Educational Module: Incorporating Sustainability Principles into the Chemical Engineering Thermodynamics Course

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Abstract

This module is intended to provide guidance to incorporating sustainable design principles into the Chemical Engineering Thermodynamics Course. Chemical Engineering Thermodynamics is typically a core course in most Chemical Engineering curricula. The concepts developed in this module are geared toward sophomore level students in Chemical Engineering. Typical engineering prerequisites for this module will include Mass and Energy Balances, Chemistry and Physics. Thermodynamic concepts such as 1st and 2nd Law Analysis, Heat Engines, Efficiency and Work, Refrigeration and Liquefaction, and Renewable Energy concepts are covered in this module. An assortment of practice problems with solutions follows this module. These problems are designed to reinforce the sustainable design concepts presented in the module.

Sustainability and Chemical Engineering Education

The effects that chemical processes have on the environment and the economy are of increasing concern to the general public, the chemical and allied industries and regulatory agencies. Ensuring that the natural resources required to manufacture the products and services needed by society are utilized in a way that ensures their availability for future generations is the core of the field of sustainability. In its 1987 report titled *Our Common Future*, the U.N. World Commission on Environment and Development, also commonly called the Bruntland Commission, defined sustainable development as follows:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Bruntland, 1987)

Although there is no single accepted definition of the term sustainability, the Bruntland Commission definition of sustainable development forms the basis of what sustainability means to the field of engineering. For chemical engineers in particular, sustainability has come to refer to the goal of designing, operating and maintaining chemical processes in a manner that is economically viable, environmentally benign, and beneficial to society. In other words, a sustainable process is one that is designed, operated and maintained to meet the triple bottom line of economics, environment and society, both now and in the future. Chemical engineering graduates entering careers in the chemical and allied industries will increasingly be tasked with job functions that require both an understanding of sustainable chemical engineering principles and competency in set of sustainable chemical engineering skills. Therefore, the AIChE Sustainable Engineering Forum has developed a set of modules that will address the growing need for incorporating sustainability into the chemical engineering curriculum.

The National Academy of Engineers has expressed this need for sustainability in engineering education in its report titled *The Engineer of 2020: Visions of Engineering in the New Century* as follows:

> "It is our aspiration that engineers will continue to be leaders in the movement toward the use of wise, informed, and economical sustainable development. This should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions." (NAE, 2004)

How to incorporate sustainability in engineering education is a challenge to the academic community (Davidson, *et al.*, 2010),(Allen, *et al.*, 2006). However, by utilizing modules that integrate sustainability into core courses and concepts, we can begin to address this challenge.

Sustainable Chemical Engineering Thermodynamics

According to the U.S. Department of Energy, reliance on fossil fuels is unsustainable and contributes to economic and political vulnerability (U.S. DOE, 2003). Additionally, the Energy Independence and Security Act of 2007 (EISA 2007) (Public Law, 2007) mandates the production of 36 billion gallons per year of biofuels by 2022, of which 21 million must come from feedstock other than corn starch and at least 16 billion gallons must come from lignocelluloses (Regalbuto, 2009). Therefore, it is important to introduce the concepts of energy efficiency and renewable energy into the undergraduate curriculum. The undergraduate thermodynamics course is a natural place in the curriculum to introduce these concepts.

Thermodynamics is one of the fundamental concepts of all engineering disciplines and chemical engineering is no exception. Likewise, thermodynamics plays a central role in the analysis of sustainable systems, especially from the perspective of energy usage and energy efficiency. The concepts of heat engines, turbines and compressors, refrigerators and evaporators are central to discussions of energy utilization. Furthermore, an understanding of the 1st and 2nd laws is key to analysis of more complex systems and processes. This module will introduce various thermodynamic concepts and present an overview of how they can be an integral part of sustainable design and renewable energy. Specific example problems illustrating these techniques are included with this module.

Overview of Sustainable Concepts in Chemical Engineering Thermodynamics

1st and 2nd Law Analysis

The 1st and 2nd Laws are key concepts in any thermodynamics class. As such, their application to sustainability should be discussed. A key technical challenge to many renewable systems, such as those based on solar or wind energy, is storing energy for use during times when the primary source is unavailable. Converting energy to different forms is an application of the 1st Law that would typically be covered in a Thermodynamics course. Example problems illustrating this concept are included in this module. Furthermore, applications of the 2nd Law can be used to illustrate concepts of efficiency. Problems including efficiency of thermodynamic operations are also included in this module.

Heat Engines

Heat engines are used as a tool for evaluating thermodynamic efficiency. The heat engine concept can be used to analyze the performance of energy saving systems such as home heating and cooling using underground or underwater heat sinks as well to analyze renewable energy systems like passive solar heating and power generation using geothermal energy.

Efficiency and Work

When considering the influence of thermodynamic principles into sustainability and sustainable design, the importance of work and efficiency are among the most important topics. Understanding work and efficiency are key to reducing the energy usage and potential environmental impacts of thermodynamic processes.

Refrigeration and Evaporation

From the perspective of potential environmental impacts, not all refrigerants are created equal. The tradeoffs between thermal characteristics and improved environmental performance can easily be demonstrated using the concepts of refrigeration. An example of this calculation is included in the supplementary problems section of this module.

Evaporation is another concept that can be illustrated using sustainable design principles. Using evaporative cooling instead of refrigeration for home cooling during warm months is an example of this process.

Renewable Energy

Renewable energy sources like biomass are fundamentally different from fossil based energy sources in both molecular composition and energy density. Thermodynamic analysis can be applied to characterize the heating values of fuels, either biomass or fossil based. Determining the heating value of a potential fuel source is important to assess its utility as a renewable energy source.

Alternative energy sources like solar can also be analyzed using thermodynamic principles. The utility of solar energy can be illustrated by using the heat engine concept. Since work can be generated when heat from a high temperature source is rejected to a low temperature sink, the concept of a heat engine is useful to illustrate the work generating potential of solar energy.

Educational Objectives

The objective of this module is to provide a framework for incorporating sustainability into the Chemical Engineering Thermodynamics Course. After completing this module, students should have achieved the following objectives:

- Demonstrate an understanding of the importance of thermal efficiency in the design of sustainable systems.
- Demonstrate an understanding of the relationship between heat and work in the analysis of energy systems.
- Demonstrate an understanding of the use of solar energy for industrial and home power generation.
- Explain how a variety of thermodynamic principles can be used to analyze the impacts of systems such as heat engines, refrigerators, evaporative coolers and compressors.
- Demonstrate an understanding of the utilization of biomass as a fuel.
- Demonstrate an understanding of the role the principles of thermodynamics plays in design for sustainability.

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Sample Problems

Note to Instructors*: A complete set of solutions to the sample problems is available to credentialed instructors by contacting the corresponding author at jseay@engr.uky.edu.*

1. Evaporative Cooling

In areas of hot, dry climates, evaporative cooling has become a sustainable alternate to air conditioning. Commonly referred to as "swamp coolers," these units employ basic thermodynamic concepts to provide for cheap cooling of both homes and commercial buildings. Saturated media inside an evaporative cooler allow water to evaporate when warm air with a low relative humidity enters the unit. This process of evaporation results in the temperature of the air decreasing as its relative humidity increases. A fan blows the cool, moist air into the home or business. Consider the following conditions and use a psychrometric chart to determine the lowest possible temperatures to which each could be cooled. Use this data to determine the final temperature of the air entering the home if it leaves at 80% relative humidity. Assume pressure = 1 atm.

(a) 100 °F, 40% relative humidity
(b) 110 °F, 30% relative humidity
(c) 90 °F, 20% relative humidity
(d) 95 °F, 10% relative humidity
(e) 90 °F, 10% relative humidity
(f) 100 °F, 20% relative humidity
(g) Based on your results, research climate patterns for your region of the country. Based on the average relative humidity, would this option be effective for you home?
(h) How does relative humidity affect comfort, quality of life and worker productivity? Discuss the costs and benefits to society of indoor air conditioning versus its energy requirement.

2. Refrigerants

Many common refrigerants, such as R-12 have been replaced in recent decades in an effort to curb the release of greenhouse gases and ozone-depleting substances into the atmosphere. While older refrigerants were efficient and cheap, their replacements have been developed to be just as effective. One such new refrigerant is R-410a (ASHRAE, 2010).

Analyze the effectiveness of both R-410a and R-12 as the working fluid of a commercial refrigeration unit. The refrigeration cycle can be described as follows. The working fluid enters the compressor of a refrigerator at 0.15 MPa and -10°C. Assume that the refrigerant leaves the compressor at 0.9 MPa and 55°C and is cooled in the condenser to 0.6 MPa and 15°C. The fluid is then throttled to 0.2 MPa. If the required amount of heat removal for the refrigerated space is 10 kW, determine:

(a) The mass flow rate of the working fluid for the R-12 and R-410a case.
(b) The rate of heat rejection from the working fluid to the atmosphere.

(c) The coefficient of performance of the refrigerator for each case.
(d) Discuss why new refrigerants like R-410a are preferred in terms of sustainability.

3. Minimizing Compressor Work

Engineers often have the greatest contribution towards minimizing energy in the earliest stages of process design. By improving the efficiency of a process, design engineers can save both energy and money. When designing a process that involves compressors, work is minimized by attempting to approach an internally reversible process.

(a) What approaches could be suggested to minimize the required work for a compressor system you are designing? State any assumptions and explain your reasoning.
(b) What factors prevent real processes from achieving true reversibility, and how does this affect the sustainability of thermodynamic processes?
(c) Why don't engineers always design processes to be as efficient as possible? Discuss the costs and benefits associated with increased efficiency.

4. Minimizing Work

Considering the approaches used in the previous problem (#3), apply your understanding of sustainability and thermodynamics to the following scenario:

With the goal of keeping the air that is compressed as cool as possible, you have two potential design options.

1) Operating the compressor as an isothermal process through the use of cooling jackets
2) Employing multi-stage compression and intercooling

Compare both design options and determine the best choice for energy savings. The compressor system operates under the following conditions: a real gas enters the compressor at 150 kPa and 293 K. It exits the compressor at P = 1000 kPa. Consider option #2 to be 2-stage compressor with a c_p/c_v ratio of 1.2.

5. Thermal Efficiency

Every work producing system results in wasted energy. Thermal efficiency gauges the conversion of heat to work in a heat engine and can illustrate how much heat is lost in a process. A goal of design engineers is to maximize the thermal efficiency of their process to reduce cost and improve the overall sustainability. Improving thermal efficiency is a direct way to reduce energy costs. Consider two different heat engines that are powered by biomass. Research has shown that, once dried and densified, certain biomass sources have a heating value in the same range as that of coal, 15 – 45 MJ/kg (McGowan, 2009). Consider a hardwood with a heating value of 20.5 MJ/kg (McGowan, 2009). Determine which heat engine under the given conditions has the more favorable thermal efficiency.

(a) If the first heat engine has a power output of 80 MW and 148 MW of waste heat, determine the thermal efficiency and the amount of biomass consumed.
(b) If the second heat engine consumes 48 tons/hour of biomass and has a power output of 80 MW, determine the thermal efficiency, amount of wasted heat, and the heat supplied from the heat source.
(c) In terms of sustainability, discuss the potential costs and benefits of utilizing biomass as a fuel source.

6. Deep Water Heat Sinks

Even in warm climates, the water from the bottoms of lakes, oceans and rivers is cold enough be used as a sustainable means of heat dispersion in both industrial and residential heating/cooling systems (Banks, 2009). For example, water at the bottom of Lake Barkley, a large lake in western Kentucky, remains at a temperature of approximately 60°F (288 K) all year long. Deep water source cooling uses a fraction of the energy of typical cooling systems. As with any heat engine, it is important to attain the maximum temperature difference for the process. Colder water will provide a greater power output. Consider a heat engine rated at 100,000 KW that generates steam at 600 K cooled through the use of cold water from Lake Barkley.

(a) Determine the heat from the heat reservoir, the heat discarded to the lake water, and the thermal efficiency of the heat engine.
(b) How would these values change if the process were located in a northern climate where water at 278 K is used instead?
(c) Describe how the geographic location of the lake affects the sustainability of this process?

7. Solar Heating

Solar power continues to be a promising source of sustainable energy. However, generating power from the sun is no simple task. The ability to convert the sun's heat energy to work is limited by thermodynamics. Without concentration of the sun's rays, the maximum high temperature for a heat engine would be around 150°C. This fairly low temperature limits the work that can be generated between the high temperature source and a low temperature reservoir at 25°C. In order to produce more than just a limited amount of power, the sun's energy must be concentrated. A concentrating solar tower system uses a series of mirrors to intensify sunlight on a central point in order to heat a fluid and generate electricity. This process can raise the temperature to up to 600°C (Tester, 2005).

(a) Consider a simple solar power plant that collects the sun's rays using solar panels without the use of concentrating mirrors. Calculate the heat energy created if the plant is rated at 1 MW.
(b) Consider a solar power plant utilizing a concentrating tower. Calculate the heat energy created if the plant is rated at 10 MW and assume a high temperature of 600°C.
(c) Estimate the total tons of coal that could be displaced per MW of solar energy.

8. Electricity from Solar Power

As public concern for renewable energy has grown, many homeowners are exploring solar power as a means of saving on electricity costs. Solar power technology has improved while the costs have decreased. You have decided to research the potential benefits of using solar power to provide the power required for your home. If the cost of electricity from the power company is 11.75 cents/kWh and the cost of installing a solar power system for your home is $1.85 per watt, calculate the payback time of the solar power system if your home uses an average of 25 kWh of electricity per day.

(a) Assume you live in a sunny climate and that, on average, your home gets 5 hours of direct sunlight per day.
(b) Explain how your geographic location would impact the applicability of utilizing solar energy to offset electrical costs.
(c) Discuss whether the calculated payback period is reasonable for the typical homeowner.

9. Converting Work to Potential Energy for Later Use

Because energy production from wind turbines can fluctuate with the forces of nature, it is prudent to develop a system of storing energy for use during times of low production. Work can be converted to potential energy in many different ways. List some possible methods of doing so. Next consider a wind turbine system that stores energy by raising a large piston within the turbine tower. Wind energy raises the piston to its full height and then sends all of its energy to the power grid. During periods when the wind is not blowing, the piston falls and compresses a gas which then generates power. Assume this piston functions like a basic thermodynamic piston-cylinder device. Apply the first law of thermodynamics and eliminate unnecessary factors from the energy balance. If the tower shaft is 80 meters tall, determine how much potential energy is stored if the piston weighs 750 kg. Clearly, if the wind turbine is raising a piston, it isn't providing electricity to the grid. Considering the overall sustainability of the process, is compressing a gas a reasonable way to store wind energy?

10. Utilizing Biomass as Fuel

Before the industrial age, biomass was the primary fuel source for heating. However, recently, there has been renewed interest in biomass as feedstocks for heating and power generation. The high heating value, HHV, of a biomass source is the heat released during the complete combustion of the fuel (ie., the complete conversion of the hydrocarbon fuel source to CO_2 and H_2O) from reactants at a given reference temperature and pressure to products at the same reference temperature and pressure (McGowan, 2009). The HHV is best determined experimentally using a calorimeter, but an equation has been proposed to estimate this value based on the weight percent of carbon, hydrogen, oxygen and nitrogen in the feed material (Demirbas, 1996). This equation is:

$$HHV = [33.5(C) + 142.3(H) - 15.4(O) - 14.5(N)] \times 10^{-2}\ \text{MJ/kg}$$

Assume that you have a hardwood source with a solid composition of 45 wt% cellulose ($C_6H_{10}O_5$), 30 wt% hemicellulose (Assume hemicellulose is primarily xylose with the chemical formula:

$HOCH_2(CH(OH))_3CHO$) and 20 wt% lignin (Assume lignin is comprised primarily of polylignols with an average molecular formula of: $C_{10}H_{12}O_3$) (Scurlock, 2009). For simplicity, you may assume the balance is water.

(a) Calculate the HHV of this fuel source using the given equation.
(b) Compare your results to literature values for the HHV of various hardwood sources as well as subbituminous and bituminous coal. List the possible reasons for this difference.
(c) How would the life cycle impacts of biomass transportation affect the sustainability of utilizing this fuel source?
(d) Compare the emissions for the combustion of coal to the combustion of biomass (without pollution controls). Discuss the impacts in terms of sustainability of power generation from the combustion of biomass.