Educational Module: Incorporating Sustainability Principles into the Fluid Mechanics Course

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Abstract

This module is intended to provide guidance to incorporating sustainable design principles into the Engineering Fluid Mechanics Course. Fluid Mechanics is typically a core course in most Chemical and Mechanical 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 Chemical Engineering Principles, Thermodynamics, Chemistry, Physics and Calculus. Fluid Mechanics concepts such as Friction Loss, Drag Coefficient, Pump Hydraulics and Gravity Flow 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 Fluid Mechanics

Fluid Mechanics is one of the first applied engineering courses encountered by students of Chemical and Mechanical Engineering. Typically, students enter the Fluid Mechanics course having completed their introductory courses in chemistry, physics and thermodynamics. Although the Fluid Mechanics course is taught to both Chemical and Mechanical Engineering students, this module is geared towards Chemical Engineering Students. While Fluid Mechanics may at first seem an unlikely place to find sustainable design principles, overcoming loses caused by friction and drag is critical to reducing the energy required for industrial systems. Likewise, applying simplifying principles such as gravity flow can reduce the need for pumping. Because the movement of fluids play such a large role in chemical processes, an understanding of how to make them more sustainable is important to chemical engineers. This module will introduce various Fluid Mechanics concepts and present an overview of how they can be an integral part of sustainable design. Specific example problems illustrating these techniques are included with this module.

Overview of Sustainable Concepts in Engineering Fluid Mechanics

Friction Loss

Friction loss is one of the key causes of loss of efficiency in flowing systems. Therefore, an understanding of its effect is key to the design of sustainable systems. By reducing friction losses, less energy is required to move a fluid. This concept is illustrated in the example problems included with this module. The trade-offs between pipe size and friction loss, particularly with regard to material selection, should be addressed in a discussion of friction loss. The impacts friction losses have on pumping systems will also be explored with this module.

Drag Coefficient

Much like friction loss, understanding drag coefficient is important to understanding the causes of loss of efficiency in vehicles. As engineers strive to improve vehicle efficiency, lowering the drag coefficient is a key consideration, again, particularly with regard to material selection. Linking this concept to energy efficiency is a key concept in sustainability that relates to fluid mechanics. This concept is illustrated using an example problem with vehicle design.

Pump Hydraulics

Moving liquids is one of the most common applications in the chemical process industries. Pump efficiency, static head and fluid properties, as well as friction loss and pipe sizing, play an important role in the overall energy utilization of the process. This concept is also illustrated with an industrial pumping design problem in this module that explores the trade-offs between piping design and energy usage.

Gravity Flow

Gravity flow can be a sustainable alternative to pumping. Gravity flow also satisfies in simplification principle of the 12 Principles of Green Chemistry (Anastas). The key concepts of gravity flow and self-venting flow are illustrated in this module.

Educational Objectives

The objective of this module is to provide a framework for incorporating sustainability into the Engineering Fluid Mechanics Course. Although Fluid Mechanics is typically offered in the

Mechanical Engineering curriculum as well, the module is specifically geared to Chemical Engineering students. After completing this module, students should have achieved the following objectives:

- Demonstrate an understanding of the importance of friction losses in the design of sustainable piping and duct work systems.
- Demonstrate an understanding of the use of Drag Coefficient in the design of moving systems.
- Demonstrate an understanding of the role pumping systems play in the design of sustainable fluid flow system.
- Demonstrate an understanding of the trade-offs between gravity flow and pumped flow in the design of fluid systems.
- Demonstrate an understanding of the role the principles of fluid mechanics 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. Wind Turbines

As the search continues for renewable and sustainable energy sources, wind turbine technology has arisen as one of the more viable and thriving solutions. Wind turbines do not require fossil fuels and thus leave no carbon footprint from emissions. In fact, since there is an unlimited supply of wind, turbines represent a truly renewable source of energy. However, while turbines generate power from a free and renewable source, their performance is tied to variations in wind currents.

(a) Consider a 40 meter diameter HAWT (Horizontal Axis Wind Turbine) with a power coefficient of 38%. Assuming an air temperature of 25 °C and disregarding the efficiency of the gearbox and generator, estimate the electric power produced by the turbine at air speeds of: a) 5 m/s, b) 10 m/s, c) 15 m/s, and d) 20 m/s.

(b) Perform the same analysis, but take into account a combined gearbox and generator efficiency of 80%.

(c) Investigate how geographic location can affect the performance and viability of wind turbine technology.

(d) Brainstorm possibilities for providing continuous power, even when the wind stops, since power must be available 24 hours a day.

2. Drag Coefficients of Vehicles

As the marketplace has begun to reflect the growing public awareness for the environment, automobile manufacturers have moved toward developing more energy efficient, economical, and sustainable vehicles. New commercial models boast greater fuel efficiency and lighter, sleeker designs. One way of achieving these sustainable goals is through the implementation of new energy sources such as hybrid-electric technology. However, the efficiency of a vehicle is also inherently impacted by its physical design. The height, width, weight, and shape of a vehicle have a direct relation to energy efficiency. Designers often modify these factors in an attempt to make the drag coefficient as low as possible. Compare a typical car design to that of a “new,” more efficient design. The “new” design has a drag coefficient of 0.25, a width of 1.7 m, height of 1.5 m, and an overall drive train efficiency of 40%. The typical car design has a drag coefficient of 0.30, width of 1.8 m, height of 1.7 m, and overall drive train efficiency of 30%. Assume both vehicles weigh the same.

(a) Determine how much fuel and money would be saved by using the “new” design if both vehicles travel an average of 20,000 km per year at an average speed of 85 kph. You may make the following assumptions:
Fuel costs $0.80/L and has a density of 0.74 kg/L.
The heating value of gasoline is 45,000 kJ/kg.
The density of air is 1.20 kg/m^3.

(b) Discuss other factors that can affect the efficiency and economy of modern vehicles, such as materials of construction.

(c) Discuss the sustainability aspects of modern materials from a Life Cycle Assessment point of view.

3. Impact of Pipe Size and Pressure

When designing a process, an engineer can impact energy efficiency in many ways. A goal of sustainable design should be to optimize a process for maximum efficiency. A typical chemical industry process design project will involve a multitude of pipes, units, and connections. In terms of fluid flow, it is important to understand how pipe size and pressure changes can impact the energy requirements of a process. Optimization of pipe diameters and analysis of pressure changes are simple means of creating a more efficient process. Consider water flowing through copper piping at 150 °F with a flow rate of 0.3 ft^3/s. Assuming steady-flow, determine the Reynolds number, pressure loss, head loss, and power requirement for a 325 foot section of pipe.

(a) Perform calculations for pipe diameters of both 2 inches and 2.5 inches.
(b) How can a better understanding of pressure changes, friction factors, and power requirements impact the sustainability of a process design?
(c) Estimate the weight difference between 2-inch and 2.5-inch steel pipe. From a life cycle perspective, discuss the potential trade-offs between installing heavier pipe versus the reduced frictional losses.

4. Wastewater Treatment

Wastewater treatment is one example of the practical applications of fluid mechanics in conserving water usage, limiting the release of pollutants, and creating a more efficient process. Often wastewater from one process can be reused in other processes on the same site. If it cannot be reused, it can at least be treated to remove pollutants and avoid potential toxic buildups. Recycling and treatment of wastewater not only conserves water, but also can reduce operating costs. Wastewater can be treated in a variety of ways, including the use of open-air remediation.

Consider an open channel of finished concrete that collects wastewater and transports it to a set of remediation trenches. The channel is 1 m wide at the bottom and the minimum flow height is 0.5 m. The channel gradually descends 0.15 m every 150 m as it approaches the remediation area.

(a) Assuming steady, uniform flow and a constant bottom slope and friction coefficient, determine the volumetric flow rate. Assume a Manning coefficient of n = 0.012.
(b) Discuss the importance of wastewater treatment with regard to sustainability in both industry and the public sector.
(c) Evaporative losses are a potential problem with open channel flow systems. Discuss the sustainability implications for evaporative losses and brainstorm engineered solutions to minimize losses.

5. Pump Hydraulics

Consider a process to pump isopropanol at 150 gallons per minute from a railcar at atmospheric pressure and ambient temperature to a storage tank. The pump sits at ground level with a minimum static head of 3 feet and pumps the isopropanol to the storage tank through a pipe rack at an elevation of 30 feet above the pump discharge. The storage tank pressure is maintained at 2.0

psig. Assume negligible friction losses in the inlet piping. Assume the discharge piping is 200 equivalent feet of 3” schedule 40 piping and that the pump operates at 65% efficiency.

(a) Draw a sketch of this system and label the appropriate lengths and elevations.
(b) Calculate the total differential head and brake horsepower for the system.
(c) Assume that the piping is changed instead to 3” schedule 40 piping. Calculate the change in break horsepower for this piping change.
(d) Discuss the trade-offs with regard to sustainability for this design change.

6. Natural Ventilation

Many European cities have implemented the concept of natural ventilation in building designs as a means of climate control. While commonly accepted in Europe, the application of this concept is still growing in the United States. Stack-driven natural ventilation utilizes the thermodynamics of the pressure differences between warm interior air and cooler exterior air. By allowing cooler air to enter into the bottom of a building and warmer air to escape through vents in the roof, it is possible to maintain a comfortable interior climate without the large energy consumption of standard air conditioning. A further advantage of the stack-driven method is that it does not require wind. However, regional climate has proven to be a significant factor in the use of natural ventilation. Cool to moderate climates, such as in northern Europe, tend to be ideal.

Consider a building on the northern California coast that has been designed with stack-driven natural ventilation. A square 0.5 m wide commercial steel ventilation duct runs from the bottom of the building to a vent at the top. Cool ocean air at 15 °C enters the bottom duct and travels 60 m through the building to the vent. The interior temperature is 25 °C. Use the following equation for air flow from the ASHRAE Fundamentals handbook to determine the air flow rate (m^3/s) through the duct:

$$Qs = Cd*A*\sqrt{\left(2 * g * Hd * \frac{Ti - To}{Ti}\right)}$$

Cd is the discharge coefficient (assume 0.65), g is the gravitational constant, and A is the cross sectional area of the duct. Hd is the distance from the bottom duct to the midway point between each opening (assume the bottom duct to be at height = 0). Ti is the interior temperature and To is the exterior temperature. Use this information to determine the friction factor for the duct. Assume an average temperature in order to determine density and viscosity data.

(a) What would be the minor losses and total head loss (assuming a constant diameter) for the duct with two 90° miter bends, a sharp-edged inlet, and a sharp-edged exit?
(b) Comment on the potential advantages and disadvantages of such a system with regards to sustainability.
(c) Discuss the importance of material selection when designing such a system. What are the sustainability implications of material choice?

7. Simplification of Design Through Gravity Flow

The need for available, clean water continues to be an important issue for industries and communities alike. The treatment and transport of water can often be made more efficient and cost-effective through the application of sustainable design concepts. One example of this is the simplification of a design through the use of gravity flow. Gravity flow can be used in place of or as a supplement to pumps. The result is often not only more efficient, but also contributes to a more sustainable and inherently safe design.

Consider a water supply system with a required flowrate of 150 gallons per minute. The pressure in the origin and destination vessels is 1 atmosphere, the temperature is ambient and the equivalent feet of pipe for this system is 500 feet in the discharge line and 50 feet in the suction line. The height difference between the origin and destination vessels is 10 feet. It is proposed that gravity flow be used to meet this demand. You may assume the vapor pressure of the water is 0.45 psia.

(a) Assuming a 3 inch pipe, calculate the potential energy savings for switching to gravity flow if the pump operated at an efficiency of 65%.
(b) Determine the diameter of pipe required to meet the 150 gallon per minute requirement for emptying the tank if gravity flow is utilized.
(c) Describe as many industrial processes as you can that could utilize gravity flow to minimize energy usage.

8. Deep Water Heat Sinks

Cold water from deep within lakes, rivers, and oceans is often used as a sustainable means of creating a larger heat sink for heat dispersion in industrial and residential heating/cooling systems. While these systems often use a fraction of the energy of typical cooling systems, the energy required to pump the water from the bottom of a lake must also be considered.

Consider a facility that uses water from 100 meters below the surface of a lake for cooling purposes. A pump works at an efficiency of 70% to bring the water up the length of the pipe at a flow rate of 0.1181 m^3/s. The water must also be pumped an additional 15 meters from the lake to the facility. Assume an irreversible head loss for the system of 3 meters and a density of 1000 kg/m^3.

(a) Determine the useful mechanical power and the shaft power of this pump.
(b) What are some potential problems that such a system might encounter as opposed to standard cooling water systems?
(c) How do these potential problems affect sustainability? Present specific issues as quantitatively as possible.

9. Desalination

Improved water management and conservation have become necessities to ensuring that the needs of an ever-growing world population are met, as well as continued economic growth. Since the vast majority of water on the earth is saltwater, desalination systems represent a practical means of increasing freshwater supplies. Desalination is particularly useful in locations that lack sufficient rainfall or groundwater, but it can also supplement existing reserves. There are potential risks to the environment with desalination. The marine ecosystem can be damaged as the highly concentrated brine that results from the process is returned to the ocean. One way of mitigating this threat is to dilute the brine with a waste water stream.

a) Consider a 50 gal/min stream of brine with a salt concentration of 15 wt % that must be diluted to 4.6 wt % before being released to the ocean at a depth of 95.6 ft. The brine collects in a vessel and is held at a constant level by pressurization. A similar vessel contains a constant level of fresh water that is mixed with the brine before entering a 250 ft stainless steel pipe that empties into the ocean. Calculate the necessary flow rate of fresh water to be mixed with the brine.
b) Using the flow rates from part a, determine the pressures (in kPa) at the top of the fresh water and brine vessels. Both vessels are maintained at a constant level of 10 ft. The fresh water pipe and brine pipe have equivalent diameters of 3 in and 2 in, respectively. The fresh water pipe is 25 ft long and the brine pipe is 50 ft long. After the mixing point, the descending pipe has an equivalent diameter of 4 in. Assume all pipes to be stainless steel. Assume the density of fresh water, brine, and the diluted stream to be 1000, 1107, and 1030 kg/m^3, respectively. Assume all viscosities to be equivalent to that of water at 25°C.

10. Biodiesel Production

The biodiesel industry continues to grow as the need for sustainable, alternative energy sources increases. A variety of renewable biodiesel feedstocks are available, including sugar, soybeans, and switchgrass. The oils from these feedstocks are typically pumped into the reactor using positive-displacement pumps. These pumps are ideal for the high viscosities of such oils.

(a) Determine the closed volume (V_{closed}) of a two-lobe rotary positive-displacement pump that operates at 600 rpm with a flow rate of 150 m^3/hour.
(b) What are some potential biodiesel feedstocks available in your community and surrounding region?