Thermodynamic Analysis of Petroleum and Bio-Based Fuels in Internal Combustion Engines
Module Example Problems

Example 1: Thermal Efficiency using Biomass

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.

Example 2: 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 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 or various biomass sources. List the possible reasons for this difference.
(c) How would the life cycle impacts of biomass transportation effect the sustainability of utilizing this fuel source?

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Example 3 – Efficiency of Thermodynamic Cycles

Pikes Peak is a mountain in Colorado with an elevation of just over 14,000 feet above sea level.   Unlike most mountains of this elevation, it is possible to drive to the summit via the Pikes Peak Highway.

From a thermodynamics standpoint, we know that the inlet air temperature and pressure are factors in calculating the power output of an internal combustion engine. The relationship between elevation and atmospheric pressure under adiabatic, ideal conditions in SI units is given by:

$$\frac{dP}{dz} = -\frac{g \cdot MW \cdot P}{R \cdot T}$$

The relationship between temperature and atmospheric pressure under adiabatic, ideal conditions in SI units is given by:

$$\frac{dT}{dz} = -\frac{g \cdot MW}{Cp}$$

Consider a drive from Colorado Springs, Colorado, elevation 6,000 feet above sea level to the top of Pikes Peak In a 2.0 Liter 4-cylinder, compression ignition engine operating on the Diesel cycle, with a compression ratio of 20 and a cutoff ratio of 5 (Note: Cutoff ratio is the ratio of the expanded volume due to combustion to the post combustion volume of the cylinder). Conditions in Colorado Springs are 65°F and 29.7 in Hg at the start of the drive. Calculate the change in engine efficiency for this drive for the following internal combustion engines.

a) Calculate the loss in engine horsepower due to the change in elevation. Assume a constant engine RPM of 3000.
b) Calculate the required increase in engine RPM to maintain the original horsepower.
c) Explain how the use of a turbocharged engine could overcome this loss in engine power due to altitude change.
d) Research how modern fuel injected engines operate to account for changing oxygen concentrations in the combustion chamber.