Finding COP: A Project to Unify Topics in Fundamentals of Thermodynamics Course

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Abstract

In a typical introduction to thermodynamics course, concepts such as the first law, property relations, second law, etc. are usually taught in succession. To aid in further understanding these concepts, and to help solidifying the “point” of studying thermodynamics, a high-stake project that unifies some of the major topics is necessary. Such a project should be readily relatable to everyday life, and yet should require a higher-level exploration of meanings.

An example of such project has been successfully implemented in a basic thermodynamics course for a number of years. The goal is simply to find the coefficient of performance (COP) of students' refrigerators at home, without having to analyze the refrigeration system (which generally is studied in intermediate thermodynamics). Instead, students are expected to approach this problem from the angle of the refrigerator compartments, by estimating the amount of heat to be removed from inside the refrigerator. The electrical work may be determined experimentally, either via an instrument or by observing the frequency and duration of the refrigerator's operation.

This project may be assigned as soon as the first law for cycles has been introduced, and may be split into two phases: Methodology followed by Experimentation and Solution. For the Methodology phase, students may be teamed up to brainstorm the meaning of the problem statement, research how a refrigerator works, identify the physics involved, and develop a strategy for collecting data necessary for the calculations. In the Experimentation and Solution phase, to be assigned as an individual project once the second law is introduced, students proceed to conduct experiments, solicit data that may be unavailable in the textbook, and assemble results into a report. The expected outcome of the project is an appreciation of the first law applied to incompressible substances (e.g., foodstuffs), ideal gas (air inside the compartment and its relation to door opening), electrical power and work, as well as the ability to construct and solve equations in a real-world setting.

Assessment of effectiveness includes comparison of average test and course grades between control groups and other terms with this project implemented. End-of-semester course evaluation data and comments are also compiled and analyzed. Both quantitative and qualitative data indicate a positive and compelling effect of the project.

Introduction

Thermodynamics is a challenging class,[1] and is an important subject relevant to multiple engineering disciplines. An introduction to thermodynamics course, therefore, is typically required across majors. The diversity of student body in such a class presents unique challenges for teaching and learning. The topics covered are mostly conceptual, such as property relations, heat, work, first and second laws, etc.[2] and topics are usually presented piecemeal. While some materials are inherently interrelated, e.g., heat, work and first law, others are inevitably decoupled from the rest, making it a challenge for students to progress through the Bloom's taxonomy.[3] Recent evidence shows that engineering students enrolled in intermediate-level thermodynamics course often do not retain basic understanding of thermodynamics and struggle to advance to the next stages of learning.

To enable higher-level cognition and knowledge retention, a means to unify topics in introductory thermodynamics may be necessary. One such means is the use of projects. Project-based learning, or PBL, has been studied by many researchers and its positive impact has been well documented. In engineering, PBL is a particularly useful tool to enhance student learning and performance. An important element in overcoming conceptual challenges, as often encountered in thermodynamics, is the self-guided process where students rely, and eventually trust, their cognitive resources to form a knowledge base.[4] PBL, if implemented with care, can serve as a powerful way to enable self-reliance. Savage et al.[5] investigated, and ascertained, the effectiveness of PBL throughout the engineering curriculum, while cautioning that its success requires that the project be relevant, not overly complex or resource intensive, and easy to implement by the instructor.

Many educators have integrated PBL, of varying capacity, in introductory thermodynamics,[6-13] including some projects that have been creatively implemented.[14-15] While the consensus is overwhelmingly encouraging, the methods of assessment used in these studies vary significantly, from anecdotal evidence to quantitative analysis. As Savage et al.[5] concluded, quantitatively evaluating the effect of PBL in the individual level is a difficult task, and alluded to the grander challenge of defining the measure of student success.

In this paper, a project that attempts to unify key concepts in introductory thermodynamics is presented and detailed. It is immediately relatable to students, is easy to adopt, and does not require specialized tools or instruments. The implementation requires little faculty time or resources other than a simple update of grading policy and mentoring of students (or teams) throughout the course of the project. The mentoring, and guiding, effort is crucial in achieving the learning objectives,[16] and may be fulfilled by the already-existing office hours, supplemental instructions, recitation sessions, or planned in-class activities. The project's flexibility means it is suitable for both conventional or flipped model of instruction.

The impact of this project is measured by the following methods: 1). Quantitative analysis of final exam data, including comparison with a control group consisting of multiple terms where no such project was incorporated. 2). End-of-course student comments. 3.) Anecdotal evidence.

The topics to be unified are:

- Property relations for ideal gas
- Property relations for incompressible substance
- Heat and adiabatic process
- Work and power
- Energy as a property (particularly internal energy)
- First law of thermodynamics
- Closed system vs. open system
- Cycles and performance

- Second law of thermodynamics

While the list above may seem vast, the project naturally ties one concept to another in a subtle and unintimidating way that invites meaning exploration, from comprehension to evaluation stage of learning.

This project has been integrated into three instances of introductory thermodynamics since 2013. A control group that consists of seven prior terms without the project is compared, and the results are discussed and conclusion drawn in later sections.

The Project

The project description and expected outcomes are detailed in this section, complete with a sample calculation.

Problem Statement

Simply put, students are tasked with calculating both the actual and ideal coefficients of performance (*COP*s) of their refrigerators at home. The problem statement may seem simplistic at first, but would soon yield layers of complexity once the definition of *COP* is revealed:

$$COP_{\text{actual}} = \frac{Q_{\text{c}}}{W}\ ,\ \ COP_{\text{ideal}} = \frac{T_{\text{c}}}{T_{\text{h}} - T_{\text{c}}}$$

where Q_{c} is the total amount of heat removed from the cold reservoir, W the total work supplied to the refrigerator, and T_{c} & T_{h} the temperatures of the cold and hot reservoirs, respectively. The complexity built into these equations requires exploration of meaning, and the sample calculation presented below illustrates the multilayered process. Nevertheless, the concepts spanning this project are rather straightforward, and the process involved in solving the problem is logical and challenging without being excessive.

Objectives & Outcomes

The project is designed with the following objectives:

- Enhance understanding of thermodynamics through experiential learning through an everyday object
- Incentivize self-guided research, planning, and project management
- Obtain data with relative ease, without the need to examine refrigerant properties and flow, and without having to fuss over accuracy
- Compare actual and ideal efficiencies

Upon successful completion of the project, students are expected to exhibit the following learning outcomes:

- Be able to model an otherwise complex phenomenon, make reasonable assumptions, and formulate the physics involved
- Draw a meaningful connection between textbook and the real world
- Appreciate the interrelationship of the various elements in the first law of thermodynamics, property relations of incompressible substances (e.g., foodstuffs), property relations of ideal gas (air inside the refrigerator compartment, electrical power and work
- Demonstrate knowledge gained through performance in final exam
- Demonstrate knowledge retained through performance in a subsequent course (e.g., intermediate thermodynamics or heat transfer).

Constraints

As an important and fundamental restriction to this project, students are prohibited from approaching the problem by analyzing the refrigeration system, i.e., the refrigerant flow. Instead, students must explore the meaning of the quantities involved, particularly heat and work, by examining the refrigerator *compartments*. In other words, instead of investigating where the energy is *going to*, students should question where it is *coming from*.

It should be noted that the actual *COP* may also be defined in terms of the rate of energy transfer:

$$COP_{\text{actual}} = \frac{\dot{Q}_{\text{c}}}{\dot{W}}$$

Students are encouraged to consider both definitions (i.e., Joule vs Watt), and select one that is more convenient to use.

Why Refrigerator?

Since the industrial revolution, refrigeration has helped shape cultures and lifestyles, and is an essential element in today's societal functions. As commonplace as they are, refrigerators are however often taken for granted. Questions such as "how does it work?" and "what does Energy Star, or kWh, really mean?" may not be in a student's mind every time he or she uses the refrigerator. Meanwhile, for students studying thermodynamics, the theories are in fact hard at work before their eyes day in and day out. Investigating the refrigerator efficiency, therefore, is convenient and does not require specialized instrumentation.

Tools Necessary

The only required instrument is a clock. Optional tools may include a thermometer, barometer, scale, ruler, and watt-hour meter.

A Sample Calculation (SI Units) and Caveats

An easy start to this project is calculation of the ideal, or maximum, *COP*. The choice of the cold reservoir, however, warrants some thoughts. Since a reservoir is defined as, among other conditions, a volume whose temperature remains constant, the freezer compartment is chosen for T_c calculation. For most domestic multi-compartment refrigerators, the freezer is a separate space having a regulated, steady temperature. In addition, the evaporator coil, the heat exchanger where Q_c occurs, is typically located adjacent to the freezer inside panels. The choice of freezer compartment is, therefore, justified.

To obtain T_c , one may either use a thermometer, look up manufacturer's specifications, or approximate by using any available – and reliable – published data. A quick internet search reveals that the U.S. Food and Drug Administration recommends setting T_c at -18°C for consumer refrigerators.[17]

T_h is the temperature of the room the refrigerator is located. A simple consultation of the home thermostat or an estimate of the kitchen temperature would suffice. A better model would account for the fluctuating home temperature throughout the day, especially if the refrigerator is exposed to direct sunlight or another heat source or sink. For simplicity, T_h is taken as 22°C.

Converting all temperatures to Kelvin,

$$COP_{\text{ideal}} = \frac{255}{40} = 6.375$$

The actual *COP* is where it gets interesting. First, a decision must be made regarding the unit of the energy involved. If the total amount of energy is preferred, then Q_c and W will be expressed in Joules or kilo-Joules, and the sum of all energies are calculated. If the rate of energy is desired instead, then $\dot{Q}_c$ and $\dot{W}$ will be used, expressed in Watt or kilo-Watt, and the time-averaged quantities are used in the calculations. In either case, the total observation period (or experiment interval) needs to be defined, and the same duration must apply to the data collection of both Q_c and W (or $\dot{Q}_c$ and $\dot{W}$). The longer the duration, the more meaningful the data becomes, since one should expect substantially different use behavior of a refrigerator during the day and at night. A 24-hour interval, therefore, is a good choice, although a few hours may also be acceptable, since accuracy is less important here. In this sample, the duration is chosen to be 24 hours, and the unit of kilo-Joules is used.

Arbitrarily, the first piece of the puzzle is the electrical work, W. No other forms of work exist. Most of the electricity, as one should conclude after some research, is consumed by the compressor, a device responsible for enabling refrigerant flow. Other components and accessories that also require power include cooling fan for the condenser, fan between the freezer and refrigerator compartments, defrost heater and timer, sensors, light bulbs, ice maker, electronic display, etc.

To precisely determine the total electrical work supplied to the refrigerator during the 24-hour period, a watt-hour meter may be used. However, most students and households may not have access to such a device. An alternative, and a more practical method, is by observing the "hum" of the compressor. Students are expected to notice that the refrigerator does not "run" constantly. When it begins to operate (i.e., during startup), a low clicking or rumbling may be heard. During steady operation, it may emit a sustained buzzing sound. Just before the operation terminates, a rattling can usually be heard, and vibration felt on the refrigerator walls.

Assuming that all electrical work is utilized by the compressor, one may begin to collect data by recording the duration and frequency of the compressor operational behavior through aural observation. The compressor power consumption (or "rating") can be found by either inspecting the compressor label (which requires accessing the rear of the refrigerator - an arduous task for some), perusing and deciphering manufacturer's specifications (in owner's manual or label inside the refrigerator compartment), or looking up information on the internet for similar refrigerators. In the event that electrical voltage (V) and current (I) data are available, then the electrical power is $P = VI$, in Watt. For convenience, $P = 120 \times 2 = 240\ W$ in this sample calculation.

It is noted that the indicated or calculated power rating is the maximum power consumed by the refrigerator. For the purpose of this project, no further explanation or research is necessary regarding the various speeds and other technical details of a compressor.

Students may opt to observe the on-off cycles over a manageable time interval, e.g., two hours, as shown in Figure 1 below. Further assumptions are made regarding the square-wave usage pattern for the remainder of the 24-hour observation time. Since one should suspect that the power consumption is less frequent during nighttime, a correction factor may be introduced whereby the total electrical work, in kilo-Joules, can be estimated.

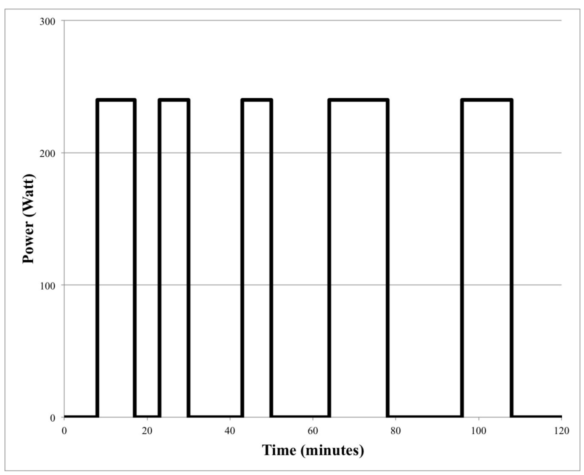

Figure 1. Power Consumption Behavior.

Adding the areas under the squares in Figure 1, the total electrical work is approximately 700 kJ over the two-hour period. Multiplying by the number of repetitions, and assuming a correction factor of 50%, the total electrical work is $W = 700 \times 12 \times 0.5 = 4{,}200\ kJ$.

Next, the meaning of Q_c is explored. Q_c is the total amount of heat that must be removed from inside the refrigerator in order to maintain a steady and food-safe temperature. The sources of heat, therefore, need to be identified. An obvious guess is foodstuffs. Other sources include mass transfer through opening of refrigerator doors or gaps in door gasket, heat transfer through insulation (i.e., refrigerator walls), light bulbs, and other accessories directly or indirectly exposed to the interior of the refrigerator.

Foodstuffs: Assuming no heat is generated from the chemical reactions as food spoils, the "new heat" introduced into the compartments comes from placing food items initially at some temperature higher than the steady, target temperature of the refrigerator. Applying first law of thermodynamics to each food item modeled as an incompressible closed system, and assuming no phase, volume or mass change occurs:

$$\Delta E = Q_{\text{food}} - W = Q_{\text{food}}$$
$$\Rightarrow Q_{\text{food}} = \Delta U = \sum_{i=1}^{j} m_i c_{p,i} \Delta T_i$$

where j is the total number of items. No boundary, electrical, or mechanical work exists for each foodstuff, and the only change in total energy is the internal energy (U) change due to temperature difference. The mass m, in kilogram, can be found by either weighing each item or, if available, reading the product label. The specific heats (c_p) for food are most likely absent from most textbooks but are readily available via online databases.[18] It should be noted that, for simplicity, containers are considered "foodstuffs" and may be lumped as a single material.

A sampling of food and containers at room temperature (25ºC) is placed inside the refrigerator during the 24-hour observation interval, and is listed in Table 1 below. The refrigerator is otherwise assumed to either be empty or already contain items at the target, steady temperature of 0ºC. The freezer compartment is unused in this calculation.

Table 1. List of Foodstuffs to be Refrigerated.

	m (kg)	c_p (kJ/kg-K)	ΔT (ºC or K)	Q_{food} (kJ)
Containers (Glass)	3.0	0.75	25.0	56.3
Raw Chicken	2.5	3.22	25.0	201.3
Sweet Potato	1.5	3.14	25.0	117.8
Water	5.0	4.18	25.0	522.5
Total				897.9

Mass Transfer: To accurately calculate the heat that accompanies warm air entering the refrigerator (and replacing the cold air inside) every time the door is open, an open system analysis is necessary whereby fluid dynamics must be accounted for. This makes for an intimidating circumstance and thus should be simplified. A manageable model would once again involve a closed system: The air, as an ideal gas, inside the refrigerator. The initial condition is the moment the door has closed, and the final condition when the air has reached the steady, target temperature (of 0ºC). Applying first law to a closed system of ideal gas,

$$\Delta E = Q_{\text{opening}} - W = Q_{\text{opening}}$$
$$\Rightarrow Q_{\text{opening}} = \Delta U = \sum_{k=1}^{j} [m c_v \cdot (T_i - T_f)]_k$$

where j is the total number door-opening instances. The initial temperature (T_i), just after the door has closed, is yet another variable that needs dissection. Experience suggests that it is a function of the speed at which the door swings open and closed, the condition of the kitchen air, the geometry of all solid objects in the fluid's path, and the duration of air exchange. To model this process, T_i may be assumed directly proportional to how long the door stays open, and the proportionality constant may be an arbitrary constant, i.e., $T_i = c \Delta t$. If every 10 seconds of air exchange results in 1 degree rise in temperature, then c is 0.1.

The mass of air is calculated from the equation of state:

$$pV = mRT$$
$$\Rightarrow m = \frac{pV}{RT}$$

where p is the atmospheric pressure, V the air volume inside the refrigerator, R the gas constant (287 J/kg-K), and T the air temperature. The air volume may be either simply taken from the "capacity" specified by the manufacturer (e.g., 21 cu. ft. = 0.6 m^3), estimated from visual inspection, or measured using a ruler. The pressure may be assumed 100,000 Pa, and the temperature the final, target temperature of the refrigerator. Using the above data, air mass is a constant:

$$m = \frac{100{,}000 \times 0.6}{287 \times 273.15} = 0.765\, kg$$

The specific heat c_v is a function of temperature, and is evaluated at the target temperature of 0^{o}C, i.e., c_v = 0.717 kJ/kg-K. The equation for $Q_{opening}$ can then be simplified as

$$Q_{\text{opening}} = m c_v \sum_{k=1}^{j} (\Delta T)_k$$

An assumed door-use behavior is given in Table 2 below (j = 5):

Table 2. Pattern of Refrigerator Door Opening.

	Duration of Air Exchange, Δt (s)	$T_i = 0.1x\Delta t$ *(^{o}C)*	$\Delta T = T_i - 0$ *(^{o}C or K)*
Door Open #1	35.0	3.5	3.5
Door Open #2	40.0	4.0	4.0
Door Open #3	30.0	3.0	3.0
Door Open #4	50.0	5.0	5.0

Door Open #5	25.0	2.5	2.5
Total			18.0

Therefore, $Q_{\text{opening}}=0.765\times0.717\times18=9.873\,kJ$.

Note that if broken door seal (gasket) or other air leakage is taken into account, then $Q_{opening}$ will need to be updated by adjusting the proportionality constant c or multiplying the above calculated Q by an arbitrary factor.

Insulation: Due to imperfect insulation, as is the case in all real-world problems, heat will get transferred from the kitchen to the refrigerator compartment even when the door is tightly shut. To capture the phenomenon of heat transfer through insulation, one-dimensional Fourier's law (heat conduction) needs to be invoked, where the exact dimensions and insulation materials and configuration need to be known. Since in a typical ABET-accredited curriculum, introductory thermodynamics takes place before a heat transfer course, simplification and modeling are again necessary here.

One way to determine heat transfer through insulation is by isolating the effect of insulation. One may begin to observe the refrigerator once it has reached a steady condition, typically long after the last use (e.g., opening door and placing warm food inside). The time it takes between compressor operations (i.e., off-on cycle) may be used as an indicator of heat transfer. This method, while fundamentally sound, may be time consuming.

An alternative is to research, and adopt, publicly available data or model for a consumer-grade refrigerator. Melo et al.[19] reported experimentally-determined heat flux data through the walls of a refrigerator, with the total heat transfer rate being 41.93 Watt. Applying this data to the 24-hour observation interval of this sample calculation, one obtains

$$Q_{\text{insulation}}=3{,}623\,kJ$$

which is a rather large number compared to the other heat sources considered above. Upon further reflection, one should realize that even when the refrigerator is unused, as long as it is plugged in, it will consume electricity (i.e., compressor will run) throughout the day and night, and imperfect insulation is, largely, to blame.

Others: All other heat source contributions may be lumped into an arbitrary constant without the need for in-depth analysis. For simplicity, it is assumed zero.

Putting everything together, rounding up to the nearest integer, the actual COP is

$$COP_{\text{actual}}=\frac{Q_{\text{c}}}{W}=\frac{Q_{food}+Q_{opening}+Q_{insulation}+Q_{others}}{W}=\frac{898+10+3623}{4200}=\frac{4531}{4200}=1.08$$

Since this number is less than the ideal COP of 6.375, all assumptions and calculations are acceptable and do not violate the second law of thermodynamics.

Method of Implementation and Deliverables

In order to ascertain effectiveness, this project needs to be an integral part of the grade, and be comparable to other high-stake assessments. It is recommended that this project be worth 10%-20% of the overall grade.

This project may be administered as a one-time, stand-alone work or a multi-part assignment with sequential due dates. In the latter case, the project can be administered in two phases: Methodology (Phase 1) and Experimentation & Solution (Phase 2). In Phase 1, students, either in teams or individually, conduct research on the fundamentals of refrigerators, develop methodology of analysis, brainstorm assumptions, and establish a plan for collecting data. No calculations are necessary in this phase. In Phase 2, individually students proceed to execute the plan laid out in Phase 1: Perform experiments, acquire data (from observations and referenced material), complete the calculations, and document all findings as well as reflections in a report.

Phase 1 (or the entire project as one) may be assigned as early as the start of the term or as late as when first law for cycles is introduced. Students may work individually or in teams. During this phase, students are expected to define the problem statement in detail, research how a refrigerator works, develop the relevant physics and associated equations, and establish a plan for collecting data. No calculations are required in this phase.

In Phase 2, assigned as in individual work, students carry out the plan and document findings. The tasks may include making an inventory of data sources (e.g., foodstuffs) and instruments (e.g., stopwatch and measuring tape), data collection (e.g., weighing food and recording compressor on-off cycles), assembly of data, and writing a report or technical memorandum that captures the entire process including a reflection of what has been learned.

The report is graded on the merits of originality, comprehensiveness of the physics considered, the correct use of relevant equations, and overall impression. Accuracy is secondary and nearly irrelevant. The instructor should instead place an emphasis on the documentation of learning progression and student thought process.

It is reiterated that during the course of the project, and between phases, feedback and mentoring from the instructor or teaching assistant can be of tremendous value and is highly recommended. In fact, students (or teams) may be incentivized to discuss progress with the instructor, earning credits along the way.

Assessment

The project's effect on learning, instead of the project scoring itself, is used as assessment and is presented here. Specifically, end-of-course student performance, measured by final exam scores, is analyzed. The project was incorporated into three semester terms since 2013, and seven prior terms without the project serve as the control. While all courses assessed were taught by the same instructor (the author), the class size differed and will be discussed below.

Data from the control group is first discussed. Figure 2 presents the class-average final exam and overall (semester total) scores across seven control terms. Standard deviation is also included, since it measures level of departure from the mean and therefore is a powerful indicator of learning by a cohort. Among the control terms, the class-average final exam scores range from 74.2 to 82.9, with the "average of average" being 78.9. The standard deviation ranges from 10.1 (best) to 18.1 (worst), with an average of 14.7.

The class-average semester overall scores among the controls, ranging from 76.8 to 85.7, are also averaged (83.3). The standard deviation ranges from 9.3 to 15.0, with an average of 11.2.

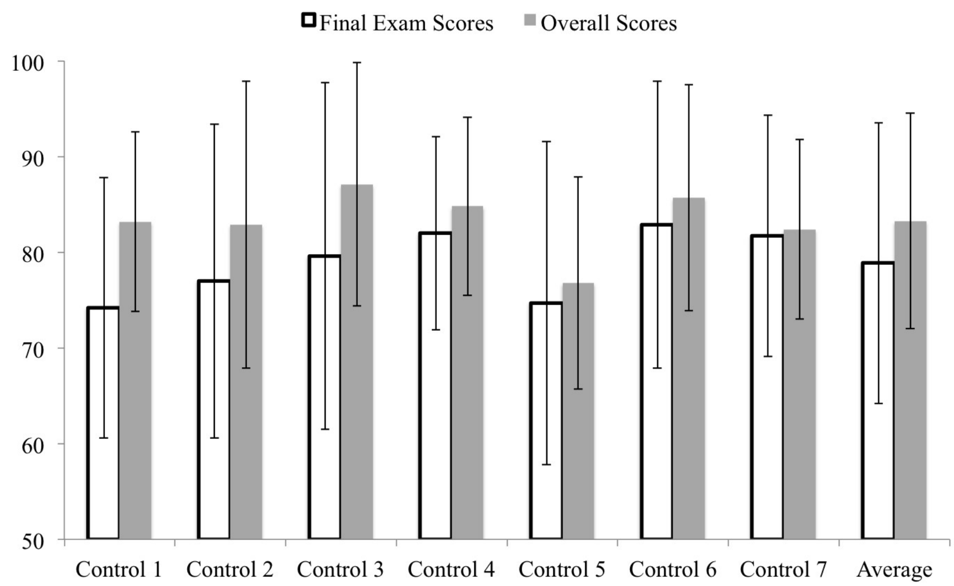

Figure 2. Performance Data from Seven Control Terms.

Before presenting the data from the project terms, whether the control terms and project terms can in fact be compared needs to be justified. Firstly, all classes involved were taught at ABET-accredited institutions. All seven control terms took place at Purdue University Calumet (PUC), and the three project terms at the University of Illinois at Chicago (UIC). Secondly, all terms shared the same learning goals and outcomes. Thirdly, as mentioned above, all courses were taught solely by the author, with similar instructional approach and style, even though the execution of techniques and delivery of content invariably differed. Fourthly, both control and project groups shared a similar student makeup including gender (ranging between 7:1 to 8:1 male-to-female ratio), class standing (all sophomores), and cultural and economic diversity (both PUC and UIC are located in or near Chicago, and both institutions share similar admissions criteria). Lastly, as shown in Figure 3, students from both control and project groups achieved similar overall end-of-term grades, indicating that the learning outcomes were consistently met. Calculation of overall scores were consistent among the control and project groups, where the final exam made up 20% of the overall score, quizzes 20%, regular tests 20% each (1-2 tests per term), and projects/homework 20-40%. The last two items (tests and projects/homework) differed between the control and project groups: The control terms had two tests (thus altogether weighing 40% of overall) and only 20% of projects/homework. In the project terms, the inclusion of this high-stake project necessitated a reduction of test weight, through elimination of one regular test. It is argued that, however, grading of projects was held at the same expectation as test grading, even though the rubrics were inevitably different.

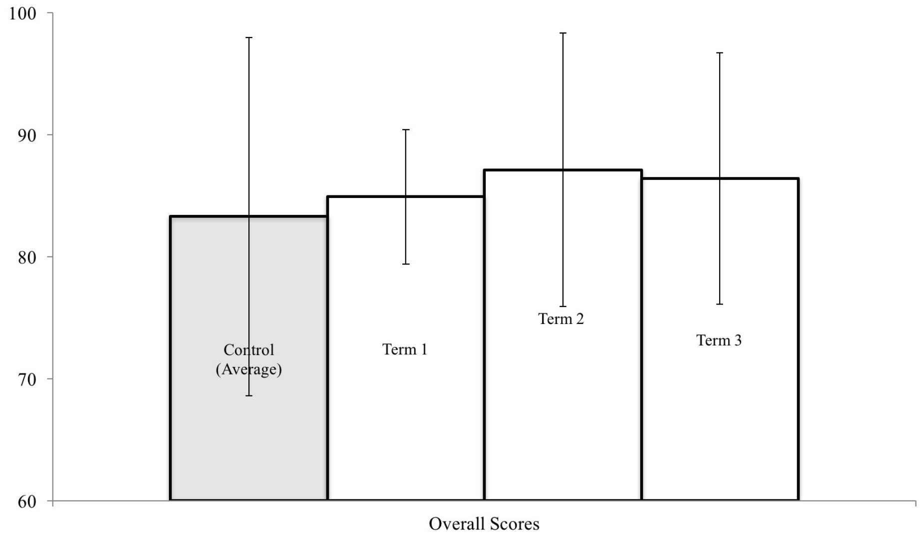

Figure 3. Overall Grades Between Control and Project Groups.

Final exam grades from control and project terms are now presented and compared, shown in Figure 4. Weighting of the final exam across all terms ranged between 20% and 25% of the overall grade, and all final exam papers shared similar characteristics, including duration (two hours), scope (comprehensive), and problem types (a mix of well-defined number-crunching questions and modeling problems). All exam papers were graded by the author alone, using identical grading rubrics.

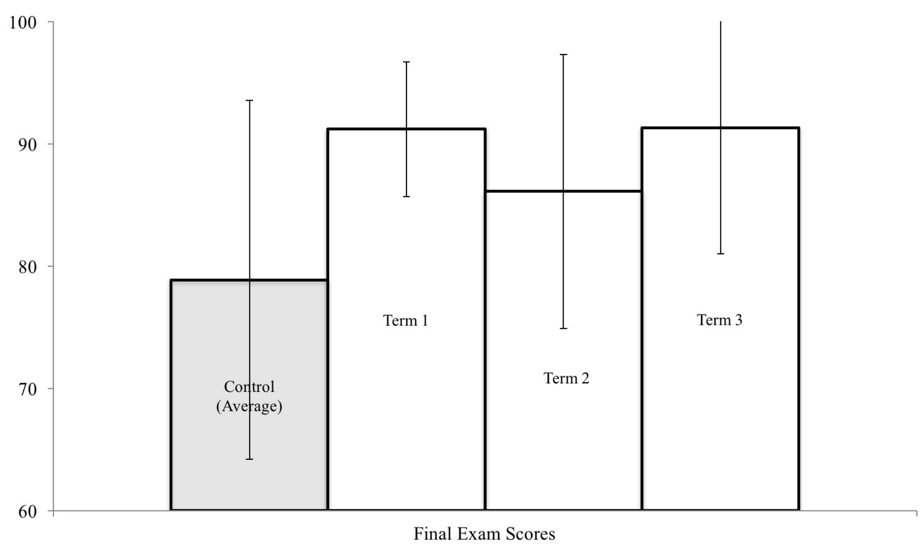

Figure 4. Student Performance in Final Exam: Control and Project Groups.

A consistent improvement over the control can clearly be seen in Figure 4. The average among the three project terms carries a 10.7 points improvement over the control, while the average standard deviation has shrunk by 5.7 compared to the control average.

Gibbs[20] studied the relationship between class size and student success in higher education, and concluded that adverse effect of large classes definitively exist. The larger the class, the lower the expected student performance. Figure 5 shows the enrollment numbers for all terms involved. An irrefutable difference can be seen, where the project terms have class sizes significantly higher than the control. The average control enrollment is 31 whereas the project terms are averaging 57. While no correlation models exist that can be adopted for the current study, qualitatively speaking the larger class size among the project terms further reinforce the positive impact of the project.

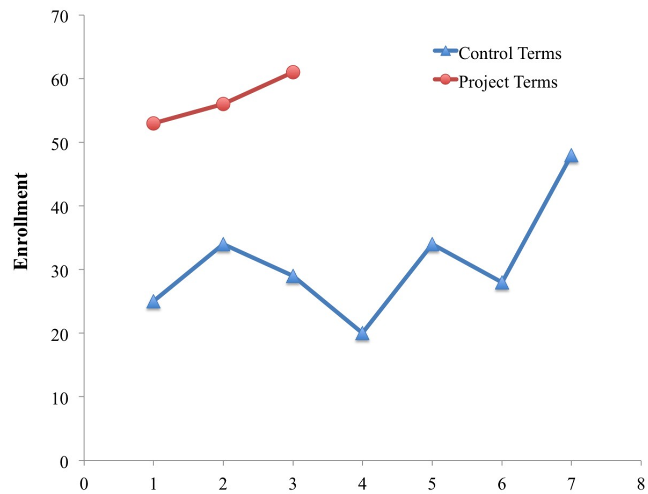

Figure 5. Enrollment Numbers: Control and Project Groups.

To a lesser extent, the project may be assessed using anecdotal evidence, including anonymous student comments in end-of-term evaluations as well as direct communications made in class or outside. A sample of anonymous comments includes:

> "Projects helped to understand the thermo equations better."
>
> "The projects made students actually think for themselves, and actually solve problems on their own."
>
> "Definitely the projects. The projects helped me better visualize and understand some concepts."
>
> "Projects and assignments relate to lecturing material."
>
> "I believe the projects were the reason I was able to understand the material better than doing homework. Professor [...] has been an absolute inspiration and a huge contributor to my interest in engineering. His teaching methods are invigorating, involved, and

incredibly thorough."

"Projects having more weight than [other] grades is another thing I really liked about Professor [...]; it makes sense... when would you ever be faced with a problem in real life where unlimited resources were not available. That's why doing projects is much more constructive, as I have the time and resources to ensure I receive a good grade."

"Most beneficial for me from his class were his projects. His projects take the learned material of the class and apply them to a real world problem/solution, which gave me a much better and well rounded understanding of the material."

"Projects and in-class problems were the most beneficial part of the class. Overall, very complex class, it is not an easy A or B. However, professor makes it easier that it is."

"Projects are time consuming but allowed me to apply equations and knowledge from class. Real world connections are made between the course material and everyday life, which helps me understand why the concepts we learn are important and useful. This allows me to feel confident while doing problems and to think through them rather than looking at a solution manual."

"Projects were helpful as they were more interesting than book problems. Projects also prevented the use of answer keys when stuck and forced me to think about it."

"Projects were very important. it allow students to interact more with the subjects, class. in some instance this was a interactive lecture."

Finally, during an office visit, a student from a project term reported successfully securing an engineering internship due largely to this project.

Reflection and Conclusion

A project to unify major topics has been implemented in an introductory thermodynamics course with success. The project is high-stake, highly relevant to everyday life, and tremendously rewarding for students and the instructor. While some students may complain about the extent of the project at first, with persistent encouragement and guidance from the instructor, students will come to the realization that the project has helped them connect the dots, obtain a deeper understanding of the material, and retain information for years to come.

As a greater effort to improve student learning, work is currently underway to (re)define success. Assessing student performance across a sequence of courses is being proposed. As soon as data becomes available, student from the project terms reported here will be re-evaluated by assessing their retention of knowledge in an intermediate-level thermodynamics course.

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