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HEAT TRANSFER EDUCATION: INTEGRATION OF THE THERMAL SCIENCES STEM

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ABSTRACT

Integration of the thermal sciences stem refers to changes in objectives, pedagogy, and content being driven by curriculum reform. We provide a 15-year history of how the discipline has sought to better prepare students for industrial practice. The results of a recent survey identify the drivers for and extent of reform as well as the trends, content and barriers. The reform activities represent a strengthening of the traditional three-course stem, as well as the spawning of combined courses, with opportunities for including materials on new technologies.

INTRODUCTION

This paper focuses on the activities over the past 15 years of the ASME Heat Transfer Division as related to heat transfer education in our mechanical engineering programs. Because heat transfer is part of the thermal sciences (TS) stem, we have broadened the discussion to include issues related to thermodynamics and fluid mechanics learning. Our review includes that of several panel sessions and symposia directed toward innovation in teaching. The paper follows a chronological path, which in itself offers interesting insight into how changes in technology – both in engineering practice and in the educational environment – influence our approach, views, and framework for education.

The aims of this paper are to provide a summary of contributions that address the challenges, to assess the impact of change, and to identify opportunities to enhance the educational process. Particular emphasis is given to the curriculum reform effort referred to as the integration of the thermal sciences.

NATIONAL LOOK IN 1988

As part of the celebration of the 50th anniversary of the Heat Transfer Division (HTD) at the 1988 ASME Winter Annual Meeting (WAM), a panel session was devoted to the future of heat transfer education [1]. The four panelists representing industry and academe were in agreement that heat transfer education had been brought to a mature pedagogical approach.

At the undergraduate level, heat transfer was the third in the sequence of courses with thermodynamics and fluid mechanics comprising the TS stem. While the educational process was seen as producing engineers with a strong understanding of the fundamentals, the graduates were thought weak in addressing industrial applications that typically involve complex or multi-disciplinary phenomena. Heat transfer, it was agreed, should be the key course in the TS stem for imparting judgment required to address real-world applications.

The panelists cautioned that the increased accessibility of computers and powerful software using modern computational techniques represented a potential distraction from hands-on analysis requiring judgment. Further, computer accessibility provided opportunities to automate experiments and perform virtual experiments that could seriously diminish students' experiences in experiment design, measurements, and analysis. The industrial panelists raised issues about adequate preparedness in communications, economics and ethics, as the practicing engineer is concerned about matters of reliability, cost, manufacturability, safety and product liability. The challenge was to remedy the foregoing concerns at a time when serious efforts were underway to reduce curriculum total credits, and faculty were faced with increased pressures to maintain productive research programs. Clearly, meeting the challenge would require significant changes and innovations to the delivery system.

In 1995, the HTD proposed the formation of an Ad Hoc Education committee to strengthen education-research-practice interactions and thereby enhance the relevance of education to practice. The main mission of the committee was to organize paper or panel sessions under the general theme of "Innovations in Heat Transfer Education" and student poster sessions entitled "Student Research and Design in Heat Transfer." The committee achieved permanent status (K-21) in 2002 [2]. The outcomes of these sessions are discussed below.

INNOVATIONS IN HT EDUCATION

In this brief overview, we describe the general features of advances in heat transfer teaching methods as evidence that serious attention is being given to meet the challenges posed by 1988-WAM panel, as well as to ABET-inspired curriculum requirements.

At the initial session of the new Education Committee in 1997 [3], twelve contributions were presented, half of which dealt with laboratory development. Novel experiments were described for heat exchangers (USNA), two-phase flow (Nevada), microelectro-mechanical systems and integrated circuits (Stanford), and conduction phenomena (Kansas State). At Purdue, the role of the laboratory was expanded to cultivate systems integration and multidisciplinary, complex-problem solving skills by replacing traditional experiments with design-type project assignments developed with an industrial partner. As a means of enhancing classroom theory learning, a simulated fluid flow laboratory at Minnesota allowed students to explore the behavior of real fluid systems. Software-related topics included two learning modules: one illustrating conduction phenomena (Federal University of Santa Catarina, Brasil); and another illustrating classical topics on conduction, forced convection, and radiation view factors (Virginia). An equation-solving package to improve student problem-solving skills and increase their computational productivity was described (Purdue). An elective heat transfer system design course at Virginia Tech provided students with realistic design experience using a commercial industrial-strength software package. Novel ways to teach the classical topics were described including an algebraic, lumped-model approach to solving Heisler-Gröber problems (Idaho State), and an electrical analogy approach to solving two-dimensional conduction problems (Pozan, Poland).

In the 1998 session [4], progress and experiences in the integration of the thermal sciences at Clemson, RPI and Carnegie-Mellon were described. Information was provided on new curricula content, motivations for revising the traditional thermal science three-course sequence, and assessment. Academe-industry relationships at Kettering were presented; one about the process of forming relationships and launching useful collaborations, and another about the experiences derived from using the under-hood compartment of a vehicle as the platform for innovative laboratory experiments and multi-disciplinary projects. An update was given on classroom experiences and impact evaluation using the conduction phenomena educational software (Federal University of Santa Catarina, Brazil) described in the 1997 session.

Khounsary, et al. [5] provided a written summary of the 1996-IMECE panel aimed at identifying issues to keep heat transfer education relevant and exciting. The academe-industry participants thought that steps to ensure the desired outcomes in heat transfer education should include: a better understanding of the interaction between the student, course content, and market needs; an appreciation of the need in multidisciplinary industrial environments for engineers trained with a broad background; and, a revision of introductory heat transfer courses to incorporate insightful industrial examples and case studies that would reinforce problem-solving abilities and emphasize multidisciplinary issues present in modern thermal management applications. These issues have much in common with those identified by the 1988-WAM panel, but there was growing evidence that educators have recognized the importance of forging industry connections and of building students' practical-problem solving skills

In the 1999 session [6], co-sponsored with HTD Energy Systems Committee (K-12), ten contributions were presented. A partnership with the university's engineering services department provided opportunities for students at Michigan State to conduct experiments and perform systems thermal analysis on campus power plant facilities as part of their senior-level heat transfer laboratory course. A laboratory course at Michigan State was organized in two parts, the first with traditional skill-building experiments, and the second a design-project competition. The project work required synthesis of thermal and mechanical systems skills for the design and realization of the device. Serving as synthesizing experiences with interdisciplinary, real-life open-ended problems, senior-level projects were described in separate papers on a hybrid combustion-fuel cell cogeneration plant (Tufts) and a loop heat pipe with transient heat load (Clemson).

Novel ways were described for teaching classical topics including implications of critical radius on conduction heat rates for cylindrical and spherical coordinate systems (Southern Illinois - Carbondale) and a finite-difference method to obtain temperature distribution and heat rates in annular fins in place of an analysis using Bessel functions (Idaho State).

Progress was reported on work at Clemson to implement an introductory thermal-fluids sciences course. The transformation of the introductory heat transfer course from a lecture format into a partial studio model at Virginia was described. Lectures were supplemented with a two-hour session using computer-based teaching modules that allow students to explore with tools for solving classical conduction, convection and radiation problems.

This session saw the first appearance of contributions on learning techniques. From Nevada, an evaluation was given of cooperative learning, a technique where students work in small groups to accomplish specific educational tasks jointly. The peer-group setting has been more commonly used in design-type projects, and less so in problem-solving classes involving engineering science and analysis. From Texas Tech, an evaluation was presented on investigative active learning, a more rational alternative to learning by rote memorization. Implicit in this notion were the concepts of investigation, mentoring, feedback, modeling and interaction that can be implemented with computer-based instruction techniques.

In the 2000 session [7], a description was given on the collaboration between RPI and Tufts to establish a research-curriculum development program in the area of thermal manufacturing and materials processing. A central aspect of the collaboration was the concurrent development of two new graduate courses at their respective institutions, one with a process-physics focus and the other dealing with thermal aspects. Also reported were experiences with a distance-learning version of one of these courses. A description was given of a program at Iowa State in practical thermal system design that encompassed project-oriented teaching for undergraduate, graduate and off-campus professional students. The approach integrated the thermal science disciplines, and involved industry-university collaboration and community outreach. Extensive use was made of information technologies for virtual project group meetings, interactive design-laboratory sessions and computational software. Virginia Tech's experiences were described in implementing a new sophomore-level course that provided a sequential introduction of thermodynamics, fluid mechanics and heat transfer; majors were expected to take follow-on courses in each of the disciplines.

The outcomes of these sessions covering a period of five years provided evidence that heat transfer education is undergoing enrichment and notable changes, and that the issues identified by the 1988-WAM and 1996-IMECE panels were being seriously addressed.

NATIONAL LOOK IN 2001

In summer 2001, the K-21Committee sent a survey to all 250-plus ABET accredited mechanical engineering programs in the United States. The intent of the survey was to identify new trends in TS education and to understand the motivation behind and the experiences gained from such changes. The respondent was either the department chair or, as in a few cases, the program coordinator. While we recognize that their comments reflect individual opinion, we take the collective responses from 101 respondents as being representative of the current state and trends in mechanical engineering education.

The survey results were presented as part of a panel session on integrating the thermal science curriculum at IMECE 2001. Panelists were D.A. Kaminski (RPI), F.A. Kulacki (Minnesota), R.A. Gaggioli (Marquette), and R.S. Figliola (Clemson) with P. Norris (Virginia) serving as moderator. The panelists from Marquette, RPI and Minnesota related their experiences in how discipline materials were integrated, and provided student and faculty reactions on the new formats. The overall message was that integration efforts are underway, but the packaging of the new content is challenging, and the student outcomes, as well as faculty views, vary between the schools.

The survey queried the following topics: comparison of curriculum content in 1990 to 2000; current required TS stem courses; future plans or considerations for changes in the curriculum; barriers to change in curriculum; assessment information on integrated course offerings, if any; and, any other relevant comments.

The results indicated that while the fractional portion of the curriculum specific to TS education has not changed much over the past few decades, the approaches to how we introduce, present and package the delivery of these subjects are changing. Further, technological and political pressures on the entire mechanical engineering curriculum are likely to force continued changes in TS education. However, there appear to be barriers to changing a system that has been in place for so long and that has successfully served the profession in the past. Clearly, the challenge is for TS education to be represented in the curriculum in a manner that is relevant and reflective of changes in the profession.

Curriculum Content

Over the past decade, the portion of the mechanical engineering curriculum devoted to TS education has remained at between 12 to 16 semester credit hours (or equivalent in quarter credit hours). This is to be expected. as past mechanical engineering accreditation requirements have mandated that there be a visible stem of course study devoted to TS education. Through the late 1990's, the credit hour equivalent of one full semester was still expected. Current ABET Engineering Curriculum 2000 (EC 2000) requirements are more flexible in order to allow programs to be innovative in how a capability in thermal systems is facilitated and in how to package such material to meet individual degree program objectives. But directed study in thermal systems is still required in EC 2000 [8]. As a consequence, and due to other pressures discussed later, we should expect to see TS concepts remaining well represented in our curriculums but the portion directed specifically to TS education reducing in the future.

The most traditional program of study in TS education became well established over the past 50 years. With the exception of a few distinctively different programs, this meant programs offered at least a separate course in each subject of fluid mechanics, thermodynamics, and heat transfer, with extra study in thermodynamics and/or fluid mechanics, and accompanying laboratory study. Electives and design courses completed the study. To this end, textbooks were written and their pedagogy fine-tuned, but most reflected the approach that featured a strong individual subject focus. It should also be noted that subject topics developed 50 years ago still hold a prominent position in our textbooks. For example, we can still see a strong emphasis on large power systems in these texts: power cycles, heat exchangers, and corresponding devices. Over time, new material has been added to keep pace with technology, but without a change in emphasis. Certainly while many applications of TS principles to design are mature concepts (such as large energy exchange systems), there are a host of applications, typically at smaller scales (such as in microdevices and nanomanufacturing), that challenge our knowledge and skills and will be the focus of many of our students during their professional careers. As educators, we now want to address these new challenges, provide experiences that prepare our new engineers for their careers, and enable young engineers for a lifetime of learning.

Curriculum Trends

The major shift occurring in our programs is a growing trend towards requiring some sort of integrated TS course; that is, combining the subject matter of the disciplines of fluid mechanics, thermodynamics, and/or heat transfer within a single course devoted to this material. In fact, about one-half of all programs now include some type of integrated TS introductory course. There are many variations in how such an integrated course is offered. Some programs integrate material through a design experience that incorporates the three disciplines. Others choose to blend the material within a systems-oriented, engineering science format. And others package a sequential treatment of the disciplines within a single course.

A growing number of programs now follow the introductory integrated course with a second offering, effectively replacing the traditional stand-alone discipline courses. One of every six programs reports abandoning the three discipline course approach, substituting a suite of integrated courses, and leaving advanced study in any discipline as a technical elective.

A second shift is placing a stronger focus on TS design and realization. About two out of three programs now offer a course emphasizing integrated thermal design or projects as part of their culminating program experiences. With this approach, a few programs introduce heat transfer fundamentals within a design course format.

Other important recent shifts are attempts to integrate new topics not previously stressed in the undergraduate curriculum into TS courses. Material pertinent to length scales and basic science applications (chemistry and biology) were mentioned most often. These topics relate to a broader discussion on new directions in mechanical engineering and how to accommodate the growing needs of the profession within an undergraduate curriculum [9].

Motivations for Change

Why are these changes occurring, and where will they lead? Fully one-half of the respondents mentioned that their curriculum is under review for change. There appear to be a number of drivers for change which include: a desire for design integration; a fascination with a multi-disciplinary systems approach to problem solving; the less prescriptive accreditation requirement environment; and state imposed credit limits.

An often-mentioned reason is the desire to add more TS design-oriented courses and projects, and to address vertical integration of design into the programs. This reason is consistent with an accreditation requirement for students to be able "to work professionally in the thermal systems area including the design and realization of such systems [8]." The introduction of TS concepts in an integrated format makes available early in the curriculum a natural palette of systems material for problem-solving and project activity. Proponents of the systems-oriented approach argue that it is more indicative of professional practice and, with its implementation during the early courses, allows a new engineer to develop a systems-level mentality for design as s/he matures within the program. It also fills a need for a broad TS course for non-mechanical engineering majors. Certainly, the softer accreditation requirements that provide more freedom for programs to decide how their graduates will develop the capabilities to practice thermal systems opens the door for trying new approaches.

One strong influence for change is the pressure most programs are under to reduce credit hour requirements. Fully 40% of the respondents noted this. Some state legislatures are mandating credit hour limits for state-assisted, undergraduate degree programs, typically requiring substantial cutbacks in engineering programs. Driving this political pressure are the tuition costs and a desire to increase four-year graduation rates. Likewise, neighboring schools are obligated to match these requirements closely or risk losing a traditional source of quality students. Reducing the number of explicit course offerings in thermal systems and repackaging essential material can accommodate these financial and political pressures. The acute question arises: if fewer credit hours are a goal, and we must scale back material, then what material is critical?

Further pressure comes from the growing needs of the mechanical engineering discipline requiring instruction in other areas and the application of TS material across disciplines, including material sciences, manufacturing and biologically-inspired applications. A recent workshop conducted by the ASME Mechanical Engineering Department Heads Group [9] developed recommendations for the future of mechanical engineering education that will have a broad impact on curricula and TS education: expanding faculty expertise in emerging technologies; revising curricula to include new material on atomic and molecular physics, quantitative biology, organic chemistry, micro fabrication, and modern computing; and, revising ME labs to include biotechnology and micro/nano-scale systems. This message makes clear the need for repackaging and integration, given the real matriculation time and credit hour limits, and given the nature of future needs in the mechanical engineering profession. Cited was the need for drawing mechanical engineering faculty from a broader, multidiscipline pool of expertise, producing agile graduates who can absorb and use new tools from other disciplines to develop new products, and focusing on a systems approach to broaden the “design-space” of mechanical engineering.

Barriers to Change

Even though significant changes are underway, there are roadblocks, as many survey respondents suggested. Changing the mode of business that has been in place for decades is not a clear or simple process.

First and foremost, the need was brought up for adequate textbooks and teaching materials. Our modern subject-specific textbooks have evolved to provide sound pedagogy and a complete treatment of their subject. Developing new textbooks having a different slant takes time and trial. Development is impeded because the specific materials to be covered in an integrated course of study are not well codified. As a consequence, instructors are spending large amounts of time developing their own materials, both written text and software tools. Transportability to a national scale has not been their focus. But these may be growing pains that will work out with time. The larger questions may be: do these approaches by nature require a substantially higher commitment from the faculty and students; and, if so, are the outcomes advantageous to justify this? We don't have good answers to these questions yet.

The second most cited impediment was a lack of instructors with that special ability to synthesize, integrate and teach combined TS applications. This situation can be expected to compound as universities hire more multidisciplinary professionals into their faculty. For example, should someone specializing in solid-state thermodynamics be expected to be sufficiently proficient in the broad area of thermal-systems design to develop teaching materials?

In project-based courses, students tend to learn subjects as needed to complete the project. Should a student’s exposure to material in any of the subjects be well established? How do we ensure understanding with depth on critical material? With project-oriented learning, outcomes may be harder to tie to basic concepts, emphasis changes with tasks, and student proficiency may change with the projects used to integrate the subjects. This is a significant pedagogical issue.

CONCLUSIONS

Many of the changes we've identified through the sessions and survey must be viewed as events in an evolutionary process to improve the delivery system. Faculty has been continually seeking novel ways to involve industry as partners, import applications-driven issues into the classroom, cultivate problem-solving skills, address thermal systems analysis / design, and use computer-based learning tools.

However, the process has become complicated because of the urgent need in all schools to include materials on the new technologies, and because of the reduction at many schools in credit hours available to the TS stem. The traditional three-course sequence TS stem remains intact in many programs, while elsewhere it's being reduced into fewer courses that combine the traditional disciplines in novel ways to meet newly defined learning objectives.

Dealing in creative ways with the aforementioned barriers for change will strengthen the stem regardless of what path reform will take. New textbooks and learning materials are driven by need, which is evolving as different teaching approaches are tried and assessed. Staffing the stem with faculty having non-traditional specialties will enrich the enterprise through new cultures and content. Capitalizing on the use of project assignments to learn and reinforce fundamental concepts is a worthwhile adjunct to the usual lecture-home problem methodology. In a broader context, the barriers represent opportunities that will be seized by those who have the vision and energy to support change.

Surely there are other creative approaches for dealing with TS stem changes. The reform should also be viewed from the perspective of the total curriculum. Reform isn't just about yielding or sharing turf (credit hours), but about how to prepare engineers under conditions of diminished resources for the marketplace that has higher expectations. We should seek and promote changes in all parts of the curriculum, including general education courses that could strengthen thermal science education.

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REFERENCES

1. Johnson, C.E., F.A. Kulacki, David Larson, L.S. Fletcher, and R.K. Shah (moderator), "Heat Transfer Education: An Assessment of Its Current Status and Future," ASME Winter Annual Meeting, Chicago, IL, November 1988 (from unpublished transcript, K-21 archives).

2. ASME, Heat Transfer Division, K-21 Education Committee, www.asme.org/divisions /htd/committees/ techcomm.html.

3. Bianchi, M.V.A., P.M. Norris, A.M. Anderson and A. Duncan (Eds.), *Innovations in Heat Transfer Education and Student Heat Transfer Designs*, Proceedings of the 32nd National Heat Transfer Conference, Vol. 6, HTD-Vol. 344, ASME 1997.

4. Nelson, Jr., R.A., L.W. Swanson, M.V.A. Bianchi, and C. Cami (Eds.), *Application of Heat Transfer Equipment, Systems, and Education: Thermal Sciences and Energy Systems Education*, Proceedings of the ASME Heat Transfer Division, HTD-Vol. 361-3 / PID-Vol. 3, ASME, 1998.

5. Khounsary, A.M., J.R. Mondt, T. Simon, D. Agonafer, D.P. DeWitt, R.S. Figliola, W.L. Grosshandler and F. Kreith, "Heat Transfer Education: Keeping It Relevant and Vibrant," Proceedings of the ASME Heat Transfer Division (R.A. Nelson, Jr., et al. Eds.), HTD-Vol. 361-3 / PID-Vol. 3, pp 17-24, ASME, 1998.

6. Witte, L.C. (Ed.), *Energy Systems Education*, in Proceedings of the ASME Heat Transfer Division, HTD-Vol. 364-4, ASME, 1999.

7. Kim, J.H. (Ed.), *Innovations in Heat Transfer Education*, in Proceedings of the ASME Heat Transfer Division, HTD-Vol. 366-1, ASME, 2000.

8. *Accreditation Policy And Procedure Manual,* Accreditation Board for Engineering and Technology, www.abet.org, 2002.

9. Akay, A. (Ed.), *New Directions in Mechanical Engineering Education*, ME Department Heads Workshop Report, ASME, www.asme.org, January 2002.