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Development of an Integrated Thermal-Fluids Engineering Curriculum

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Abstract

We present a new approach to teaching the core thermal/fluids curriculum for undergraduate programs in engineering. Traditional introductory thermodynamics, fluid mechanics, and heat transfer classes are being replaced with two integrated courses and an integrated laboratory course in which the three disciplines are taught simultaneously. The approach is intended to show interconnections and transferability of concepts and ideas, with an emphasis on the way they occur in engineering practice. Both courses are being taught in a new multimedia studio classroom, permitting student-student interactions, the use of in-class computer tools and examples, as well as individual desktop experiments and demonstration experiments. Our experiences in teaching through this innovative format, in using case studies to motivate student learning of introductory material, and in integrating the laboratory course experience to that of the studio classroom, are recounted.

Introduction

Fundamental changes in the core thermal-fluid science curriculum for engineers have been initiated at Rensselaer. We seek to improve the context in which material is presented, so that the physical intuition of our students is enhanced, their ability to think critically and to synthesize information is stimulated, and the relevance of the learning process to advanced analytical and computational tools available to the students is made clearer.

This has been accomplished through the development of two distinct, but closely related, courses. The ***first course***, *Thermal and Fluids Engineering I* (TF1), is a consolidation into a single four-credit course of the essential, fundamental aspects of classical thermodynamics, fluid mechanics and heat transfer, in a context consistent with engineering practice. The overlapping and reinforcing nature of these subjects is exploited to provide students with a comprehensive foundation in the thermal sciences. The new course provides rigorous coverage of carefully selected topics, suitable for students who need only a limited exposure to thermal and fluid sciences. However, the experience gained by the students also permits them comfortably to take higher level courses in thermodynamics or transport phenomena.

The ***second course***, *Thermal and Fluids Engineering II* (TF2), designed to be taken in sequence, is a similar consolidation at a higher level for students whose majors require more depth in this area. This course is being characterized by a context-driven presentation and is being integrated with a hands-on laboratory, *Thermal and Fluids Engineering Laboratory* (TFLab), into a coordinated six-credit hour experience, which serves as one “leg” of the core mechanical engineering curriculum. In this methodology, the students are posed a problem, they identify what they need to know, they learn what they need to know, and they apply that knowledge to solve the problem. These "problems" will be being presented in the context of four large-scale case studies that are flexible enough so that the problems can be varied from semester to semester. Realistic systems will be presented, discussed, and dissected so that the governing concepts can be identified and understood in the *context* where they will be encountered. For each concept being studied, multiple problems from different fields of engineering and applications are presented to illustrate the concept so that the students will start thinking expansively. Specific material is presented as it is needed to solve a problem—a "just-in-time" approach to learning. The separate (but integrated) laboratory experience ties together the material presented in TF2 with physical reality of the operating equipment. Because the lab and the lecture are coordinated, students may better appreciate the connections between their theoretical studies (*e.g.*, entropy, Navier-Stokes equations, boundary layer analysis, differential form of conduction equation, finite difference discretization) and the physical reality.

A concomitant objective has been to develop a highly interactive, student-centered studio format for TF1 and TF2, consistent with other successful, large enrollment courses at Rensselaer. Both courses are being taught in a new multimedia studio classroom, permitting active student-student interactions, the use of in-class computer tools and examples, as well as individual desktop experiments and demonstration experiments.

Background

Consider, for example, two engineering problems and how we apply the disciplines of thermodynamics, fluid mechanics, and heat transfer to these applications in the traditional teaching approach. The first problem is a large-scale installation: a combined cycle consisting of a Brayton topping cycle and a Rankine bottoming cycle. In a thermodynamics class we investigate the effects of varying system parameters (*e.g.*, pressures, flowrates, isentropic efficiencies, etc.) on the overall system efficiency. Pressure losses between devices are ignored. Heat transfer is taken into account either by stating that a given rate of heat transfer is known or by prescribing inlet and outlet conditions of the fluid passing through each device. In fluid mechanics, we provide the flowrate and fluid conditions, and we calculate pressure loss through a pipe or, perhaps, calculate the pressure loss across a heat exchanger. These losses are rarely related to the performance of the overall system in which the pipe or heat exchanger is used. In heat transfer, we rate (or design) a heat exchanger with given fluid temperatures and conditions; pressure loss often is not calculated. Trade-off between the heat exchanger effectiveness and its size/design versus the overall Brayton/Rankine cycle performance is seldom considered. In each of the three courses, we view the analysis as if each component stands alone.

The second problem is smaller in scale and is related to automotive design. Consider the problem of estimating the time required for a passenger compartment to be conditioned to a desired temperature. In thermodynamics we give the students an initial and a final temperature, information about the volume, possibly something about the mass of the seats, metal, etc., a heat addition/rejection rate, and a flowrate of air at a given temperature into the compartment. The students do not need to develop any information from their heat transfer background about heat transfer rates through the roof or doors of the car. Likewise, they do not need to estimate the heat transfer coefficient on the outside and inside surfaces of the compartment to quantify the heat addition/rejection rate. Sizing of the fan to blow air into the compartment is ignored. Again, each separate discipline treats a portion of the problem, but the unified problem is seldom presented.

As illustrated above, the structure of present thermodynamics, fluid mechanics, and heat transfer courses does not lend itself to showing the overlap, interconnections, and synergy. Traditional courses focus on teaching the details of each discipline in isolation. Because of the amount of material presented, we sacrifice discussion and the use of other disciplines, which invariably come into play in many “real-life” situations.

Two other factors contribute to the present arrangement of courses in thermal/fluids engineering. First, we generally intend our courses to perform “double duty;” that is, we prepare our students for advanced study within the discipline and for a career in industry. While many more students opt for industry immediately after the BS than for graduate school, traditional courses are skewed more toward satisfying the needs of those who will choose advanced studies. The second factor is that textbooks (whether or not they include more than one topic such as thermodynamics and heat transfer) present material in a narrow, disciplinary fashion.

Finally, several fundamental changes have occurred which suggest that serious reform and/or revitalization of the thermal/fluid science curriculum has been needed. Not all these changes are characteristic of every university environmentor every university student, but we have observed elements of each at Rensselaer.

- Although most students are significantly more computer-literate than earlier generations, they exhibit less *physical* intuition. They have a diminished ability to relate the physics of a problem to the analytical tools used to develop engineering solutions than when the majority of the students were “tinkers.”
- Laboratory content, which demonstrates physical principles, of most curricula has diminished or been eliminated.
- Students’ ability to synthesize information from different courses or fields is weak.
- Interest in thermal/fluid systems has diminished.
- Many universities are seeking to improve the overall learning environment for their students and to use faculty time more efficiently.

One approach at Rensselaer to reinvigorate the teaching of thermodynamics, fluid mechanics, and heat transfer has been to rethink completely what we wish to achieve with these courses and, from this blank slate starting point, develop courses that satisfy the objectives stated below.

Rensselaer recently underwent a university-wide curricular restructuring[1]. Change was driven, in part, by the introduction of “interactive learning,” an educational mode which actively involves students in thinking and doing[2-4]. The traditional three-credits per course standard was replaced, for the most part, by four-credit courses to reduce the number of classes students take each semester, although the total credit hours required for graduation were decreased by only three percent. In Mechanical Engineering, the curriculum has been changed to emphasize the two major stems: thermal/fluid systems and mechanical systems[5]. This has necessitated a complete reevaluation and overhaul of the thermal/fluids offerings. The new lecture/studio courses (TF1 and TF2) were introduced during the 1998-99 academic year, while the laboratory course (TFLab) was implemented in fall 1999. A discussion of the preliminary development of these courses was described by Jensen, *et al*.[6]

Philosophy of the New Courses

The *curricular* objectives of classical thermodynamics, fluid mechanics and heat transfer revolve around *conservation principles and second law considerations*. The ability of an engineer to identify a control volume for a system and formulate balances of mass, momentum, energy (mechanical and thermal), and entropy is essential for success in understanding and improving any engineering process involving energy and fluids.

There are many potential advantages to an integrated approach. The majority of real-world applications of thermal/fluids, such as the design of refrigerators, power plants, automotive engines, etc., require the simultaneous application of thermodynamics, fluid mechanics, and heat transfer. Students who have studied these topics in different courses often have difficulty in establishing the connections among them. We can take advantage of the fact that each of the three disciplines relies on fundamental balance principles involving mass, momentum, energy, and entropy. This underlying unity can best be demonstrated in a curriculum that integrates all three topics. In addition, by strongly linking the classroom material to physical demonstrations and hands-on experiments, students have the opportunity see the connection between their theoretical studies and the physical world. Thus, the relevance of the basic material becomes more salient which should improve students' motivation to learn.

The three courses (TF1-4 cr. hr.; TF2-4 cr. hr.; and TFLab-2 cr. hr.) replace four three-credit hour courses (no lab content), two in thermodynamics and one each in heat transfer and fluid mechanics. Because of the overlap of topics and the synergy to be gained from this integrated approach, we believe we can present more effectively in ten credit hours materials that have needed twelve credit hours in the past. Some previously presented material has not been included in the new courses. However, the loss of this information is expected to be counterbalanced by the students' improved physical understanding and ability to synthesize ideas from different disciplines.

Through these courses and particularly through the laboratory, students will appreciate the richness of the subject matter and the interconnectedness of thermal/fluid principles in practical equipment. They will be prepared to practice engineering in relevant, complex, real-world systems. The courses, at the same time, teach the fundamental principles needed either to enter professional practice or to prepare for graduate study. The fundamentals are presented in the same depth as in traditional courses at this level to form a logical and cohesive body of knowledge. Each building block of knowledge is presented in depth with a variety of examples before it is used in combination with other principles to understand complex, integrated systems. Some details of the three courses are presented below.

Thermal and Fluids Engineering I

The goals of the first course are manifold:

- It is an *applications*-oriented course in which students are introduced to the laws of thermodynamics and to the use of control volume balances of mass, momentum, and energy in the types of systems and in the manner they are commonly encountered by practicing engineers.
- For curricula requiring no other thermal-fluids courses (*e.g.,* Computer and Systems, Electrical, and Management Engineering), it helps students become more comfortable with the physical modeling of actual systems, so that they can make better design decisions when energy transfer and fluid flow are involved.
- The coverage of material is sufficient to replace the six credit hours (Thermodynamics and Fluid Mechanics) currently required by some curricula (*e.g.,* Civil, Biomedical, and Environmental Engineering) with a single, four-credit hour course.
- It provides a practical basis for students whose curricula require more advanced and in-depth courses in this area (*e.g.,* Aeronautical, Chemical, Materials, Mechanical, Nuclear Engineering, and Engineering Physics).
- It is a "stand-alone" course, which will provide a sufficient preparation for students who will take the EIT examination.

The following topic areas indicate the scope of material to be covered in this four-credit hour course. It must be emphasized that fluid mechanics and heat transfer are approached within the context of momentum and energy balances on control volumes, not through the solution of field equations.

Conservation/Balance principles.

Mass; momentum; mechanical, thermal, and total energy; and entropy. The concept of balance equations forms the common thread in the course. We consider mainly one-dimensional situations; vectors are not a major topic.

Properties.

Ideal gas, incompressible substance, and use of tabulated data. These models and approaches suffice for most engineering applications and serve to illustrate the physical principles governing the behavior of real material properties.

Laws of thermodynamics.

Application to closed and open (steady and transient) systems. The principal background required of students here is their own day-to-day experience, since that is the primary way that our understanding of these concepts arises. Elementary heat transfer rate equations for steady state conduction, steady pipe flow, and lumped capacity transient systems reinforce the links between traditional heat transfer and thermodynamics at an early point in the learning process.

Fluid mechanics with applications.

Concepts of fluid statics draw on the students' experience with force balances from previous courses. The extended Bernoulli equation is presented in the context of a mechanical energy (or flow "head") balance on a control volume. Conservation of momentum is discussed in terms of simple force balances on control volumes. Then the characteristics of viscous flows are described in terms of the need for friction coefficients, drag coefficients, and heat transfer coefficients

Thermal and Fluids Engineering II

The second course reinforces the basic material taught in *Thermal and Fluids Engineering I* and extends that knowledge to advanced topics. The format of the class is a coordinated four-credit classroom course with an associated two-credit laboratory (discussed in the next section).

We are developing a "problem-based learning" approach[7] to present the concepts through case studies[8-10]. In this methodology, the students are presented problems, they identify and learn what they need to know, and then they apply that knowledge to solve the problem. The students are required to take an active role in the learning process by focusing on specific problems. These "problems" will be presented in the context of four large-scale case studies, which will be flexible enough that the problems can be varied from semester to semester. The first case study involves material processing and describes the engineering problems of designing and operating a continuous-flow cookie baking oven. This has been developed and used in the fall of 1999. The choice of a cookie baking oven was made to relate the diverse material (transient conduction, radiation, multimode heat transfer, etc.) to something within the student's experience. The remaining case studies have yet to be written in detail, although the ideas have been introduced in TF2.

For whatever concept is being studied within the classroom, multiple problems from different fields of engineering and applications will be presented to illustrate the concept so that the students begin to think expansively. Specific material will be presented as its need to solve a problem arises. Topics being covered and the projects in which they are encountered are listed in Table 1.

(The numbers after the individual topics in the first table correspond to one of the projects listed in the second table. Additional information is given about these projects in the next section.) These lists are not all-inclusive, and specific projects within the four case studies can vary from year to year.

Table 1. Thermal and Fluids Engineering II Topics

Subject Area	Topics
Thermodynamics	second law 1, 2, 4; power cycles 1, 4; refrigeration/heat pump cycles 2, 4; combustion 1, 2, 4; compressible flow 1; psychrometrics 2,4
Fluid Mechanics	internal flows 1, 2, 4; piping networks 2; external flows 2,4; incompressible 2-D flow 4; rotating machinery 1; forces 4.
Heat Transfer	conduction (transient and steady state) 3,4; convection 1, 2, 3, 4; radiation 3; change of phase 2; heat exchangers 1, 2, 4

Case Study Project	Topics
1. Brayton Cycle	Combustion; compressors/turbines; 1-D flow; second law; nozzles/diffusers; compressible flow; heat exchangers; electrical generator efficiencies, gearbox efficiencies, etc.
2. HVAC System	Refrigeration cycle; psychrometrics (humidification or dehumidification); air duct flow; heat exchangers; liquid & two-phase flows; insulation.
3. Thermal Processing of Materials	Transient conduction; radiation; mixed convection; properties of materials; automation; multimode heat transfer.
4. Heat Transfer Windtunnel	Otto cycle; external flow (vortex shedding/wakes, drag lift); internal flow (oil, coolant, air flows); heat exchangers (blockages, maldistribution, enhancement, etc.); transient conduction (rear window defrost); air conditioning/psychrometrics.

TF2 is designed to accomplish two objectives. First, the proposed structure and material coverage can provide better preparation than the existing sequence of courses for a BS level engineer to contribute professionally. Second, the course fits in well with advanced undergraduate and beginning graduate level courses. Because of the combination of experiments and lectures and the coverage of both fundamental (e.g., limited solutions to the conduction and Navier-Stokes equations) and applied topics, the stage is set for specialty courses in advanced topics. Those students who seek more in-depth knowledge would then be motivated to take courses in advanced heat transfer or fluid mechanics since they have the requisite practical background, control volume formulation skills, and physical intuition needed for more detailed analyses.

Thermal and Fluids Engineering Laboratory

The laboratory experience ties together the material presented in the studio classroom and the physical reality of the operating equipment. Students perform experiments at the same time as they learn the fundamentals in class. The major case studies lead to consideration of complex processes in which two or more disciplines interact. The four laboratory projects chosen for demonstrating the interconnectedness of thermodynamics, fluid mechanics, and heat transfer are discussed below. Because one of these has yet to be constructed, a fifth interim experimental system is also described.

1. Gas Turbine Power Generation

The first case study builds on first and second law analysis of thermodynamic systems first encountered in TF1. Energy transformations among chemical, mechanical, and electrical forms will be measured and analyzed. The thermodynamic concepts of the conservation of energy and of entropy increase, i.e. both First and Second Laws of Thermodynamics, and cycle thermal efficiencies will be examined. Various thermodynamic property spaces, e.g., pressure-volume, temperature-entropy, and enthalpy-entropy, will be used to analyze the processes taking place within each component and throughout the overall cycle. The combustion process will be analyzed through adiabatic flame temperature calculations. The system selected to illustrate these principles is a fully functional Brayton cycle.

The system consists of a two-shaft gas turbine, where a gas generator supplies high enthalpy flow to a power turbine, which extracts usable work from the gas. The gas generator section consists of a radial compressor that is driven directly by a radial turbine. The power turbine, which is also radial in design, extracts work as the gas further expands to near atmospheric pressure. The mechanical power extracted by the turbine is converted to electricity via an AC generator. Complete instrumentation permits the recording of all important operating parameters, including the temperature and pressure at each stage, fuel and air flow rates, and the generator current and voltage. Experience with a fully functional power cycle should increase the students' understanding of power generation and of the importance of thermal/fluid phenomena in this critical industrial process.

2. Heating, Ventilating, and Air-Conditioning System

The second case study and experimental project will demonstrate the effect of irreversibilities on the efficient utilization of energy. Topics to be addressed include: the isentropic efficiency of compressors which involves both First and Second Laws of Thermodynamics and property evaluations; heat exchanger characteristics such as effectiveness, energy balance, and psychrometrics; and pressure losses with both working fluid and air flows. The links among thermodynamics, fluid mechanics, and heat transfer are especially strong in this case study. The specific system chosen for study is an air-conditioning loop coupled to a vapor-compression refrigeration cycle.

Students will calculate ideal coefficients of performance and compare these to actual values obtained experimentally. Extensive instrumentation on the airside (temperatures, flowrates, humidities), refrigerant side (temperatures, flowrates, pressures), and fan (power input) permit evaluation of the complete system. Because of the instrumentation available, many different assessments of the entire air conditioning system/ refrigeration cycle combination can be performed. This ensures that each semester we do not repeat exactly the same experiment.

3. Thermal Processing of Materials

The third case focuses on transient multi-mode heat transfer. Students will be introduced to surface-to-surface thermal radiation, which appears in many processing applications. They will also study conduction, mixed free and forced convection, and overall energy balance. During processing, materials often undergo physical and chemical changes that alter their properties. An example is the firing of ceramics; the uncertainty in material thermophysical properties must be addressed.

There are several considerations that come into play in the design of this experiment. As a practical matter, the material to be processed must be easy to prepare and inexpensive to produce. In addition, it must relate to the personal experience of the students while at the same time being industrially significant. The case chosen for study is the baking of cookies in a continuous feed oven.

The cookies will be instrumented with thermocouples as they travel through the oven on the conveyor belt. The top surface temperature will be monitored with an infrared detector, thus introducing students to the basics of pyrometry. A mirror will traverse the oven in tandem with the belt to keep the cookie in view of the detector. Radiant heaters at the top of the oven will supply the heat.

4. Heat Transfer and Fluid Mechanics for a Windtunnel Flow System

Students measure velocity profiles and heat transfer coefficients on a heated flat plate in a wind tunnel. This experiment comes at the time of the semester when the students are being exposed in greater depth to the concept of a temperature and a velocity "field." The case study we plan to relate to this system is the flow around an automobile or similar vehicle. Numerous investigations could be developed, but an attractive specific problem is the defogging of an automobile windshield. This case treats a problem that is both practically significant and familiar to students from their daily experience. The concept of the velocity field and boundary layers will be introduced in describing convective heat transfer coefficients. Thermal resistances linking conduction and convection will be introduced. This supplies information on the convective heat transport from the exterior air to the outer surface of the windshield.

The thermodynamic content in this case lies in the psychrometrics, which show students how cold the inside of the windshield must be before water vapor starts to condense there. In class, they will use heat transfer models to compute the temperature drop across the windshield and determine under what conditions fogging/defogging would occur.

The experiment will have greater meaning since students have a concrete application in mind while taking their measurements. They will learn, among other things, the use of a traversing pitot probe, an array of thermocouples, and a data acquisition system. They will become familiar with blowers, flow straighteners, and manometers, all-important equipment in thermal-fluid measurements.

5. Hydraulic Flow Loop

As of the end of 1999, the experimental system comprising Project No. 3 has yet to be constructed. In its place, students are conducting experiments on a full-scale hydraulic flow loop, which is designed to measure pipe flow pressure drops due to friction and minor losses, the performance of practical flow metering devices, and the hydraulic performance of pumping systems.

Course Format and Structure

The format of these courses is an entirely new way of presenting this material. This suggested that a new approach to classroom operation also was needed. The *Studio Classroom* permits an educational mode which actively involves students in thinking and doing. Lectures are no longer the sole focus of the classroom activity. Instead, faculty manage the classroom time so that students learn not only by passively listening to lectures, but also by actively solving problems or performing experiments right in the classroom. Learning can be enhanced because students work through applications rather than just studying theory and principles. In a typical interactive class, topics are introduced in short, to-the-point lectures. Then students perform analytical exercises, desktop experiments, and/or calculations using computer tools. Students work both individually and in teams and are guided by instructors. A wrap-up session and explanation, introduction of a new topic, and a repeat of the cycle follow each interactive exercise. Our paradigm shift to interactive, student-centered learning is embodied in what is termed the *studio course*, and some general experiences with teaching such courses at Rensselaer and the ways in which their successes and drawbacks may be assessed has been documented elsewhere[2-4].

Within the context of broader efforts at Rensselaer to evaluate critically the studio learning environment, the development of the *Thermal and Fluids Engineering* courses offers a unique opportunity. Building on our experiences with other studio courses, we are compiling a complete case study of the transition process between a traditional lecture-based course and a studio. We want to be in a position to show other engineering programs how they may adapt our successes and failures to improve their own needs for curriculum modifications, not by copying our new courses and classrooms, but by being able to understand what we have accomplished within the context of their own university situations and student bodies.

Specific accomplishments are necessary to create these two studio courses: Specific curriculum modules, as described above, must be developed. Further, we must examine just what it means pedagogically to replace traditional lecture content with interactive exercises, simple desktop experiments, computer-based exercises, and classroom demonstrations, without eliminating any overall presentation content. What does it take to change the traditional engineering faculty approach to teaching to make this process occur? What is required for a new instructor to begin teaching an established course in a studio environment? How must the student's approach to learning be altered as well? Does the new studio environment for the synchronous learning experience require a significant change in the asynchronous modes of learning, as well? We speculate that a student must be better prepared for each individual classroom experience—one can not walk into the classroom "clueless." However, one also can not be expected to have a complete command of the material in advance. What is the new role of traditional homework? Can asynchronous modes of interactive computer exercises be used effectively in place of traditional 5 to 6 problems per week from the textbook? These issues will be addressed as the studio model is applied to teaching the thermal-fluid sciences, which has experienced very little change in pedagogy over the past quarter century.

Summary

A new approach to the teaching of thermodynamics, fluid mechanics, and heat transfer has been described. Rather than following the traditional structure of independent and isolated courses to present these disciplinary topics, we have developed three courses that integrate the materials into two classroom courses and a laboratory. The overlapping and reinforcing nature of these subjects are exploited to provide students with a comprehensive foundation in the thermal/fluid sciences. This approach can potentially improve the physical understanding of the students and their ability to synthesize ideas from the different disciplines. Presenting the information in the context of applications and case studies, combined with the studio approach to the classroom, is expected to permit the presentation of material in ten credit hours instead of twelve credit hours.

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