COUPLING OF A DESIGN COURSE TO A THERMODYNAMICS/ENERGY-CONVERSION COURSE IN THE SOPHOMORE-YEAR CORE CURRICULUM

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1. Introduction

The recent revision of the engineering curriculum at Stevens to create a *Design Spine* is intended to significantly enhance the design experience and to develop key competencies in our graduates in concert with the goals of ABET EC 2000. The *Design Spine* provides a design experience in each of the eight semesters for all of our engineering programs¹. A key feature is the extent to which the core design courses are coupled to the core engineering-science courses to enhance learning. Open-ended projects together with experiments in the design courses are chosen to provide context for and reinforce the engineering science taught concurrently. The *Design Spine* also provides the vehicle to develop key competencies in problem solving, effective communication, project management, ethics, economics of engineering, teaming and industrial ecology in an evolutionary manner throughout the sequence. The embodiment of this approach in the first semester of sophomore year is the coupling of a design course, Engineering Design III (2-credit lecture/lab.) to the introductory course in thermodynamics. The latter has been expanded from 3 to 4 credit-hours to include energy-conversion topics.

2. Integration of Engineering Courses

The revised engineering curriculum at Stevens puts high priority on at least some integration among different courses. While very tight integration is not necessarily a goal, interplay between different courses is required to be conscious, recognizable, and representative of the mutual interdependence that exists among “different” engineering subjects.

In the third semester, opportunity exists for integration of the design laboratory with Thermodynamics & Energy Conversion, a first course in thermodynamics taken by all engineering students. There is also potential for integration with the concurrent first course in electrical engineering, Circuits and Systems. However to date, coupling to the latter has not been explicitly developed, and the major integration has been between Thermodynamics & Energy Conversion and the Engineering Design Lab. III.

Integration of the engineering-science course and the design laboratory has been produced in several respects:

First, like earlier and later design laboratory courses, Engineering Design Laboratory III includes **experiments relevant to the coupled Thermodynamics & Energy Conversion course**. These are described in detail below, and all have the aim of either anticipating or following up topics in the Thermodynamics course.

Second, the coordinator of the design laboratory was one of the planners as well as an instructor in the Thermodynamics course, enabling **closer coupling** than would otherwise have been likely.

Third, exercises, experiments and one design project give **concrete context** to discussion of actual devices in the Thermodynamics course and to some extent in the electrical Circuits & Systems course. For example, a product-dissection/reverse-engineering exercise with a domestic coffee-maker serves to make phase-change phenomena tangible, concerns for heat transfer realistic, the measurement of both large and small currents a thoughtful process, and energy conversion and its efficiency readily apparent early in the semester. The product-dissection exercise continues a thread started in the two Freshman design courses ².

3. Engineering Design III Laboratory

3.1 Overview

The design course, E 231 – Engineering Design Lab. III, is a 2-credit course, offered to all engineering students in their third semester. The course meets for 3 hrs. per week in the laboratory and for 1 hr. per week as a lecture (see Table 1). As a combination of a 1-credit lecture and a 1-credit lab. course, the laboratory is not intended to require significant work by students outside of the laboratory periods. The lecture may, of course, demand some outside work, consistent with other lecture (or recitation) courses. The course was offered for the first time in the Fall of 1999 and repeated in Spring of 2000 as part of the initiation of the second year of Stevens' revised engineering curriculum.

In addition to experiment and project work, the lecture and laboratory components include instruction and exercises on “professional” topics such as written and oral communication, project management and team dynamics, ethics and engineering economics. These competencies are developed throughout the design-course sequence. Since they are not strongly coupled with the engineering-science courses, they will not be described or otherwise dealt with further in this presentation.

3.2 Format and Support

Each laboratory class session, of which there are 6 throughout the week, includes a 30-student section each of which has an instructor who is an adjunct faculty member supported by a senior undergraduate (peer) teaching assistant. In addition, a course coordinator (regular faculty) and a graduate teaching assistant offer planning and support for the instructors as do an Associate Dean of Engineering and the Dean himself (during the course-development phase). An Engineering Technical Services group and the Institute Machine Shop provide support via design and fabrication of experimental and support equipment. The one-hour-per-week design-course lecture is given separately to larger sections of approximately 60 students.

The content of the course is in the form of four experiments, three projects and associated skills development mentioned above.

3.3 Design Laboratory Facilities

The course uses 1800 ft² (30' x 60') of floor space newly reconstructed from what had been a Physical Chemistry laboratory. The laboratory provides 6' x 5' workbenches each shared by two three-person groups working on opposite sides. The laboratory is completely networked, one network connection for each of the 30 students simultaneously occupying the space. Networking will be fully utilized next year when all students will have laptop computers. The laboratory is equipped with power tools, specifically with a band saw, drill presses, scroll saw, and a sanding center. A central area in the lab. contains space for "chalk talks" and short presentations by the instructor or by students. A white board, projection screen, and portable overhead projector and RGB computer-display projector are available. A "support area" of 450-ft² adjoining the lab. allows stowage of out-of-use experimental equipment, materials, supplies, etc.

Wk. No.	Lecture	Lab. (Hour 1)	Lab. (Hour 2)	Lab. (Hour 3)
1	Objectives, Grading, Outline Projects 1, 2 & 3.; Intro. to Experiment 1	<i>Product Analysis Module</i> Disassemble coffee makers, measure "efficiency"; identify & analyze functions; compare 2 different designs		Design Project 1 - Energy and Life Support Paper project (runs whole semester)
2	Intro. to Project 2	Experiment 1 –Phase Change (with intro. to temp. & pressure measurement)		Project 1 (cont'd.)
3	-	Design Project 2: Heat-Activated Pump System (Introduction, discussion, formulation of basis for design, and alternative conceptual designs)		
4	Introduction to Solar-Cell Energy Conversion Experiment	Project 2 (cont'd.) - Evaluation of alternative designs		
5	-	Experiment 2 – Solar-Cell/Electrolysis Energy Conversion Explore cell and electrolyzer characteristics		Project 2 (cont'd.)
6	<i>Project management/group skills</i>	Project 2 (cont'd.) – Freeze prelim. design and order necessary components		
7	<i>Project management/group skills</i> (cont'd.)	Project 2 (cont'd.) - Construction		Project 1 (cont'd.)
8	-	<i>Project management/group skills module</i> - "Team Developer©" and Project 2 Review		Project 2 (cont'd.) - Construction
9	Intro. to Binary-Mixtures Experiment	Project 2 (cont'd.) – Construction & trial testing		
10	Intro. to Project 3 (paper project)	Experiment 3 - Binary Mixtures		Project 2 (cont'd.) – Revision
11	<i>Ethics</i>	Project 2 (cont'd.) – Testing and oral reports		Project 3 – Solar-Energy Conversion & Storage
12	Intro. To Fuel-Cell Expt.	Project 3 (cont'd.)		
13	<i>Eng'g. Economics</i>	Experiment 4 - Fuel Cells		Project 3 (cont'd.)
14	<i>Eng'g. Economics</i> (cont'd.)	Project 3 (final revisions)	Project 3 - Oral presentations	

TABLE 1 - Topical Outline: E 231- Engineering Design Laboratory III

3.4 Faculty & Staff

The course instructors are adjunct faculty drawn from industry and consulting firms. The proximity of a variety of industries allows the course to benefit from instructors of a variety of ages (30's to 60's), some relatively new to the engineering workforce, some retired from a range of engineering disciplines. Judging from student evaluations and observations of instructors' interplay with students, the use of adjuncts that are practicing engineers has been successful. Practicing engineers, particularly some of the younger ones, seem to establish credibility quickly as "real-world" engineers.

3.5 Course Content

Table 1 shows a topical outline of the course content with lecture and laboratory. The 3-hour lab. periods are subdivided into nominal periods of approximately one hour for scheduling, with more than one activity planned most weeks to provide variety.

4. Projects:- the following projects were required in the Fall semester of 1999.

4.1 Project 1 was a paper project that considered the thermodynamics of the human body. The topic was an engaging one for sophomores. Students were asked to develop an energy balance for the human body and this exercise reinforced the First Law concepts from the lecture course. Energy content of food was therefore introduced and the students were also asked to estimate the ecological impact (land area under agriculture) of providing food for the human population. This contributed to the ecology thread in the curriculum, which was additionally addressed with a lecture and exercise associated with the second design project, where wood as a renewable fuel was evaluated. Introductory material on heat transfer was provided in the lecture course and students were asked to estimate how various modes of heat transfer during the day might influence their energy balance model of the body.

4.2 Project 2 was intended as a "hands-on", construction project in which concepts of thermodynamics were applied and in which thermodynamic modeling could be accomplished.

The stated purpose of the project was to develop a prototype of a heat-driven water pump for use in remote and/or undeveloped regions where fuel (e.g., wood or agricultural waste) is available, but no electricity. For the sake of low maintenance, a minimum number of working parts were specified as necessary.

The "pump" can be visualized and analyzed as comprising the heat-input, heat-rejection and work-output processes of a heat-engine cycle with the device operating cyclically to do work on the throughput fluid which is also the means of heat rejection. Specifications for the prototype were as follows:

1. Must pump water (initially at ambient temperature and pressure) through an elevation of 8 ft.
2. Must be constructible of commonly available materials (e.g., plumbing components) with commonly available tools
3. Minimum cost
4. Adaptable to a variety of fuels (e.g., wood, biomass, animal dung, etc.)
5. Pressures developed should not exceed 5 psig. (for safety and low cost)

Grading was based on a combination of factors:

Pumping performance (quantity pumped through 8' rise in 10 min.) – Note that this quantity or the rate of pumping represents not only the device's capacity, but also the efficiency of the device (since heat input is fixed by the Bunsen burner design)	40%
Workmanship, esthetics, innovation	10%
Written report	30%
Oral report	20%
	<u>100%</u>

Typical designs were some form and size of vessel (even a tin can or a length of copper tubing) with check valves at entrance and exit with fresh liquid supply through one check valve and delivery of heated water and steam through the other. Figure 1 illustrates such a device, schematically.

A budget of \$50 was available to each group to be applied to requisitioned materials and components for construction of their design. No custom machining was provided

Emphasis in the design process was on the items that were specified as required to be covered in the written report:

1. What alternative design concepts were considered and what are their relative strengths and weaknesses?
2. Specific reasons for selection of the final design concept.
2. The maximum performance (and on what basis) predicted theoretically for a device using your selected concept. How does the device's performance compare with this maximum achievable performance?
3. Suggestions for possible further improvements in concept, construction, operation or whatever.

The operation of such a pump might be modeled as displayed on the accompanying P-v diagram (Fig. 2) for which details are available from the first-listed author, if desired.

Some components for construction were available from inventory in the lab. Others (e.g., check valves) had to be requisitioned by the design groups and were ordered and delivered before the next class meeting. As this process turned out, students learned much more about pipe and tubes than had been anticipated; one student observed loudly that it was "bizarre" that 1/4" pipes and 1/4" tube wouldn't fit together. He learned a lesson many engineering students don't learn until much later (if at all).

4.3 Project 3 was a short paper design project towards the end of the semester which examined the selection of a reversible chemical reaction to enable the storage and then release of solar

FIGURE 1 – Schematic of possible heat-actuated pump (not to scale)

energy to meet a defined need, such as the provision of house heating or of process steam. Students were given background material (through lecture and web-based sources) on solar collection and on possible storage schemes. The reaction choice was dependent on the

FIGURE 2 – Pressure/Volume Diagram for Heat-Actuated Pump “Cycle”

application, as the latter dictated the allowable temperatures of the forward (endothermic storage) and reverse (exothermic release) reactions. The project was intended to provide context for the material on chemical thermodynamics covered towards the later part of the Thermodynamics/Energy Conversion course. Students needed to examine the temperatures at which the forward and reverse reactions occur at significant rates for various candidate reaction schemes and choose the most appropriate chemical system for the application. Consideration of the possibility of side reactions reducing conversion efficiency was also needed. Safety (check MSDS data) and ease of storage were also considerations.

5. Experiments

Four short experiments were carried out during the course. The thermodynamic topics for these were chosen so as to be of interest to a wide variety of engineering disciplines. The experiments are distributed through the semester to be correlated with topics treated in the corresponding classroom course. Figure 1 shows a topical outline for the course.

5.1 Phase-Change Experiment

Pressure and temperature were measured simultaneously for a liquid/vapor mixture of H_2O . Pressures from atmospheric down to the lowest pressure can be maintained by the “aspirator” (An ejector powered by tap water.) during boiling (e.g., 2 – 3” Hg absolute or 27 – 28 “ Hg vacuum). A thermocouple is used for temperature measurement and a Bourdon-tube “combination” gauge for pressures from – 15 “ Hg to + 15 psig. The apparatus is shown in Figure 3 and was designed to also serve for Experiment 3 (Binary Mixtures) with minor modifications.

FIGURE 3 - Boiler and Associated Apparatus for Phase-Change Experiment

The early introduction of this experiment allows it to reinforce coverage of phase-change, which is typical in the early weeks of a first course in engineering thermodynamics. The vapor-pressure data obtained are compared with accepted values, and discrepancies are rationalized based on error analysis. The ability to watch boiling at temperatures considerably below the “normal” boiling point is unfamiliar to most students. Student experience with common measurement methods for temperature and pressure is an intended outcome as is concern for errors, running plots, and issues of thermodynamic equilibrium (the boiler temperature can be measured at different elevations above and below the phase interface).

5.2 Experiment on Solar-Cell/Electrolysis Energy Conversion

The second experiment (and the first emphasizing energy conversion) couples a photovoltaic solar panel (Model SP3-300-6 silicon solar-cell panel, nominal 3v, 300 ma., Plastec Inc., Webster, MA) with a water electrolyzer (KOH electrolyzer, Warsitz Enterprises Inc., Sunnyvale, CA) and naturally introduces concepts of energy conversion in general as well as “direct” energy conversion. Overall conversion efficiency for a series of conversions is a natural component of the experiment along with necessary concern for energy storage. Figures 4 and 5 show, in two parts, a schematic of the apparatus.

Use of a 90-W. halogen spot lamp to simulate solar radiation and an infrared-reflecting film (to minimize infrared heating of the cells) add an additional dimension to the experiment. To determine the efficiency of conversion of radiation from the lamp into electrical power, it is

necessary to integrate the radial variation of light intensity over the rectangular area of the solar panel. This is a worthwhile, practical, and non-trivial application of integral calculus. The experiment is intended to emphasize energy flow and conversions but is too early in the se-

FIGURE 4 – Schematic of the Solar-Panel Part of Experiment 2

mester to allow analysis based on Gibbs free energy; consequently, efficiency values are based on heating value of the hydrogen produced. Observations of non-stoichiometric production ratios of hydrogen and oxygen led to concern for unsteady operation and the storage of one component or the other as electrolyte levels changed in response to pressure imbalances on the two sides of the electrolyzer. This can be rationalized in the context of unsteady control-volume analysis of mass conservation.

FIGURE 5 – Electrolyzer and Gas Collector Part of Experiment 2

5.3 Experiment on Binary Mixtures

The vessel used in Phase-Change Experiment was adapted to use as an “Othmer Still” (see Fig. 6) but was designed and fabricated to resemble industrial rather than chemistry-lab. equipment. The binary mixture used is ethanol and water, a safer combination than some of those (e.g., acetone/water, benzene/toluene) frequently used in physical chemistry laboratories (the practical significance of ethanol/ water mixtures also does not need to be justified).

The concept of a “reflux” flow is naturally introduced with this apparatus and serves to connect with typical chemical-engineering concerns, a benefit considering the all-engineers make-up of the student pool for the course. Liquid and condensate are sampled, and their composition is determined by the specific-gravity method. Specific-gravity bottles (10-ml calibrated bottles,

FIGURE 6 – Modified Othmer Still for Exploring Binary-Mixture Equilibrium

Fisher Scientific Co.) are filled and weighed first with mixtures of known composition. This calibration becomes a basis for deducing compositions from measured masses of samples taken during the experiment. This physical (rather than chemical-analysis) measurement to determine composition was chosen over gas chromatography or other such methods in order to reinforce the student perception that this is not a chemistry-lab. and chemical-analysis course.

The major thermodynamic emphasis is, of course, the contrast in phase-change behavior between this binary mixture and the pure water tested earlier. That is, emphasis is on compositions of liquid and vapor phases being different and on the occurrence of boiling over a range of temperatures despite the fact that all tests are at 1-atm pressure.

5.4 Fuel-Cell Experiment

What is probably the most unusual, timely and mind-stretching experiment for the students involves direct energy conversion via a hydrogen/air fuel cell with a proton-exchange membrane (“PEM”). The 4-cell, 10-W unit was designed and constructed specifically for this experiment (This unit may be marketed by the manufacturer, H-Power Inc., of Belleville, NJ for use by others.). By this time, late in the semester, students have been introduced to thermochemistry, and are just becoming involved with Gibbs free energy, etc. Again, the experiment’s emphasis is on energy conversion. An introductory lecture emphasizes current interest in fuel cells (e.g., by auto manufacturers) because of their high efficiencies, independence from the Carnot-cycle, heat-engine limitations of the 2nd Law, and also because of their low emissions. A Voltage/Current characteristic curve is generated along with conversion efficiency data (up to near 70%, based on either heating value or Gibbs free energy of reaction). Achievement of high efficiency at part load is emphasized, in contrast to the low efficiency at part load typical of internal combustion engines. Figure 7 shows the apparatus schematically and Figure 8 is a photo of the bench top system

6. Coupling of the content between laboratory and engineering science courses

6.1 Phase change phenomena: The first experiment (pure substance), the heat-actuated pump project and the third experiment (binary-mixture phase equilibrium) are coupled with the classroom course. The $p - T$ relations of saturation conditions for a pure substance are observed and measured, the continuity of temperature across a phase-change interface is observed, the profound volume-change accompanying phase change is observed and used in design. The range of boiling points and their compositions dependence is observed for binary mixtures as is the easily observed difference between liquid and vapor compositions. All of these are “exploratory” experimental results, anticipating treatment of these topics in the lecture/recitation Thermodynamics & Energy Conversion course.

6.2 Direct Energy Conversion: Photovoltaic and fuel-cell energy conversion is used in two experiments. The grouping of solar cells into solar panels producing increased current and voltage and the stacking of fuel cells for the same purpose are both experienced. Both first-law and second-law efficiencies are illustrated, as is the determination of overall conversion efficiency for sequential energy conversions.

6.3 Thermal energy conversion: Energy conversion by (part of) a heat engine is illustrated and worked over conceptually in the product-dissection exercise (with the coffeemaker) and, more significantly, in the design of the heat-actuated pump. The pump

FIGURE 7 – H₂/Air Fuel-Cell System

focuses on conversion of heat to a change in potential energy with heating of the pumped liquid being largely incidental (though numerically dominant). While few student groups have in the past offering of the course analyzed their pumps in any thermodynamic detail, such modeling and analysis will be better encouraged in future offerings.

6.4 Chemical Thermodynamics: In the electrolysis portion of Experiment 3, in the fuel-cell experiment, and in Project 3, chemical thermodynamics are involved. Early in the semester, electrolysis necessarily is dealt with via “chemical energy”, the first-law concept of heating value, and the need for energy storage which can be accomplished chemically. This first-law approach is built on in the heat-actuated pump project. The end-of-the-semester experience with the fuel cell reviews exothermic oxidation reactions in terms of second-law, “maximum possible work” and related concepts. The solar-energy-storage component of Project 3 extends this concern to a reaction run in both exothermic and endothermic directions.

6.5 Basic Thermodynamic Measurements: Basic, common thermodynamic measurements are part of the experiments (and also the coffee-maker exercise), and hardware for such (thermocouples, bimetallic thermometers, Bourdon gauges) is introduced during recitation sessions (*via* “exploded” and “cut-away” demonstration hardware) of the Thermodynamics course and, then, used slightly later in the laboratory experiments. The concept of “calibrating” for heating/cooling rate by monitoring temperature rise/fall, etc. could and should be an assured part of the saturation-curve and binary-mixture experiments; it was not in the first offering of the design laboratory course.

FIGURE 8 Photograph of Fuel Cell Apparatus

6.6 Electrical Measurements: Students gain experience in multi-meter measurements of voltage, current and resistance, not merely at low-voltage and low-current electronics levels but at “power” levels (110 v., up to 10 amps) concurrent with their Circuits & Systems course. This course comes one semester prior their Electronics & Instrumentation laboratory course. Problems with blowing fuses in the multimeters have made it clear that the students have not been well prepared (by earlier work) for careful, thoughtful application of electrical principles to routine measurement situations. In the fuel-cell experiment, they encounter a low-resistance, precision resistance as a basis for current measurement via voltage measurement.

7. Future Plans

Future plans for continuing and enhancing integration of the experiments of the design course and the classroom course include:

- (1) Better synchronization of topical coverage between the two courses.
- (2) Introduction of data, e.g., binary-mixture and fuel-cell thermodynamics from design-lab. experiments into the classroom treatments of associated topics.
- (3) Better acquaintance of instructors in classroom course with content and progress of Design Lab. course.
- (4) More distinct scheduled deliverables to encourage task planning and timely progress,

- (5) Better direction to instructors to encourage thermodynamic modeling of experiments and in project conceptualization and development.
- (6) More direction of student efforts from instruction materials and less from tutoring by instructors
- (7) More resources provided to acquaint student with hardware issues, e.g., check valve performance parameters, tubing vs. pipe connection and fittings, alternative methods for pressure-tight connections of components, multimeter operation, etc.
- (8) Use of notebook computers in lab. to develop models of project concepts.

Bibliography

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