Two Courses in

FLUID MECHANICS

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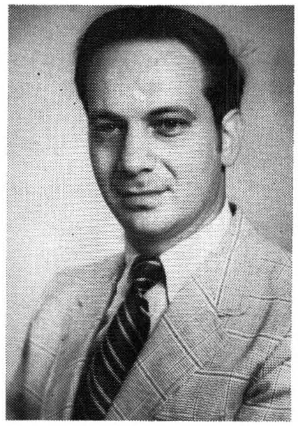

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FLUID MECHANICS plays a central role in many problems of interest to chemical engineers, yet it is only in recent years that courses have been developed which meet the unique requirements of the chemical engineer, as distinguished from the traditional aerodynamical orientation of the subject. For example, chemical engineers need to devote considerable attention to moderately slow flows of viscous materials, frequently in the laminar regime, and in many cases the problems are associated with the flow of complex materials with a memory for their deformation history. It is in recognition of needs such as these, taken together with the more traditional fundamentals of the subject, that we have developed our graduate courses.

The fluid mechanics program at the University of Delaware is typical in structure and philosophy of the way in which we do most of our graduate instruction. There are three levels of activity. The first course is designed partly to strengthen and supplement the student's undergraduate understanding of an area, and partly to develop more general and more powerful analytical tools. The course emphasizes material which is likely to be of design importance to the student, Masters or Ph.D., who goes into industry. We offer the basic fluid mechanics (and thermodynamics) course during the fall semester so that a firm foundation in fluid mechanics can be assumed and efficiently built upon in the basic heat and mass transfer and kinetics and reactor analysis courses offered in the spring.

The second level course, offered in the spring or summer in this subject, is provided for those students with a particular interest in fluid mechanics and proceeds to the frontiers of the area. This course is "team-taught" by four or five faculty, each emphasizing his own particular research specialty. In this course the distinction between student and instructor is no longer as great, and postdoctoral fellows may participate in both roles, as do advanced graduate students. Finally, we have regular seminars which are primarily for the benefit of faculty and students with research interests in an area. In these the student-faculty role is, ideally, completely blurred. Such seminars are probably common to all good departments of chemical engineering and differ only in the specific subject areas of interest. (During each semester of the recent academic year we had two seminars in areas of fluid mechanics, one emphasizing two phase flows, the other viscoelastic fluid mechanics.) In the discussion which follows we shall emphasize only the two courses, which we believe have been quite successful and may be somewhat unique.

BASIC COURSE IN FLUID MECHANICS

ALL OF OUR graduate students are from other departments and bring to Delaware a variety of experiences in undergraduate in-

The first course emphasizes material of design importance and the second level course carries one to the frontiers of the subject.

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struction. Though undergraduate courses in fluid mechanics have become increasingly rigorous in recent years, the new graduate students rarely have a firm fundamental understanding of the subject. This may be due in part to the continuing aerodynamics bias of many undergraduate courses in which, because interest is confined to Newtonian fluids, no clear distinction is made between *basic conservation principles* and *constitutive approximations*. As a result we find it efficient to start from the beginning and to develop the entire subject in an orderly manner which carefully distinguishes between rigorous principles and necessary, but often crude, approximations, and which emphasizes chemical engineering interests. Since the students are a select group it is possible to proceed rapidly with material which has been covered in part before and so any partial redundancy does not result in appreciable loss of time. The following course outline has been utilized for several years.

Our course begins with a consideration of the algebra and calculus of teensors. This represents the "natural" language when dealing with fluids exhibiting complex physical properties and is thus the doorway to much of chemical engineering fluid mechanics, as well as providing for an increased efficiency in the way in which classical material may be treated. The initial material is thus intended to serve as a foundation for all of non-linear continuum mechanics. The specific subjects covered include addition, subtraction, and multiplication of tensors; tests of tensor character; the metric and conjugate metric tensors; and the significance of tensorial and physical components of tensors. The Christoffel symbols are developed and differentiation of tensors is considered in some detail.

The notion of stress and the equations expressing the basic conservation principles, conservation of mass, momentum, and energy, are developed in a fixed Cartesian coordinate framework. Utilizing the algebra and calculus of tensors developed earlier, these equations are then efficiently transformed into other coordinate systems. A significant number of example problems are provided both at this point and previously to enable the student to develop competence and confidence in his ability to understand the basic conservation principles and to derive them for any coordinate system of interest in a given problem.

Thirdly, constitutive approximations for purely viscous fluids are introduced. Since the thermostatic constitutive equations for fluid density and internal energy are the simplest to understand, these are considered first. Following a quantitative description of deformation rate and vorticity, the rheological constitutive equations for description of the stress-deformation rate relationships for purely viscous fluids are developed. Some simple constitutive approximations for the stress-deformation rate relations of viscoelastic liquids may be introduced as well. Finally, for purposes of completeness, though in fact little use is made of this in the first course, the constitutive equations for relating heat fluxes to the temperature field are also introduced and illustrated by means of a few example problems.

The above provides the student with a sound understanding of the difference between those equations which represent universally valid descriptions of conserved quantities and the perhaps crass and empirical nature of the constitutive equations introduced to describe the psysical properties of particular materials. Unidirectional flow problems are now solved in large quantity. These enable the student to proceed by first applying the general relationships, in order to describe the problem as fully as possible without introducing empirical approximations, and then, when he has gone as far as he can on a perfectly general basis, to introduce the appropriate linear or nonlinear constitutive description necessary to provide enough information about the material being processed in order to obtain a solution to the required problem. These problems also serve to introduce the student to the methods of measuring pertinent physical properties of fluids. Incidentally, the student quickly learns through these simple flow problems that the usual way of solving problems in fluid mechanics is to anticipate the form of the answer in advance and then to construct the details of the solution by using the conservation principles and constitutive approximations. This sequence is implied in all treatises on fluid mechanics but rarely stated.

Simple flow problems are usually confined to laminar flows, and we next introduce the student to the simplifying approximations of Prandtl for flows which are nearly unidirectional and in which the Reynolds number is large. This area of boundary layer theory is used to sharpen the abilities of the student to make simplifying approximations, rather than to solve a large number of problems of interest onl yto the aerodynamicist. The presentation in this part of the course is classical, except that the important pedagogical contributions of Acrivos are used in order to illustrate clearly the fact that one can obtain much information from the differential equations without solving them fully.

Finally, we deal with the nature of turbulent flow, its description by means of the Reynolds equations, and the approximate solutions to these obtained by individuals such as von Karman, Taylor, Prandtl and Milliken. This does not provide any insight into the more recent developments in turbulence theory but it does provide the student with essentially all of the information on turbulence which is of design value at the present time.

SECOND LEVEL COURSE IN FLUID MECHANICS

THE FIRST COURSE provides the student with the basic mathematical skills necessary for work in all areas of fluid mechanics and additionally provides him a substantial body of design information and an ability to develop this for himself when new problems are encountered. It has not, however, taken him to the forefront of current research activities in any of the areas enumerated. This is achieved in the second course by subdividing the total course into four or five sections, each of which is taught by an individual who is an active researcher in the specialty being considered. This "team teaching" requires a great deal of faculty time but it represents an extremely effective way of taking a substantial number of students to the frontiers of research in a variety of areas. The subjcts covered vary from year to year depending upon when an area was last taught and the special interests reflected in the research activities in the department.

In the 1969-70 academic year the following topics were covered:

1. Stability theory, including the linear theory and both exact and approximate solution techniques. (In other years we have also included the nonlinear sufficiency theory fol'owing Serrin and the eigenfunction solutions for nonlinear problems following Stuart and later workers.)

2. Turbulence, including a careful development of multipoint correlation functions and the von Karman-Howarth equation, spectral energy and transfer functions. Closure techniques, both classical and the recent work of Kraichnan, are considered in substantial detail.

3. Shock phenomena, including the elements of compressible flow and development of shock waves, shock tubes for high temperature research, shock structure, and shock formation in relaxing gases and viscoelastic media.

4. Deformation and flow of viscoelastic materials, including the proper description of fluids with a memory for previous deformation states, methods of determining physical properties, behavior in flow fields with large Weissenberg or Deborah numbers, consequences of finite shear wave propagation, the peculiar effects of vorticity upon stress levels in visco-elastic media and approximations employing a diagonal deformation rate tensor.

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Topics covered in 1968-69 included the structure of interfaces and surface waves; bubble and droplet formation, motion, and coalescence; low Reynolds number hydrodynamics; turbulence and shock phenomena. Other topics covered in recent years have included two-phase flows of gas-liquid mixtures and fluidization, though the fundamentals of the former area are now usually treated during the first weeks of the regular seminar on that subject and the latter in the second level course on reactor analysis. During the coming year we expect that new faculty additions will enable the inclusion of material on surface tension driven flows and transport at high Knudsen numbers. A recent grant for the strengthening of the department will enable us to bring to the campus distinguished visitors in greater numbers. Prof. G. Marrucci participated in this course in 1968-69 and in 1970-71 the expertise of Prof. V. K. Stokes in the area of liquid crystals and other anisotropic media will enable the presentation of this subject, especially significant for its removal of cobwebs concerning the role of angular momentum and its conseration. In future years we look for

The courses represents our attempt to provide a background in fluid mechanics which is uniquely of value to the chemical engineer faced with gunks and goos, multiphase flows and instability phenomena, as distinguished from the usual aerodynamics bias of the subject.

coverage of numerical methods in fluid mechanics in an intense way, biomedical topics and — if current research in several locations is successful —the use of fluid mechanics to control polymeric crystallization processes.

Thus, a Ph.D. candidate with a strong interest in fluid mechanics can move to the frontiers of 7-10 areas, in a painless way, during his tenure. Perhaps even more important than the factual material covered is the clear manner in which a substantial number of complimentary approximation techniques can be brought to bear on various aspects of the subject, and the role and limitations of each. Too, the greatest weaknesses — the simplistic empiricism of almost all constitutive approximations, both thermodynamic and rheological — emerge vividly and focus attention on areas of research in which the chemical engineer is peculiarly well qualified to play a role.

IN SUMMARY, we have attempted to describe the separate roles and goals of our first and second level courses in fluid mechanics. Similarly structured is the presentation of heat and mass transfer, chemical kinetics and reactor design, and for the first time this year, thermodynamics. We believe such multi-level instruction to be important and exciting.

BIOENGINEERING: Leonard

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are done, mostly by the students in small groups, using modern equipment.

Participating in this much biological course work takes about one-half of a student's time for a calendar year. How he spends the balance of this time may importantly influence his professional attitude. So much biological course work is not intended to convert the engineer into a biological scientist. Contact with and progress within the engineering curriculum should be maintained during this period. However, challenging courses in engineering which do not relate to bioengineering create a disturbing intellectual bifurcation in students at this stage. At least two semester-courses which integrate engineering with biology should be available. Such courses are difficult to construct. At Columbia we have used a bioengineering seminar at which contemporary research problems are discussed, about 50% by guest speakers, 25% by students in research, and 15% by engineering faculty. The seminar is school-wide, but because of the particular composition of interests at Columbia, more than half of the subjects are of direct interest to those with chemical engineering backgrounds. So broadly based a seminar might not be effective in other circumstances. Frequently, students will be beginning a thesis or research paper while taking biological courses. This effort may provoke satisfactory integration of concepts, but at a high cost in faculty time.

AT WHAT STAGE of education should such studies be undertaken? At present it seems best to begin at the master's level. To satisfy minimum point requirements in engineering at many schools, the M.S. program may need to be extended in time and credits. However only psysiology need be taken at the graduate level, so that it is possible for the undergraduate to anticipate much of the biological science desideratum. It is, of course, also possible to commence biological studies at a later stage. In each of these suboptimal situations, however, it is substantially more difficult to achieve integration of engineering and biological concepts.

Artificial organs technology has been, for us, a valuable educational vehicle. These devices can be considered with only limited amounts of biological background although the treatment becomes more sophisticated and more satisfactory as the available background increases. We have given a one-semester course accessible to senior chemical engineers but designed to be challenging at the master's level. All possible emphasis is put on the integration of engineering concepts and biological fact. The behavior of blood in extracorporeal circuits is considered in terms of rheology, shear-susceptibility, undesired reactions with artificial surfaces, and problems of intraphase transport. Comparisons are made with intracorporeal circumstances and the problems, surgical and mechanical, of acute and chronic cannulation are considered. Primary and secondary specifications are established for cardiac replacement and assistance devices, comparing actual prostheses and their rationales with the heart and the characteristics and demands of the circulatory system. The artificial kidney and blood-gas exchangers are introduced as artificial capillary beds; specifications are established for transport capability, allowable volume, and pressure-flow characteristics, with recognition of how limitations imposed by con-