A Course in

PROCESS HEAT TRANSFER:
"Sufficient Conclusions From Insufficient Premises"

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> **"Life is the art of drawing sufficient conclusions from insufficient premises."** — Samuel Butler, **Notebooks**

GRADUATE EDUCATION in chemical engineering is overwhelmingly oriented towards preparing the student for a career in research. Yet a substantial majority - 80 per cent for an arguable estimate - of the total professional careers of chemical engineers with M.S. and Ph.D. degrees will *not* be in research. And, to anticipate a later point, it is conceivable that even a Ph.D. chemical engineer who spends his entire career in research or teaching would benefit from an occasional abrasive contact with that part of the world that he is trying to improve upon.

Recognizing and accepting the above statements as having some useful implications for graduate education, the chemical engineering faculty at Oklahoma State University has always emphasized in both course work and research the *application* of fundamental principles to the several aspects of chemical engineering practice. We have also emphasized the role of problems arising in practice in pointing out the most profitable areas in which to conduct research.

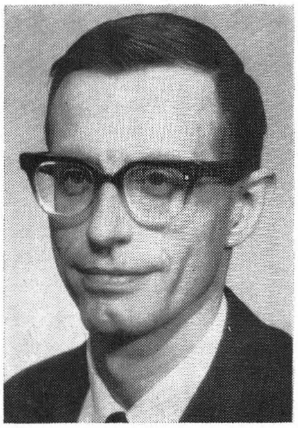
Further, we have found it vital to at least introduce the graduate student to the philosophy and technique of solving those engineering problems which must be solved and for which available theory tells us little more than what cannot be done. A majority of real problems falls in this category, and I submit that it is the failure to recognize and admit this fact that accounts for much of the estrangement between academia and industry.

For the long run, one basically optimistic point of view holds that research is catching up — that more and more fundamental understanding is available to underpin our solutions, and that we may witness the day when real problems may be quantitatively solved in their essentials by the rigorous application of comprehensive mathematical statements of the physical and chemical processes involved, subject to socio-economic constraints and objective functions. Another point of view argues that our technological problems are growing in several dimensions more rapidly than our theories and that the role of pragmatism is expanding. There are other kinetic models of engineering knowledge that may be put forth, but the common lesson of all is that chemical engineers practicing in industry in the foreseeable future must be proficient in knowing how to solve problems that are not well-set mathematically and indeed may be only poorly comprehended on any level. The operational imperative is that the problems must be solved; the engineer cannot be too nice about the means.

One such attempt to construct and teach a course emphasizing the solution of real, full-scale problems within this context is described here. It is not the only course so conceived and so dedicated either at Oklahoma State or elsewhere, but it does have certain possibly unique features that are worthy of consideration if not emulation.

THE COURSE IS Process Heat Transfer, a 3-credit hour course taught in three lectures per week for 15 weeks to all M.S. and M.Ch.E. (professional program) students in chemical engineering at Oklahoma State. Some undergraduate students and graduate students in other departments elect the course and it is available to employed engineers in a number of cities in Oklahoma via talk-back TV (more about that later). Prerequisites are the usual undergraduate courses in fluid mechanics, heat transfer, and thermodynamics; a process design course and a graduate course in transport theory are considered very desirable. Chemical engineering students have all of these courses; those from other fields will generally lack the latter two. In that case, particular care must be taken to provide more detailed explanations and outside references. Industrial experience is extremely valuable.

On completion of this course, the student should be able to:



Kenneth J. Bell received his BSChE at Case Institute of Technology and his MChE and PhD degrees at the University of Delaware, where he was a graduate assistant to the late Professor Allan Colburn. He joined Oklahoma State University in 1961 after working for General Electric and teaching at Case. He is a consultant to Phillips Petroleum Co. and Heat Transfer Research, Inc., and was associated with D. Q. Kern until the latter's death in 1971.

- Find, evaluate, and use fluid dynamic and heat transfer analytical solutions, empirical correlations and data to predict pressure drop and heat transfer coefficients in component geometries during single phase flow, boiling and condensation.
- Select a feasible and efficient heat exchanger configuration (involving both single and multiple units) to meet a given process application, using estimation techniques to quickly obtain approximate sizes.
- Use published design procedures for rating standard exchanger configurations.
- From available correlations, develop design methods for new exchanger configurations or new process heat transfer problems.
- Analyze laboratory and plant exchanger data in order to develop new correlations or to troubleshoot plant problems.

One objective that cannot be described in the precise form demanded by the educational theorists is the development of an intuitive comprehension for what is important about a problem—less delicately put, a gut feeling for what real fluids will do in equipment of real metal built and operated by real people.

The topic list of the course is as follows:

I. Introductory Concepts
    Conduction: one-dimension, steady-state
    Film and overall heat transfer coefficients
    The basic design equation
    LMTD and configuration correction factors
    NTU - ϵ method
    Single phase flow inside tubes
    Single phase flow across tube banks
    Criteria for heat exchanger selection
    General types of heat exchangers
II. Single Phase Heat Exchangers
    Design of double pipe exchangers
    Construction features of shell and tube exchangers
    Selection of shell and tube exchangers
    Analysis of shell side heat transfer and pressure drop
    Special shell-side problems
III. Condensation and Condenser Design
    Two-phase flow
    Filmwise condensation
    Desuperheating and subcooling in condensers
    Condensation with non-condensables
    Approximate method for multicomponent/partial condensers
    Analysis of multipass and crossflow condensers
    Dropwise condensation
    Direct contact condensation
IV. Vaporization and Reboiler Design
    Pool boiling
    Reboiler configurations
    Kettle reboiler design: narrow boiling range
    Kettle reboiler design: wide boiling range
    Thermosiphon reboiler design
V. Air-cooled Heat Exchangers
    Extended surface; fin efficiency
    Finned tube banks: friction factor and heat transfer correlations
    Design of air-cooled equipment
VI. Mechanically-aided Heat Transfer
    Mechanically-aided heat transfer equipment
    Heat transfer in agitated vessels
    Close-clearance heat exchangers
    Mean temperature differences in mechanically-aided equipment
VII. Other Heat Transfer Equipment

The course emphasis is on equipment: selecting and designing it in the first place, troubleshooting it, modifying it for a new service, or making it operate within the inherent uncertainties and instabilities of process systems. It follows that the student needs to learn about the construction of heat exchangers in sufficient detail that he can visualize the problems of their construction, installation, operation, and maintenance.

Particular attention is paid to the visualization of the physical processes occurring inside heat exchangers, especially flow patterns. Anticipation of the interrelationship between the structure of the heat exchanger, the operating conditions, and the flow mechanisms (real, not idealized for the sake of analysis) is basic to selecting valid heat transfer coefficient correlations and evaluating the basic design equation, and to calculating the local and total pressure effects in the exchanger.

The student is given realistic design problems and is expected to come up with practical designs. The design methods presented in class are feasible for hand calculation (through Fair's method for thermosiphons strains that idea to its limits).

Computer design methods exist for most of the equipment considered and the student is made aware of their existence and, in one or two example cases, their fundamental basis and logical structure. But it is only by cranking through the sequence of preliminary design estimate, rating, design modification, relaxation of constraints, etc., that the student comes both to understand the interplay of the many variables in the design and to appreciate the design philosophy. Once the student develops some competence and flair in making the engine go, he can add the bells, gongs, and whistles that come with a computer.

THE STUDENT IS encouraged to do rapid, back-of-the-envelope calculations to come up with preliminary designs in some detail. Not only are these calculations necessary to get started on a more rigorous design procedure, but they serve to keep the student's attention on the critical factors in a problem, rather than upon the details. Also, for many purposes, the preliminary designs thus obtained are quite sufficient. With a little practice, most students are able to estimate designs to within the limits of uncertainty in the basic operational data and design correlations for many run-of-the-mill applications.

The fact of uncertainty and the design consequences thereof are emphasized. Uncertainty in the basic correlations, in the way the correlations are assembled in the design method, in the physical properties and flow rates and compositions of the process streams, in the fouling characteristics, seasonal variations in the service streams, long-term changes in plant product composition and rate and in operating philosophy — all of these have design implications that the student should keep in mind while making his calculations. On the one hand, for example, this will keep him from making excessively precise calculations of one film coefficient when the other coefficient — or the fouling — is controlling. However, the other side of the same coin is that the student is expected to take some care in calculating the controlling coefficient, and in estimating and allowing for its inherent uncertainty, or to choose a design where fouling is minimized or can be controlled. The student is always expected to ask himself, "How wrong can I be? What are the consequences of being wrong? What can I do about it in the design?"

Optimization, in the sense in which most current literature deals with the subject, gets short shrift. Apart from ignoring the uncertainty alluded to above, the usual heat exchanger optimization procedure misses the boat by choosing the wrong objective function (usually something to do with the cost of the heat exchanger) and failing to consider operational problems. In another sense, however, the whole course deals with optimization using an objective function having to do with the cost of the product. This almost always means that the heat exchange system (not just the individual units) is designed so that it will achieve the specified changes in the thermal condition of the process stream over the entire operating cycle of the plant between turnarounds and do this with a minimum amount of attention. Avoiding a couple of days' lost production per year may completely outweigh the cost of oversurfacing or duplicating a critical exchanger.

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Thus, in a mild fouling situation, the student may select a single large heat exchanger for a given service, designing it to operate satisfactorily over the entire cycle; in a more severe fouling case, he may select two smaller heat exchangers piped so that one may be cleaned while plant operation is modified to permit the other exchanger to hold the load; in a critical fouling case, he will specify two large exchangers, i.e., full standby capability. Some day, the whole task of optimizing a plant design in this sense may be taken over by computer — just as soon as one of our more creative computer manufacturers develops a randomly accessible crystal ball in core.

More attention is devoted to the correct analysis of the temperature difference than is customary in textbook or even design-manual discussions of heat exchanger design. It is quite easy in process problems to specify terminal temperatures and exchanger configurations that result in a zero true mean temperature difference, whereas no one has yet managed to reduce a heat transfer coefficient to zero. The basic design equation,

$$A_O = \int_0^{Q_T} \frac{dQ}{U_O(T-t)}$$

(where A_O is the heat transfer area required, Q the heat transferred, U_O the local value of the overall heat transfer coefficient, T and t the local temperatures of the hot and cold streams respectively) is introduced at the beginning. Only later

— and only after a complete exposition and careful examination of the assumptions and their range of validity — is the idea of a mean temperature difference (MTD) formulation of the design equation presented.

I am something of a fanatic on the "Zeroth Assumption" in the LMTD derivation: "All elements of a given stream in a heat exchanger have identical thermal histories." Specifically, this means that the MTD concept cannot be simply applied to any heat exchanger with bypassing or internal leakage, which in turn means that almost all of the heat exchanger data in the literature and the correlations developed therefrom are of questionable validity and little generality. Laying this on the class in about the third lecture is roughly equivalent to using a 2 x 4 to get their attention. Some never quite recover their faith in anything (which is at least a step in the right direction); most begin to show signs of thinking about their assumptions simultaneously with working through a design procedure.

AS WITH ANY course, there is the question of a textbook. There is none available. The only book that comes close to having a suitable approach and objective is Kern's "Process Heat Transfer," and the students are encouraged to read in Kern to see a Grand Master at work. Unfortunately, this book is over 20 years old, there is hardly a correlation or a design procedure in the book that hasn't been improved upon in the interim, and there is no hint of the possible role of the computer. So I wind up using notes that I have prepared and that I have cadged from others, notably Al Mueller of du Pont, Jerry Taborek and Joe Palen of HTRI, and Bill Small of Phillips. (Proprietary material is not used, but knowing what is in the proprietary material keeps one from saying a lot of things that are not true). The notes suffer from being uneven, incomplete, and often insufficiently detailed for use apart from the lecture material. From time to time, some of us talk about writing a textbook; something may come of it yet.

There should be in every student's career one or more courses presenting the philosophy and technique of solving real problems, warts and all.

This is obviously a highly personal course, one closely tailored to my interests and experience. Citing Samuel Butler again: "Every man's work, whether it be literature or music or pictures or architecture or anything else, is always a portrait of himself." I regard this as a very positive attribute: one of the advantages of using a live classroom teacher or lecturer in preference to or in addition to books, tapes, etc., is the opportunity of watching him in action—confronting a problem, discussing the circumstances surrounding it, seeking a solution, pointing out Scylla and Charybdis, and perhaps at the end being able to say, "We tried it and it worked."

I wish to avoid undue emphasis upon how unique in detail this course may or may not be. And I am not suggesting that every graduate student should be highly skilled in process heat transfer or any other particular body of engineering effort.

I do want to emphasize that there should be in every engineering student's academic career one or more courses presenting the philosophy and technique of solving real problems, warts and all. This is the art of engineering. This is the end to which all else of the academic curriculum and engineering research is directed. I would like to think that every engineering faculty member was capable of teaching one such course.

ADDENDUM ON TV TEACHING

In the spring of 1972, this course was taught on closed-circuit talk-back television for the first time. There is a state-wide TV system in Oklahoma that links the three major universities (Tulsa, Oklahoma, Oklahoma State) and the major industrial centers. TV courses may be taken for full graduate credit; homework assignments and solutions are transmitted by a daily courier; examinations are proctored at the receiving end and then returned by courier.

The on-campus students are in the TV studio, so the lecturer does have a live audience in front of him. There are two cameras, one in the back of the studio, the other vertically above the lecturer's note pad. The back camera can be focused on anything from the blackboard (green) running the width of the studio to just the lecturer's face; the vertical camera can also yield excellent close-ups of small objects held in the hand. Both cameras are always on and an operator in the control room at the back of the studio selects which image is to be transmitted to the remote viewers on the system and to the two TV sets in the studio.

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In the example that we have been carrying along as a guide, we find that we aren't ready to communicate our results as they violated a presumption. An iteration of the *model* is required. However iterations are possible at several different levels, as shown in Figure 1, which rests on the lists of modeling steps in Table 1.

2-II. **Assembly of Information.**
Assumptions:
1. *Temperature dependent fluid properties.*
2. *Turbulent flow on tube side.*
3. *No multiple tube effects.*
4. *Constant Dowtherm temperature.*
5. *Variable film temperature, and Temperature difference.*
6. *Steady state.*

New correlations are needed, and the solution method becomes a computer technique.

8-II. The value of the exit temperature is 464.7°F.

PEDAGOGY

It is moderately difficult for the instructor, and unsatisfactory for the student, to spend much time talking about the philosophy or even the structure of modeling. It seems so self evident that it is boring—but still the students go astray simply by virtue of overlooking a modeling step. Therefore, to make all this work, and to make it interesting at the same time, a variety of pedagogical tricks have been developed and used. These have included:

1. **Omit problem statement.** The "problem" is presented as a demonstration: a vessel is allowed to drain through a square hole and the level measured vs time; a hot sphere is immersed in a vessel of water and its temperature measured; a beaker of molten paraffin is allowed to solidify. Model this situation is the instruction. This focuses thought upon securing a precise problem definition. The students must pry it out of both the instructor and reality.
2. **Give problem solution.** A problem from a preceding course (where it is presumed that the principles of modeling had *not* been taught!) is chosen and the instruction is to recast it into the algorithmic solution format given in Figure 1. This focuses the student's attention upon *procedure*: the work of "solution" has been completed in advance within some other procedure, be it derivation or formula-plugging.
3. **Trial by fire.** A student is asked to solve a problem before the class, with no prior preparation. The whole reasoning process is thus brutally exposed. A kinder approach is to successively question class members to develop the model step-by-step, following the modeling algorithm of Figure 1.
4. **Tweak by paradox.** A "completely logical" example is presented, which leads to a clearly ridiculous result. The location of the flaw in reasoning is a superb educational device.
5. **Math made illegal.** A fairly detailed report, containing no math but explaining the model and results, is requested on a problem. ☐

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The lecturer has a small monitoring screen on the desk in front of him that shows exactly what is going on to the viewers. (The monitor is an insidious and ruthless device: lecturers have been known to start yawning in boredom while watching it.) The studio audience mostly watches the two TV screens, because that's where the action is when the lecturer is working on the note pad; this is somewhat distracting to an experienced lecturer, who relies upon eye contact to see if the audience is with him. I don't use the board because it is hard to remember to work in properly scaled modules so that the whole image fits the TV screen and yet is legible. This is readily controlled by using a 6 in. by 8 in. buff-colored note pad. The material to be presented in class is written or drawn upon the pad in yellow ink, which is readily visible to the lecturer and nearly invisible to the camera; during the lecture, the notes, etc. are made visible to the audience by writing over them with a black felt-tip pen. (By forcing the lecturer to do the writing, the speed of the presentation is held closer to the speed at which the students can make notes.)

Acclimatization to the TV system took only two or three lectures. The most important single change that I noticed was that I was better prepared to lecture when I came to the studio. Having to prepare the notes in yellow ahead of time not only forced me to review, but also to organize the material so that the contents of each sheet made sense. ☐