Session 2551

Developing students' reasoning with models and equations through Cequel™

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Abstract

Expert's tools can develop engineering students' ability to reason about complex systems (turbines, rockets, internal combustion engines etc) using thermodynamics principles. These energy conversion systems can be difficult to understand because of the complex interaction between multiple factors and the wide range of operating conditions. Building experiences for students to explore this complexity can be difficult with traditional instructional methods. Students typically apply their knowledge to textbook problems using paper and pencil to compute a system's performance for a single operating condition. This activity only provides a starting point for exploring the complexity of a system. We are exploring the potential of Cequel, a plug in for Excel, for constructing models to evaluate a systems' performance. An important part of this activity is the ability to construct a graph that illustrates the dynamic interaction between factors influencing the system's performance. We expect that students will understand how these graphs represent the governing equations of a system better compared to students who have not used Cequel as part of their thermodynamics course. In the Fall 2004 semester, Cequel was used to support homework assignments in a second level thermodynamics course. Assignments were presented as experiments that required constructing a model followed by explaining several "what if" scenarios based on that model. Students worked in small groups to build and evaluate the model, then wrote a report complete with a short essay describing the phenomena. Students' perceptions of these activities were measured using a survey completed at the end of the course. In addition, the standard course evaluation was used as to compare across years illustrate the value added of these activities compared with traditional homework assignments. Several observations were made of two groups during their homework sessions. These observations provide some insights into how students approached the activity and how that approach could affect the final outcomes of the small group activity. This paper describes the course materials designed around Cequel and put into a class package. Students found these learning activities challenging and valued them as important to their future as professional engineering students. Several students began to use Cequel as a general purpose tool, but not all students had sufficient experience constructing models with Cequel to have sufficient confidence to use it to verify their homework assignments.

Introduction

Thermodynamics is a complex domain that requires multi-variant analysis of abstract concepts to predict the behavior of a system. In addition, the interdependence between thermodynamic parameters is often non linear. Therefore, academics and engineers in industry who study complex systems, like gas turbine engines, internal combustion engines and rocket engines, construct computational models. They use these models to evaluate the system's performance over a range of operating conditions. This is especially important in evaluating various design alternatives for components in the system. Without modeling tools these professions would perform an endless amount of hand calculations to evaluate each design consideration. The ability to construct and critic models are the kinds of skills we would like our students to have by the end of a course in advanced thermodynamics. However, traditional homework assignments ask students to perform hand calculation for a specific set of boundary conditions. Time constraints can limit students' opportunity to solve a range of problems that illustrate subtle details of how thermodynamic principles describe the behavior of a system. We are leveraging this ideas of using tools to think with, or "cognitive tools", is an important process in evaluating the performance of a system. This same evaluation process can also be an excellent learning opportunity. Therefore, our hypothesis is that students could develop a more comprehensive understanding of thermodynamic properties and modeling if they were to use professional modeling tools to evaluate how thermodynamic parameters change for a wide range of boundary conditions.

Course Lectures, Homework and Design Project

We wanted to explore the potential of using an expert tool to increase students' ability to explain the interaction between thermodynamic properties and to critically evaluate a model's limit for predicting specific behaviors of a system. We selected a program called Cequel™ (Chemical Equilibrium in Excel®) as the primary modeling tool students would use to explore various thermodynamic cycles. Cequel™ "is an Excel® Add-In chemical combustion analysis tool for assessing the products of combustion under equilibrium conditions using the minimization of the Gibbs free energy. The NASA Lewis chemical equilibrium computer program is the underlying solver." [1] Vanderbilt University initiated a laptop program several years ago so that every student would have a similar laptop configuration. This year's cohort of students is the first to have these computers for the thermodynamics. The follow describes the redesign of the course and homework assignments to support the learning of thermodynamics using the Cequel code.

One of the course goals was to prepare students to complete a term project that compares various design changes to a turbine engine combustor. A variety of learning activities were used to prepare students for this experience. Traditional lectures were used to derive and explore the fundamental properties of thermodynamics. Table 1 illustrates the course outline used during this study. In prior years the order of the main topics were reversed (ie Module I and Module III were reversed). This version was chosen for a number of reasons: (1) momentum conservation is introduced at the start of the course, following review derivations of conservation of mass and energy; normal shocks are studied immediately after rocket performance at the design point is discussed; the Hugoniot curve and analysis results can be used as the basis for the introductory lecture on combustion in Module II; flame temperature solutions for chemical equilibrium in the burned gas are covered on the last test in the course, as in the unmodified course (see Table 1); in the revised course these flame temperature solutions with the second law allow use of fuel-air cycles for air-breathing engine modeling (Brayton, Otto and Diesel).

Weekly homework assignments consisted of two to three homework problems from the textbook. Some effort was made to select straightforward problems in order to minimize the time required for solution, but no effort was made to quantify any success in this approach.

In addition to these textbook problems, there were eight Classpak (Mellor et al., 2004) problems designed to use the Cequel modeling environment. One problem was assigned per week starting in Week 3. Generally the subject matter of the Classpak problems was limited to material already discussed in class or in the textbook, but there are deliberately designed a few parts of these problems that require students to stretch what they have learned (and thus anticipate material covered slightly later in the course). The semester project was handed out in the first lecture following Thanksgiving Break, and was due at the beginning of the last lecture in the next week, that is, the last week of classes.

The first two Classpak assignments (A1 and B1) were completed by individual students and require simple equations for speed of sound or pressure exerted by an ideal gas, both as functions of two variables. In the first assignment, two graphs of the solution were prepared, one for each independent variable. In the second assignment, a surface (three-dimensional) graph was prepared, showing in an isometric view the dependent variable as function of the two independent variables. In the final part of each problem the student is asked to write short essays explaining the graphs he or she has generated and how this information applies to a different situation. Similar problems are available for Mach number or thermal efficiency of an Otto cycle operating on a working fluid with constant specific heat.

The second set of ClassPak problems (C-F) involved more complex activities of comparing hand calculations with output of the Cequel model. Each assignment requires students to apply fundamental concepts presented in lecture such as flame temperature, shock, detonation, air/fuel ratio and products of combustion. The challenge for students is to compare and contrast the results of their hand calculations for a specific condition with the output of the Cequel code for a wider operating range. For example, Classpak assignment E1 is a structured problem that requires students to generate and graph a data set they must analyze.

> **E1. Flame Temperature -** (a) Perform hand solutions for adiabatic flame temperature (K) in a steady-flow device burning CH_4 with air. Model air as 21.01 volume percent O_2 with balance N_2. Assume all reactants enter at 298 K and 1 atm, and that the reaction goes to completion. Consider

equivalence ratios of 0.5, 1 and 2. (b) Using the Pressure-Enthalpy option in Cequel®, perform flame temperature calculations with the same reactants at the same conditions for equivalence ratios of 0.5, 0.7, 0.9, 1, 1.1, 1.3, 1.5, and 2. (c) Graph flame temperature versus equivalence ratio for your solutions to parts (a) and (b). (d) Explain the observation found in both sets of results that flame temperature is a maximum at approximately stoichiometric. (e) Explain why your hand solutions indicate higher flame temperatures at stoichiometric but nearly equal values if quite lean or rich. Include your spreadsheet and graph as part of your solution. (f) Which model do you consider more accurate and why?

These problems were designed to help students progressively refine their use of Cequel code and broaden their understanding of fundamental thermodynamic properties. The combination of these assignments should prepare students to perform well in their term project.

Design Teams

Students were organized into "design teams" to work on the second set of ClassPak problems (C-F). For these assignments the course instructor selected thirteen teams of four individual students and captains (in 2004, enrollment necessitated a fourteenth team of three students; team strength was not static, however, since four students dropped the course after teams were assigned[1]). To make up the teams, cumulative score on the first two Classpak problems was ranked, and the top fourteen students were designated captains. Adding the student with the lowest cumulative score to the team whose captain had the highest cumulative score then began forming teams; the other two members were those with scores closest to the median cumulative score. The intent was to generate teams with nearly the same average performance on the first two Classpak problems, and this goal was accomplished within about five percent. In addition, instructor team selection avoided the situation whereby students form their own teams and elect their own captains.

In the last two weeks of the course, the design teams were given actual performance data of a General Electric (GE) combustor designed to reduce emissions. The students were asked to use Cequel to evaluate the two models for evaluating the combustor design. The first was a Thermal Equilibrium model and the other was a Chemical balance model. Each team wrote a report explaining the difference between these models and made recommendations on how to improve the design of the combustor. Three of the groups gave a class presentation of their project.

[1] But one team was disbanded at Thanksgiving Break when a member came to the instructor and explained that since he was doing all of the work for the weekly team reports, he wanted to be reassigned. After contacting the appropriate captain for objections (there was no response whatsoever), each member of that team was placed on one of the teams who had lost a member to course dropping, since the original three-person team had requested no reinforcements on two occasions.

Table 1 – Course outline, Cequel Homework Schedule and Survey
*Indicates opportunity to introduce project using Cequel®.

Week	Module I – Compressible Flow		Homework
1	Introduction and Review	Conservation of mass, conservation of energy Conservation of momentum	Text 1,2
2	Isentropic Flow	Second law, state equations Sound speed	
3		One-dimensional isentropic flow *Converging-diverging nozzles	Text 2,4,ClassPak A1
4		*Rocket frozen flow specific impulse *Nozzles with shocks	Text 5,6, ClassPak B1
5	One-dimensional Waves	Mixture properties, free energies TEST 1	
6		Test review	
Module II – Combustion and Fuels			
6		Hugoniot equation and curve	Text 7,8, ClassPak C1
7	Energy and Mass Balances	*Shocks, sound waves, detonations, and deflagrations Combustion	Text 9, 10, ClassPak D2
8		Stoichiometry Enthalpy of reaction	Text, 11,12,13
9	Chemical Equilibrium	*Adiabatic flame temperature Second law	Text, 14, 15, 16, ClassPak E1
10		*Equilibrium constant TEST 2	
11		Test review	
Module III – Energy Conversion and Control			
11		*Adiabatic flame temperature	
12	Gas Power Cycles	*Brayton cycle Reheating, intercooling and regeneration	ClassPak F1
13		*Diesel/Otto cycles Air pollution	ClassPak F2 – Benefits Survey
14		Power generation Project presentations	Course Eval. Student Pres.
Exam Week		TEST 3	

Methods

This study evaluated the use of an expert tool, Cequel, as an instructional tool to increase students' ability to explain thermodynamic relationships and model thermodynamic systems. The study was conducted in a third year Thermodynamics II course in Mechanical Engineering. Fifty-one students were registered for this course that meets 2 times a week for one hour and fifteen minutes over a 13-week semester. The comparison is a within subjects design to evaluate the increase in a group's performance on their project reports and a student questionnaire evaluating their perception of the benefits of the assignments.

Students completed the series of ClassPak assignments, described in the previous section (see Table 1) over the last two thirds of the course. The first three assignments (A-C) were basic exercises to orient students to Excel's functions and the general features of Cequel. Each student completed assignment (A-C) independently. The last assignments (D-F) have students' compare and contrast their hand calculations with the results from the Cequel model.

Each week the groups submitted a short report consisting of their output from Cequel, their hand computations and their responses to the essay question. The instructor scored these assignments and returned them to the students.

A short questionnaire, called a Benefits Questionnaire, was designed to capture students' perceptions of the ClassPak assignments which use Cequel as a tool. The first part of the survey asked students to rate their agreement to various statements about the ClassPak assignment. They were given a 5 point Lykert scale were 1 = strongly disagree and 5 = strongly agree. Each statement targets one of four major outcomes for this study. Table 2 summarizes these statements relative to specific outcome.

Students were also asked to rate how valuable the ClassPak experience is relative to what they anticipate doing after graduation, how well the feedback on the assignment helped them and their perception of how good they are in this class (1=poor 5=excellent)

A qualitative section of the survey asked students to answer these questions –

1. What was worthwhile for you about the Cequel Program and the ClassPak Assignments?
2. What was not worthwhile for you about the Cequel Program and the ClassPak?
3. What did your team captain do to optimize the performance of your group?
4. If you were team captain, then what would you have done differently to improve the performance of your group? (If you were a team captain, then answer what would you do differently to improve your team's performance.)
5. Please provide any additional comments on how the ClassPak assignments could be used more effectively in this class.

For this study we only report on questions 1 and 2.

Table 2. – Categorization of Questionnaire Items based by desired outcome

Outcome	Statement to be rated by the students
1. Thermodynamic Knowledge - Exploring wider range of interactions between factors (temperature, pressure, enthalpy, entropy).	7. I feel confident that I can explain the interaction between thermodynamics principles applied to rocket and engine performance problems. 8. I feel confident I can use graphs of thermodynamic parameters to analyze and predict the performance of rocket and engine system.
2. Explore the benefits and limits of models	1. Each Classpak assignments has further increase my ability to model complex systems 6. I know much more now about to use models of thermodynamics systems than I did prior to the course. 9. I have become more critical of how to use models to solve engineering problems after completing the ClassPak assignments.
Cequel as a tool - Will use Cequel to verifying hand calculations with model	4. By the end of the course I use Cequel to help me work on the book problems. 10. I feel confident in my understanding of Cequel to know how to use it to double check my hand calculations. 5. I feel confident that I can use Cequel to perform basic thermodynamic computations
Progressive refinement - Sequence of activities leads builds toward progressive refinement	5. I feel confident that I can use Cequel to perform basic thermodynamic computations 2. The Classpak assignments have prepared me well for the Semester Project. 3. I think writing the essays question became easier with each new Classpak assignment.

In the last two weeks in the course the students received the description of the term project related to analyzing various models for evaluating the performance of a GE combustor using two different models of the system. The instructor handed out the assignment and answered questions. The class period after that session students completed the Benefits Questionnaire.

Three teams were selected to give class presentations of their design project. Teams were selected based on their overall performance on the other assignments (C-F). One group was selected from high, medium and low achieving groups.

Finally, the ClassPak assignments are major addition to the homework assignments used in prior years. Therefore, the standard course evaluation form (from the college of engineering) was used to indicate the value added by these new assignments compared with prior years.

Results

Thirty seven students completed the Benefits Survey administered near the end of the semester. Figure 1 summarizes the average scores students gave for each of the major outcome categories. The standard error bars provide an indictor of how far from a neutral answer the class responded to a specific category of questions. Three of the four categories were in the agree range of the scale. The forth category, Cequel as a tool, was still within the neutral area. This indicates a split decision in the class with slightly more students disagreeing with the idea that Cequel has become a tool they would use regularly. The qualitative questions and observations of the groups provide some indications for why this might be the case.

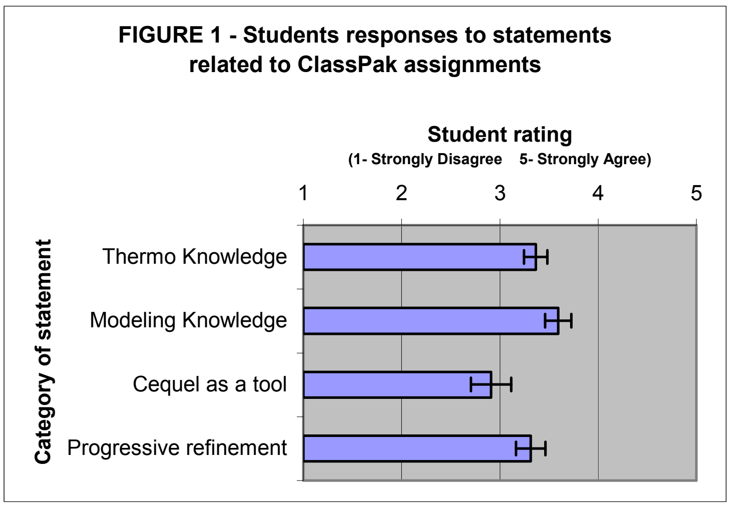
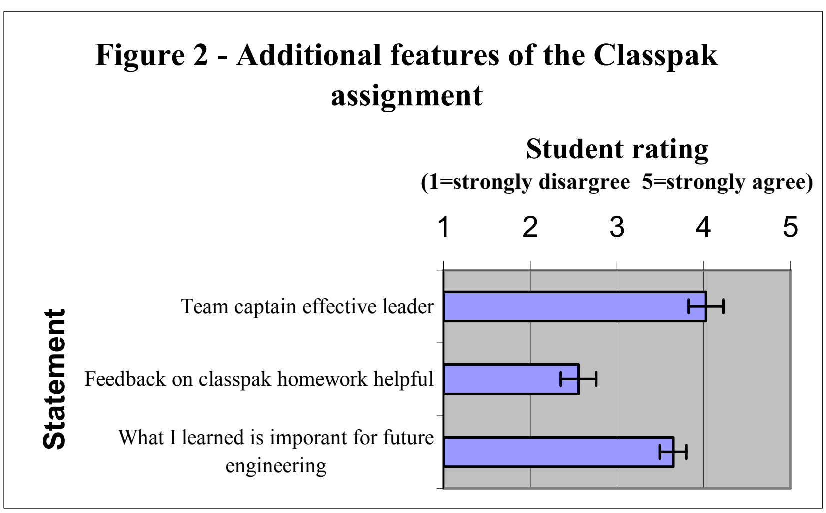
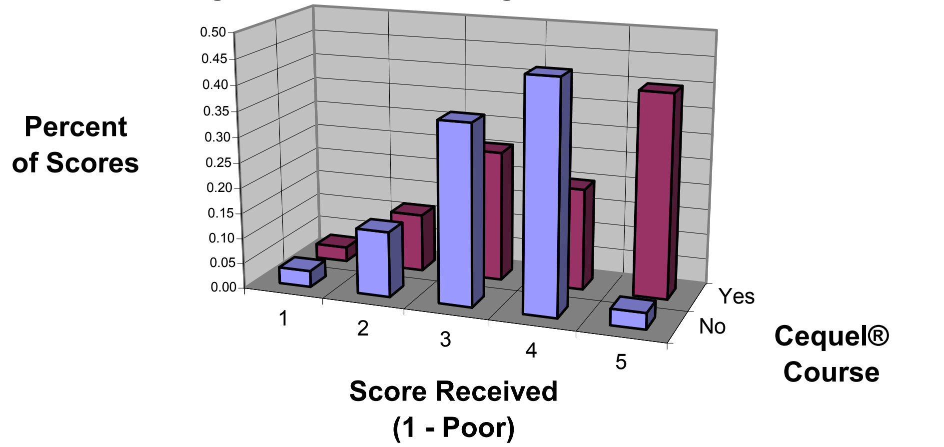


Figure 2 summarizes students' responses to the usefulness of this assignment in the future, the utility of the feedback and an estimate of how good they are in the class.



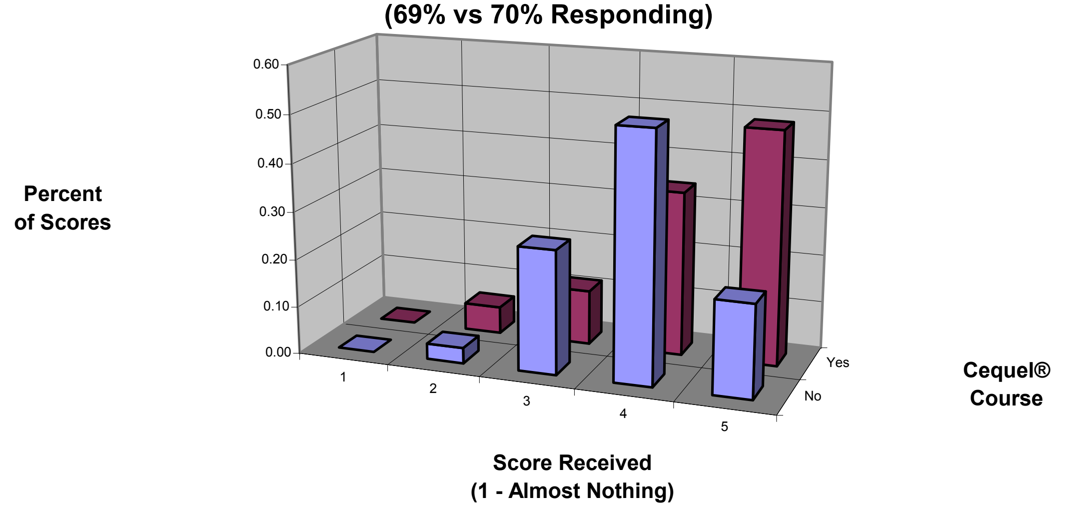
The addition of the Cequel assignments should affect students' abilities to apply their knowledge to interesting real world problems. The shift in knowledge could influence their interest in the course and how challenging the course is compared to prior years. Therefore, we compared the course evaluation results for a course using Cequel and a course from the prior year that did not use the Cequel assignments. Figure 3 illustrates students increase in how well the course stimulated their interest compared to prior years. Other categories with a similar upward trend include intellectual challenge, overall instructor rating and overall course rating.

Figure 3 - Q3. Stimulating Interest



Finally, Figure 4 shows a positive shift in students' ratings of how much they learned in this course compared to prior years.

Figure 4 - Q7. Amount Learned in the Course
(69% vs 70% Responding)



Discussion

The ClassPak assignments using Cequel as the primary analysis tool increased students' confidence to apply thermodynamic properties to solve problems and their confidence to use models to analyze a system. The majority of students agree that after doing these assignments they feel confident they can explain how to use thermodynamic properties to solve various rocket and engine problems. In addition, they are comfortable with using graphs and charts as tools to solve these problems. Also, the Cequel assignments increase students' awareness of how to use models to analyze complex systems and how to be more critical of how models are used.

The results of the course evaluations provide an additional indicator that students are engaging in an intellectual challenge that students may not have experienced in prior offerings of this course. The ClassPak represents the only major change in the course. All the lecture materials are similar to prior years. The ClassPak activities raised the students' expectation of the course requirements, which they may perceive as an intellectual challenge. This is indicated by an increase in percents of scores for both the course requirements and the intellectual challenge ratings this year compared to a prior years. In addition, figure 3 illustrates how students' interest is stimulated more compared to prior years. Therefore, the Classpak assignments engage students in activities that require them to use their thermodynamic knowledge in a way that is more challenging than textbook problems and lecture only.

We anticipated that students would begin to use Cequel as a general tool after using it for the ClassPak Assignments. We had hoped that students might start using Cequel to verify their homework. In fact, on the last textbook homework assignments 6 students generate graphs in Cequel to assist them in their analysis of the textbook problems. However, the survey results indicate the majority of students do not agree that they use Cequel as a tool to verify their work. Several reasons could explain this result. First, most of the difficult assignments using Cequel were done as a group. Our observation of several groups indicated that a divide and conquer approach was used for the assignment. Therefore, one or two students in a group would become the groups' expert at using Cequel. These students would explain their approach to the group, but did not necessarily provide the details of how they achieved the particular results. Therefore, not all the students became familiar enough with Cequel to make is part of their normal routine. Students' comments also highlighted that they are still uncertain about how Cequel models a system. They understand that the Cequel model includes more parameters in its computation compared with their hand calculations. They see the model as a black box and fear that they are unaware of what else is being considered, therefore, they are not comfortable trusting it to verify their homework.

Students report that the sequence of ClassPak Assignments did prepare them for the final design project they completed in the last week of the course. We wanted to construct experiences for students to continually build their learning through quasi-repetitive steps where they revisited fundamental thermodynamic principles to perform complex analysis and design tasks. As a result they were ready for the final challenge of designing a turbine engine combustor to meet specific design requirements.

In general the materials met our expectations, but refinements could be made to enhance the learning for all students. First, students requested additional assistance up front on how to use the Cequel program. Many students were not aware that on line documentation was available in the Cequel program. Others indicated that they were uncertain about some of the nomenclature used in this expert tool. Therefore, one option is to construct several simple tutorials that students could use to learn about the program. Most students eventually figured out how to use the interface, but using simple online tutorials could reduce this learning time. Reducing the threshold for learning to use this tool may invite a number of students in a group to become more expert at using the tool.

Finally, additional research needs to be done to explore how changes in students learning of thermodynamics compared to prior implementation of the course that did not use Cequel. Think aloud protocols are planned to assess students' ability to use graphical representations to predict system performance in several "what if" scenarios. Also, students from last year's class, who didn't use the program, will participate in a similar protocol. We anticipate that students using Cequel program will be better prepared to reason about "what if" situations.

Acknowledgements

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References

[1] CEQUEL - Chemical Equilibrium in Excel® - http://www.seainc.com/cequel.d.html

Biographies

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