AC 2012-5004: MATERIAL AND ENERGY BALANCES TAUGHT IN A MULTIDISCIPLINARY COURSE

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Material and Energy Balances Taught in a Multidisciplinary Course

Abstract

This paper will describe the challenges and rewards associated with introducing Chemical Engineering students to material and energy balance concepts using an accounting principles approach in a multidisciplinary course. All engineering students (Chemical, Civil, Electrical, Computer, Fire Protection, and Mechanical Engineering) take a sophomore engineering course, Introduction to Modeling of Engineering Systems, which includes topics drawn from electric circuits, mass and energy balances and force balances. The course is designed to help students develop an organized approach to solving problems and uses a conservation and accounting approach to provide a broad framework for the diverse topics. The paper will consider the common challenges associated with the first major course in any engineering discipline, particularly focusing on common stumbling blocks.

There are some significant challenges with using the multidisciplinary approach to material and energy balances. One of the primary challenges is that it is difficult to include reactive systems with coverage limited to areas of common interest, such as combustion reactions and fuel cell reactions. Students often appear to be resistant to materials that they perceive as being outside of their declared major area of study.

For the Chemical Engineering student, the challenges are balanced with a broader exposure to other balances not typically seen in the major courses. Using the accounting principles approach, the students explore force balances (such as structures) and charge balances (circuits) in addition to the typical mass and energy balances. The approach taken in this course applies the recurring themes of flows into and out of a system and generation and accumulation within a system for a wide variety of properties. This broader exposure should help to limit the compartmentalization of information that is typical of engineering students.

Within the context of this course two questions will be considered. First, does the chemical engineering student learn material and energy balances as well as in a traditional M&E course. Of course, the students in this curriculum take a follow-up course in the major the following semester to build on the background.
Second, does the significant focus on force balances, linear momentum, and energy better prepare the chemical engineering student for subsequent transport phenomena courses.

Introduction

In typical chemical engineering curricula, the sophomore year includes one or two courses which focus on the fundamental concepts needed for further study in chemical engineering. This is often a two semester sequence of courses that focus on mass and energy balances or a single mass and energy balance course plus a thermodynamics course. At the University of New Haven all engineering students take a sequence of common, multidisciplinary engineering courses in the freshman and sophomore years before developing depth in their chosen discipline. The details of this integrated curriculum have been discussed in previous publications[1,2]. In this integrated curriculum, the topics of mass and energy balances are introduced in a multidisciplinary course, EAS211 Introduction to Modeling of Engineering Systems, which also applies the balance approach to momentum (including force balances) and electric charge. This paper considers the important question: does a multidisciplinary approach to the fundamental topics adequately prepare students to succeed in upper level chemical engineering courses? In addition, the paper discusses the idea of introducing mass balances to students in disciplines outside of chemical engineering,

Prior to the class entering in 2004, chemical engineering students at the University of New Haven took a 2-semester sequence in their sophomore year to learn the basics of material and energy balances. This pair of courses, Fundamentals of Chemical Engineering I and II (CM201 and CM202) followed a traditional approach with topics aligned with the popular textbook by Felder and Rousseau[3]. In the new multidisciplinary approach, students first take a broad course based on the conservation and accounting approach applied to mass, energy, charge and momentum (EAS211). Chemical engineering students follow this with a course that applies mass and energy balances to more complex systems of particular interest to chemical engineers (CM220 – Process Analysis). The table below provides a comparison of the sophomore courses in the old and new curriculum:

Table 1 – comparison of multidisciplinary curriculum to traditional curriculum

	Old Curriculum		New Curriculum	
Sophomore Year, Fall semester	**CM201 Fundamentals of Chemical Engineering I**	Process variables, basic mass balances, ideal and non-ideal gas models	**EAS211 Introduction to Modeling of Engineering Systems**	Introduction to mass, momentum, energy and charge balances
	Engineering Elective – choice of engineering course other than chemical	Choice of statics, strength of materials, material science	EAS213 Materials in Engineering Systems	Property estimation for gases, liquids and solids
Sophomore Year, Spring Semester	**CM202 Fundamentals of Chemical Engineering II**	Simple phase equilibrium, energy balances	**CM220 Process Analysis**	More advanced topics in mass & energy balances, simple phase equilibrium
	EE201 Basic Circuit Analysis	Traditional circuit analysis topics	EAS224 Fluid-Thermal systems	Thermo, heat transfer, fluid mechanics
Junior Year, Fall Semester	CM301 Transport Phenomena Analysis	Fluid mechanics, heat transfer, intro to mass transfer	EAS 230 Fundamentals of Analog Devices	Electrical circuits, signals and related topics
	CM 321 Reaction Kinetics & Reactor Design	Chemical kinetics and design of chemical reactors	CM 321 Reaction Kinetics & Reactor Design	Chemical kinetics and design of chemical reactors
	CM310 Transport Operations I (taken in spring of Jr year)	Analysis & design of fluid processing and heat transfer equipment	CM315 Transport Operations I (taken in Fall of Jr year)	Analysis & design of fluid processing and heat transfer equipment

The interface between the multidisciplinary engineering foundation courses (EAS prefix) and the chemical engineering courses occurs in the spring of the sophomore and fall of the junior years. As shown in Table 1, the chemical engineering reactor design course, CM321, is taken at the same point in the old and new curriculum (fall of year 3). Thus it provides a good point for comparison of the new to the old curriculum. The transport operations I course (CM315) is the first chemical engineering course in transport (unit) operations in the new curriculum. It has been slightly modified to reflect the different sequence of courses, but covers much of the same material as the older version (CM310). It can also provide a point of comparison for the curriculum model, however it builds on content in EAS224 as well as EAS211.

Introduction to Modeling of Engineering Systems (EAS211) includes students from all engineering majors: chemical, civil, computer, electrical, fire protection, mechanical and system. The depth of study of mass and energy balances is limited due to time considerations and issues of relevance to the audience. Topics are chosen to be of broad interest across the various disciplines, for example combustion reactions and fuel cells. Complexities such as systems with multiple reactions or recycle are avoided in this course, primarily due to the limited time allowed for coverage of material balances. Chemical engineering students study these topics in the first chemical engineering course (CM220) taken in the following semester. By the end of the sophomore year, chemical engineering students are expected to reach the same level of understanding of mass and energy balances as they achieved under the old curriculum. In the new curriculum, they will have seen these concepts applied in a wider variety of circumstances due to the multidisciplinary nature of the EAS courses.

EAS211 – Introduction to Modeling of Engineering Systems – Using a Conservation and Accounting Approach to Develop Models

The goal of EAS211 is to help students develop an organized approach to solving engineering problems from a variety of disciplines, including the development of a phenomenological approach. A basic tenet of the course is that all engineering students should understand the basics of the major areas of engineering study, including many of the topics found in the Fundamentals of Engineering Exam[4]. Introducing these topics in a multidisciplinary course provides an opportunity to emphasize the complexity of real situations which generally require analysis from more than one topical area. For example, modeling the behavior of a fuel cell requires consideration of both mass and charge balances. One expected outcome of this approach is that students will recognize and will be better prepared to deal with the more complex mixture of phenomena found in realistic problems. In other words, it is an attempt to reduce the degree of topical compartmentalization that engineering curricula tend to foster.

A unifying theme for EAS211 is the use of conservation and accounting principles to develop the basic equations which describe various physical systems. The general accounting equation can be applied to any extensive quantity, and takes the form:

$$\{\text{Input}\} - \{\text{Output}\} + \{\text{Generation}\} - \{\text{Consumption}\} = \{\text{Accumulation}\}$$

For quantities which are conserved, such as total mass (excluding nuclear reactions), the generation and consumption terms drop out. If mass is aggregated in terms of moles, generation and consumption terms are used to account for the effect of chemical reactions. Thus the general accounting approach can be applied to mass (total mass, mass or moles of a specific compound, atoms), energy, momentum (linear and angular) and electric charge. The equation may be written in rate form or integral form (for a specific period of time). This approach makes it possible to introduce time-varying situations very early in the course and to allow students to apply calculus in the solution of simple problems.

Consider one simple example used in the first week of the class: the case of a boat with water leaking into it. This example provides a familiar, visual application of this method. Students can readily develop the equation to track the amount of water accumulated in the boat and set up numerical or analytical solutions. For many, it is one of the first practical applications they have seen of differential calculus in an engineering class. The situation can be made more complex by adding a pump to remove water at a rate that varies with the amount on board. Thus students discover the physical meaning of a differential equation before actually studying this topic in a math class. Perhaps some will find inspiration to motivate their study of math from such engineering examples. A detailed description of EAS211 may be found in a previous publication[5].

The idea of using the conservation and accounting approach for teaching mass and energy balances is familiar to chemical engineers. Extending this approach to include other quantities (charge, momentum) has been done before, beginning with the work of the Foundation Coalition[6]. Similar courses may be found at a number of other institutions, including Texas A & M[7] and Rose-Hulman Institute of Technology[8,9,10]. Although the authors have not done an exhaustive search, it appears that current implementations at other institutions focus on students in a specific discipline. At present, there are relatively few textbooks available for a sophomore-level course of this nature. Perhaps the best known is the text *Conservation Principles and the Structure of Engineering*[11], by Glover, et. al. of Texas A & M. This was developed and used by engineering programs in the Foundation Coalition. Students in mechanical engineering at Rose-Hulman Institute of Technology use a manuscript developed by Don Richards[12]. A relatively new text, "Bioengineering Fundamentals" by Saterbak, et. al[13,14], has been published for use in biomedical engineering programs. We have adopted this book for use in EAS211. Although much of the content, examples and homework problems have a biological emphasis, the presentation of the basic concepts aligns well with the philosophy of EAS211.

It should be clearly understood that EAS211 is intended to provide an introduction to each of the topical areas, with further understanding developed in courses which follow. For example, after EAS211 chemical engineering students take a course which focuses on mass and energy balances (CM220 Process Analysis) as well as a course that focuses on thermodynamics and mechanical energy balances (EAS224 Thermal-Fluid Systems) in their sophomore year. These are followed by more traditional chemical engineering courses in the junior and senior years.

The outcomes listed for EAS211 are stated as follows:
Upon completion of the course, students should be able to:

- *Apply the balance principle in the solution of simple engineering problems.*
- *Develop models by applying the balance principle and selecting the appropriate empirical relationships.*

- *Given a set of problems from different areas, explain the similarities and differences in solution methods and underlying concepts*
- *Apply the modeling process in the solution of engineering problems*
- *Model engineering systems using fundamental principles:*
    - *Mass balances applied to systems with changes in composition and quantity*
    - *KVL and KCL applied to circuits including resistance and capacitance.*
    - *Linear and angular momentum and force balances applied to static and dynamic systems of solids and fluids*
    - *Energy balances applied to systems with changes in thermodynamic and other relevant properties*

The sequence of topics in the most recent offering of EAS211, Introduction to Modeling of Engineering Systems, is as follows:

Table 2 – Summary of Topics in EAS211 Introduction to Modeling of Engineering Systems

weeks	Topic	Details
1, 2	Introduction / Problem-Solving	Course Introduction, Review of Engineering Calculations, Problem-Solving Strategy, The Conservation and Balance Principles
3 - 5	Mass Balances	Integral & Differential Mass Balances on Single & Multi-component Systems Mass Balances: concentration variables, mixing, Multi-unit systems, Mass Balances with reactions, Batteries and electrochemical reactions, Transient Mass Balances
6 - 8	Charge Balances	Analysis of resistive circuits using KVL/KCL, power, Independent/Sources Models for real sources, Capacitance, RC Circuits (first order circuits)
9 - 11	Energy Balances	Forms of energy (kinetic, potential, internal), heat and work, conservation equations, closed and open systems, mechanical & thermal energy equations, analysis of the energy changes in solid, liquid and gas systems undergoing changes, Dynamic Systems, Fluid dynamics, velocity profile, flow in pipes, flow regime, friction factor
12 - 14	Force and Momentum Balances	Conservation of linear momentum, stress, strain, Conservation of angular momentum Rigid body statics, distributed loads, analysis of trusses, Pressure due to static fluid, force on submerged objects, Open systems, Transient systems

Approximately half of the course topics map to the sequence found in a traditional chemical engineering mass and energy balance course. A table is attached to this paper to show the detailed list of topics in the current sophomore courses (EAS211 and CM220) in comparison to the topics included in the previous version of the curriculum (CM201 and CM202 Fundamentals of Chemical Engineering I and II).

The authors feel that the pace of any introductory, sophomore level engineering course is set by students' development of problem-solving skills, rather than mastery of the particular principles involved. For example, in a traditional statics course students struggle with the development of an appropriate diagram, application of force balances and using the math they have learned to solve sets of equations. While the concepts involved are also challenging, it seems that the slow step in the development for many students is the willingness and ability to adopt an organized approach (the methodology of problem-solving) as needed for the more complex problems encountered in engineering. It is difficult to give up the expectation that the task would be simplified by just finding the right equation. In discussing the difficulty of chemical engineering students mastering mass balances, Ollis points out the need for students to translate information from verbal to visual to analytical forms[15]. Precisely this same translation is required for introductory courses in statics (momentum balances), circuits (charge balance) and thermodynamics (energy balance). The approach used in EAS211 provides a lot of opportunity to develop such skills across a wide range of problems.

Challenges of a Multidisciplinary Audience

A number of challenges have emerged in teaching EAS211. Some of these are common difficulties for sophomore level engineering courses, such as convincing students to use an organized problem-solving approach which begins with an understanding of the situation rather than a search for the right equation. Many students resist the idea of drawing a diagram as a means of organizing information and understanding the problem. Still more students have difficulty defining unknowns – selecting symbols to represent one unique quantity and using units with these symbols as they would with number. For almost all students, an engineering course at this point is the first encounter with a problem whose solution cannot be visualized before beginning to solve it. The complexity of multistep solutions can render good students "clueless" during the initial weeks of the class. It is also difficult for many students to understand that they need to actually use the material they learned for the exams in chemistry, math and physics. Students need to recall and use basic conversions and to implicitly know that mass flow = average velocity * area * density. We believe, however, that these issues emerge in any of the sophomore-level disciplinary courses as well.

For students to be willing to commit the considerable time and effort to master new skills and content, they must be convinced of the relevance of the content of the course. In the first few years of teaching EAS211, the instructors assumed that the students understood why they were taking the class and spent little time explaining the rationale. They did, however, attempt to highlight examples from many disciplinary areas when teaching the course. In more recent offerings, we have taken more time to discuss the relevance of the course to each of the disciplines represented in the class. Some students still remain unconvinced and will indicate their displeasure on end of course surveys. One example is a civil engineering student who complained that he didn't see the relevance of anything in the class, because all he wants to do is design earthquake-proof buildings. Despite a few students who fail to see the relevance, the majority seem to accept that this course is needed. When asked to respond to the statement "This course is relevant to my career", 85% of respondents chose "agree" or "strongly agree" (choices 4 and 5 on a 5 point scale) in fall 2010, up from 75% in fall 2009.

Many of the students in engineering have a dislike for chemistry, in some cases a very strong dislike. Generally such students are not attracted to chemical engineering, but we see many such students in other majors. In response to this, the scope of coverage of some mass balance topics has been selected to focus on situations which are of broader interest. For example, separation problems selected for the course included water desalination, food processing and hydrogen recovery for fuel cells. Reaction systems discussed were primarily combustion reactions and electrochemical reactions found in batteries or fuel cells. In order to minimize complexity, most reaction problems involved a single reaction. While this avoids some of the more complex issues, it does leave an issue unaddressed in EAS211, which the chemical engineering students can tackle in the follow-up course. In the earlier offering of EAS211, we included combustion problems which produced both CO and CO_2. A common mistake for many students was to write a single stoichiometric equation with both products rather than two independent equations. It is important to include this topic in the follow-up course to make sure chemical engineering students can properly handle situations with multiple reaction products.

Another topic of importance to chemical engineers that is not covered in EAS211 is the concept of recycle and purge. Students typically struggle with this in a traditional mass and energy balance class. This complex topic is included in the follow-up course (CM220).

Assessment – Do Chemical Engineering Students Learn Mass & Energy Balances?

One of the outcomes for EAS211 is directly related to the application of mass balances:

- Model engineering systems using fundamental principles:
    - Mass balances applied to systems with changes in composition and quantity

This outcome was assessed in 2010 across 4 sections of EAS211, about 90 students taught by 3 instructors. The metrics used included specific problems on quizzes (early part of semester) and questions and problems involving mass balances on the final exam. In light of the fact that the metric was from time-pressure exam situations, the acceptable performance level was set at 65%. Using this metric, 84% of students met the requirement. The averages for each class ranged from 55 to 93%. This data is for students from all majors; chemical engineering students make up about 10% of the total. For comparison, the table below shows similar assessment data for the other areas covered in the class.

Table 3 Percent of Students Meeting Target for Fundamental Principles in Each Area

Mass Balance	Electric Charge Balance	Momentum Balance	Energy Balance
84%	97%	96%	83%

Since this data is for students from all majors, another assessment is needed to determine in particular if chemical engineering students are well-served by EAS211. Since these students take a follow-up class (CM220 Process Analysis) which focuses on mass and energy balances, we can use results from the final exam in CM220. The obvious problem with this approach is that it is not a direct measurement of EAS211, but a combination of EAS211 and the disciplinary course CM220. However, the important issue is whether the curriculum prepares students to apply mass and energy balances in subsequent courses. If we consider that the new approach of EAS211 and CM220 replaced a two-course sequence (CM201 and CM202, discussed earlier), then a useful metric is to compare students at the end of the second course in the new curriculum to students at the end of the second course in the old curriculum.

Data in the table below shows average final exam grades from CM220 (new curriculum) in 2009 and 2010 to final exam grades in CM202 in 2004 and 2005. The last offering of CM202 was in the spring of 2005. The most recent offering of CM220 for which data is readily available is 2010.

Table 4 Comparison of the means for final exams in CM202 with CM220

	Number of students	Average on Final Exam	T-Test statistic (p)
CM220, (new curriculum)	21	73.7	0.37
CM202, (old curriculum)	16	71.9	

There is not a statistically significant difference between the mean of students' final exams for the new version compared to the old version of the curriculum.

The new curriculum is intended to prepare students for junior level chemical engineering courses which are essentially the same as those in the old curriculum. Thus a useful assessment measure is a comparison of students' grades in the first set of junior level courses. The junior course CM321 Reaction Kinetics and Reactor Design, draws heavily on the students' understanding of mass and energy balances as applied to reacting systems. Results are shown below for student performance in CM321:

Table 5 - Average final grades in CM321 Reaction Kinetics and Reactor Design

	Number of students	Average Grade	T-Test statistic (p)
Students in New Curriculum	22	2.98	0.99
Students in Old Curriculum	24	2.98	

The average grade is no different for students experiencing the multidisciplinary approach compared to students in the traditional approach. It appears that students are as well prepared to apply mass and energy balances in junior level chemical engineering classes as they have been in the past.

The instructor teaching CM321 was asked to compare students from the older curriculum to the current students in terms of 1) their ability to apply mass and energy balances, 2) their ability to handle complex problems and 3) their analytical capability. This faculty member reported that he has observed no significant change in students' ability to handle complex problems or their general computational ability, but has observed that they appear to be somewhat better in their understanding of mass and energy balances.

Assessing their ability to perform in transport phenomena is more complicated, as the sequences of courses are more varied. However, a common point for comparison is our course CM315 Transport Operations I (number was CM310 in older curriculum). This course focuses on analysis and design of equipment for fluid processing (momentum transfer) and heat transfer, with an introduction to mass transfer. In the old curriculum it was taken in the spring of the junior year; in the new curriculum it appears in the fall of that year. As seen in Table 1, both the old and new curriculum had an additional course introducing these topics prior to the Transport Operations I class: CM301 Transport Phenomena Analysis in the old curriculum and EAS224 Fluid Thermal Systems in the new curriculum. Thus the grades in the Transport Operations I course is a reflection of preparation from several courses, not just the ones of interest in this paper. Nonetheless, the results are of interest:

Table 6 - Average final grades in CM315 (CM310) Transport Operations I

	Number of students	Average Grade	T-Test statistic (p)
Students in New Curriculum	19	3.08	0.94
Students in Old Curriculum	20	3.06	

The average grades in Transport Operations I is essentially the same for students under the new curriculum as those in the old curriculum. It appears that the new approach adequately prepares students for the study of transport concepts.

Conclusion

Faculty at the University of New Haven have implemented a multidisciplinary engineering core which includes a first semester sophomore course that provides background in mass, energy, electric charge and momentum balances. This course, along with a follow-up chemical engineering course, provides the foundation in mass and energy balances needed by chemical engineering students. The new approach has the advantage of giving students a broader view of the modeling process to include the fact that realistic problems are multi-facetted. It allows for the introduction of transient problems at an earlier stage than is typically found in traditional mass and energy balance courses. The multidisciplinary approach highlights the fact that the mathematical models for systems from disparate areas are surprisingly similar. It also allows students to focus on developing strong problem-solving skills, by applying the methodology to analysis of problems from different areas, before dealing with the issues encountered in more complex mass and energy balance problems (eg, recycle, multiple reactions). It should be noted, however, that the first course (EAS211) alone would not provide the level of mastery of mass balances needed for chemical engineering students. The follow up course, CM220, is needed for this population. Thus the assessment includes both courses.

Available assessment data suggests that students are at least as well-prepared to apply mass and energy balances by the new approach as they were under the previous curriculum. Performance in subsequent chemical engineering courses that require mastery of mass and energy balances is the same for students experiencing the multidisciplinary approach as it was for students in the traditional curriculum. Student performance in junior level transport operations classes also appears to be very similar for the current approach in comparison to the previous approach.

In general it can be concluded that the multidisciplinary approach used in the sophomore year, combined with a single chemical engineering sophomore course, prepares students for the study of chemical engineering as well as the traditional sophomore chemical engineering fundamentals two course sequence.

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Comparison of Topics in Older Curriculum (left) and New Curriculum (right)	
CM201 Topics	**EAS211 Topics**
Introduction: Course, Chem Eng Profession, A.I.Ch.E.	Review of Engineering Calculations, Problem-Solving Strategy
Calculation Basics, Units, Significant Figures, Mean and Variance	The Conservation and Balance Principles - General Applications
Data representation, Analysis, Modeling	Integral & Differential Mass Balances - Single component
Process Variables	Multi-component Systems, concentration variables, mixing
Material Balance Concepts	Multi-unit systems, Transient Mass Balances
Balances on Multi-Unit Processes	Mass Balances with reactions
Processes with Recycle	Batteries and electrochemical reactions
Chemical Reaction Basics	Analysis of resistive circuits using KVL/KCL
Balances with Reactions	Power, Ideal/Sources, Models for real sources
Reaction Systems with Recycle and Purge	Capacitance, RC Circuits (first order circuits)
Combustion Systems	Forms of energy, heat and work, conservation equations
Single Phase Systems - Density, Ideal Gas	closed and open systems
Real Gases - Equation of State Models	mechanical & thermal energy equations
Real Gases - Equation of State Models	energy changes in solid, liquid and gas systems
Real Gases - Compressibility Factor Methods	Conservation of linear momentum, stress, strain
	Conservation of angular momentum
	Rigid body statics, distributed loads, truss analysis
	Pressure due to static fluid, submerged objects
CM202 Topics	**CM220 Topics**
Course Introduction, Vapor Pressure Models	The chemical process industry, Raw materials
Single Condensable Component, Saturated Gases	Reaction paths and chemical reactions
Vapor-Liquid Equilibrium, Bubble & Dew Points	Generation-consumption analysis, Atom and process economy
Equilibrium: Dissolved Solids	Process flowsheets, Chemical process equipment & variables
Liquid-Liquid, Gas/Solid, Liquid/Solid	Mass balance equation, Process flow calculations
Stage Calculations, Equilibrium & Material balance	Degree of freedom analysis
Energy Forms, First Law of Thermodynamics	Matrix solutions, Iteration and Regression
Thermodynamic Properties - Tabulated values	Chemical reactors, conversion, reactor flowsheet synthesis
Mechanical Energy Balances	Multiple reactions, Selectivity, yield, equilibrium
Thermodynamic Paths, Press. & Temp. Change	Separation methods, performance specifications
Balances with Phase Changes, Psychrometric Chart	Phase equilibrium
Mixing and Solution Heat Effects	Equilibrium-based separations
Heats of Reaction, Formation, Combustion	The energy balance equation
Energy Balance Procedures	Working with enthalpy
Fuels and Combustion,	Process energy calculations
	Safe and efficient energy use