Using Energy Modules to Introduce Sustainable Engineering and Improve Retention of Chemical Engineering Undergraduate Students

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Abstract

In the present economy, state appropriations are beginning to be tied more closely with student retention and graduation. This can have a big impact on engineering programs in particular, where student engagement can be an important component in improving retention. At Mississippi State University, we are using active learning with energy modules for hydrogen production or hydrogen use in fuel cells, solar energy, and alternative energy carriers in the classroom.

The introduction of energy technology provides a vehicle to apply the chemical engineering fundamentals to broad problems in sustainable energy production and use. This is particularly helpful in chemical engineering, as most of our majors choose chemical engineering as a career so that they can help others.

This paper describes the use of energy modules in the chemical engineering curriculum at Mississippi State University. The paper outlines efforts in the freshman seminar course, mass and energy balances course, the mass transfer / separations course, the engineering materials course, and the chemical engineering reactor design course, as well as an elective course on hydrogen energy fundamentals.

The modules illustrated in this paper show a connection between traditional chemical engineering fundamentals and applications to real world energy problems, such as how a chemical engineer can impact both domestic energy independence and worldwide energy availability. In addition, students become more aware of the stewardship of energy resources.

Introduction

Industrial and academic research and development in renewable energy sources has been a recent focus during the past decade. In chemical engineering, it can be challenging to integrate current research topics into the curriculum as textbook content often lags behind research advances. However, modules can be used to take topics from emerging areas and allow an instructor to add them into the curriculum rather easily.

A review of the literature shows that there are other listings of modules and materials to use in the classroom. These include: the bioengineering educational materials bank\(^1\): (http://www.bioemb.net) the materials digital library pathway\(^2\): (http://matdl.org), the Massachusetts Institute of Technology open courseware site\(^3\) (http://ocw.mit.edu), and the Multimedia Educational Resource for Learning and Online Teaching site\(^4\) (http://www.merlot.org).
In the summer of 2006, several faculty began a “Fuel Cell Curriculum Development Project” with seed support from the CACHE Corporation (Computer Aids for Chemical Engineering), with additional support from the United States Department of Energy, Michigan Technological University, and now Mississippi State University. The results of this project are the development of nearly four dozen modules in chemical engineering, over two dozen modules in mechanical engineering, and over a dozen modules in electrical engineering developed. The modules are available\(^5\): [http://www.che.msstate.edu/pdfs/h2ed/](http://www.che.msstate.edu/pdfs/h2ed/) with links to the separate curricula from that page. The chemical engineering modules are listed in Table 1 below.

Table 1. Chemical Engineering Modules Arranged by Course

*Introductory Material:*
- Overview of Hydrogen Energy and Fuel Cells
- Fuel Cell Sizing Made Easy (Knovel Engineering Cases)
- The Short-Term Hydrogen Economy: Fueling Fuel Cells (Knovel Engineering Cases)

*Material and Energy Balances:*
- Heat of Formation for Fuel Cell Applications
- Material Balances in a Solid Oxide Fuel Cell
- Energy Balances in a Solid Oxide Fuel Cell
- Generation of Electricity Using Recovered Hydrogen
- Material Balances in Fuel Cell Systems
- Heats of Reaction and Energy Balances in an SOFC

*Thermodynamics:*
- Equation of State for Hydrogen Fuel
- Equilibrium Coefficient and Van’t Hoff Equation for Fuel Cell Efficiency
- Fuel Cell Efficiency
- Vapor Pressure / Humidity of Gases
- Nernst Equation

*Fluid Mechanics:*
- Pressure Drop in Fuel Cell Bipolar Plate Channel
- Finite Difference Method for Flow in a Fuel Cell Bipolar Plate
- Compressor Sizing and Fuel Cell Parasitic Losses

*Heat and Mass Transfer:*
- Conduction and Convection Heat Transfer
- Microscopic Balances Applied to Fuel Cells
- Diffusion Coefficients for Fuel Cell Gases
- Conduction, Convection, and Radiation Heat Transfer in a Solid Oxide Fuel Cell
Kinetics and Reaction Engineering:
- Tafel Equation and Fuel Cell Kinetic Losses
- Hydrogen Adsorption and Catalyst Surface Coverage
- Pressure Drop in a Water Gas Shift Reactor
- Water Gas Shift Reaction in a Palladium Membrane Reactor
- Equilibrium Simulation of a Methane Steam Reformer
- Reaction Kinetics in a Solid Oxide Fuel Cell
- Reactor Design Applied to a Solid Oxide Fuel Cell

Separations:
- Hydrogen Purification
- Air Separation for Coal Gasification
- Hydrogen Production by Electrolysis with a Fuel Cell
- Hydrogen Production by Natural Gas Assisted Steam Electrolysis

Process Safety and Process Design:
- Stoichiometric Analysis of Fuel Combustion
- Energy Value of Fuels
- Hydrogen Production Cost
- Fuel Energy Cost and Energy Density
- Hydrogen Flammability
- Theoretical Fuel Consumption and Power
- Unisim Modeling of a Proton Exchange Membrane Fuel Cell
- Unisim Modeling of a Solid Oxide Fuel Cell

Materials Science and Engineering:
- Ion and Electrical Conduction in a Solid Oxide Fuel Cell
- Non Steady-State Carbon Diffusion in Solid Oxide Fuel Cell Interconnects
- Mechanical Failure of Solid Oxide Fuel Cell Electrolyte

There are additional energy modules that have been developed as part of this project. These modules are focused primarily on hydrogen as an energy carrier and also on energy consumption, energy efficiency, battery energy, solar energy, and wind energy. Efforts are underway to continue to develop additional modules in alternative energy. The published modules are listed in Table 2.

In order to effective in the classroom at any university, we have developed a uniform format for all of these modules. Each module consists of a problem motivation, example problem statement, example problem solution, home problem statement, and home problem solution. It is noted that the home problem solution is available to instructors by emailing the first author on this paper. The modules also contain additional information that often lists the chapter of the most popular chemical engineering textbook for that course, in order to aid instructors in identifying when to use these modules in their courses. The modules developed in this course can be
quickly downloaded and used in any chemical engineering undergraduate course.

Table 2. Additional Energy Engineering Modules Arranged by Topic

*General Energy Analysis:*
- Energy Consumption Analysis
- Energy Efficiency Analysis
- Energy Emissions Analysis
- Battery Energy Analysis
- Battery / Fuel Cell Vehicle Range
- Solar Energy Analysis
- Wind Energy Analysis
- Power and Energy Analysis of Transient Driving Schedules

*Coal Energy:*
- Material Balances on CO₂ Absorption / Stripping Process

*Solar Energy:*
- The Power of Solar Energy
- Solar Water Heating
- Solar Steam Turbine
- Module Design

Use of Modules at Mississippi State University

Table 3 identifies the chemical engineering courses in which the energy modules have been used. It is noted that this paper builds upon prior results delivered at a regional ASEE meeting. The intent is to highlight sustainable energy concepts during each year of undergraduate study.

In CHE 1101 in fall 2012, the module on Unit Conversions was used, to make the freshmen aware of the area of hydrogen fuel cells while giving them important exposure to the practice of unit conversions. Students reacted positively to the assignment and at least 80% of the 90+ students worked through the assignment with no trouble. The assignment was prefaced with in-class practice problems.
### Table 3. Chemical Engineering Courses

<table>
<thead>
<tr>
<th>Course Number</th>
<th>Title</th>
<th>Year / Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHE 1101</td>
<td>CHE Seminar</td>
<td>Freshman / Fall</td>
</tr>
<tr>
<td>CHE 2213</td>
<td>CHE Analysis</td>
<td>Freshman / Spring</td>
</tr>
<tr>
<td>CHE 2114</td>
<td>Mass &amp; Energy Balances</td>
<td>Sophomore / Fall</td>
</tr>
<tr>
<td>CHE 3223</td>
<td>Mass Transfer Operations</td>
<td>Junior / Spring</td>
</tr>
<tr>
<td>CHE 4113</td>
<td>CHE Reactor Design</td>
<td>Senior / Fall</td>
</tr>
<tr>
<td>CHE 3413</td>
<td>Engineering Materials</td>
<td>Senior / Fall</td>
</tr>
<tr>
<td>CHE 4223</td>
<td>Process Instrumentation and Automatic Control</td>
<td>Senior / Spring</td>
</tr>
<tr>
<td>CHE 4990</td>
<td>H₂ Energy Fundamentals</td>
<td>Elective</td>
</tr>
</tbody>
</table>

In CHE 2114 in fall 2011, the module on material balances in fuel cell systems was used as a homework problem. This course uses the textbook *Elementary Principles of Chemical Processes* by Felder and Rousseau. The module was introduced while chapter 4 of the text was being covered, after the concept of extent of reaction was taught. Anecdotal comments from the students suggested that the problem was very interesting in that it showed a new application of the fundamentals that they were learning in class. Furthermore, many students enjoyed the challenge of the problem and the fact that it integrated all aspects of what they had learned previously in the course. Also, some students felt they were finally able to grasp the concept of extent of reaction after solving this problem. Finally, students liked having an example problem to refer to as they completed the module home problem. Some students did indicate a need for additional background in fuel cells. Some also indicated that they were unprepared for a problem of this difficulty level and/or the use of matrices (which is not required to solve the module home problem, but is demonstrated in the example problem).

During the Fall of 2012 the same instructor taught the class, and assigned the same module to 94 students of the Mass and Energy Balance class. The module was offered as a means of obtaining a bonus to their grade on the 2nd exam which covered only Chapter 4 of Felder and Rousseau. Of the 94 students 82 provided their solutions for credit. The grade distribution was as follows: 5% received a D or less, 34% a C, 51% a B, and 10% an A. The consensus of the students was that this was a very challenging problem with more than half feeling they were prepared to solve the material balances. They also stated that the example problem was most helpful. There were a number of students that really enjoyed learning and working on a fuel cell problem.

The module “Air Separation for Coal Gasification” was used as a homework problem.
in CHE 3223: Mass Transfer Operations in spring 2012. Lectures on membrane processes (general overview, module configuration, membrane materials, economic benefits) and the processes of gas permeation and pervaporation had been previously covered in class. With respect to gas permeation, lecture content included nomenclature, historical development of the process, current uses in industry, as well as basic calculations (determination of permeability from experimental data; evaluation of permeate and retentate compositions, and determination of membrane area). The use of this novel technology was contrasted with cryogenic distillation in terms of energy consumption and economy of scale. The module provided a practical example of where this technology can be effectively employed to produce streams with enriched oxygen content on a smaller scale. Student performance on the homework assignment was satisfactory with an average of 7.5/10.

In the Engineering Materials (CHE 3413) course in fall 2012, portions of the module on non steady-state carbon diffusion in solid oxide fuel cell interconnects were used as an examination problem. The text used in this course is Material Science and Engineering: An Introduction, by Callister and Rethwisch. In lectures leading up to the exam, an extensive discussion of diffusion and applications of Fick's second law for unsteady state diffusion in a semi-infinite domain were provided. When the surface concentration is held constant, the application of boundary conditions and the initial condition yields the solution involving the complementary error function.

A journal article was posted to the student-accessible myCourses website and they were required to read the article prior to the class discussion. This journal article provided the basis for discussion and covered a wide variety of interesting applications of carburization and decarburization including: 1) the high rate of carburization by reduction of CO and H₂; 2) the insignificant rate of decarburization by H₂; 3) the disproportionation of CO; and 4) a comparison of the rate of decarburization of CO₂ and H₂O at the specified temperature. Also examined were surface hardening of a steel gear and carburization of an FCC iron alloy. These cases were selected as model systems for determination of treatment temperature as well as diffusion time required to achieve a given composition at a specified distance from the surface of the steel gear. These applications involved the same knowledge as the energy module. The energy module provided the students with an emerging application of this timeless analytical solution for the diffusion PDE for solid oxide fuel cell interconnects. Overall, the students performed well on this graded component.

In CHE 4113 in fall 2011, two modules were used. The first module employed focused on estimation of the pressure drop in a water-gas shift reactor. In this module, students were given an example problem that showed how to perform pressure drop calculations in a laboratory reactor. In their homework assignment, the students needed to apply the same technology to an industrial reactor. This enabled them to see the differences in the order-of-magnitude of the pressure drop as well as which terms in the pressure drop
equation were important for each scale. In addition, in many of the problems from the Elements of Chemical Reaction Engineering text by Fogler involving the Ergun equation, the parameter, $\alpha$, which quantifies pressure drop, was simply provided, and students did not have to actually evaluate it. Thus, the experience they obtained in performing the calculations for the energy module will be beneficial should they have to evaluate pressure drop in an industrial reactor once they are working as chemical engineers. The $\alpha$ value won't simply be given in such a situation; students will have to use porosity and superficial mass velocity along with fluid and particle properties and system dimensions to calculate the pressure drop parameter. They liked actually performing the calculations, making sure that they had appropriate units and conversions and using the end result to evaluate the reactor performance and pressure drop.

The second module used in CHE 4113 was the module discussing site balances to determine hydrogen adsorption and catalyst surface coverage in a fuel cell application. In class lectures on catalysts and catalytic processes, the steps in catalytic reactions as well as developing an expression for the catalytic rate given a proposed mechanism with surface reaction being the slowest step were provided. Single-site and dual-site adsorption processes were discussed as were dissociative and molecular adsorption and their governing rate expressions developed. Thus, students were able to readily integrate the Tafel reaction where hydrogen undergoes dissociative adsorption into their existing knowledge structure. In the module home problem, students were asked to determine surface coverage by hydrogen on the catalyst surface at a particular current density, as well as properly interpret their answer. Discussions in class regarding mass-transfer limited processes as well as kinetically-controlled processes were drawn upon as they were able to correctly interpret their calculated answer to the module home problem.

A different instructor taught CHE 4113 in fall 2012. Two modules or parts therein were used as graded components on the final exam for the CHE 4113 Chemical Reactor Design Course. Previously through lecture material, students have been exposed to PEM fuel cells and the water-gas shift reaction in a packed bed reactor followed by a fluidized bed reactor (or vice versa). Students had to evaluate the validity of the assumption of zero pressure drop through the fluidized bed reactor. Students learned that failure to include the pressure drop in the packed bed reactor resulted in underestimation of required catalyst to achieve a given conversion. They also had to evaluate the contributions from the various terms present in the Ergun equation and determine which term was dominant based on the flow regime. Students were provided literature from Quantachrome that discussed the measurement of the true density, particle density and bulk density of porous solids and powders. Thus, students knew the appropriate measurement methods and could distinguish between bulk density, particle density and true density. They also were exposed to how the viscosity of a gas mixture should be calculated.
The first module, “Pressure Drop in a Water-Gas Shift Reactor”, formed the basis for a problem involving calculations with the Ergun equation. All necessary parameters were specified for the estimation of pressure drop. To successfully complete the examination problem, students had to start from the Ergun equation in differential form \( \frac{dP}{dz} \), and through proper substitution/manipulation of gas and solid densities and other parameters, integrate to develop an expression representing the pressure drop through the reactor.

The second module, “Simulation of a Methane Steam Reforming Reactor”, formed the basis for a problem involving multiple reactions. Students had previously been exposed to problems of this type as part of their semester design project. The reactions, when written in the reverse direction, form a reaction scheme that may prove beneficial for reduction of carbon monoxide and carbon dioxide in streams where they might otherwise poison a catalyst in hydrogenation processes including ammonia production. This problem required students to develop the necessary mole balances for various species (methane and carbon dioxide) in a PBR. Expressions for the net rate of production of CO, CO\(_2\), and CH\(_4\) were also developed. Students were also required to develop the energy balance expression for this multiple reaction system if the reactor was operated adiabatically. Given a need to evaluate pressure drop in the reactor, students were queried as to what additional information might be required in order to use the Ergun equation.

As part of the Department of Energy grant described earlier, two new courses were developed: Fuel Cell Fundamentals and Fundamentals of Hydrogen as an Energy Carrier. Each of these one credit courses was taught at Michigan Technological University by the lead author on this paper. After moving to Mississippi State University, the courses were expanded and combined into a single three-credit course. The course outline is shown in Table 4 below along with the modules that were assigned in this course.

The modules were incorporated into the course in the following manner:
- There is a short lecture on an energy topic
- The students are given a module to serve as an in-class problem
- The students work through the example problem in the module during class
- The students begin solution of the homework problem during class
- The instructor circulates around the room and assists students if they have any questions
- The homework problem is due at a future class meeting
- Alternatively, some class sessions students were not given the entire module but only a homework problem to solve.
Table 4. Course Outline for Hydrogen Energy Fundamentals

<table>
<thead>
<tr>
<th>Week</th>
<th>Topics</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Course Introduction</td>
<td>Fuel Energy Cost (M)</td>
</tr>
<tr>
<td></td>
<td>Basics of Energy &amp; Power</td>
<td>Electric Bill (H)</td>
</tr>
<tr>
<td></td>
<td>Energy Production</td>
<td>Energy Consumption (M)</td>
</tr>
<tr>
<td>2</td>
<td>Energy Sources, Emissions, and Capacity</td>
<td>Energy Efficiency (M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuel Combustion (M)</td>
</tr>
<tr>
<td>3</td>
<td>Internal Combustion Engines</td>
<td>Emissions (H)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transient Driving (M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine Simulator (H)</td>
</tr>
<tr>
<td>4</td>
<td>Quiz 1</td>
<td>Battery Energy (M)</td>
</tr>
<tr>
<td></td>
<td>Electric and Hybrid Electric Vehicles</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Fuel Cells and Fuel Cell Vehicles</td>
<td>Vehicle Range (M)</td>
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<tr>
<td></td>
<td>Fuel Cell Internals</td>
<td>Fuel Cell Calculator (H)</td>
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<td></td>
<td></td>
<td>Material Bal. in SOFC (M)</td>
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<tr>
<td>6</td>
<td>Fuel Cell Mass Balances</td>
<td>Fuel Cell Balances (H)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass Balances in FC System (M)</td>
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<tr>
<td>7</td>
<td>Quiz 2</td>
<td></td>
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<tr>
<td></td>
<td>Hydrogen Public / Government Policy</td>
<td></td>
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<td>8</td>
<td>H₂ from Natural Gas: Steam Reforming</td>
<td>Steam Reforming Equil. (M)</td>
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<tr>
<td></td>
<td>H₂ from Natural Gas: H₂ Purification</td>
<td>Hydrogen Purification (M)</td>
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<tr>
<td>9</td>
<td>Hydrogen from Coal</td>
<td>Air Separation (M)</td>
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<td></td>
<td></td>
<td>Coal Gasification (H)</td>
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<tr>
<td>10</td>
<td>Hydrogen from Biomass</td>
<td>Biomass Gasification (H)</td>
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<tr>
<td></td>
<td>Quiz 3</td>
<td></td>
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<td>11</td>
<td>Hydrogen from Electrolysis / Wind</td>
<td>Wind Energy (H)</td>
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<td>Hydrogen from Solar Energy</td>
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<td>12</td>
<td>Hydrogen from Nuclear Energy</td>
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<td>13</td>
<td>Hydrogen Economy</td>
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<td>Quiz 4</td>
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<td>Project Preparation</td>
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<td>15</td>
<td>Project Presentations</td>
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</tr>
</tbody>
</table>

In total, there were twelve modules assigned and nine homework problems assigned. The students were given time in class to complete some of the work and have questions answered by the instructor. Student attendance was 90% or greater for almost all of the class sessions.

Conclusions

This paper has described the use of hydrogen and other energy modules in the chemical engineering curriculum at Mississippi State University. These modules are being
integrated throughout the core courses at Mississippi State University in the freshman, sophomore, junior, and senior years. Additional information is added through an elective course, Hydrogen Energy Fundamentals. The modules allow students to see a connection between the fundamentals of chemical engineering and in new applications to real world energy problems. Additional emphasis is placed on the need for domestic energy independence and on worldwide energy availability, as well as in the ethical use of energy resources. As these modules are taught in our curriculum, assessment data will be collected and reported on in a future article.

Bibliography