Thermal Fluids Systems Engineering at the United States Air Force Academy

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Abstract

This paper describes the new pedagogy used to teach thermal fluid systems engineering (TFSE) to cadets who major in either mechanical engineering or engineering mechanics. Previously taught as a 4-course sequence consisting of separate and distinct subject material on Thermodynamics (ME 312), Fluid Mechanics (ME 341), Heat Transfer (ME 441), and Energy Conversion (ME 467), the current presentation integrates this subject material in each course. To reinforce the integration, the course titles have been changed to TFSE I (ME 312), TFSE II (M341), and TFSE III (ME 441). The fourth course, Energy Conversion, has become a technical elective in thermal systems design. A common text is used in all four courses. The goal of this new pedagogical approach is for the cadets to learn the fundamentals of thermal fluids systems integrally as they occur with mass, momentum, and energy transfer processes in nature. The course sequence is also supported by a thermal fluids laboratory consisting of a variety of fluid dynamic, thermodynamic, and heat transfer studies. This paper also contains details for development and implementation of the TFSE pedagogy.

Introduction

The thermal-fluids coverage in the mechanical engineering (ME) and engineering mechanics (EM) curricula at the United States Air Force Academy (USAFA) is undergoing a metamorphosis from the more conventional method of separate topical coverage (i.e., thermodynamics, fluid mechanics, and heat transfer) to a synthesized, integrated form of instruction wherein topics from all three areas are covered in each of three terms. This method of instruction allows the cadets to see that all three areas are indeed physically connected, producing a synergism which will hopefully allow them to better understand and retain the material.

Background

Previously, cadets in the ME and EM majors were required to complete courses in thermodynamics (ME312) and fluid mechanics (ME341); additionally, ME majors were required to take courses in heat transfer (ME441) and energy conversion (ME467). The first two columns

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of Table 1 provide a synopsis of the courses and the topics covered in each, and the term in which each course is normally taken. Since cadets can declare a major as late as the end of the first semester sophomore year, and since many of their "core" courses (required of all cadets, regardless of major) are taken up to this point, the thermal fluids sequence starts approximately a year later than it would be taught in similar curricula at many other colleges or universities. A total of 147 semester hours is required in the ME and EM majors.

Depending on the population of the ME and EM majors each term, the numbers of cadets enrolled in each course may range from 45 to 90. Every effort is made to keep each section size small (between 15 and 20 cadets) to enhance the laboratory experiences. A single course director works with 2 or 3 other instructors during the term, coordinating syllabus, web site, homework assignments and solutions, quizzes, tests, and the final examination.

The Traditional Approach

A problem noted by the authors, not only at USAFA, but from their experiences at other colleges and universities, is that the more traditional approach (i.e., separate topical coverage) generally results in a failure by cadets to recognize common themes that occur in each of the three courses. The ideas of mass conservation, energy conservation, boundary layer, open and closed systems, etc. are learned and relearned by many cadets, and yet the significance of how these concepts form the underlying basis in each of these courses is not learned or understood. On a more conscious level, cadets see each course as an academic requirement, and seemingly cannot wait to "unlearn" the material at the end of each term so that they may "make room" for the new material in the semester to come. Additionally, the cadets are often required to purchase a separate text for each course, of which only a portion is actually used. In effect, the cadets have bought "more" text than was actually needed to cover the material. Most cadets end up selling their texts at the end of the term in which they were used.

Moreover, texts in each of these areas provide example and exercise problems which are usually limited to just that one subject: thermodynamics, fluid mechanics, or heat transfer. Such texts usually fail to provide realistic problem scenarios, and the cadets are not exposed to situations involving the integration of physical effects in an engineering system—these are situations they are likely to encounter in engineering practice.

A More Integrated Approach

To overcome the shortcomings of the traditional approach, the authors sought a pedagogy wherein a similar amount of material might be covered in a more integrated sequence. The British secondary education system employs a scheme wherein algebra, geometry, and trigonometry are not taught as separate subjects. Rather, these three areas are taught and tested in each term, with increasing degrees of difficulty and/or scope provided in successive terms. A similar pedagogy was adopted for the TFSE sequence in the ME/EM curricula at USAFA. Using thermodynamics as a foundation, topics from heat transfer and fluid mechanics are introduced at appropriate points in each course. For example, when heat and work modes of energy transfer are presented in the development of the conservation of energy, several lessons are devoted to studying work modes; several more lessons are used to introduce the heat transfer rate relationships for conduction, convection, and radiation, which are, in turn, followed by several lessons devoted to one-dimensional steady state conduction. As another example, study of boundary layer phenomena includes both hydrodynamic and thermal boundary layer applications. The third column of Table 1 shows how each course was renamed, and the topical coverage in each.

In many respects, TFSE I mirrors a classic thermodynamics course for the first half of the term. The concepts of work and heat are applied to closed systems, with emphasis on the polytropic process. The 1^{st} and 2^{nd} laws of thermodynamics are introduced, and the concept of entropy is developed and applied to the Carnot cycle; the Gibbs equations are developed. A brief introduction into all three modes of heat transfer is included, sufficient to cover the requirements of engineering mechanics majors who would not have had any detailed heat transfer coverage under the more traditional approach; a more detailed introduction to one-dimensional plane heat conduction is included. Additionally, the Reynolds transport theorem is introduced, thereby allowing relatively rapid coverage of the conservation of mass, energy, and momentum for application to a control volume. Fluid mechanics is introduced by presenting the fundamental aspects of hydrostatics.

TFSE II continues with the entropy balance applied to an open system, with a transition to isentropic processes in single entrance/single exit systems—isentropic efficiencies are then covered for plant components. One-dimensional radial conduction and heat transfer through extended surfaces are then covered. Dimensional analysis, modeling, and similitude are covered, and the differential momentum, Euler, and Navier-Stokes equations are derived. The Navier-Stokes equations may then be simplified to allow study of boundary layers, internal and external flows, etc.; the Bernoulli and mechanical energy equations are covered. Finally, convection heat transfer is covered in detail, including the various non-dimensional parameters, appropriate correlations, and a final application to heat exchangers.

At this point, engineering mechanics majors will not normally take either of the remaining two courses in the TFSE sequence. They will have been exposed to the essential elements of thermodynamics, fluid mechanics, and heat transfer in a more thorough and integrated fashion than was accomplished under the more traditional approach.

TFSE III begins with a more detailed treatment of radiation, and continues with finite difference solutions for one- and two-dimensional conduction (coupled with a convective boundary condition), and one-dimensional fluid flow; steady-state and transient problems are studied. Moment-of-momentum is developed, with applications to turbomachinery in general, and with a concentration on pumps. Basic analyses of the Rankine, Otto, Diesel, dual, and Brayton cycles are followed by study of one-dimensional compressible flow in nozzles and diffusers (to include the case of constant specific heats). The course concludes with a study of psychrometrics applied to HVAC systems.

ME467 (now offered as an elective to ME majors) may be thought of as "TFSE IV," since it builds on the material in the first three courses in the sequence. It begins with a more detailed analysis of the power cycles enumerated above, including cycle improvements such as reheat, regeneration, intercooling, combined cycles, cogeneration, etc; the essential elements of combustion analysis are covered. Refrigeration and heat pump cycles are studied, as are alternate energy sources (wind, nuclear, solar, etc.) and energy storage schemes. A major portion of the grade for this course derives from completion of a thermal analysis of a combined cycle, cogeneration, or similar power plant.

The change to the new system began in the fall of 2003 with the juniors who took ME312 as TFSE I; ME441 was taught as a conventional heat transfer course that same semester to the seniors. In the spring of 2004, ME341 (now as TFSE II) and ME467 were taught; the transition will be complete in fall 2004, when ME312 and ME441 will be offered as TFSE I and TFSE III, respectively.

To further enhance the cohesiveness of the TFSE sequence, a unified intraweb site has been constructed which provides not only the usual course administrative support, but also links to additional sites of interest, historical perspectives on the topic matter, and the like.

Metrics for Success

It would be difficult to try to directly compare cadet performance in courses under the more traditional system with how they fared under the new TFSE approach, course-by-course. Perhaps the most effective way will be a topic-by-topic comparison of results from the Fundamentals of Engineering examinations which are taken by the majority of cadets in the spring of their senior year. Additionally, if the same types of tests and final examination were employed in ME467 (the fourth course in the thermal fluids sequence), another comparison could be made.

Text Selection

The text[1] that was chosen is essentially a distilled version of the texts for each of the 3 disciplines: thermodynamics[2], fluid mechanics[3], and heat transfer[4], all of which were being used in the mechanical engineering and engineering mechanics curricula at USAFA. A CD accompanies the text, and includes not only the entire printed text, but also several sections which are not in the bound volume. Although it does an excellent job of presenting the essential elements of each topic, it seems that it had been "written by committee." Notation is inconsistent ("h" stands for either enthalpy or film coefficient, "Q" represents volumetric flow rate or heat, etc.). There are several topics for which the text does not provide the desired coverage (turbomachinery, numerical methods, Reynolds transport theorem, combustion, etc.); since the three texts used previously were issued by the same publisher as the TFSE text, permission was obtained for specific chapters from the three texts to be used in conjunction with the new curriculum. The long-term solution is to print a tailored paperback supplement to the hard-bound text, and/or to produce a locally-written text.

One of the major objectives for adopting the TFSE sequence was to have problems which were not only open-ended, but which required the cadets to utilize all aspects of the thermal fluids discipline, not just one at a time. Since this is exceptionally difficult to do when writing an undergraduate text which covers the entire discipline, several such problems were designed for homework during each term. Another major objective was for the cadets to adopt a standard solution methodology which would help them as problems became more nebulous and/or detailed. Although such a methodology is outlined in the text and used throughout in example problems, many of the problems in the solutions manual for the adopted text did not adhere to that format.

Other texts are becoming available to meet the increasing desire to provide a single volume with coverage of all three areas.[5,6]

Labs

In conjunction with the change in the pedagogy associated with the thermal fluids discipline in the mechanical engineering and engineering mechanics curricula, a major effort was undertaken to devise and build numerous laboratory experiments which could be used to enhance classroom instruction. While time may not permit all of the laboratories to be conducted in the TFSE sequence, the wide variety of labs from which to choose provides sufficient latitude to allow change from one year to the next. Many of the newer experiments were devised, designed, and built by senior cadets during the spring 2003 term.

Prefabricated labs included the Technovate Conduction 9051 table, Technovate Radiation 9053 table, Technovate Hydrodynamic 9093 water table flow demonstrator, and the aeronautical engineering laboratory low-speed wind tunnel (for a momentum deficit laboratory). Laboratory experiments built by cadets include:

- Isentropic compressor efficiency
- Forced convection heat transfer
- Pump head
- Pipe losses
- Refrigeration
- Mass flow rate
- Boiling
- Shell and tube heat exchanger
- 2-D heat transfer: electric analogy
- Schlierren photography demonstrator

Summary

The shift in pedagogy to the new thermal fluids course sequence requires an integration of the subject matter by both faculty and cadets. It is intended to interweave and reinforce the various topics of thermodynamics, fluid mechanics, and heat transfer in a more cohesive fashion than individual treatment of each branch of study, resulting in the cadets thinking in terms of a single discipline: thermal fluids. This methodology should also pay dividends in the fashion in which cadets attack problems, where they are viewed from the more global standpoint of a thermal fluids system, rather than merely as a thermodynamics, fluid mechanics, or heat transfer problem. A future article will report on a comparison of the efficacy of the TFSE approach to the more traditional one.

Title and Term	Previous Sequence	Thermal Fluids Systems Engineering (TFSE) Sequence
ME312 1st Semester Junior (ME & EM Majors)	**Engineering Thermodynamics** Concepts of work and heat Polytropic process 1st/2nd laws of thermodynamics Closed/open systems Material properties, tables, charts Conservation of mass/energy Entropy balance Gibbs equations Component isentropic efficiencies Carnot cycle Psychrometrics	**TFSE I** Concepts of work and heat Polytropic process 1st/2nd laws of thermodynamics Closed/open systems Material properties, tables, charts Closed system entropy rate balance Carnot cycle Gibbs equations Introduction to 3 modes of heat transfer Conduction (1-D): same topics as in ME441 Heat Transfer Reynolds transport theorem Conservation of mass/energy/momentum Hydrostatics/manometry Head losses
ME341 2nd Semester Junior (ME & EM Majors)	**Engineering Fluid Mechanics** Description of fluid matter Hydrostatics/manometry Momentum equation Bernoulli equation Mechanical energy equation Dimensional analysis/Buckingham Pi Modeling and similitude Differential momentum equation Euler/Navier-Stokes equations Introduction to CFD CFD: Steady state/transient conditions Pipe flow: laminar/turbulent Boundary layers Pumps and turbomachines	**TFSE II** Open system entropy rate balance Isentropic processes/component isentropic efficiencies Radial conduction Extended surfaces (fins) Dimensional analysis/Buckingham Pi Modeling and similitude Differential momentum equation Euler/Navier-Stokes equations and simplifications Pipe flow: laminar/turbulent Momentum and thermal boundary layers Bernoulli/mechanical energy equations Drag/lift Convection: same topics as in ME441 Heat Transfer Heat exchangers
ME441 1st Semester Senior (ME Majors)	**Heat Transfer** Introduction to 3 modes of heat transfer The heat equation/thermal diffusion Conduction: steady state transient generation fins finite difference solutions Convection: thermal boundary layers internal/external flows forced/free heat exchangers Radiation: thermal emission blackbody band emission real surfaces view factors blackbody radiation exchange	**TFSE III** Radiation: same topics as in ME441 Heat Transfer Finite difference solutions for 1-D/2-D heat transfer and fluid mechanics; steady state and transient Turbomachinery Basic cycle analysis (Rankine, Otto, Diesel, dual, Brayton) 1-D compressible flow Psychrometrics
ME467 2nd Semester Senior (Elective for ME Majors)	**Energy Conversion** Further application of 1st/2nd laws to major energy conversion systems (steam, internal combustion, gas turbine) and combined cycles Cycle improvements (reheat, regeneration, intercooling, cogeneration, etc.) Combustion analysis Energy storage Refrigeration systems Alternate energy sources Thermal analysis project	

Table 1: Comparison of Conventional and TFSE Sequences

[1] Moran, M.J., H.N. Shapiro, B.R. Munson, D.P. DeWitt. *Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics, and Heat Transfer*. New York: Wiley, 2003.
[2] Moran, M.J., and H.N. Shapiro. *Fundamentals of Engineering Thermodynamics, 4th ed*. New York: Wiley, 2000.
[3] Munson, B.R., GD.F. Young, T.H. Okiishi. *Fundamentals of Fluid Mechanics, 4th ed.* New York: Wiley, 2002.
[4] Incropera, F.P. and D.P. DeWitt. *Fundamentals of Heat and Mass Transfer, 5th ed.* New York: Wiley, 2002.
[5] Cengel, Y.A. and R.H. Turner. *Fundamentals of Thermal-Fluid Sciences.* New York: McGraw-Hill, 2001.
[6] Potter, M.C. and E.P. Scott. *Thermal Sciences: An Introduction to Thermodynamics, Fluid Mechanics, and Heat Transfer.* Belmont CA: Thomson, 2004.

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