DOCUMENT RESUME

ED 452 048		SE 064 601

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TITLE	A Design-Oriented Approach to the Integration of Thermodynamics, Fluid Mechanics, and Heat Transfer in the Undergraduate Mechanical Engineering Curriculum.
PUB DATE	1999-08-00
NOTE	13p.; Paper presented at the International Conference on Engineering Education (Ostrava, Prague, Czech Republic, August 10-14, 1999).
AVAILABLE FROM	For full text: http://www.ineer.org/Events/ICEE1999/Proceedings/papers/292/292.htm.
PUB TYPE	Reports - Descriptive (141) -- Speeches/Meeting Papers (150)
EDRS PRICE	MF01/PC01 Plus Postage.
DESCRIPTORS	*Design Build Approach; Engineering Education; *Fluid Mechanics; *Heat; Higher Education; Integrated Activities; Teaching Methods; *Thermodynamics; *Undergraduate Study
IDENTIFIERS	*Massachusetts Institute of Technology

ABSTRACT

This paper describes two parallel efforts that attempt to implement a new approach to the teaching of thermal fluids engineering. In one setting, at the Massachusetts Institute of Technology (MIT), the subject matter is integrated into a single year-long subject at the introductory level. In the second setting, at Victoria (British Columbia, Canada), the design-oriented approach is used in the traditional separated presentation at a more advanced level where the material is focused on heat transfer. In both cases, the subject concludes with a design project that synthesizes the subject matter in the context of a real application. It is concluded that the students are much more engaged, develop a greater sense of accomplishment, and are much more capable of analyzing complex problems. (SAH)

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by

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Abstract: In the traditional undergraduate mechanical engineering curriculum of most engineering schools, the introductory subjects of heat transfer and thermodynamics are presented in serial fashion as though the subject matter of these two engineering sciences is somehow independent. Typically, the thermodynamics subject is presented first followed by the heat transfer subject since the development of the fundamental theory of heat transfer draws heavily upon the notions of equilibrium and the role of the temperature as the driving potential for heat transfer. Often, a demonstration of the intimate connection between the two subjects is deferred to a design subject and/or a project laboratory that synthesizes much of the subject matter of the curriculum. This is unfortunate since the two subjects are inextricably linked through the unique character of the heat transfer. The heat transfer stands apart from the work transfer in that it transfers both energy and entropy. This fact provides an excellent opportunity to integrate the two subjects in a fashion that can lead to a deeper understanding of the subject matter and provide valuable engineering insight.

In this paper we describe two parallel efforts, in widely different settings, that attempt to implement a new approach to the teaching of thermal-fluids engineering. In one setting, at the Massachusetts Institute of Technology, the subject matter is integrated into a single year-long subject at the introductory level. In the second setting, at Victoria, the design-oriented approach is used in the traditional separated presentation at a more advanced level where the material is focussed on heat transfer. In both cases, the subject concludes with a design project that synthesizes the subject matter in the context of a real application. We find that the students are much more engaged, develop a greater sense of accomplishment, and are much more capable of analyzing complex problems.

Keywords: thermal engineering, integration, design-oriented approach, thermodynamics, heat transfer, fluid mechanics

1 Introduction

Because it applies to all engineering systems regardless of their nature, the subject of thermodynamics is considered to be one of the most general of the engineering sciences. For decades, its universal character has encouraged engineering educators to teach the subject in a manner that emphasizes its abstract nature rather than its practical nature. Most often, thermodynamics is taught as a collection of laws, axioms, or postulates that are highly generalized so that they can be "easily" applied to all manner of engineering systems. Usually, educators illustrate the application of the science through a set of worked-out examples structured in the "given - find" configuration in which students are "given" a set of facts and asked to "find" a specific piece of information. Students are then expected to "learn" to apply this abstract theory by solving a collection of structured "practical" exercises also set in the "given - find" configuration by the instructor. The implication is that by imitating the solutions of the instructor, the students are "learning" thermodynamics -- "practice makes perfect." However, what typically happens is that the "learning" that students accomplish is actually "learning" to do "pattern matching", i.e. they learn to search through the collection of worked-out examples to find the best match for the problem they are trying to solve and then mimic that solution. To be sure, "pattern matching" is not confined to the study of thermodynamics alone; it is one of the most ubiquitous practices in modern education -- a practice that often passes for "learning" and leads to a false impression of mastery of a particular subject.

While the science of thermodynamics can be taught and learned as an abstract science in its own right, in engineering practice the application of the abstract theory presents a formidable challenge to the design engineer, who quickly comes to realize that the "patterns" that were so familiar in the classroom are nowhere to be found in practice. The fact of the matter is that the typical engineering situation is not structured in the "given - find" configuration. It is not always obvious what is "given" and what the engineer needs to "find." This confusion is further exacerbated by the way in which educators have packaged the subject matter in the learning environment. The material is usually compartmentalized or broken into pieces that are convenient for instruction and supposedly more easily absorbed by the student. Teaching or learning units are formed by combining together related subject matter that somehow forms a coherent package based on mechanism or models with little or no regard to the manner in which the material will be applied in engineering practice.

In broadest terms, the typical thermodynamic system involves some sort of fluid, the "working fluid" of the thermodynamics lexicon, that is moved from one location to another where it experiences some sort of rate process involving the transfer of energy or both energy and entropy. As a consequence of these interactions, the working fluid experiences a change of state. Hence, engineering educators often find it convenient to break the general subject of thermodynamics into separate units or subjects devoted to: (1) thermodynamics, (2) fluid mechanics, and (3) heat transfer. These same educators can often make cogent arguments about the logic of this fractionation of the subject matter. For example, "*Thermodynamics* is the study of the cause and effect relationship between interactions and changes of state of matter without regard to the rate processes that govern these interactions and the resulting changes of state. Hence, in a sense all physical situations can be viewed as "static" in terms of their thermodynamic behavior. *Thermodynamics* is a science in its own right. *Fluid mechanics* , on the other hand, has its roots in the science of mechanics and is concerned solely with motion of the working fluid from one location to another with little or no regard for the ways in which this motion may change the state of the fluid or the interactions that the fluid may experience along the way. Finally, *heat transfer* focuses on the rate processes associated with the interactions resulting in the transport of energy and entropy and uses thermodynamics and fluid mechanics as supporting sciences."

While this separation of subject matter into three separate areas of study may be pedagogically convenient, it is not pedagogically sound since it can create in the minds of students the mistaken impression that the design and analysis of thermodynamic systems can be similarly subdivided. In general, the thermodynamic, fluid dynamic, and heat transfer aspects of thermodynamic systems are inextricably interconnected. When the neophyte engineer enters the practice of the profession and is confronted with a thermodynamic system, he or she usually performs as trained. First try to classify the situation into one of these three categories, i.e. the engineer asks himself or herself, "Is this a thermodynamics problem or a fluid mechanics problem or a heat transfer problem." Having decided that it is usually one of these three (when it is actually all three), the engineer then falls into the old pattern matching process. When this fails, the engineer begins to flounder and enters into a frustrating, complex thought process that, over an extended period of time, will usually result in a new pattern of thinking about these complex situations. This is a highly inefficient process that can often lead to the development of poor engineering design skills or, if the level of frustration is high enough, possibly even to the abandonment of the practice of the profession altogether.

This does not need to be the case. Our experience has shown that it is possible to teach thermodynamics, or perhaps more properly thermal-fluids engineering, in an integrated fashion via a design-oriented approach that abandons both the long-standing tradition of separation into three separate subject areas and also the pattern matching approach to learning. In this paper we describe two parallel efforts, in widely different settings, that attempt to implement this new approach to the teaching of thermal-fluids engineering. In one setting, at the Massachusetts Institute of Technology, we have developed a year-long subject at the introductory level that integrates these three subject areas into a coherent format that teaches the fundamental principles of thermodynamics, fluid mechanics, and heat transfer with a focus on the design of thermal-fluids systems and hardware. In the other setting, at the University of Victoria, we have chosen to build upon an existing separatist or compartmentalized approach at the introductory level with the integration through design being introduced a bit later in a slightly more advanced subject.

In both cases the goal of these courses is to build upon the fundamental knowledge of the student through an analytical and design point of view aimed at the application of fundamental principles to real-world problems. In addition to integrating the subject material on a practical level, this approach facilitates the study of such advanced topics as compressor/turbine/pump design and heat exchanger design, while simultaneously exploring compressible flow, two-dimensional transient heat transfer, multi-phase and multi-mode heat transfer, combustion, chemical availability, and availability analysis.

2 Features of a Design-Oriented Approach

Our design-oriented approach to the teaching of the engineering of thermodynamic systems has three features: (i) the extensive use of analysis of real systems and components, (ii) the integration of advanced-level thermodynamics, heat transfer, and fluid mechanics, and (iii) a major design project. In many instances, the analysis of real systems necessitates the integration of the thermal engineering subjects, thus point one and two above are not mutually independent, but often achieved simultaneously. The analysis of a real system is much like a "case study" where a reverse-engineering approach provides the context within which we explore the function, operation, and design of the system components. We begin with the thermodynamic principles on which energy conversion and refrigeration systems are based and progress to individual components. These components are introduced and analyzed in terms of their role in the system, rather than as an isolated flow device. The study of the real component (turbines, compressors, and heat exchangers) permits the student to understand what role the component plays in the overall system, why the component is designed as it is, and how the component's operation can be optimized.

This presentation begins with the analysis of a particular cycle implemented in a real system, for instance, a refrigerator. We have chosen a refrigerator because it is a familiar device for the students, and its components are simple yet illustrate a wide range of thermal engineering problems. The system is literally presented to the students; its components pulled apart and examined. The theoretical analysis is presented as a means to describe the function of the system and its components. Subject material in a particular area, for instance thermodynamics, that is specific to each component is introduced as it is needed and placed in context with the related concepts in heat transfer and fluid mechanics. Subsequently, other thermodynamic cycles and their components are presented to cover the full range of energy conversion devices and the thermal engineering subject material necessary to analyze them.

The ability to analyze thermodynamic systems is not the only goal of our approach. To develop the skills necessary for more multidisciplinary problems, which are encountered in professional practice, the students must complete a design project comprising a major component of work of the course. The second half of the course focuses on preparing the students to complete a detailed design of an actual thermodynamic energy conversion system- an open-ended project requiring a full and complete integration of the three subjects for successful completion. This preparation includes the presentation of problems that extend the principles presented in the first half of the course during the "case study" and gives the students the practice necessary to become familiar with the iterative process of design.

3 The Experience at MIT

During the past several years, the faculty of the Department of Mechanical Engineering at MIT have been implementing a new curriculum in response to the rapidly accelerating technological needs of society and the ever-changing nature of the students entering the educational stream. The changes being introduced are extensive and pervade every aspect of the curriculum, but in all cases the emphasis has been on the integration of teaching materials and methods across disciplinary lines with a view toward educating engineers who will have a holistic perspective of the practice of their profession. Special courses have been introduced to provide students with opportunities for hands-on learning reminiscent of the master-apprentice approach of bygone eras. While it remains to be seen how well these students will be able to deliver the goods and services that modern society demands, early indications point to an increase in a sense of accomplishment by these students.

As a part of this new curriculum, the introductory courses in thermodynamics, heat transfer and fluid mechanics are taught as integrated components of a full-year course in Thermal Fluids Engineering. As described above, the traditional mechanical engineering curriculum compartmentalizes the study of thermodynamic systems is into the three separate subject areas of thermodynamics, fluid mechanics, and heat transfer. While this traditional separation of subject matter into three separate areas of study may be successful in some settings it fails to capitalize on the opportunity to synthesize the material in a way that can lead to an improved understanding of the subject matter and superior engineering design of these systems. Furthermore, the integrated approach used at MIT has lead to a deeper understanding of the subject matter and provided valuable engineering insight to the student.

In implementation of the integrated approach, it must be recognized that given the limited backgrounds of the students at this stage of their academic careers, it is not possible to provide an integrated presentation constantly throughout the entire academic year. There are times when it is necessary to provide isolated fundamental principles, but once these have been introduced, the illustrative examples are presented in an integrated context. Frequently, these integrated examples can be used to establish the context for the subsequent material.

At MIT, the integrated approach consists of two one-semester subjects that are taken serially. In the first semester, the emphasis is on the exposition of fundamental principles of the traditional subject areas of thermodynamics, fluid mechanics, and heat transfer with simple fluid models, namely the ideal gas model and the incompressible fluid model, used to illustrate the principles. In the second semester, a more complex fluid model, the pure substance, is introduced early in the term and used as a vehicle to delve into the more complex aspects of the traditional subject areas. From the very start of the first term, the problem solving exercises emphasize the design of thermal-fluids hardware. The examples are all drawn from industry and the physical world familiar to the students. As the academic year progresses, the student exercises become more comprehensive as the physical systems under analysis become larger in scope and embrace more complex physical processes. In both semesters, there is an end-of-term design project that synthesizes the subject material.

As shown in Table 1, the first-semester course begins with the development of the first and second laws of thermodynamics and a collection of simple fluid models that are used to illustrate their application. The static and dynamic mechanical behavior of these fluids is explored with a view toward the introduction of the underlying physical principles of the quasi-static model widely used to model thermodynamic processes. Introduction of the rate processes associated with the three classical modes of heat transfer facilitates the further development of the quasi-static model and the approach to equilibrium. The classical formulations of steady-state and transient conduction heat transfer in solids are presented and used to illustrate the notion of internal and external reversibility. The concept of reversibility is quantitated by studying the heat transfer rate processes that influence it. These concepts are then used to demonstrate the manner in which system performance is limited by the generation of entropy. The study of open thermodynamic systems leads to the development of the fundamental principles of fluid mechanics and the laws of thermodynamics for open systems through the introduction of the Reynolds transport theorem.

As shown in Table 2, the second-semester course begins with the introduction of dimensional analysis. The application of these principles and the Reynolds transport theorem to internal flows leads to the study of convective heat transfer. Heat exchanger design is considered in detail to illustrate further the need for an integrated approach. With the introduction of the pure substance model, condensation and boiling heat transfer are introduced to further the coupling of the thermodynamics, fluid mechanics, and heat transfer. The performance of steady flow components of thermodynamic plants and cycles are illustrated with the aid of the full spectrum of fluid models. The overall performance of these plants and cycles are studied with a particular view toward the ways in which they are limited by heat transfer and the second law of thermodynamics.

This single subject in thermal-fluids engineering is not meant to provide a comprehensive treatment of these three subjects in exhaustive detail that would preclude further study in concentrated areas. Rather, the objective is to provide a thorough understanding of the traditional areas of thermodynamics, fluid mechanics, and heat transfer at a fundamental, but integrated level that facilitates the design of complex thermal-fluids systems. It is hoped that this approach will point the way to further study and research in thermal-fluids systems.

4 The Implementation at University of Victoria

At the University of Victoria, the thermal sciences are taught in a traditional or compartmentalized approach. Introductory thermodynamics is taught in the first term of second year, followed by fluid mechanics in the next term. In the third year, advanced thermodynamics (energy conversion) is studied, followed by heat transfer in the last term of the third year. Despite this compartmentalized approach, it is still possible to implement a design-oriented presentation for particular topics in more advanced courses. We have developed a course for the heat transfer subject that uses a design approach to introduce the topics of heat transfer, and simultaneously integrates the subject matter of the previous courses.

First, a commercial refrigeration system is examined in order to establish the principles used to design individual components. This analysis includes the determination of the working fluid and the thermodynamic cycle, the detailed design of the compressor and heat exchangers, and the sizing of fluid handling elements. In addition to synthesizing the fundamentals of the introductory subjects, this approach develops in the students an appreciation for the practical limitations of purely thermodynamic analysis alone. During the latter half of the course, the students develop a detailed design of a thermal energy conversion system. To complete this design project, the students must make decisions about the working fluid, thermodynamic cycle, system components, and system configuration that require the integrated application of the fundamentals of thermodynamics, heat transfer and fluid mechanics. Although the project in this heat transfer course focuses on the design of the components to permit the heat transfers, it is the first time that the students attempt a realistic design of a thermal system. Through this design-based approach, students develop the skills necessary to analyze and design the thermal-fluid systems likely to be encountered in professional practice.

The presentation of the course occurs in 39 fifty-minute lectures, or approximately three times a week over 13 weeks and consists of two main parts: (i) a "case study" -- reverse engineering of a refrigeration system and (ii) design of solutions to other thermal problems by extending the principles learned. Table 3 provides an outline of the course syllabus and the topics covered in each set of lectures. The analysis part of the course begins with a review of thermodynamic cycles to refresh the students' knowledge of thermodynamics, but also to motivate the need for studying techniques to analyze heat transfer. The modes of heat transfer are presented as the physical means to achieve the necessary energy transport for a particular device, and then the components of the refrigerator are analyzed as examples of practical devices, created to exploit the modes of heat transfer. The subject material, therefore, is motivated by the need to design components for an engineering purpose, instead of solely a means to describe certain physical processes.

4.1 Design Principles for Components

Rather than presenting a set of formal definitions, the course starts with the examination of an actual refrigerator with cut-away components that is brought into the classroom and shown to the students. The function of each component is discussed and used to construct the cycle by using the students' responses to questions aimed at their experience with such systems and their knowledge from introductory courses.

The classic Carnot refrigeration cycle summarizes the fundamental operation of the system. The operation of the system is constructed on a T-s diagram by assuming isothermal heat transfer processes and closing the cycle isentropically. Examining the actual components and reviewing the T-s diagram of real refrigerants motivates the ideal refrigeration cycle using a real working fluid. The concept of a coefficient of performance and its analog, an efficiency for the case of a heat engine, are reviewed together with the role of the second law of thermodynamics as a limitation to performance. The concepts of a cycle and the processes that comprise it are also reviewed by concentrating on the cyclic machinery, which acts to transport entropy between the two thermal reservoirs. This first lecture constitutes the review of the first and second law of thermodynamics, the energy and entropy balances, thermodynamic processes and cycles, and the limiting role of the second law on performance. Most importantly, this lecture firmly sets the study of heat transfer in the context of thermal engineering systems.

With this context defined, we present the modes of heat transfer and the laws used to describe them. The phenomenological expressions for conduction, convection, and radiation are presented and combined with the energy balance. The concept of a thermal resistance, derived from these expressions, and the formation of networks to model more complex system are presented. Using the refrigerator as an example of such a complex system, a network of resistance elements is obtained, clearly showing the types of parameters that we must measure or obtain to establish the performance of the components of the refrigerator.

Before addressing the techniques to determine these parameters, we consider a solid object that is put into the refrigerator and cooled. We do this to illustrate the relative importance of the various conduction and convection resistances to heat transfer in the refrigerator. We start by introducing the lumped capacitance model and progress toward transient effects with the derivation of the Biot and Fourier numbers. We discuss the generation of entropy and its relation to the reversible and irreversible domains of this simple solid-fluid system.

The first eight lectures constitute the introduction to the engineering analysis of heat transfer interactions. By introducing the concepts in the context of a real practical refrigeration system, we motivate the need for such analytical techniques and formally illustrate the relation of heat transfer processes to the operation of thermodynamic cycles. As shown in Table 3, the remainder of the lectures presents the usual topics in an undergraduate heat transfer course. The order, however, may be somewhat different than usual. By focussing on the operation and design of the condenser and evaporator in the refrigerator, we present techniques to analyze the various modes of convective heat transfer. We start with boundary layers and move toward the empirical methods for determining heat transfer coefficients in external, internal and free convection. In addition, we cover boiling and condensation heat transfer to be able to fully address the design issues of the evaporator and condenser.

All through this presentation, periodic reference to the refrigerator and its components clarifies, focuses, and motivates the particular topic being studied. After having presented the necessary analytical techniques, the various methods of heat exchanger design are presented. Study of the log-mean temperature difference and the effectiveness-NTU methods permits the full integration of the thermodynamics of the system cycle and the heat transfer in thermal engineering design.

We complete the system analysis by looking in greater detail to the operation of the compressor. Analysis of this device permits the integration of fluid and thermodynamic considerations. While not usually part of a heat transfer course, we feel that time used to describe the design of these components offers the opportunity to place the earlier work in thermodynamics and fluid mechanics in a design context that would not ordinarily be possible in a more strictly compartmentalized curriculum.

4.2 Applications of Thermal Systems

In the analysis of the refrigerator, little opportunity was available to detail the processes of conduction. In particular, two-dimensional and transient problems were only presented in passing. Furthermore, radiation and multi-mode heat transfer were not covered. For these reasons, the second half of the course is focussed on the design of other thermal systems in which these modes of heat transfer dominate. We continue, however, to keep the presentation firmly grounded in the context of real applications and relate the fundamental heat transfer processes to the thermodynamic and fluid mechanic considerations wherever possible.

We examine the details of conduction by studying the various techniques for cooling of electronic equipment. We start the analysis by deriving the heat conduction equation and relate the boundary and initial conditions to the various heat transfer modes. Conduction cooling, forced convection and fan selection, and air cooling by natural convection and radiation are used to illustrate typical applications of heat transfer analysis techniques. We present two-dimensional conduction and transient conduction analyses to permit the detailed design of cooling solutions for printed circuits and electronic devices.

Applications of heat transfer in industrial processing and materials processing complete the course. These lectures are designed to teach the fundamentals of heat transfer by radiation as well as draw together techniques for analyzing systems in which several modes of heat transfer may be equally important. These more advanced topics in thermal engineering include systems in which multi-mode heat transfer, mass transfer, fluid mechanics and thermodynamics are coupled. Examples include refrigeration and freezing of foods, heat pipes, and heat transfer and fluid flow in porous media. Transient effects are studied using quenching and furnace heating examples.

5 Design Project

The objective of the design project is to provide experience in the application of the principles and concepts in thermal-fluids engineering to open-ended design problems in an environment as close as possible to that experienced by practicing engineers. The context for the project is that the student has been employed as a consultant working as part of a team to do the preliminary design for a new product or process concept and to assess its technical feasibility. Selecting the right topic for the project is not easy. It must be a project that can somehow be related to student experience, usually a product used in the home or school setting. Large projects that are industry based, such as power plants, are not good choices because the students have no way of knowing if their designs are even close to something realistic. To be sure, they can find appropriate reference materials on the World Wide Web, but they have no first-hand knowledge of these systems.

Examples of projects that have been used at the introductory level have included a very simple and inexpensive hand held blower that will deliver a short burst of air for dust removal and cleaning applications (U. Of Victoria), a portable refrigerator for RVs and recreational use (second semester, MIT), a cooling system for personal computers (first semester, MIT), a chiller plant with two stage turbo-compressors (second semester, MIT), and a finned tube heat exchanger for a room air conditioner (first semester, MIT). For the advanced-level course, a higher degree of detail is expected with more complex projects being assigned such as the application of novel energy conversion systems for off-grid portable electricity generation.

The design problem is assigned at the start of the semester and progress is expected in several stages. Problem set assignments include the design of components for systems similar to the one being developed for the project, as well as the accomplishment of project milestones. After each stage, the students are required to submit progress reports, and assignments for the next stage allows the students to improve upon their work from previous stages and then extend the work as required for the next stage. The progress reports and the final report determine the grade for the project for each student.

At MIT the design project is an individual effort in the first semester and a team effort in the second semester. In the team approach, the students must create their design by working in teams of four students that must remain together until the project is completed. No changes of team membership are allowed, and a single grade is given based on the final report of each team, thus emphasizing the need for teamwork. However, the progress reports submitted by each student are graded on an individual basis. Reports are evaluated for both technical content and writing style. Because creative design work pays off in industry by increasing sales, 20 percent of the project grade is devoted to creative aspects of the design. Each team makes an oral presentation of 5 minutes with a maximum of 5 slides per presentation. The members of the class evaluate these presentations and these scores become a part of the final project grade.

The first progress report focuses on the conceptual stages of design work. A statement of the scope of the problem and the student's plan for developing a design is expected with a description of a conceptual design. These plans include the subdivision of the analysis into simple steps with the design parameters and variables for each step and show how the values selected as inputs into the simple step-by-step analysis lead to the desired output of the particular device. The student is required to assess the concept, including favorable and unfavorable aspects of the design and its performance. The student is encouraged to build skills necessary to answer simple questions of scale and feasibility, such as, "Is the design too large or too heavy?", "Will it cost too much to produce?" The reports become more detailed and complex as the term progresses and are aimed to teach proper management skills by encouraging the students to spread work over the entire period of time available.

Another aim of the project is to give an economic context of the engineer's professional environment. Engineering designs that are cost effective are stressed. Final reports must include cost estimates for their manufacture and operating costs as well as full technical specifications of such components as tubing sizes, fin sizes, motor sizes, compressor sizes, etc. All specifications must be supported by detailed analyses. Many of the design constraints are left unspecified so that part of the design effort involves establishing these design parameters.

6 Results and Conclusions

Clearly there are advantages and disadvantages of the integrated approach relative to the traditional approach, but the issue here is the design orientation aspect of both approaches rather than integrated versus traditional approaches. Our experience has shown that the design orientation has worked well as evidenced by the response from students who have completed the experience. Although they complain of the time required to complete the design project, they appreciate the fact that it has helped them synthesize the subject material in a meaningful way. Students also report from the workplace that they are able to engage in meaningful design work on thermal-fluid systems immediately upon entering the workplace as a result of their experiences on campus. One of the most attractive features of the approach is the sense of accomplishment that students have upon completing the classroom work. They believe, and rightly so, that they can design and analyze complex thermal-fluid systems in ways that were not possible for our graduates prior to the development of this approach. They readily acknowledge their lack of hands-on experience with engineering systems and believe that this design-oriented approach has helped ameliorate this deficiency somewhat.

However, they continue to request more hands-on work to eliminate this deficiency entirely. A lab subject to accompany the classroom work would be an ideal way to do this, but the present curriculum at MIT is so crowded now that there is no room to accommodate such a lab course. However, we have been able to incorporate in our curriculum a multipurpose subject known as Mechanical Engineering Tools. In this subject, the students do build a Sterling cycle heat engine in addition to engaging in a variety of other activities designed to equip them with a set of skills that will serve them well as they progress through our curriculum. In addition, we are in the process of designing and building demonstrations that can be wheeled into the thermal-fluids engineering classroom to show the hardware that matches the system designs that we are depicting in symbolic fashion on the blackboard. Clearly, it is not possible to demonstrate a power plant with a capacity in the megawatt range, but we are able to demonstrate the operation and appropriate components and sizing for refrigeration cycles, small internal combustion engines, heat exchanger configurations, pumps, fans, blowers, combustors, and a host of other thermal-fluid system components. We are also able to demonstrate a number of complex thermodynamic, fluid dynamic, and heat transfer phenomena such as the critical state, dropwise and filmwise condensation, various boiling heat transfer regimes, and viscous and compressible flow phenomena. We have employed the students in the subject to do the design and fabrication of these devices so that at least a few of them will have the pleasure of extended hands-on experience.

One of the more interesting pieces of "fallout" from this approach, has been renewed interest in the field. At MIT, all undergraduate mechanical engineering students must complete a thesis. Since the transition to the new integrated, design-oriented approach, the numbers of students doing theses in thermal-fluids engineering have increased. In addition, there has been a demand for more advanced offerings in this field; accordingly, the faculty have added at the undergraduate level an advanced elective subject in the design of thermal-fluids systems.

Table 1: Course outline for the first-semester course in thermal engineering at MIT.

Lecture	Topic
1	Introduction to basic principles of energy and the First Law
2	Equilibrium and the Second Law: Entropy and Pure Thermal System Model
3	Uncoupled Thermodynamic Systems
4	Solids vs. Fluids : Mechanical Equilibrium and Intro. to Fluid System Models
5	Pressure Distribution in a Fluid and Archimedes?™s Theorem and Buoyancy
6	Pressure Forces on Surfaces and Work Transfer
7	Mechanical Matching Elements and Reversible Work Transfer
8	Thermal Matching Elements and Reversible Heat Transfer
9	Reversible Processes in the Ideal Gas Model
10	Modes of Heat Transfer and Thermal Resistance
11	First Law for Pure Thermal System (Solid): Conduction Equation
12	Second Law for Solid: Entropy Generation Equation
13	Steady Heat Transfer between a Fluid and a Solid: Extended Surfaces
14	Transient Heat Xfer between Fluid and Solid: Equilibrium between Systems
15	Lumped Thermal Capacitance: Biot Number and Fourier Number
16	Systems with Reversible and Irreversible Domains: Bi>>1; Bi<<1
17	Reversible Entropy Transfer between Heat Reservoirs
18	Entropy Transport by Reversible Cycles
19	Heat Engine Efficiency, Heat Pump COP, and Second Law Limits
20	Second Law Limits on Heat Transfer and Work Transfer

21	Examples of Second Law Limits
22	Open Thermo. Systems and Control Volumes: 1-D Bulk Flow Model
23	Conservation of Mass for Control Volumes
24	Conservation of Energy and Entropy for Control Volumes
25	Steady-Flow Control Volumes
26	Unsteady Flow with Uniform State in the Control Volume
27	Fluid Continuum: Conservation of Mass (Integral and Differential Forms)
28	Reversible and Irreversible Flow in the Continuum: Reynolds Number
29	Inviscid (Reversible) Fluid Model: Acceleration of Fluid Particle
30	Inviscid Fluid Model: Euler's Equation
31-32	Inviscid Fluid Model: Bernoulli's Equation
33	Fluid Continuum: Conservation of Momentum
34-35	Linear Momentum Theorem
36	Applications of Linear Momentum Theorem
37	Angular Momentum Theorem
38	Applications of Angular Momentum Theorem
39	Viscous Fluids: Viscosity and Entropy Generation
40	Viscous Fluids: Equation of Motion (Navier-Stokes Equations)
41	Viscous Fluids: Fully-Developed, Inertia-Free Flows
42	Viscous Fluids: Couette Flows and Entropy Generation
43	Viscous Fluids: Poiseuille Flow
44	Viscous Fluids: Internal Flows with Friction
45	Viscous Fluids: Entrance Effects and Head Loss
46	Viscous Fluids: Piping Systems
47	Viscous Fluids: Unsteady Laminar Flows
48-51	Viscous Fluids: Laminar Boundary Layers
52	Review

Table 2: Course outline for the second-semester course in thermal engineering at MIT.

Lecture	Topic
1	Introduction

2	Dimensional Analysis: Physical Quantity, Dimensions, Dimensionless Nos.
3	Non-dimensionalization of Conservation Equations
4	Modeling of Fluid Flows and Heat Transfer: Similarity
5	Turbulent Viscous Flow
6	Turbulent Skin Friction and Drag in Internal and External Flow
7	Convective Heat Transfer: Laminar Pipe Flow
8	Convective Heat Transfer: Turbulent Pipe Flow
9	Convective Heat Transfer: Axial Temperature Distribution
10-11	Convective Heat Transfer: Laminar and Turbulent Ht. Xfr. Correlations
12	Convective Heat Transfer: Boundary Layer Heat Transfer
13-14	Convective Heat Transfer: Heat Exchangers
15	Pure Substance Model
16-18	Two-Phase States of the Pure Substance Model
19	Natural Convection
20-21	Heat Transfer by Condensation: Physics of the Process
22	and H. T. Correlations in Condensation and Boiling
23	Design of Evaporators and Condensers
24	Steady-flow Components of Thermodynamic Systems
25	Shaft Work Machines: First and Second Law Analysis
26	Shaft Work Machines: Fluid Dynamics
27	Nozzles, Diffusers, and Throttles: First and Second Law Analysis
28	Nozzles, Diffusers, and Throttles: Fluid Dynamics
29	Head Losses in Piping due to Friction: Moody Chart
30	Head Loss Due to Entrance and Exit Effects and Piping Components
31	Pumps and Turbines: Head Gains and Losses - Component Efficiencies
32	Piping Systems with Pumps and/or Turbines
33	Thermodynamic Plants: Carnot Cycle Plants
34-35	Thermodynamic Plants: Rankine cycle Plants
36-37	Thermodynamic Plants: Gas Turbine Plants
38	Thermodynamic Plants: Refrigeration Plants
39	Thermodynamic Plants: Reciprocating Internal Combustion Engines

40	Thermodynamic Plants: General Design of Thermodynamic Plants
41	Thermodynamic Plants: Power Cycle Design
42-44	Design of Thermal Systems
45	Fundamental Physics of Radiation Heat Transfer
46	Black Body Model and Radiative Transfer Between Black Bodies
47-48	Gray Body Model and Radiative Transfer Between Gray Bodies
49	Radiation from Flames and Luminous Gases
50	Multimode Heat Transfer
51	Review

Table 3: Course outline for use of a design-oriented approach in a heat transfer course at the University of Victoria.

Topic	Lecture	Material Covered
Analysis of Refrigerator: Design Principles for Components		
Overview of Thermal Sciences	1	Presentation of refrigerator and its components. Review of 1st and 2nd Law, cycles, limiting role of 2nd Law, role of heat transfer
	2 - 4	Modes of heat transfer. Conduction (Fourier's Law), convection (Newton's law of cooling), radiation (Stefan-Boltzmann Law) Thermal resistance. Formulating a network for the refrigerator
Heat Transfer between a Solid and Fluid	5 - 6	Lumped capacitance model. Cooling of objects in refrigerator. Steady and transient heat transfer between solid and fluid
	7 - 8	Role of Biot and Fourier numbers. Reversible and Irreversible domains: $Bi \ll 1$, $Bi \gg 1$, $Bi \sim 1$. Entropy generation in relation to heat transfer process

Heat Exchangers	9 - 13	Convection transfer equations. Boundary layers, similarity solutions, Reynold?™s analogy
	14 - 18	Correlations for heat transfer coefficients. The empirical method, correlations for external, internal, free convection, laminar and turbulent flow
	19 - 20	Boiling and condensation heat transfer. Physics and correlations
	21 - 24	Design of evaporators and condensers. Heat exchanger design methods (LMTD, ε-NTU), need for iteration in the design process, examples of convective processes and use of empirical data in design
Compressors and Turbines	24 - 25	Blading diagrams, thermodynamics of compression and expansion, internal and external reversibility, relation between fluid velocity and temperature and pressure changes.
Design of Thermal Systems		
Cooling of Electronic Equipment	26 - 32	Heat conduction equation. Boundary and initial conditions, 1-D steady, 2-D steady conduction
	33 - 35	Conduction cooling of electronics. Forced air cooling, fan selection, applications of two-dimensional and transient heat transfer analysis, heat pipes
Industrial and Materials Processing	36 - 39	Radiation heat transfer. Fundamentals of radiation, blackbody model, gray model Multi-mode heat transfer, transient effects, quenching and furnace processing of materials.

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