
$$\frac{T_i - T_c}{T_h - T_i} = \left(\frac{k_h \rho_h C_h}{k_c \rho_c C_c} \right)^{1/2} \quad (11)$$

The symbols k , ρ , and C refer to the thermal conductivity, the density, and the heat capacity with subscripts h and c denoting the hot and cold liquids.

Of considerable current interest is the development of an explosion criteria for large values of T_w/T_{SL} . For example, pure liquefied methane on 300 K water has a ratio of $T_w/T_{SL} \sim 1.77$. To date no one has been able to obtain a vapor explosion by contacting liquid methane ($T_b = 111.7$ K) and

water at any temperature. The argument usually presented is not dissimilar to those invoked earlier for water-molten metal, water-smelt, etc., i.e., for large temperature differences, stable film boiling occurs and liquid-liquid contact is not possible. Yet as we have seen several times, explosions may become possible *if* there is some sufficiently severe impact event to drive the liquids into contact.

We have been investigating this possibility in our laboratory in the past year, and initial results



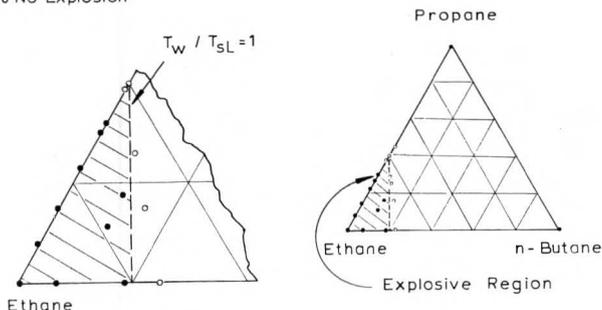
Explosive Envelope for Simple Spills of Methane-Ethane-Propane on 298 K Water

FIGURE 18

strongly confirm this hypothesis. As an illustration, pure ethane has always been somewhat of an enigma. The homogeneous nucleation temperature, T_{SL} , is 269 K yet we have never obtained a vapor explosion by spilling ethane on water at any temperature. Rapid boiling does occur with concomitant ice formation—but nothing more. Recent experiments by Jazayeri (1977) have nevertheless been quite successful in obtaining ethane-water explosions by impacting the two liquids. The experimental equipment is shown in Figure 15 and the ethane-water data in Figure 16. A high frequency quartz transducer mounted about 10 cm above the surface of the polyethylene cryogen vessel was used to measure the combined interaction pressure and the impaction pressure of the ejected mass of liquid. Usually, 350 cm³ of water was impacted on about 200 cm³ of liquid ethane. High speed motion pictures were also taken.

Rather large peak pressures were measured but the rise time was below 1 ms and it decayed very rapidly. The force was, however, usually sufficient to fragment the polyethylene vessel holding the ethane. (In one recent test, the explosion was sufficiently violent to break a Lexan shield and shatter the protective glass in a safety hood!)

- Explosion
- No Explosion



EXPLOSIVE CORNER ENLARGED

Explosive Envelope for Ethane-Propane-n-Butane Mixtures with 298 K Water. Impact Velocity = 21.5 m/s

FIGURE 17

Clearly, higher water temperatures seem to lead to a more forceful explosion, and we plan to study this effect in more detail. Finally, extrapolation of the line for a water temperature of 21°C to a peak pressure of zero gauge pressure indicates that a minimum velocity of about 5 m/s is required to be successful in attaining vapor explosions. Higher inception velocities would be expected as the water temperature increases. These values are, however, not general and are certainly related to the specific geometry and impacting technique employed.

Our "map" showing explosive regions (including impact experiments) for the ethane-propane-n-butane ternary is shown in Figure 17 for 298 K water. A similar plot, showing the theoretical limits for the methane-ethane-propane system is shown in Figure 18.

In Part 3, we discuss other types of vapor explosions and summarize theories (other than superheated liquids) that have been proposed to explain their occurrence. □

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ChE letters

BOOK AUTHOR RESPONDS TO REVIEWER'S CRITICISMS

Sir:

I very much appreciated the detailed review of my book "Biomedical Engineering Principles" by Professor E. F. Leonard in the Spring 1978 issue. I would like to point out, however, that I was every bit as disturbed as Professor Leonard that the reproduction was by photo-offset means and that the list price was set so high (\$36.50). About the style of reproduction there was really no choice—it was a simple matter of being published in that form or not being published at all. Regarding the price, I am happy to report that my own displeasure encouraged the publisher to reduce the "classroom adoption price" (5 or more copies) to \$19.75.

Finally, I agree with Professor Leonard that the biomedical engineering field seems to lack a clear direction and sense of purpose. It is thus not surprising that the book reflects this to some degree. I struggled internally while writing the book to define a clear direction, and still continue to do so as I teach in the biomedical area. Unfortunately, in the continued absence of any significant job market in biomedical engineering, I (and I would guess most everyone else) remain at least a little unsure as to what the proper pedagogical approach should be.

David O. Cooney
Clarkson School of Tech.

ON THE APPLICATION OF SIMPLE EXPERIMENTS TO THE TEACHING OF ChE THERMODYNAMICS

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HISTORICALLY, THERMODYNAMICS has been considered one of the most elegant but abstract branches of physico-chemical science. Its fundamental importance in engineering requires that it be taught both at the undergraduate and graduate levels. For that reason, however, it is one of the most difficult subjects to teach effectively. At Drexel University, the undergraduate chemical engineering student is initially exposed to thermodynamics in the common basic thermodynamics course taken by all engineering sophomores, which provides an introduction to the first and second laws, heat engine cycles, and ideal gas relationships. Concurrently, an elementary treatment of thermochemistry, energy balances, and thermodynamic properties is given in the material balances course. Instruction continues in the ChE Thermodynamics course, taken in the second quarter of the sophomore year. Finally, some aspects of statistical thermodynamics are covered in physical chemistry, taken in the second quarter of the pre-junior year. (At Drexel, the B.S. degree requires five years due to the cooperative education program; of the twelve quarters required, three each are attended in the freshman and senior

The addition of a series of simple experiments to an established lecture course is a concept novel to ChE curriculum at Drexel University.

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years, two each in the sophomore, pre-junior, and junior years. The student also works in a suitable technical position in industry for six months in each of the three middle years.)

The ChE Thermodynamics course consists of 4 credit hours devoted to such traditional classroom activities as lectures and problem-solving, and a 1-credit hour (2 contact hours) laboratory which was initiated in 1971. The main objective of the overall course is to equip the student with a basic working knowledge of the concepts and practical applications of ChE thermodynamics, thereby also providing an adequate foundation for subsequent undergraduate courses in kinetics and reactor design, transport phenomena, unit operations, and process design, and for graduate courses

TABLE 1. Lecture Topics

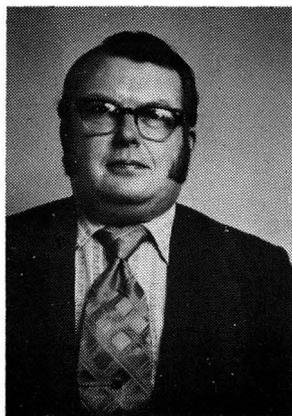
First and Second Laws of Thermodynamics (review)
Thermodynamic analysis of processes
Pressure-volume-temperature relationships for real fluids
Thermodynamic properties of real fluids
Thermodynamics of incompressible and compressible fluid flow
Phase equilibria in pure and multicomponent systems
Chemical-reaction equilibria (homogeneous systems)

in thermodynamics and kinetics. The principal purpose of the laboratory is to enhance the students' understanding of an otherwise abstract subject; instructional objectives are discussed more fully in the next section.

The topics covered in the lectures are stated in Table 1. The textbook currently used is by Smith and Van Ness [1].

INSTRUCTIONAL OBJECTIVES OF LABORATORY

THE PRIMARY OBJECTIVE of augmenting the lectures with a series of short laboratory



Kenneth M. McNeil, a consulting chemical engineer, was Assistant Professor of ChE at Drexel University from 1970 to 1976. He is presently Coordinator of the ChE Review course for the P.E. examination. After receiving a B.Sc. from the University of Edinburgh (1962), he studied under Prof. P. V. Danckwerts at the University of Cambridge (Ph.D., 1965). Between 1965 and 1970, he was on the staff of the R. & D. Department of Amoco Chemicals Corp. He is a registered Professional Engineer (Pa.), and is a member of AIChE, ACS, I. Chem. E., and Sigma Xi.

experiments was to improve the pedagogical effectiveness of the course. Thermodynamics is one of the more difficult courses conceptually, but is relatively straightforward (at this level) both mathematically and computationally. Whereas numerous worked examples and homework problems contribute significantly to the learning process, they are of little help in conveying a sense of reality to the student. The experiments fill this void, at the same time exciting curiosity and interest.

The laboratory has several further instructional objectives. It provides an introduction to simple measurements, in particular thermocouple thermometry and differential-pressure flow measurement. This serves as a valuable preparation for subsequent laboratory courses, which include transport phenomena, unit operations, and process control.

In this course, the students receive their first experience in the planning of experiments, the analysis of data, and report writing, albeit at an elementary level. This, too, is helpful preparation for subsequent laboratory courses, in which considerably more detail is required.

The class is divided into several groups which retain their identity throughout the course. Each group consists preferably of three students, one of whom is appointed group leader for a particular experiment; each student acts as group leader for at least two experiments. The course thus exposes the students to the interpersonal relationships in-

volved in group work, from the viewpoint of both the group leader and the team member.

EXPERIMENT DESCRIPTIONS

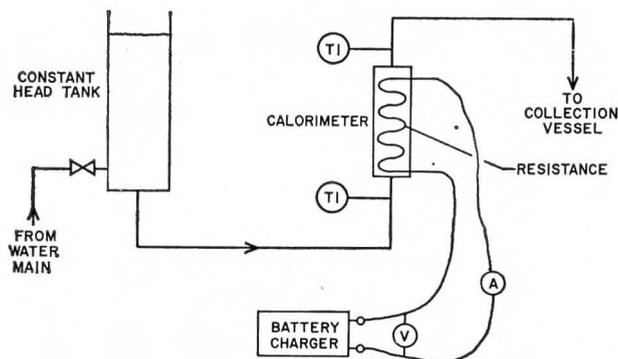
THERE IS ONE experiment corresponding to each major lecture topic, as listed in Table 2. There follow brief descriptions of the experiments, with comments on typical results that have been obtained.

**TABLE 2. List of Experiments
(with Corresponding Lecture Topics)**

EXPERIMENT	LECTURE TOPIC
Flow Calorimeter	First Law
Hilsch Vortex Tube	First and Second Laws
Refrigeration Cycle*	Thermodynamic analysis
P-V-T Behavior of CO ₂	P-V-T relationships
Throttling Calorimeter	Thermodynamic properties
Maximum Flow in Nozzle	Thermodynamics of fluid flow
Triple Point of Nitrogen	Phase equilibria
Ethanol-Acetic Acid-Ethyl Equilibrium	Chemical equilibria

*Planned

Flow Calorimeter. The equipment consists of a simple calorimeter incorporating an electrical resistance which enables electrical energy to be converted to heat and dissipated in the liquid stream. The liquid (water) is fed to the calorimeter at a constant rate from a header tank, in which the level is maintained manually. The flowrate is determined by measuring the volume of effluent in a given time interval, and the inlet and outlet temperatures are measured with mercury-in-glass thermometers (Fig. 1). By comparing the input



**FIGURE 1
FLOW CALORIMETER**

of electrical energy to the increase in enthalpy of the water, the electrical equivalent of heat can be calculated. Reasonably accurate results for this relatively crude device have been obtained by the more careful students (within 10% of the correct value).

Hilsch Vortex Tube. In this apparatus, high-pressure air is led tangentially into a tube (constructed of Plexiglas) where it expands, giving rise to a high-speed circumferential motion. As a result of this expansion, the air as a whole gains kinetic energy at the expense of its internal energy, and the temperature therefore falls. The air near the axis is withdrawn in an axial direction. It has relatively low kinetic energy (the angular velocity does not vary greatly with radial position, and the tangential velocity near the axis is therefore low), and thus remains cooler than the inlet air. The air near to the tube wall, on the other hand, has a high tangential velocity and hence kinetic energy. This air is withdrawn in the opposite axial direction. As it passes down the tube, most of the kinetic energy is dissipated by turbulent mixing and the internal energy consequently increases. The temperature of this stream becomes higher than the inlet air, as nearly all the internal energy initially converted to kinetic energy reappears as internal energy in only this part of the original stream.

The apparatus, which is illustrated in Fig. 2, is provided with means of measuring the temperatures and pressures of all three air streams, and the flow-rates of the hot and cold effluent streams. From these data, entropy and enthalpy balances

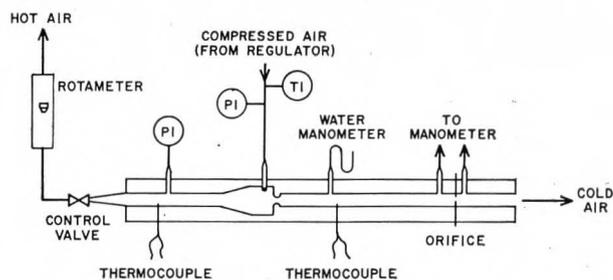


FIGURE 2
HILSCH VORTEX TUBE

can be carried out over the vortex tube. The experiment has been successful in demonstrating the applicability of the entropy function to considerations of irreversibility, as well as giving practical experience in the construction of entropy and

enthalpy balances. Furthermore, it provides an introduction to important measuring techniques: thermocouple thermometry, pressure measurement by bourdon gauge and manometer, and flow measurement by orifice meter and rotameter. Typical experimental results are presented in Table 3.

TABLE 3. Hilsch Vortex Tube:
Typical Operating Conditions and Results

Inlet air, temperature	82°F
pressure	45-90 psia
Hot stream, temperature	90-97°F
pressure	20-30 psia
Cold stream, temperature	76-71°F
pressure	~ 0.5 psig
Flow ratio, hot stream:	~ 1:2
cold stream	
Entropy generated	2.0-3.0 Btu lb mole ⁻¹ R ⁻¹
Error in enthalpy balance (adiabatic conditions assumed)	-1.5 to 4.0 Btu lb mole ⁻¹

Refrigeration Cycle (Planned). A standard vapor-compression refrigeration cycle, with temperature and pressure sensors before and after each major component (compressor, condenser, throttling valve, evaporator), will be used to illustrate the thermodynamic analysis of a cycle using a pressure-enthalpy diagram. A secondary objective is to determine the overall and volumetric efficiencies of the compressor.

P-V-T Behavior of Carbon Dioxide. The objectives of this experiment are to measure the P-V-T behavior of CO₂ over a wide range of pressure (50-900 psia) at room temperature, to determine how accurately the data can be fitted by a simple equation of state such as the van der Waals, and to compare the results with values predicted from a generalized compressibility-factor chart and also with published data. A lecture bottle of known volume is evacuated and weighed, and then charged with CO₂ at various pressures; the corresponding masses of CO₂ are measured by difference.

The results that have been obtained by the more meticulous experimenters agree well with published data, and also serve to exemplify the validity of the predictive methods under the range of conditions investigated. The non-ideal behavior of a real gas at elevated pressures is convincingly demonstrated.

Throttling Calorimeter. This simple device causes wet, high-pressure steam to be throttled

isenthalpically to atmospheric pressure. Provided that the high-pressure steam is not too wet, the expanded steam will be superheated. The quality of the high-pressure steam can then be determined from a Mollier diagram (or steam tables) if the line pressure and expanded steam temperature are known.

The experiment has proved valuable in illustrating the use of thermodynamic diagrams for a pure substance, and in clarifying the nature of the isenthalpic flow process.

Maximum Flow in Nozzle. In this experiment, the occurrence of a maximum mass flowrate of a gas through a converging-diverging nozzle is verified. In addition, the observed flowrate and critical throat pressure are compared with values predicted from theoretical isentropic flow equations. The equipment used is a Scott-Armfield Compressible Flow Bench, Model A.E.C.1. The pressure upstream of the nozzle is atmospheric, and a variable subatmospheric pressure on the downstream side is generated by a compressor controlled by a throttle on its discharge.

The concept of a maximum flowrate, which remains constant as the downstream pressure continues to be reduced below a certain value, is very difficult to present convincingly in a lecture. After having performed this experiment, students can hardly deny the evidence, even if they remain skeptical.

Triple Point of Nitrogen. The apparatus, illustrated in Fig. 3, consists of an unsilvered Dewar flask, which permits observation of the contents connected to a mercury manometer and vacuum pump. Temperature inside the flask is measured by a copper-constantan thermocouple, the reference junction being liquid nitrogen boiling at atmospheric pressure in a second, silvered Dewar flask.

Vapor is withdrawn continuously by the vacuum pump from the unsilvered Dewar flask, which contains boiling nitrogen. As the nitrogen is thermally insulated, vaporization causes its temperature to fall. Provided that the rate of vaporization is not too high, the vapor and liquid are approximately in equilibrium. Thus, simul-

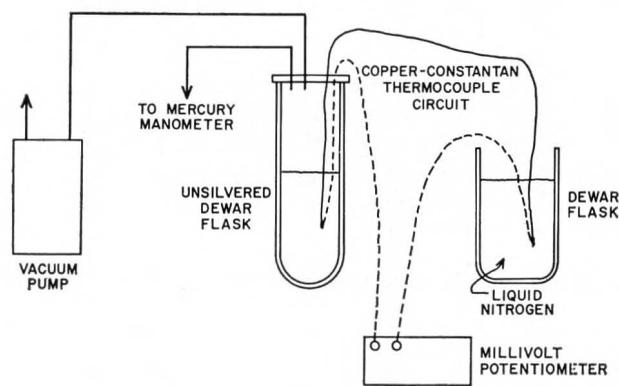


FIGURE 3
APPARATUS FOR TRIPLE POINT DETERMINATION

taneous readings of pressure and temperature can be plotted to yield a saturated vapor pressure curve. When the pressure and temperature have been lowered sufficiently, the triple point is attained, as signified by the sudden appearance of a solid phase.

Results have been surprisingly good in view of the lack of experimental sophistication; values of temperature within 10%, and of pressure within 15% of their accepted values (63.2°K, 0.124 atm [2]) having been obtained by most students. Careful experimentation by the author yielded a temperature within 2% of the accepted value, and a pressure within 3%. The experiment serves both to demonstrate phase behavior of a pure substance and to provide practice in thermocouple thermometry.

Ethanol-Acetic Acid-Ethyl Acetate Equilibrium. The equilibrium

$$\text{C}_2\text{H}_5\text{OH} + \text{CH}_3\text{COOH} \rightleftharpoons \text{CH}_3\text{COOC}_2\text{H}_5 + \text{H}_2\text{O}$$

is approached very slowly at room temperature, but can be achieved in a reasonable time in the presence of a strong acid catalyst such as hydrochloric acid. The equilibrium constant (defined in terms of mole fractions) can then be calculated from the weights of the reactants, and the total acid in the equilibrium mixture as determined by acid-base titration. The mixtures, which are stored at room temperature in small stoppered weighing

The main objective of the overall course is to equip the student with a basic working knowledge of the concepts and practical applications of ChE thermodynamics, thereby also providing an adequate foundation for subsequent undergraduate courses in kinetics and reactor design, transport phenomena, unit operations process design, and for graduate courses in thermodynamics and kinetics.

Despite these shortcomings, however, the concept of reinforcing the classroom experiences with short experiments has proved successful, and should be extended to other suitable courses in the curriculum such as transport phenomena, and chemical kinetics and reactor design.

bottles, are assumed to be equilibrated after one week.

The principal point that this experiment is intended to demonstrate is that the value of the equilibrium constant is independent of the initial and final compositions. Three different initial compositions are employed, two being ethanol and acetic acid in different proportions, the third being ester and water.

As the apparent value of the equilibrium constant is very sensitive to analytical inaccuracies [3], results of the less meticulous students have been considerably scattered. More careful experimenters have achieved remarkably consistent results. However; in the best set of results, the values ranged from 3.7 to 4.1. These results are in accord with published data, which themselves exhibit substantial scatter [3]. Disadvantages of the experiment are its relatively tedious nature (two class periods are required, cf. one period for the other experiments), and the necessity for a relatively skillful experimental technique if consistent results are to be obtained.

INSTRUCTIONAL PROCEDURES

THE LABORATORY PART of the course is introduced by means of several lectures. The first lecture consists of a general orientation, in which the course objectives, physical facilities, safety procedures, and required reports are described. This information is also supplied in a course manual, which includes general information and instructions, experimental instructions including basic references, and a detailed list of lecture topics to which the experiments correspond. In three subsequent lectures, techniques of temperature, pressure, and flow measurement are described. The students are required to augment this information with assigned readings from a reference [4].

As indicated previously, the students work in groups of three, one student being appointed group leader for the duration of the experiment,

which is one class period in most cases. Assignment of group leaders is on a rotating basis within the group. Several days before the experiment is to be performed, all members of the group attend a preliminary conference with the instructor, at which the group leader presents the experimental plans, which he is responsible for developing. The preliminary conference fulfills several functions: it motivates the group leader to prepare adequately, it serves as a forum to clarify misconceptions (which are not infrequent at this early stage in the curriculum), and it enlightens the other group members. Due to the inexperience of the students, fairly close supervision is given during the actual laboratory period.

All students are required to submit a short written report of each experiment. The required format is described by the following excerpt from the instructions.

Introduction—State purpose of investigation, and briefly describe the appropriate theory including the principal equations and the procedure for calculating the final results from the experimentally-measured quantities.

Experimental—Describe the equipment verbally, and by means of a sketch (which should be on a separate sheet of paper). State the variables that were measured, and the instruments used. Indicate what ranges of independent variables were studied, and the basis whereby these ranges were chosen.

Results and Discussion—Present all final results (not raw data) in tables, graphs, or verbally depending on which method affords the greatest clarity. Include a sample calculation. All tables and figures should have a number and title. Discuss the meaning, significance and validity of the results. State possible sources of error.

Conclusions—State concisely all significant information obtained from the experiment. Present each conclusion in a separate, numbered paragraph.

The reports are graded; the cumulative marks count *pro rata* to the overall course grade.

CONCLUSIONS

THE ADDITION OF A series of simple experiments to an established lecture course is a concept novel to the ChE curriculum at Drexel University. In quantitative terms, there has been a

From a quantitative standpoint, there has been a most definite improvement in the students' motivation and interest.

significant upward trend in grade point average, which has recently been in the region of 2.8/4.0 compared with about 2.0/4.0 before the inception of the laboratory. This is not of course a true A-B comparison, but it is generally felt that the average ability of our students has not changed noticeably in recent years. Moreover, ten out of fourteen classes were taught by the author over a period of seven years, which included the transition from a lecture course to the combined lecture-laboratory course. Consistency in standards and grading were thus maintained.

From a qualitative standpoint, there has been a most definite improvement in the students' motivation and interest. The only complaint of substance concerns the lack of multiple set-ups, which results in students performing some of the experiments before the corresponding topics have been covered in the lectures. This situation is dictated by lack of facilities rather than pedagogical philosophy. Whereas students are obliged to study unfamiliar material by themselves, which is salutary to some extent, it would be more effective from the point of view of reinforcement, if multiple set-ups were available to permit parallel operation of the lectures and experiments.

Despite these shortcomings, however, the concept of reinforcing the classroom experience with short experiments has proved successful, and should be extended to other suitable courses in the curriculum, such as transport phenomena, and chemical kinetics and reactor design. □

ACKNOWLEDGMENTS

The author is grateful to many of his colleagues for helpful discussions and suggestions, and in particular to Professor Bernard D. Wood of Syracuse University, who designed the Vortex Tube and Triple Point experiments, and Professor C. William Savery of Drexel University, who designed the P-V-T experiment.

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CARNEGIE-MELLON

Continued from page 106.

well as with people in computer science, applied mathematics and operations research. Art is the Director of the DRC which currently has 17 members. As one cooperative project, they are developing the nonnumeric processing capability of computers to do design.

Prof. Powers is actively studying the use of fault trees, a technology growing out of the aerospace industry, to evaluate process safety and reliability. He is developing methods to synthesize and then analyze fault trees, given the process components and their interconnection. He and Prof. Westerberg are also developing process synthesis techniques. They work on such problems as total process flowsheet synthesis, reaction path synthesis (getting the computer to do chemistry), separation system synthesis, energy recovery network synthesis, and control system synthesis—in each case the idea is to get the computer into the act of suggesting alternative flowsheets. Prof. Westerberg is also working on advanced approaches for performing computer-aided process analysis coupled with optimization.

OVERALL IMPRESSIONS

WHILE CARNEGIE-MELLON University may not be all things to all people, the programs in the areas of Industrial Administration, Drama, Computer Science and Engineering are strong with an unusual emphasis on professionalism. The urban surroundings of Oakland—an area filled with parks, a wide selection of ethnic restaurants, the Carnegie Library and Museum, and Scaife Art Gallery—provide a pleasant setting in which to live and work. Within the Department of Chemical Engineering, the research interests of faculty are diverse, from the abstract to the practical. Although our size is expanding, personal contacts among faculty members, and between the faculty and students, are frequent and continuous. From those first impressions of 1974, as well as from my experience of living here for three years, I conclude that Carnegie-Mellon University, as well as Pittsburgh, is “someplace special.” □

ChE news

Dr. Billy L. Crynes, professor of ChE at Oklahoma State University, has been approved to head OSU's School of Chemical Engineering. Crynes received his B.S. from Rose-Hulman Institute. His M.S. and his Ph.D. are from Purdue University.

CHEMICAL ENGINEERING AND MODULAR INSTRUCTION: A STATUS REPORT

KAREN C. COHEN,¹ JOSÉ ALONSO,²
AND ERNEST J. HENLEY³

THE CHEMI PROJECT, supported by the National Science Foundation and the Cache Corporation, is attempting to produce over 350 single-topic, stand-alone modules spanning the entire undergraduate chemical engineering curriculum. The project is now about two years old; one-third of its modules are completed to at least first-draft stage. This was chosen as an appropriate time, having demonstrated the feasibility of developing such an ambitious set, to gather implementation and dissemination data from the professors of ChE who are the potential "brokers" of these modules.

The ASEE (American Society for Engineering Education) sponsors, with industrial support, a summer college of its Chemical Education (ChEd) Division once every five years. This past summer such a one-week college was run; two members of every department of ChE in the country were invited. Approximately 200 persons chose to attend. This group was representative of ChE education in attitude and geographic distribution. It was decided to use this opportunity to:

- acquaint or reacquaint these engineering educators with the CHEMI Project, and
- obtain attitudinal and potential implementation feedback for the project. As each attendee registered on the first day, he was handed a letter and brief questionnaire, a list of the full anticipated modular set, and a sample module. Instructions were to go through all the material and return the questionnaire within a day.

On the whole, the results were extremely encouraging. 115 questionnaires were handed out; 61 persons returned completed questionnaires or approximately 52% of those who had received

them. The results of the survey were tabulated and then presented briefly at a session the following day, serving as a basis for further discussion and refinement of the findings. Thus, this survey, although based on a small sample (N = 61), yielded findings that are broadly representative and are fairly encouraging regarding the use of CHEMI-type modules in undergraduate instruction. The opportunity to discuss the findings during the meeting itself was well received and resulted in added insight into, or clarification of, some responses.

FINDINGS

THE INVESTIGATORS were particularly interested in the relationship between previous exposure to modular materials (as a student or as an instructor) and perceived implementation advantages and disadvantages in their use. There were a few interesting differences:

Previous Exposure to Modular Material

34 Yes (52%)	26 No (46%)	1 Blank (2%)
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The respondents were fairly evenly divided as to their previous exposure, indicating the possible need for this project and other module development efforts to undertake more hands-on and informational/instructional work about the teaching method. The sophistication of *all* the respondents about modules, in response to later questions, was very high, however; even those who had not used them could list many alleged benefits and drawbacks and apparently had some informed basis for their opinions.

One question asked: "How likely might you be to use modules such as the one provided and those listed in the following situations?" Responses are listed below:

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²Swinebourne Institute of Technology, Australia.

³University of Texas at Houston, Texas.

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TABLE 1
Likelihood of Module Use

	Previous Experience			No Prior Experience			Totals		
	1*	2*	3*	1	2	3	1	2	3
Supplement to Text	25	6	0	22	3	0	45	9	0
Replace Texts	0	8	23	0	6	18	0	14	41
Replace Lectures	5	14	10	2	10	11	7	24	21
Additional Practice	23	5	3	20	4	0	43	9	3
Remediation	16	13	2	18	4	3	34	17	5
Acceleration	14	12	4	15	9	0	29	21	4
Individualized Programs	18	11	2	12	10	2	30	21	4
Resource for Preparing Lectures	1	1	1	18	7	0	19	8	1
Totals**	102	70	45	107	53	34	207	122	78

Other

(Recertification 2)

(Examination Preparation 2)

1* = Very likely

2* = Perhaps

3* = Not likely

**Totals indicate likelihood of module use in any way listed.

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Karen C. Cohen is primarily interested in educational evaluation and graduate science and engineering. She received her B. A. from Harvard and M. A. and Ph.D. from Johns Hopkins University. She is currently on the faculty of M. I. T. with a joint appointment in ChE

In general, module users as well as those without previous exposure held similar opinions, i.e.:

- Modules were most likely to be used as supplements to texts, for additional practice, for remediation, for acceleration, and for individualized programs;
- Modules were not likely to be used to replace texts.

Even more important, in inspecting the data in this table, is the fact that perceived likelihood of module use, for the entire range of purposes listed, is strongly supported both by those with and without previous modular exposure. Without saying that modules can be a panacea for all teaching-learning problems, the respondents were uniformly and strongly positive about the variety of applications listed, with the exception of text replacement.

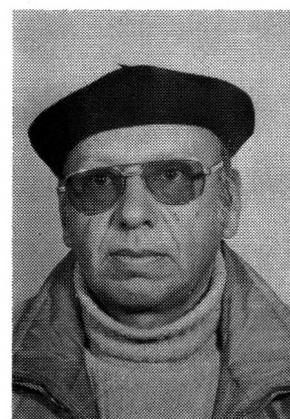
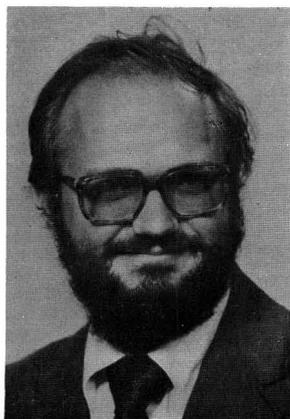
Other uses which respondents suggested on their own were the use of modules for recertification (or continuing education) and for "stealing" or "quality preparation" of examinations.

The only area where there was a striking difference between those with module experience and those lacking it was the item "Resource for Preparing Lectures." Those without experience uniformly felt modules could be a useful resource; those with experience uniformly did not feel they could be used that way. Further discussion of this issue indicated that many professors not acquainted with modules had thought the "hour's length" could be a pre-packaged lecture.

The next question involved the preference of respondents for module availability, allowing for

and the Div. for Study and Research in Education. Part of her work involves co-directing Project PROCEED (Program for Continuing Engineering Education). She also directs the Center for Educational Research and Development at WPI. The author of several books of evaluation strategies and evaluation reports, she was a consultant to the effort reported here. (C)

Professor Ernest J. Henley has been a professor of chemical engineering at the University of Houston, since 1964. He received his Ph.D. from Columbia University in 1953 and has been on the faculty of Columbia University and Stevens Institute of Technology. (R)



only two options: to purchase sets of individual modules or single modules with reproduction rights.⁴ The preference seemed to be for single copies with rights to reproduce them:

TABLE 2
Ordering Preference

	1st Choice	2nd Choice	3rd Choice (other)
Order one copy with right to reproduce	32	8	2
Order sets	12	18	0
Other	2	1	0

Concomitant with preference for in-house reproduction was the nearly universal (all but 1 respondent) feeling that costs of such reproduction could be recovered from students. The modal response was that recovery of costs would be "fairly easy to do."

TABLE 3
Recovery of Reproduction Costs

	N
Cannot	1
Very Difficult	10
Some Effort	16
Fairly Easy	28
Don't Know	2
Other	0

The responses, taken together, while they do not compare modules with other possible modes of instruction, seem to indicate that ChE professors see modules as an additional, valuable resource for a variety of purposes. They would probably like to own (or have available) the entire CHEMI set to use when, where, and in those quantities they see fit. Recovery of in-house reproduction costs does not appear to loom as a large problem.

When professors were asked to list topics in addition to those planned for the project which they would like to see developed, a very small number of suggestions were made. Generally, the entire undergraduate field seemed to be considered covered.

Finally, we were interested in the advantages and drawbacks respondents saw in modular use

- for the student,
- for the teacher, and
- for the administration.

The most striking finding involved the variety

⁴Far more detailed questions were asked of college mathematics instructors regarding such options with results available privately from William Walton, Director, Project Calc, EDC, 55 Chapel Street, Newton, Massachusetts.

in the responses. It was nearly impossible to develop meaningful coding categories for these open-ended questions that would capture, without forcing, the essence of more than two or three responses. The complete array of responses to each item appears below. Probably the most important result of this survey is the fact that one set of materials, these single topic CHEMI modules, is seen as potentially meeting a large number of diverse needs for a large number of people.

More specifically, the following *advantages* were cited:

TABLE 4
Perceived Modular Instructional Advantages

	Previous Exposure	No Exposure	Total
a) For the Student			
Self-pacing	10	9	19
Motivation	8	1	9
Acceleration/fuller coverage	5	4	9
More perceived structure/ better presentation	6	1	7
Supplement to lectures	3	0	3
Efficient review/remediation	2	0	2
Avoid problem of not knowing prerequisite	2	0	2
Good introduction	0	2	2
Same instruction for all	1	0	1
No lecture requirement	1	0	1
Easier learning	1	0	1
Organized to individual needs	0	1	1
Rich variety	1	0	1
Easy availability	1	0	1
Helpful for project work	0	1	1
Clear definition of objectives	0	1	1
Better understanding	0	1	1
Don't have to copy notes	1	0	1
Make up missed lectures	1	0	1
Less formal than books	1	0	1
Minimum cost	1	0	1
A new way to learn	1	0	1
TOTAL	47	21	68
	Previous Exposure	No Exposure	Total

b) For the Teacher

Broader coverage	6	0	6
Crutch	0	6	6
More time for 1:1 help	3	2	5
Another view presented	4	0	4
Same presentation to all students	2	0	2
Course planning aid	0	2	2
Make-up assignments	0	2	2
Back-up, lecture replacement	0	2	2
Remediation	1	1	2
Transfer learning responsibility to student	1	0	1
Acceleration	1	0	1

Extra instruction	1	0	1
Less preparation time	1	0	1
Cover more effectively	1	0	1
More current	1	0	1
Turn lectures to discussions	1	0	1
Easier feedback	1	0	1
Thoroughness	1	0	1
TOTAL	25	15	40

Without saying that modules can be a panacea for all teaching-learning problems, the respondents were uniformly and strongly positive about the variety of applications listed, with the exception of text replacement.

Responses regarding administration advantages were meager, and are not reported for that reason.

In the same vein, the following *disadvantages* were cited:

TABLE 5

Perceived Modular Instructional Disadvantages

	Previous Exposure	No Exposure	Total
a) For the Student			
None	7	6	13
Impersonal (lack of contact with professor)	3	2	5
Mastery feeling, only crutch	0	3	3
Unfamiliar method	2	0	2
Level of material varies	2	0	2
Without care can become fragmented	1	0	1
Continuity	1	0	1
Some students go slower	1	0	1
Not every student will succeed	1	0	1
Inconsistent nomenclature	1	0	1
Must include references to fill gaps	1	0	1
Harder to use as future reference	1	0	1
Different presentations from each author	1	0	1
Allows student to procrastinate	1	0	1
"Spoonfeeding"	1	0	1
Poor reproduction	1	0	1
Quality below text	1	0	1
Less interaction	1	0	1
Too many sets of paper, hard to keep together	1	0	1
Lock & key simplistic approach	1	0	1
More may be expected of student	1	0	1
Easy to fall behind	0	1	1
Some students respond negatively	0	1	1

Cost	0	1	1
Faculty use carelessly	0	1	1
TOTAL	31	15	46
	(-7	(-6	(-13
	None	None	None
	= 24)	= 9)	= 33)

b) For the Teacher

None	6	6	12
Modules not synchronized	9	1	10
Modules are a "crutch"	0	7	7
More teaching time, planning	2	1	3
Impersonal	1	1	2
Less chance to explore	1	1	2
Author's personality is too strong	1	0	1
Too dry	1	0	1
Texts are easier to use	1	0	1
Hard to get all modules to students	1	0	1
Hard to tell students have learned	1	0	1
Suppress superiority and innovation	1	0	1
Danger to expect too much	1	0	1
"Continuous contact with bitching students"	1	0	1
Lack of contact with students (if desired)	1	0	1
Hard to tell	1	0	1
Unfamiliar method	1	0	1
Difficult to "time up" the lectures to program of the class	0	1	1
May be superficial	0	1	1
Students procrastinate	0	1	1
TOTAL	30	20	50
	(-6	(-6	(-12
	None	None	None
	= 24)	= 14)	= 38)

Again, administration drawbacks cited were sparse and relatively trivial.

These comments indicate that the professors responding see far more advantages than disadvantages to modular use for students. The fact that the most frequently written "drawback" for both teachers and students was "None," and far outweighed any other perceived drawback (except lack of "synchrony" for those with previous exposure), indicates an openness, interest, and willingness to experiment with modules. Indeed, in the general discussion about the CHEMI Project and the results of the survey, there was disappointment expressed that the entire set was not available immediately both for examination and for use. In addition, the general tenor of the totally open ended comments (Question 8, other Continued on page 142.

SIMPLE AND RAPID METHOD FOR DETERMINING THE VAPOR PRESSURE OF LIQUIDS BY GAS CHROMATOGRAPHY

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CHEMICAL ENGINEERING COURSES, particularly in the field of transfer phenomena, include numerous calculations involving many physico-chemical data. Frequently, such calculations are designed to solve real industrial problems. It is not unusual, however, that the required physico-chemical data are not readily available in the literature. In these cases the data have to be either estimated or determined by some suitable experimental method.

For example, in calculations related to distillation the student has to evaluate the boiling temperatures of the major components of the mixture at a given working pressure. For this purpose the Clausius-Clapeyron or the Antoine equation is very often used. When the parameters for either equation are not known, it is advisable to determine them experimentally by measuring the vapor pressure as a function of temperature, instead of using the simple Trouton's rule for which in fact the data might also be unavailable.

However, among the several experimental methods commonly used for vapor pressure determination, only a few could easily be adapted for undergraduate laboratory courses. Those few, furthermore, would be rather time consuming. Therefore to encourage students' interest in experimental methods and to teach them to seek the experimental determination of missing physico-chemical parameters whenever possible, we have developed a simple and rapid method of vapor pressure determination. The description of this method, employing a gas chromatograph is the

subject of the present work. This method was successfully adopted for undergraduate laboratory courses at the Institute du génie chimique de Toulouse (France) and requires one laboratory session.

PRINCIPLE OF THE METHOD

A SUITABLE AMOUNT OF a liquid sample of low vapor pressure is injected into the chromatograph and completely vaporized at high temperature. The carrier gas containing the vaporized sample then passes through an empty column kept at a temperature below that of the injection port and below the boiling point of the sample. On passing through this cooler region, a part of the sample condenses on the walls, leaving

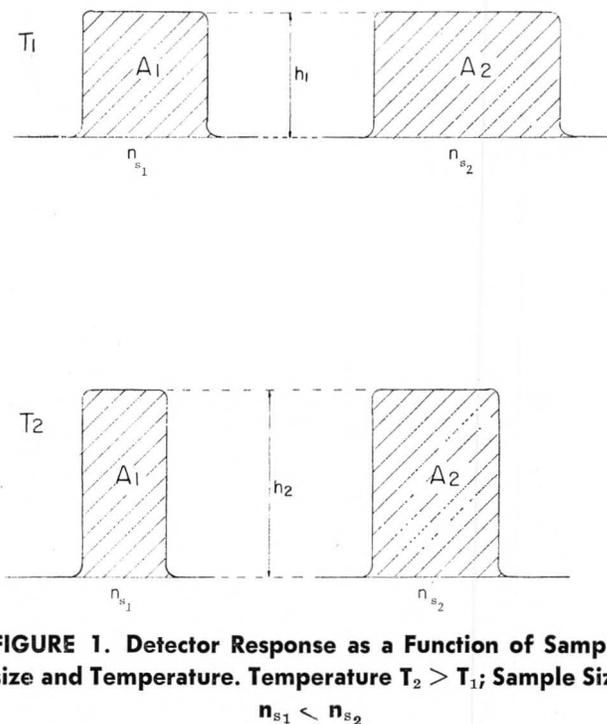


FIGURE 1. Detector Response as a Function of Sample size and Temperature. Temperature $T_2 > T_1$; Sample Size $n_{s_1} < n_{s_2}$

the carrier gas saturated at the temperature of the empty column. The sample-free carrier gas meanwhile entering the column becomes saturated on passing through the tube containing the condensed sample until the amount injected is completely taken up. The saturated carrier gas passes through the detector which monitors the instantaneous sample concentration in the carrier gas and the total amount of the sample injected. Thus, the response of the detector is recorded as an area resembling rectangle (instead of a peak) whose height depends, for given sensitivities of detector and recorder, on the concentration of the sample in the carrier gas *i.e.* its vapor pressure. The width of the recorded rectangular area depends on the total amount of the sample injected (see Fig. 1).

The equations relating the vapor pressure, the detector response and the total amount of the sample may be derived as follows.

The partial pressure of a sample P_s can be related to the pressure of the carrier gas P at the end of the empty tube by

$$P_s = x_s P \quad (1)$$

where x_s is the mole fraction of the sample in the carrier gas.

For very low concentrations, the mole fraction of the sample in the carrier gas can be approximated by

$$x_s = \frac{n_s}{n_s + n_c} = \frac{n_s}{n_c} \quad (2)$$

where n_s is the number of moles of the sample and n_c is the number of moles of the carrier gas, per unit volume.

The response of a detector, expressed in terms of the signal voltage E , is related to the mole fraction of the sample in the carrier gas passing through the detector and a proportionality constant k by

$$E = k \frac{n_s}{n_c} = k x_s \quad (3)$$

The proportionality constant k depends on the conditions of experiment and can be expressed as

$$k = C_1 C_2 C_3 \alpha \quad (4)$$

where C_1 is the recorder sensitivity in mV/cm, C_2 is the reciprocal chart speed in min/cm, C_3 is the flowrate of the carrier gas in moles/min, and α is the response area per mole (cm^2/mole), *i.e.* the ratio of recorded area A to the total number of moles n_s of the sample.

From eq. 3, the unknown value of x_s (instantaneous mole fraction of sample s) is given by

$$x_s = \frac{E}{k} \quad (5)$$

Expressing E in terms of the recorder sensitivity C_1 and the height h of the recorded area, we have

$$E = h C_1 \quad (6)$$

and x_s becomes, from eq. 4, 5 and 6

$$x_s = \frac{h C_1}{C_1 C_2 C_3 \alpha} \quad (7)$$

Thus from eq. 1 and 7 the vapor pressure of a

... to encourage students' interest in experimental methods and to teach them to seek the experimental determination of missing physico chemical parameters whenever possible, we have developed a simple and rapid method of vapor pressure determination.

sample can directly be related to the recorded detector response h as:

$$P_s = \frac{h}{C_2 C_3 \alpha} P \quad (8)$$

The parameter $\alpha = \frac{A}{n_s}$ has to be determined by calibration.

EXPERIMENTAL

THE PROCEDURE FOR THE experimental method just described is relatively simple. The chromatographic column of the apparatus is replaced by an empty tube, preferably of stainless steel (9-12 ft long and 1/8 in diameter). This tube has to be carefully thermostated and its temperature precisely measured. In our experiments we used thermocouple. The temperature of the injection port and that of the detector are higher than the temperature of the empty column; high enough to assure a complete vaporisation of the injected sample and to prevent any condensation on the detector. The flowrate of the carrier gas has to be kept constant throughout the experiment and the calibration. It is usually measured in terms of ml/min by means of a soap-bubble flowmeter. In this case, the measured volume flowrate

C'_3 is converted into the mole flowrate C_3 (moles/min) by using the equation:

$$C_3 = C'_3 \frac{(P - P_{H_2O})}{R T_a} \quad (9)$$

where R is the gas constant, T_a is the ambient temperature at which C'_3 has been measured, P_{H_2O} is the vapor pressure of water at T_a and P is the pressure of the carrier gas.

While the parameters C_1 , C_2 and C_3 can be pre-selected and kept constant for a series of experiments, the ratio $\alpha = \frac{A}{n_s}$ has to be determined by calibration.

To calibrate the apparatus i.e. to determine α , a known amount of a sample dispensed from a syringe (can be determined by weighing) is injected into the system and a corresponding response is recorded. The response area is measured by means of an integrator, or other suitable method.

RESULTS AND DISCUSSION

THE MAIN ADVANTAGE of the described method is its simplicity and relatively short experimental time. However the method has certain limitations, and its success depends on the degree of a dynamic equilibrium achieved in the "cold" column and on the precision of calibration.

To assure the equilibrium vapor pressure of the investigated sample, low flowrate of carrier gas and a relatively long, small diameter column should be used. The amount of sample has to be large enough to assure that a substantial portion condenses in the empty column. However, it is important that the instantaneous sample concentration in the carrier gas always lies within the concentration range of the linear response of the detector. Thus the method is limited to liquids with low vapor pressures at the temperatures used.

For calibration, a wider range of sample size should be used to verify the constancy of the α factor.

The vapor pressure data determined at different temperatures can be fitted to either the Clausius-Clapeyron equation:

$$\log P_s = A - \frac{B}{T} \quad (10)$$

or to the Antoine equation:

$$\log P_s = A' = \frac{B'}{t + C} \quad (t = ^\circ\text{C}) \quad (11)$$

depending on the particular liquid.

To verify the method, we have chosen dicyclohexyl and cyclohexylbenzene. For dicyclohexyl the data were fitted to the Clausius-Clapeyron equation and the parameters A and B were determined by using the least squares method:

$$A = 8.21, B = 2712.8$$

The correlation coefficient of this fit was $r^2 = 0.9997$. The cyclohexylbenzene data were fitted to the Antoine equation and the following parameters were obtained:

$$A' = 7.562, B' = 2162.0, C = 223.5$$

In this case the correlation coefficient was $r^2 = 0.998$. These results agree very well with those obtained by other methods [1]. □

REFERENCES

1. J. A. Riddick and W. B. Bunger, "Organic Solvents", 3rd Edition, Wiley-Interscience (1970).

ChE AND MODULAR INSTRUCTION

Continued from page 139.

comments) conveyed general high hopes and expectations for the project and enthusiastic anticipation for its products.

SUMMARY AND CONCLUSIONS

THE BRIEF SURVEY, administered to the entire ChEd college sponsored by the ASEE (attended by representatives of most institutes and universities where ChE is taught), was returned by over 25% of those receiving it. The survey indicated that participants held a fairly uniform view of the value of modular materials for remediation, acceleration, self-pacing, individualization and more thorough coverage of topics. In brief, they were thought to be a marvelous resource. Respondents who had had previous experience with modular materials (about 50%) had more specific opinions than those without such experience (hardly a striking finding). But the general tone, the serious nature of the comments, and the thoroughness of responses indicates a real concern with teaching effectiveness, and hope and expectation that the completed set of CHEMI modules will be able to improve teaching effectiveness in a variety of ways. □

**FOUNDATIONS OF CONTINUUM
THERMODYNAMICS**

J. J. Delgado Domingos, M. N. R. Nina, J. H. Whitelaw, eds. Halsted Press, 1973. \$29.95

Reviewed by J. C. Melrose, Mobil Research and Development Corp.

This volume constitutes the proceedings of an International Symposium on the Foundations of Continuum Thermodynamics, held in Bussaco, Portugal, in 1973. Contributors to the proceedings include many of the most prominent physicists, chemists, engineering scientists, and applied mathematicians who have been active in this field in recent years. A slight majority, perhaps, of the papers will appeal primarily to those chemical engineers who adhere to the traditional view of both equilibrium and non-equilibrium thermodynamics. According to this view, thermodynamics provides a framework within which the phenomena of molecular physics are manifested as relationships among macroscopic parameters. The remainder of the papers, on the other hand, will be of primary interest to those who find inspiration in the various degrees of mathematical complexity by which the so-called constitutive relationships of continuum mechanics can be formulated.

Among the contributors who approach the subject primarily from the point of view of molecular or statistical theory are Tisza, Callen, Prigogine, Schlogl and de Groot. The papers by these authors, along with that by Professor J. Meixner, a founder of the subject of irreversible thermodynamics, form the centerpiece of the Symposium proceedings. Protagonists representing the continuum mechanics point of view include Muller, Rivlin, Lee, Nemat-Nasser, Mandel and Pina. An introductory paper by the principal organizer of the Symposium, Professor Delgado Domingos of Lisbon, is a noteworthy review of current conceptual problems in the latter field.

An interesting feature of the book is the inclusion of five discussion papers, as well as contributions in the form of discussion remarks. These follow nine of the eleven principal contributions. A summary paper by P. Germain deals with what was intended to be a major objective of the Symposium. This objective was the reconciliation of the vastly different approaches to the physical foundations of thermodynamics which are commonly followed by the practitioners of the

two schools of mechanics: statistical and continuum. Since Germain is a representative of the latter school, his desire "to conclude on a peaceful note" is refreshing.

As may be inferred, this book is not recommended for students who are just beginning a study of the subject of thermodynamics. On the other hand, it can be highly recommended to those who, with teaching responsibilities, are perplexed by the differing approaches just alluded to. Of particular value, in the reviewer's opinion, are the discussion paper and discussion remarks of Professor J. Kestin of Brown University. Kestin points out some common difficulties of a semantic nature and stresses the importance of using terms such as thermodynamic state and thermodynamic process in a precisely defined and consistent way.

For those who may be intrigued by the appearance of greater generality which is engendered by the mathematical formalism of continuum mechanics, the two papers by D. G. Miller of the Lawrence Livermore Laboratory and E. A. Mason of Brown University are recommended. Miller's contribution reviews the present status of the experimental evidence for the validity of the Onsager reciprocal relations. Miller also discusses the well-known criticisms of irreversible thermodynamics by certain practitioners of the school of continuum mechanics. He concludes that these criticisms are overstated and issues a challenge to this school to supply arguments of a macroscopic nature by which the reciprocal relations can be derived. Professor Mason in his discussion paper provides some stimulating arguments to support Miller's challenge and suggests that the Onsager reciprocal relations be elevated to the status of a scientific paradigm (to adopt the terminology of T. S. Kuhn).

As a final comment by one who has attended several conferences of the syncretistic type represented by the Bussaco Symposium, this reviewer would like to put forward the following proposition. Stated as a theorem of unattainability, the proposition is that the ostensible objective of such a conference can never be achieved. The backgrounds, favorite approaches, and basic interests of the two schools are ultimately too divergent to be reconciled. This is not to say that this and previous conferences have not been highly successful. On the contrary, the proceedings of the Bussaco Symposium provide a stimulating record of what was clearly an outstanding meeting, devoted to one of the most central subjects in physical science. □

THEORETICAL RHEOLOGY

Edited by J. F. Hutton, J. R. A. Pearson, and K. Walters

Halsted Press, Wiley, New York, 1975. (\$25.00).

Reviewed by Chris Macosko

University of Minnesota

The last two years have brought a welcome surge of rheology text books. Messieurs Lodge (1974), Astarita and Marrucci, (1974) Huigol (1975) Walters (1975) and Han (1976) have all contributed recent volumes to the field and several other authors are preparing new manuscripts. John Wiley's Halsted Press Division who published the texts by Huigol and by Walters have also added a very nice collection of papers in "Theoretical Rheology." As the title facing page indicates it is "The Proceedings of the British Society of Rheology Autumn conference on Theoretical Rheology held at the University of Cambridge" in fall 1974. It is not a text book nor is it totally theoretical. It is a useful rheology reference book and is highly recommended to libraries and researchers in the field. It is of course not timeless but a number of good review-type papers appear in it. It does have a respectable index. The papers are typeset and printing quality is good including an admirable effort at uniformity of notation. Below is a list of the titles and authors.

Section 1: Converging and Diverging Flow

1. Creeping Flow of a Viscoelastic Liquid Through a Contraction: A Numerical Perturbation Solution. Jesse R. Black, Morton M. Denn and George C. Hsiao.
2. Deceleration of Viscoelastic Liquids. A. L. Halmos and D. V. Boger.
3. Plane Entry Flows of Viscoelastic Fluids. S. Zahorski.
4. Stability and Overstability of the Plane Flow of a Simple Viscoelastic Fluid in a Converging Channel. Karl Strauss.
5. Hydrodynamic Factors Affecting the Growth of Fibrous Crystals of Extended-Chain Polymers. M. R. Mackley.

Section 2: Thermomechanics

6. The Thermomechanics of Materials with Fading Memory. R. S. Rivlin.
7. Rheological Equations of State and Thermodynamic Principles. J. G. Oldroyd.
8. A Non-Isothermal Theory of Viscoelastic Materials. Marcel J. Crochet.
9. Thermomechanics of Compressible Materials with Entropic Elasticity. Gianni Astarita and Giulio Cesare Sarti.

Section 3: Composites and Suspensions

10. Finite Deformations of Strongly Anisotropic Materials. Tryfan G. Rogers.

11. Balance Laws for Mixtures of Granular Materials. S. L. Passman.
12. Mechanical Properties of Semicrystalline Polymers Regarded as Composite Materials. J. L. Kardos, J. C. Halpin and L. Nicolais.
13. The Mechanics of Fluid Suspensions. E. J. Hinch.
14. The Effect of the Non-Newtonian Properties of a Suspension of Rod-like Particles on Flow Fields. J. G. Evans.

Section 4: Rheometry

15. Progress in Experimental Rheology.
16. The Start-up of Steady Elongational Flow of Viscoelastic Materials. M. C. Phillips.
17. Some New Validity Tests on the Bird-Carreau Type Constitutive Equations. H. E. van ES, H. A. M. van Eekelen and M. C. Phillips.
18. The Theory of a Universal Oscillatory Rheometer for the Study of Linear Viscoelastic Materials Using the Principle of Normalised Resonance. M. Sherriff and B. Warburton.
19. Correlations Between Linear and Non-Linear Viscoelastic Data for Polymer Solutions. B. Hlavacek and P. J. Carreau.
20. The Effect of the Non-Newtonian Properties of Polymer Solutions on Flow Fields. Gianni Astarita and Morton M. Denn.
21. Report of the Discussion. J. F. Hutton.

ChE news**JOHN QUINN RECEIVES BENT PROFESSORSHIP**

John A. Quinn, Professor of Chemical and Biochemical Engineering at the University of Pennsylvania, was recently named to be the first recipient of the Robert D. Bent Professorship. The Professorship was established by a \$1,000,000 grant from the Atlantic Richfield Foundation to honor Mr. Bent who retired recently as President of the ARCO Chemical Co. and Senior Vice President of the Atlantic Richfield Co.

Professor Quinn earned his bachelor's degree in chemical engineering from the U. of Illinois in 1954 and his doctoral degree, also in chemical engineering, from Princeton U. in 1959. He joined the faculty of Chemical and Biochemical Engineering at the U. of Pennsylvania in 1971 after having been a member of the chemical engineering faculty at the U. of Illinois for 12 years. His research interests focus on interfacial phenomena, problems related to transport through membranes, and bioengineering. Professor Quinn was recently recognized for his distinguished academic career in chemical and biochemical engineering by being named to membership in the National Academy of Engineering.

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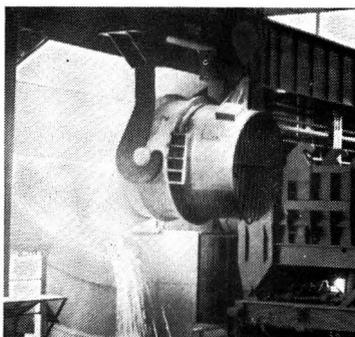
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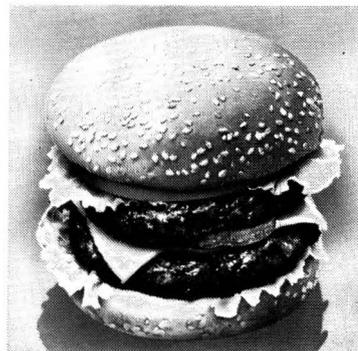


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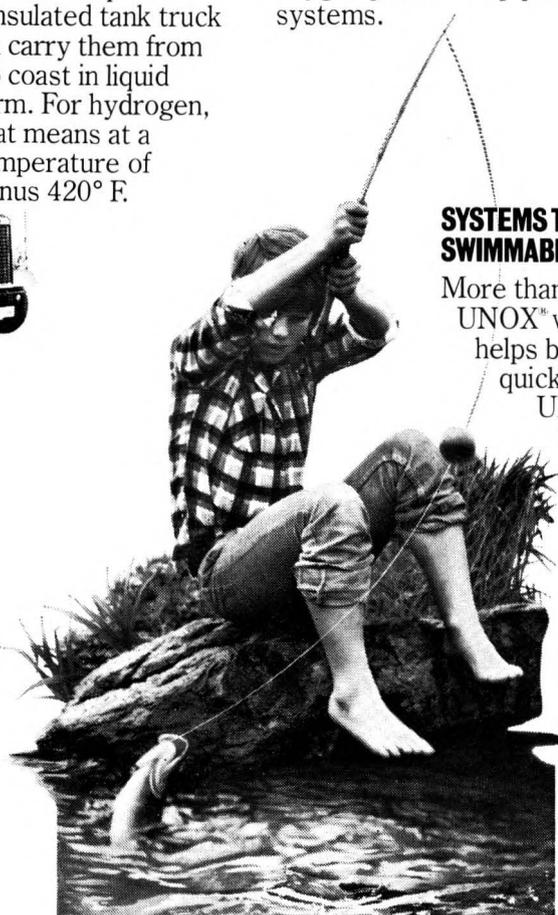
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