A Team-Oriented, Project-Based Approach for Undergraduate Heat Transfer Instruction

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Introduction

This is an exciting time in engineering education. Engineering classrooms are changing with the rapid development of new technologies and analysis tools, the desire for team-based activities by industry, and recognition by engineering educators of the value of cooperative and active learning methods.

The purpose of this paper is to describe a classroom "experiment" with the goal of converting a conventional textbook class (undergraduate heat transfer) into a team-based course that relies heavily on active learning. The class consisted of 46 students, primarily second semester juniors in mechanical engineering, formed into 12 teams of consisting of 3 to 4 people per team. Major projects were assigned as a means to guide students through the primary topics covered by an undergraduate heat transfer course. Overall, feedback from students was very positive.

In addition to changing the organizational structure of the class, the course implemented numerical problem solving techniques throughout the class with classical solution techniques used for validation of the numerical problem solving techniques. The numerical approach is based on the development of simple finite difference numerical techniques in a spreadsheet format. A series of five projects were defined that covered most of the primary topics of an undergraduate heat transfer course. Formal lectures were reduced to approximately half that of a typical class with most lectures devoted to an introduction to assigned project and homework activities, or to cover those topics not incorporated into project activities. Remaining classroom time was used for direct interaction with groups as they encountered problems in their assignment activities.

Project-Based Thermal Science Courses

Thermodynamics, fluid mechanics, and heat transfer form the foundation of undergraduate curricula in the thermal science area. Firm establishment of this foundation is important for students to progress into elective and advanced thermal science courses. These classes also make important links to students' earlier activities in other classes, such as physics and mathematics.

The team-based, project approach for heat transfer described in this paper is one that the authors feel can be transferred to an undergraduate fluid mechanics course. Implementation of some level of project activity (and certainly some teamwork) into an undergraduate thermodynamics course may also be undertaken, however, the nature of an initial course in thermodynamics is different than heat transfer and fluid mechanics courses.

Although heat transfer and fluid mechanics classes cover different topics, they are very similar in the sense that both cover a range of sub-topics that tend to rely significantly on mathematical analysis. Both of these courses help provide a direct link to a student's mathematical background. An important goal of both classes should be the development of student capability to *formulate* a problem in terms of its governing relations and constraints (generally, a differential equation with boundary conditions). Mathematics courses provide the background for *solving* a variety of mathematical problems. The linkage of an equation to the physics of a problem, however, occurs in engineering courses such as these.

Both heat transfer and fluid mechanics also have the responsibility of covering problem situations that are commonly encountered in practice. The number of textbook topics in each course is too numerous for total coverage, and an instructor must be selective in deciding which topics are most important. Often, the order of the presentations can be altered because many topics are independent of each other. For example, in heat transfer, instructors may change the order of topic presentations, such as heat exchangers and radiation. In fluid mechanics, one may substitute channel flow for compressible flow if the undergraduate population leans toward civil engineering rather than aeronautical engineering applications. The relative independence of topics allows a "parallel" coverage of topics to occur, which is a natural consequence of a project-based class.

Thermodynamics is a different type of course than fluid mechanics and heat transfer because more emphasis is placed on the conceptual development of the conservation of mass and energy, and the non-conservation of entropy. Mathematical analyses in thermodynamics classes are of a more elementary nature, but the conceptual difficulty of the material offers students a significant challenge. Unlike heat transfer and fluid mechanics courses, introductory thermodynamics material must generally follow a sequential path. Development of a student's familiarity with thermodynamic properties and processes (along with vocabulary important for future courses) is normally the first area of discussion, followed by the development of mass conservation and, in general, extensive property balancing ideas. The first and second laws of thermodynamics would then follow with a variety of situations to demonstrate their application. Because of this imposed structure, the parallel coverage of several topic areas as described in this paper would be more difficult for an initial thermodynamics class.

Traditional Versus Project-Based Organization of an Undergraduate Heat Transfer Course

The traditional organization of an undergraduate heat transfer class is one that covers material in a serial manner based on standard lecture-textbook coverage. Competency and knowledge is determined from individual homework and exams. A common path starts with steady state conduction situations (1-D, 2-D, and generally no extension to 3-D situations). Simple transient conduction situations (0-D or "lumped mass", and 1-D, with limited multi-dimensional transient problems) would be covered next. Beyond conduction, various paths are followed, such as convection (general convection background, followed by external and internal flow situations), radiation, and heat exchangers. In this serial coverage of material, very little opportunity exists for students to work with simultaneous combinations of the various topics in a manner typical of practical problems.

Although the project structure of the class discussed in this paper is one that required the formation of teams in order to accomplish assignment goals, cooperative learning can be used in this more traditional presentation of material. Boehm and Gallavan described the successful implementation of cooperative learning in a more traditional undergraduate heat transfer course[1]. Within the context of their classroom, student teams solved problems covering the primary areas of heat transfer. Lecture time was reduced to approximately one-fifth the normal time, allowing the instructor to work directly with student groups as they developed questions.

Organization of any class into a cooperative learning situation can be accomplished by following the example of others who have developed methods that help avoid many pitfalls and establish effective learning systems. Felder and Brents' workshop notebook on effective teaching contains many guidelines and references that describe active learning and cooperative learning techniques[2]. Among the most important organizational aspects are:

1. A statement of course objectives (what students should be able to do as a result of the class)
2. An explanation of teams, team member responsibilities, and peer evaluations
3. A clear statement of grading and evaluation procedures.

As teams are formed, students will ask to be assigned to teams with friends or convenient working partners. As suggested by Felder and Brent, assignment of team members independent of student requests is recommended. Examining class member backgrounds and distributing members in a manner that spreads abilities helps minimize unevenness in the average academic capability of the teams. The skills required to perform well in this situation, however, are different than those required for traditional class performance. Some students may persist in asking for specific team members. Three responses may be helpful. First, often high performing students request placement with others of similar performance levels, and it is important to let them know that you need to spread their expertise and abilities to help teach others. Second, help students realize that being assigned to a different team does not form a boundary in terms of cooperative learning activities. Last, but probably less satisfying, it may help to emphasize that the choice of team members in the job environment will be one in which they have little or no input.

Teamwork and team responsibilities must be formally explained. It is important to describe different functions and positions of responsibility that teams need to formally assign to its members. Also, it is essential that members rotate through positions of responsibility in order to evenly share the workload, to experience activities that they would not normally choose, and to develop an appreciation for the importance of each role. Some of the best functioning teams are those in which some "natural" leaders help organize the team. Often, these are not the best students in terms of technical expertise, but may be the ones with more developed social skills. Some of the most technically brilliant students often have difficulties "fitting in" because they enjoy individual, concentrated study that does not depend on the ability and motivation of others. The team environment can allow both types of students to excel as they are allowed to exercise their natural strengths and strengthen the areas where they are weaker.

In a project-based format, several topics in heat transfer are covered in parallel. These activities will be described in more detail in the next section. It is important to note that the initial impact of this type of material coverage is difficult for students as they simultaneously encounter formulation of governing differential equations, boundary conditions, numerical methods, simultaneous equation solving, Excel™ worksheet usage, and classical analysis techniques. As described by Felder and Brent, the students may experience the symptoms of trauma and grief as they assume a major responsibility in their learning activity[3]. The initial discomfort tends to pass, however, as the students mature and become familiar with the structure of the class and the primary solution techniques. The focus then shifts to one where students are concentrating on heat transfer situations commonly encountered by mechanical engineers.

Reduction of formal lecture time is important. This can be difficult to do for those who enjoy lecturing and may have lecture notes that represent several years of finely honed material meant to explain and answer every possible question. It may be difficult, as well, for those who lack the confidence to relinquish some control over the classroom or for those who feel that they are not doing what their traditional sense of classroom activity tells them should be done. The reduced lecture time, however, allows students to regularly meet in a situation where the instructor is directly available to answer questions as they occur. The questions that a team has been unable to answer are often the ones that are common to most teams. Regular group activity time during class sessions helps to answer these questions when all are present. Also, as groups brainstorm approaches for attacking their assignments, ideas can be cross-pollinated to other teams. Periodically (one week per month), a brief meeting with each team was scheduled in order to discuss progress on the current assignment activities and to discuss team organization.

Students were graded on the basis of homework and project reports. Peer evaluations were used in order to discriminate among relative team member contributions. As described by Felder and Brent, team member assessments tend to be very honest with few people who appear to have an inflated view of their contributions (but some who underestimate their value). No exams were given in the class. No individual work was assigned in the main class, but one quarter of the course credit was earned in additional laboratory activities that were graded on an individual basis.

Heat Transfer Class Activities

Class activities revolved around a series of homework problems and projects. Homework sets introduced topics of interest, developed experience with classical solution techniques, and demonstrated numerical solution techniques to be used in project activities. Five projects were assigned over the course of the semester that utilized the background developed through the homework activities in a real world engineering application.

The homework assignments and project activities were developed in an integrated manner for the class. Homework and project assignments would have occasional references to textbook material topics and examples, but the parallel coverage of topics did not readily lend itself to utilization of textbook exercises. A typical homework would request information about a particular situation, require a comparison between classical and numerical analyses, and show extension of the numerical technique to a situation in which classical analyses would not be practical. For example, when covering “fins”, students were required to determine the fin efficiencies, temperature profiles and heat transfer using classical 1-D fin analyses. Results from these analyses were compared to results obtained from a 2-D, numerical fin model developed by the student teams. After comparison of the 2-D fin model to 1-D analytical fin situations, students explored trends in the error of results obtained from 1-D analyses where realistic material properties are ignored (e.g., a plastic or glass “fin” in which lateral conduction is important). Finally, students explored and discussed the addition of other effects such as radiative boundary conditions or internal heat generation. These effects can make analytical solutions nearly impossible to obtain, but are readily incorporated into their numerical models.

A notable difference in the coverage of heat transfer topics within this class was the reliance on numerical modeling techniques. Generally, numerical modeling in heat transfer is a relatively brief portion of the class, usually discussed in conjunction with conduction topics. One reason for such abbreviated reliance on numerical techniques is that lecture presentation time covering computer programming is extensive and overwhelms the primary goal of learning about heat transfer. Students become entangled in syntax errors, logic problems, and input/output formats, and have little time to explore heat transfer. To avoid this, traditional finite difference solution techniques are developed in an Excel™ worksheet format that eliminates formal computer programming. The finite difference algorithms for solving steady state and transient heat transfer problems are readily learned by the students and gives them the capability to solve three dimensional, transient heat transfer problems with a variety of complex boundary situations (radiation, natural convection, applied heat flux). A detailed description of the numerical techniques is beyond the scope of this paper. It is important to note that the application of the numerical techniques in this format emphasizes the fundamental idea that energy should not spontaneously appear or disappear by keeping the basic governing relations intact such that students are continually evaluating conservation of energy.

Classical analytical solution techniques are utilized less and less in the practical world of engineering. However, these techniques are still important for a student’s understanding of basic heat transfer concepts and need to be stressed. The analytical formulation of a problem is the key to determining the significance of physical terms and formulating models (both analytical and numerical) of appropriate complexity for a given situation. Within this class, separation of variables, similarity solutions, and other analytical solution techniques were used as a means to verify the validity of numerical models before using the numerical models on situations where analytical methods could not be extended. The impetus in developing this class is that the traditional tools of mathematical analysis need to be extended to analysis tools and techniques which utilize modern means (PCs and spreadsheets) commonly available to engineers. The shift is similar to the one that occurred when the slide rule was displaced in the 1970’s by the advent of the calculator.

Project assignments were used as a means to implement analysis tools in real world situations. The projects were developed in a manner that did not have an “exact” right or wrong answer. At the same time, guidance and sufficient definition was given in order to keep groups from floundering. Often, additional definition was added to the original project statement as teams encountered difficulties where their expertise was too limited to recognize potential solutions. Common features of each project assignment included a description of the physical context of the problem, a statement of primary objectives, and where possible, experimental data for comparison to predicted results. Each project required a “back-of the-envelope” calculation to determine limits of expected numerical results. The “back-of-the-envelope” calculation presented the challenge of formulating an approximation to the more complex situation into so an analytical solution technique could supply information for checking numerical results.

Required results included a demonstration that energy was conserved as well as the detailed description of heat transfer flow paths through the body under study.

The project assignments were developed in such a manner as to display a variety of areas in which mechanical engineers encounter heat transfer problems, including the automotive, electronics, materials processing (plastic and metal), and environmental conditioning areas. The following list describes the class project topics and their intended coverage of heat transfer topics.

1) 2-D steady state conduction with convecting/radiating boundaries (Ice Rink Floor Project)
   -Goals: Prediction of the temperature profiles in a layer of ice and a concrete floor with encased coolant pipes. Investigate the effect of clogged coolant pipes and determine possible solutions. See Figure 1.
2) 3-D steady state conduction with composite materials (Electronic Chip Cooling Project)
   -Goals: Determination of the maximum power allowed in an 8-pin DIP, operational amplifier chip. Also required was an evaluation of energy flow through the metal legs and plastic case of the chip. See Figure 2.
3) 3-D transient simulation in Cartesian coordinates (Welding Project)
   -Goals: Prediction of temperature profiles and energy diffusion during welding of blocks of steel and aluminum. Comparison of predicted results to experimental data. See Figure 3.
4) 2-D transient simulation in Cylindrical coordinates (I.C. Engine Valve Modeling Project)
   -Goals: Prediction of temperatures and energy flows in an intake valve for an internal combustion engine. Also, an evaluation of a mass's frequency response was performed. See Figure 4.
5) 2-D transient conduction with enclosure radiation (Plastic Thermoforming Project)
   -Goals: Determine the placement and temperature of infrared heaters for minimizing the heating time required for a plastic sheet in a vacuum forming process. See Figure 5.

The first project required the most time (5 weeks), as students were becoming familiar with basic governing equations in heat transfer and learning general concepts such as convection heat transfer and radiation heat transfer. As the semester progressed, the frustration of several simultaneous learning activities relaxed as experience grew. Also, team coordination progressed to a state where members knew how to function together, whether they liked each other or not. The second project with 3-D steady state modeling was built on the foundation of the 2-D steady model activities, and gave the class the ability to begin concentrating on heat transfer issues. As the class moved into transient modeling situations, implementation of the numerical format was a natural progression. Projects 3 and 4 were assigned simultaneously, requiring strict coordination of team member activities and communication. Teams generally divided up responsibilities such that one half would work the analytical portions of one project and the numerical formulation of the other project. Project report writing duties were assigned by team members in a manner that divided these responsibilities in a fair manner.

Project 5 was unique because student groups formulated and solved a complex heat transfer situation combining transient conduction and enclosure radiation. In a traditional class format, the opportunity to combine the individual pieces of serially taught topics is rare and difficult.

The progression of the project-based class, however, made the addition of enclosure radiation to the already familiar transient conduction formulation a reasonable one.

Overall, the integration of homework assignments and project activities formed a good foundation for covering the primary topics of an undergraduate heat transfer course. The homework assignments were developed such that they would naturally lead students through important topics and establish a level of experience required for the more open project assignments. The project assignments raised the bar by placing heat transfer problems into a real world context, and requiring the teams to provide insight and explanations for their results, rather than simply working toward a specific answer.

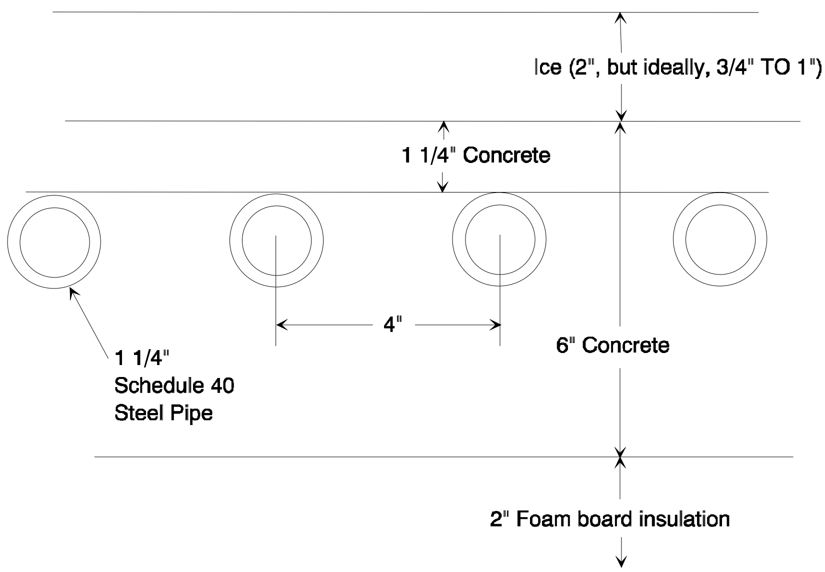

Figure 1 Schematic of a section of the University of Illinois ice rink floor used for Project 1 modeling activities.

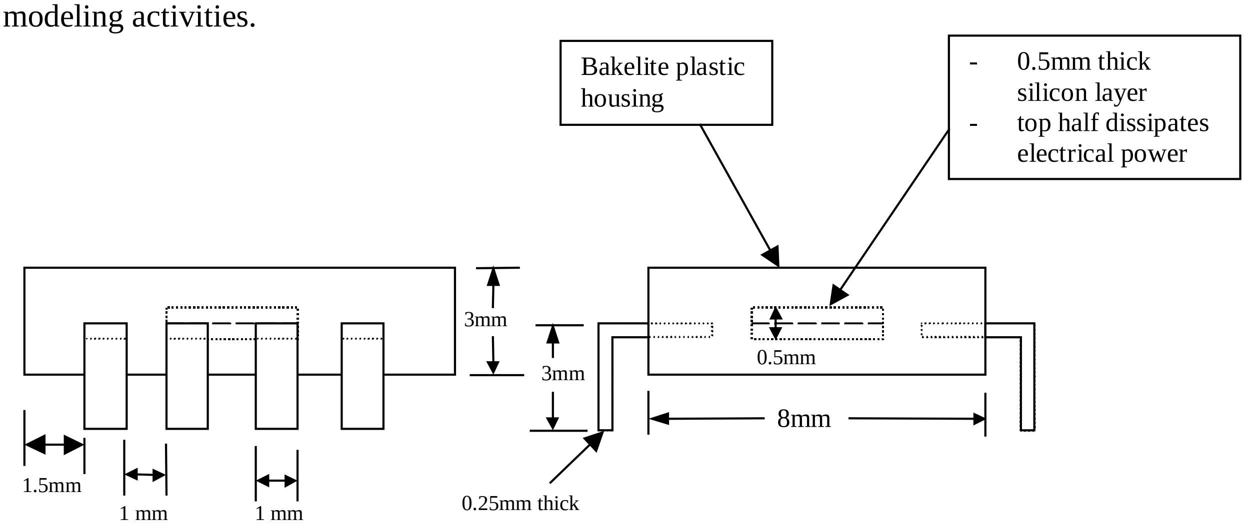

Figure 2 Schematic of an operational amplifier investigated in Project 2.

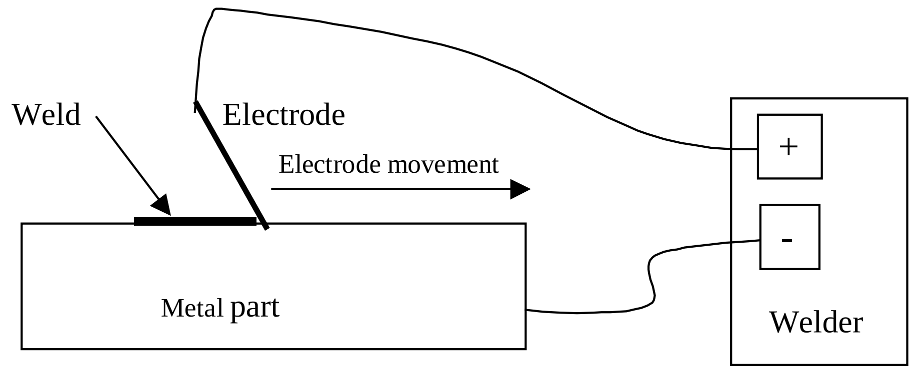

Figure 3 Schematic of the arc welding process modeled in Project 3.

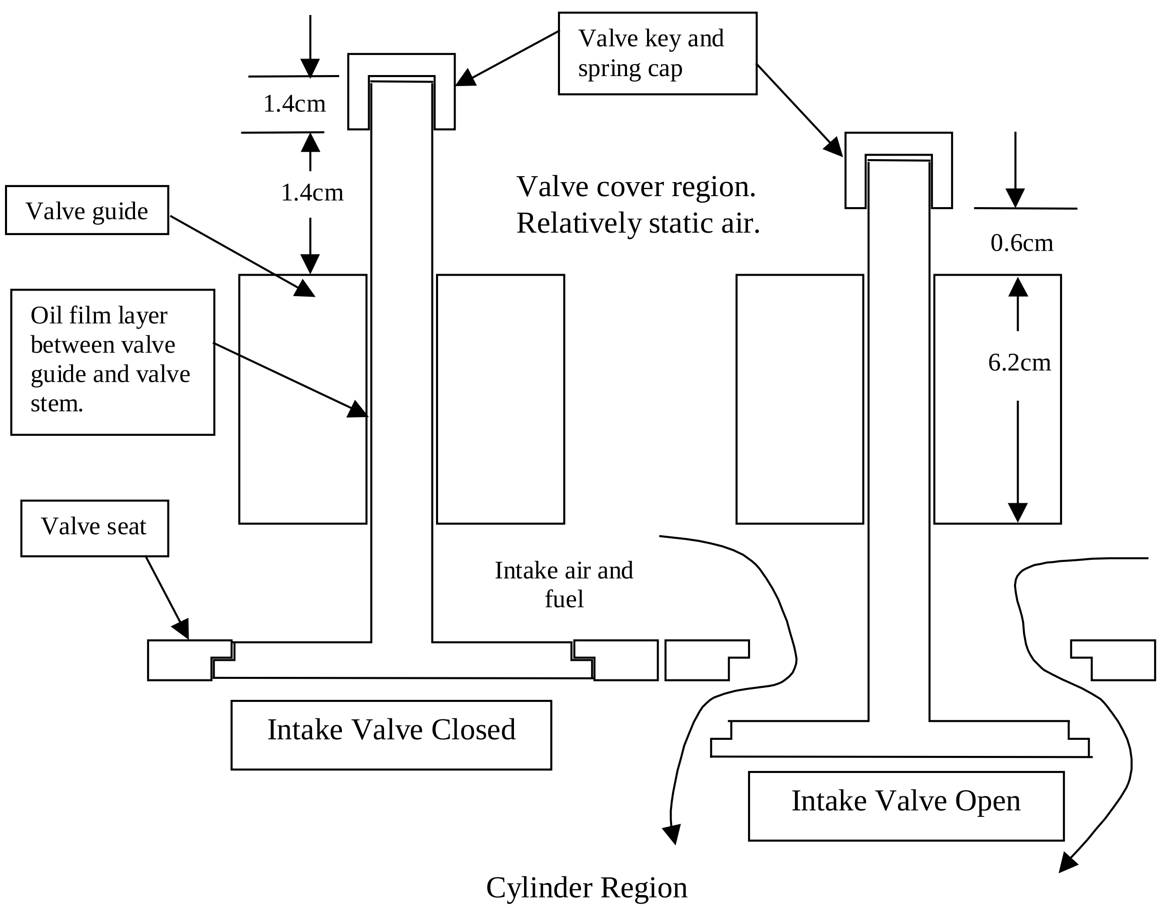

Figure 4 Schematic of the open and closed conditions of an intake valve in an automotive engine modeled in Project 4.

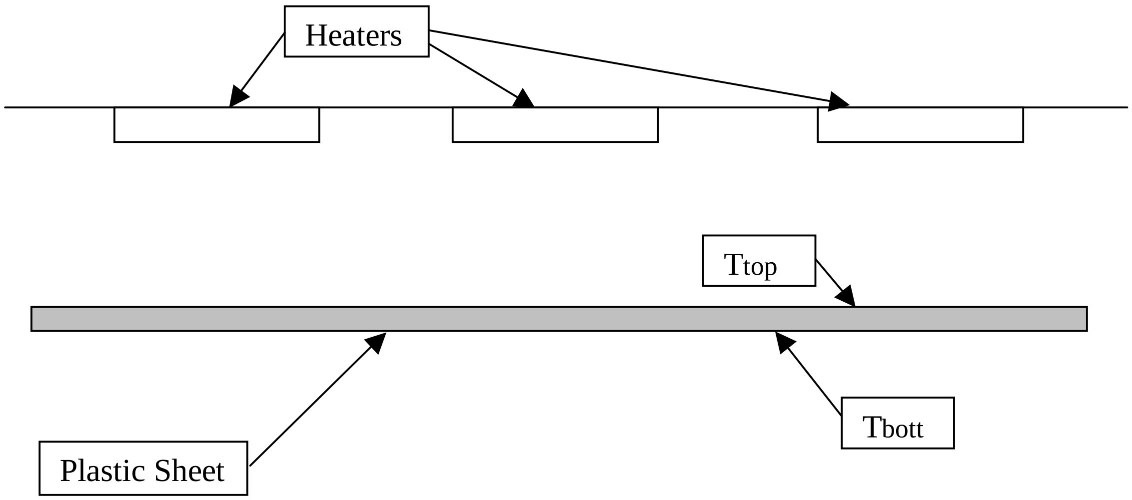

Figure 5 Schematic of the combined transient conduction and radiative heating of a plastic sheet investigated in Project 5. The process is used for manufacturing refrigerator liners.

Anecdotes and Observations

The end result of the class structure and activities was a favorable one from the viewpoint of the students and the instructors. Student evaluations indicated a perceived high level of learning, and a general enjoyment of the learning format. Students generally stated that the workload was heavy. Elimination of examinations appeared to be reasonable compensation for the workload, and resulted in additional "learning time". A common, but not overwhelming, request was for some level of individual work. Individual work can be added by assigning textbook homework problems. The reality of individual assignments, however, is that most students would complete "individual" homework problems together in either their assigned teams or their naturally selected work groups.

During the summer following the spring semester class, two students contacted us and stated that the class had developed a foundation that fit directly into the heat transfer analyses they were performing (on commercial numerical software) at work. Two other students came back during the fall semester, inspired by the methods they mastered in the class, and independently developed additional techniques to be used in the spreadsheet analysis format. One student, for example, developed an automated cell coloring algorithm that allows one to see isotherms and isotachs (in boundary layer simulations). This student also developed a routine to disengage screen updates during heavy computations (some numerical grids reached 10,000 to 30,000 cells) in order to increase computational speeds. The other student learned how to develop functions of commonly used operations, allowing the development of a "toolbox" for easier numerical problem formulations.

Our curriculum is one in which few opportunities exist for team-based project work before the senior year when capstone design courses implement this format. A favorable by-product of junior year (or earlier) teaming is that students can have a positive response during job interviews when they are asked the inevitable question: "Have you ever worked in team situation?" As related to us by several students interviewing during their senior year, the experience allowed them to describe several aspects of team organization, responsibilities, and communication, as well as their accomplishments in modeling complex heat transfer situations.

Summary

The team-based approach to teaching undergraduate heat transfer is a viable one. Most students enjoy the format and the ability to work with fellow students. Projects, based on realistic situations, give a sense of purpose and accomplishment when project goals are met. An in-depth understanding of heat transfer fundamentals can be developed with an associated confidence of being able to work through complex situations.

The format developed is one that is enjoyable for the instructors as well. Direct interaction with students, with the instructor supplying information when needed by students, is a satisfying experience. Time commitment is similar to regular course instruction in terms of classroom preparation, handout materials, and student interaction. The development of an integrated set of homework assignments and projects, however, was a very significant time commitment. Once developed, similar to the development of standard lecture notes and examples, the material can be used as a foundation for future class offerings.

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