WAS A TRANSPORT PHENOMENA COURSE IN CHEMICAL ENGINEERING CURRICULA INEVITABLE?

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This account covers primarily the years 1941-1961, which is by now "ancient history" in chemical engineering. In 1941, the United States became involved in the Second World War, and I enrolled as a freshman in ChE at the University of Maryland.

§1. Teaching of transport phenomena before and after WWII

During the period 1941 to 1951, the subject of transport phenomena was not taught to undergraduates as a unified subject in any U.S. university. The *flow of fluids* was covered at an elementary level in a sophomore physics course; this included the Bernoulli equation, the definition of viscosity, Poiseuille's law, qualitative ideas about turbulence, and other assorted topics. The *flow of heat by conduction and by radiation* was also taught in sophomore physics; but usually free and forced convection were taught only qualitatively, and heat production by viscous dissipation and chemical reactions was not included at all. The *diffusion of chemical species* was generally covered in physical chemistry, but the mass flux and the diffusion coefficient were poorly defined; convection, thermal diffusion, and forced diffusion were not taught at all. After 1945, physics departments were focusing their attention on topics in nuclear physics and losing interest in the "classical" physics topics; similarly chemistry departments were moving into new areas, and diffusion was of marginal interest.

The two unit operations books used at the time were the third edition of *Principles of Chemical Engineering*, by Walker, Lewis, McAdams, and Gilliland (1937)[26] and the second edition of *Elements of Chemical Engineering*, by Badger and McCabe (1936)[1]. These books were applications oriented and made little use of the principles of transport phenomena. Students trained in this era were able to solve important practical problems by following examples that were in the textbook, but were unable to undertake studies outside of that scope.

Olaf Hougen realized that the subject of transport phenomena was of interest in connection with the future development of many topics in chemical engineering. In the spring of 1950, he persuaded Professors J. O. Hirschfelder and C. F. Curtiss of the Chemistry Department to teach a graduate course in transport phenomena in the Chemical Engineering Department. This course covered roughly the material that appeared later in Chapter 11 of *Molecular Theory of Gases and Liquids*, by Hirschfelder, Curtiss, and Bird (1954)[16]. This course was never taught again.

§2. Early developments

Transport phenomena, as a discipline, definitely bears a "made in Europe" label. The mathematical development of the kinetic theory of gases by Maxwell (in England) and Boltzmann (in Austria) in the 19th century laid the cornerstone for the systematic discussion of mass, momentum, and energy transport; this was summarized in the classic book of Chapman and Cowling (in England), titled *The Mathematical Theory of Non-Uniform Gases* (1939)[13]. There it was shown how to derive the equations of change for mass, momentum, and energy from molecular arguments, and to derive expressions for the fluxes and transport properties in terms of the intermolecular forces.

The continuum theory of transport phenomena began much earlier with the flux of momentum (stated by Newton in England in the 17th century), the flux of energy (stated by Fourier in France early in the 19th century), and the flux of mass (by Fick in Germany in the middle of the 19th century); the radiant energy flux was given by Planck in Germany (at the end of the 19th century).

The equations of change were obtained by continuum arguments by a rather slow process, but these equations were complete by the beginning of the 20th century. An early summary of the "field equations" of transport phenomena was given by G. Jaumann (a Rumanian by birth), who in a review article in *Sitzungsberichte Akad. Wiss. Wien* (1911)[17], presented many of the basic equations found in transport phenomena textbooks today. It is unfortunate that his name is all but forgotten, and that biographical material on him is very limited (the only biographical information I know about is an article by H. Bednarczyk[2] in 1990).

The German literature on transport phenomena ("Transporterscheinungen," in German) and engineering applications was quite well developed. The extensive research and authoritative books by such giants as Prandtl, Schlichting, Nusselt, Stefan and others attest to the tremendous scholarship that was produced in Germany in the era before and between the two world wars.

An early book in English covering roughly the material that chemical engineers would find useful was R. C. L. Bosworth's *Transport Processes in Applied Chemistry: The Flow of Physical Properties in Chemical Reactors*, Pitman (1956)[12]. However, it could not be used as a textbook, since there were no illustrative examples and no unworked problems. In about 400 pages, he discusses a very wide range of topics. Bosworth's book resembles more a long review article, complete with references; however, no topic was treated in depth (e.g., the Navier-Stokes equation of motion of fluid dynamics is given in vector form in a short discussion of less than one page).

§3. Rumblings and fumblings at the University of Wisconsin

This section covers events in Madison from 1953 to 1957. The year 1953 marks the arrival of ENL and RBB in the Chemical Engineering Department at the University of Wisconsin. ENL had gotten a five-year BChE and a PhD from Cornell University and then worked for the Charles Pfizer Company in Brooklyn, NY; RBB had received a BS in ChE from the University of Illinois, and a PhD in Chemistry at the University of Wisconsin, followed by a postdoctoral year in theoretical physics at the University of Amsterdam, a year of teaching in the Chemistry Department at Cornell University, followed by a summer at the DuPont Experimental Station. (WES joined the department later, in 1956, after a BS and an MS at the University of Wisconsin and a ScD at MIT; then he worked at Sinclair Research Laboratories for about five years.)

Bob Marshall had been planning to teach a fluid dynamics course in the fall of 1953 using NACA reports by H. Schlichting and others. When Bob was promoted to Associate Dean of the college, I was asked to take over that course. I ended up using Schlichting's *Grenzschicht-theorie* (*Boundary Layer Theory*)[22] as the textbook for the course. By doing that, I became familiar with the rich experimental and theoretical literature on fluid dynamics in German. I had already had some contact with this literature at DuPont where I had been asked to study the heat production by viscous heating in polymer extrusion.[3a] None of the chemical engineers that I came into contact with at DuPont could explain where the viscous heating term in the energy equation came from. It was apparent that that chemical engineers at that time were not getting enough fundamental training in fluid dynamics to tackle problems outside of the problems that were in the unit operations textbooks.

While teaching the fluid mechanics course, I got interested in the "mechanical energy balance," which I could not understand from the unit operations textbooks. It seemed to me that all the macroscopic balances should be obtained by integrating the equations of change. Indeed, I found that the mechanical energy balance could be obtained as an integral over the flow system of the dot product of the local velocity with the equation of motion. This led to the publication in *Chemical Engineering Science* of a paper on the derivations of the macroscopic balances.[4]

The following term I taught the graduate course titled "Diffusional Operations," using Sherwood and Pigford[23], *Absorption and Extraction*. This was quite instructive, since this material was all new to me. By the end of the semester, I had worked through a lot of the basic background material needed for the teaching of the applications. Since the scientific background material was not readily available anywhere, I prepared a summary article and sent it to Academic Press, for publication in Vol. 1 of *Advances in Chemical Engineering* (1956)[5]. This article established the notation that would be used later in "BSL" and presented a number of illustrative problems as well; great care was taken with respect to the definition of diffusivity, the frames of reference for the fluxes, and the distinctions between mass and molar units.

In September of 1957, I was asked to take part in a meeting at Purdue University for showing deans of engineering what the latest ideas were on teaching and research in a number of fields. My assignment was to discuss the teaching of mass, momentum, and energy transfer in fluid systems. My talk was, in fact, a "sales talk" for a course in transport phenomena. It was in this talk that I outlined a one-semester undergraduate course that would cover the main ideas of the subject according to the following diagram:

	MOMENTUM	ENERGY	MASS
Molecular	Viscosity	Thermal cond.	Diffusivity
Microscopic	Equation of motion	Equation of energy	Equation of species diffusion
Macroscopic	Macroscopic momentum balance & macroscopic mechanical energy balance	Macroscopic energy balance	Macroscopic species mass balances

The above presentation appeared in *Recent Advances in the Engineering Sciences: Their Impact on Engineering Education* (1958), pp. 155-177[6].

In the lecture to the deans, I emphasized the following points:

a. It is important that the students see *in one course* the connections between the transport of the *three entities* (momentum, energy, mass) and the transport at the *three levels* (molecular, microscopic, macroscopic)—all in the same notation. The students should be told that, more often than not, two or three of the transport phenomena appear simultaneously, both in industrial problems and in biological problems.

b. The students should understand the similarities and differences between the items in the three main columns. The physics describing the transport of the *three entities* should be made clear, and, when possible, the similarities in the mathematical descriptions should be emphasized.

c. Equally important is the connection between the *three levels* of description. The students should be told that one can go from the molecular level to the microscopic level, and also from the microscopic level to the macroscopic level. It is important to know how one gets the macroscopic mechanical energy balance from the microscopic equations (without invoking unnecessary and irrelevant thermodynamic arguments).

d. In addition, under *momentum transport,* I wanted to introduce the students to some of the non-Newtonian models for describing polymeric fluids and thick suspensions. Under *energy transport*, I wanted to make it clear how the heat capacity gets into the energy equation. And under *mass transport*, I wanted to explain carefully the role of various reference frames and the definition of diffusivity.

Somewhat earlier, it had been decided that a Department of Nuclear Engineering should be formed at the University of Wisconsin, with Bob Marshall as chairman of the planning committee. I was asked to serve on that committee. When it came time for developing a proposed curriculum, it was decided that a course in the basic principles of transport phenomena would be needed. I was asked to propose such a course to the Physical Sciences Divisional Committee, which had to approve new courses. The Physical Sciences Divisional Committee sent a note to the ChE Department with the query: "Why don't you have a course like this in your curriculum?" This forced the ChE Department to take up the matter. After considerable discussion, it was decided by a vote of 5 to 4 to institute the course, with the proviso that RBB would prepare a set of notes during the summer of 1957 so that the course could be instituted in the fall. RBB indicated his willingness to do this, and, within a matter of minutes, WES and ENL had indicated their interest in participating in a joint venture.

§4. BS&L roll up their sleeves

During the first half of August 1957, RBB wrote the text for Chapters 1 to 12 and then took off for a 2-week canoe trip in Canada. When he returned to the campus, assignments were made for all three authors to prepare the remaining 10 chapters. Then began a frantic semester of text preparation, making up problems, preparing figures, mimeographing the chapters, and meeting the classes. RBB held a two-hour session every week for instructing the faculty members on how best to teach the material. All three of us had other teaching duties and research supervising.

Clearly BS&L were "rushing in where angels fear to tread." No one of us was really properly prepared to undertake our task. RBB and ENL had been on the faculty for only four years, and Warren for just one. In the 21st Century, such an activity would be considered preposterous—a sure recipe for "academic suicide". But life was very different in the 1950s, when teaching and book-writing were encouraged. Furthermore, Olaf Hougen had been a great teacher and a very successful book-writer, and the three of us were greatly inspired by his wonderful accomplishments.

By the end of the fall semester of 1957, BS&L were exhausted, but the spring term was looming ahead. WES and ENL were going to make up more problems and illustrative examples during the spring, in order to make the book more useful for teaching; this was a demanding assignment, which they tackled energetically. Their years in industry had prepared them well for thinking up interesting and practical problems.

RBB, however, could not participate in this activity, since he had already arranged to spend the spring and summer in Delft (The Netherlands), supported by the Fulbright and Guggenheim Foundations. He was attracted there by the presence of Hans Kramers, who had been teaching transport phenomena since 1956 and who had prepared a set of lecture notes, titled *Physische Transportverschijnselen*[18]. RBB enjoyed very much his interactions with Hans, and we had many discussions about how to teach and use the material. During the spring term RBB gave the transport phenomena course and prepared a set of mimeographed notes *Transportverschijnselen in Stromende Media*[7].

During the summer of 1958, John Wiley & Sons prepared a limited edition of our book called *Notes on Transport Phenomena*[9]. Then between 1958 and 1960 we completely rewrote the text, making many improvements, and all the chapters were read aloud with all three authors present; in this way, we hoped to make the text homogeneous and smooth reading. In the fall of 1960 the book *Transport Phenomena*[9] was finally published.

We had a lot of fun telling our students about the secret messages in the book. In the preface, reading the first letters of the sentences gives: "This book is dedicated to O. A. Hougen. TTTM" (the last four letters stand for "this terminates the message"). And in the postface, reading the initial letters of the paragraphs gives "On Wisconsin"–the well-known school song.

The book went through 62 printings, and is now in its second edition (2002), with a "revised second edition" (2007). The first edition was translated into Spanish, Czech, Italian, Russian, and Chinese; the second into Spanish, Portuguese, and Chinese. All three of us went on to publish books in our research areas: In 1974, ENL published *Transport Phenomena in Living Systems*[20], which was the first book to combine the topics of biomedicine and transport phenomena. In 1977, RBB (together with Armstrong, Hassager, and Curtiss) published *Dynamics of Polymeric Liquids*[10,11], which included both continuum and molecular approaches. Finally in 2008, *Computer-Aided Modeling of Reactive Systems* by WES (and Caracotsios)[25] finally saw the light of day.

When the BSL book first appeared, it got a mixed reception. Young faculty members were generally enthusiastic, whereas older teachers were rather antagonistic. T. K. Sherwood of M.I.T., in a book review in 1961 in *Chemical Engineering Science*, wrote: "In a sense this is a dangerous book, for it is so well done that it will probably accelerate the trend towards emphases on analysis in the ChE curricula." Our feeling was that the transport phenomena course was, in fact, supposed to play the supporting role of an intermediate physics course that would enable chemical engineering teachers to do a better job of teaching unit operations, process control, kinetics and catalysis, and other applied subjects. We also felt that it could provide useful background for teaching courses in such diverse areas as mechanical engineering, metallurgy, soil mechanics, meteorology, and analytical chemistry.

At the same time that the department instituted the lecture course, we also established a laboratory course. For this E. J. Crosby developed a very fine set of laboratory experiments, as well as a laboratory manual, titled *Experiments in Transport Phenomena* (1961)[14]. He wanted the experiments to be valuable teaching tools and to be "student-proof." He included experiments on measurement of transport properties, measurement of profiles (velocity, temperature, and concentrations), determination of interphase transfer coefficients, and the use of the macroscopic balances. By actually performing the experiments, the students would then get a better physical feeling for the subject. These experiments proved to be so successful that he collaborated with a company to reproduce the experiments and make them commercially available to other universities.

The curricula in chemical and biological engineering, and also nuclear engineering, at UW still contain the chemical engineering course in transport phenomena. It wasn't long before Geiger and Poirier (both then at the University of Wisconsin) produced their textbook *Transport Phenomena in Metallurgy* (1973)[15], and this course is still being taught, although the authors are now at the University of Arizona. To date, the mechanical engineering department has not felt the need for a transport phenomena course in their curriculum, despite the fact that the second major textbook to appear on the subject (by Rohsenow and Choi[21] in 1961) originated in the mechanical engineering department at MIT).

It would not be appropriate to close this story by leaving the impression that we were the only engineering department that was working on a transport phenomena course in the late 1950s. We do know that several textbooks appeared shortly after ours:
Heat, Mass, and Momentum Transfer, Rohsenow & Choi (1961)[21]
Momentum, Heat, and Mass Transfer, Bennett & Myers (1962)[3]
Kagaku gijitsusha no tame no idô-sokudo-ron, Shirotsuka, Hirata & Murakami (1966)[24]
Idô-sokudo-ron, Kunii (1966)[19]
It is clear that the question posed at the beginning can be answered in the affirmative.

Finally, I would like to pay tribute to my two coauthors, Warren Stewart and Ed Lightfoot, whose contributions to the two editions of our book were substantial. Their industrial experience, their subsequent research programs, and their unique perspectives gave the book extra breadth and meaning. Along the way we had many heated arguments, but from these disagreements there usually emerged a better understanding of the subject. Our triumvirate had just the right mixture of scholarship, impatience, and "iconoclasticity."

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