A Senior Level Experiment on Developing an Energy Efficient Biomass Gasification Process

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Abstract:

The continuing depletion of non-renewable fuels has prompted the search for alternative sources of energy. Biomass is waste derived from previously living materials such as wood and Municipal Solid Waste, and has been identified as a potential source of energy because it is renewable and abundant. Gasification is one process that can be used to extract energy out of this biomass. Typically used with fossil fuels such as coal, gasification of biomass can generate syngas, which is a mixture of carbon monoxide and hydrogen.

Despite the increasing popularity of green engineering, full stand-alone courses addressing this topic would be difficult to insert into the already full chemical engineering curriculum. One potential way to expose students to green engineering is through the senior level unit-operations laboratory.

To this end, a new unit-operations lab experiment centered on the biomass gasification process will be developed. Students will vary the temperature and heating rate of the gasifier, along with volume and moisture content of the biomass. Moreover, students will use gas chromatography to analyze the composition of the syngas produced, and will perform empirical mass and energy balances to serve as a theoretical basis of comparison. These results will allow students to determine the optimal parameters for extracting the most energy from the gasification system. In addition to this experimental work, the background and theory section of the lab report will provide a venue for students to independently explore the process of gasification and the potential of biomass as an alternative fuel. Taken together, this experiment exposes students to green engineering without having to create a semester-long independent course.

Introduction:

"The need for energy and fuels is one of the common threads throughout history and is related to almost everything that man does or wishes to do [1]." For the past one hundred years, the primary sources of energy producing materials have been crude oil and coal. And with the prices of crude oil increasing and the availability of natural resources decreasing, the development of alternative fuels is now on the forefront of the scientific and economic world. Globally since 1860, our energy consumption has increased exponentially. This trend can be seen in Figure 1:

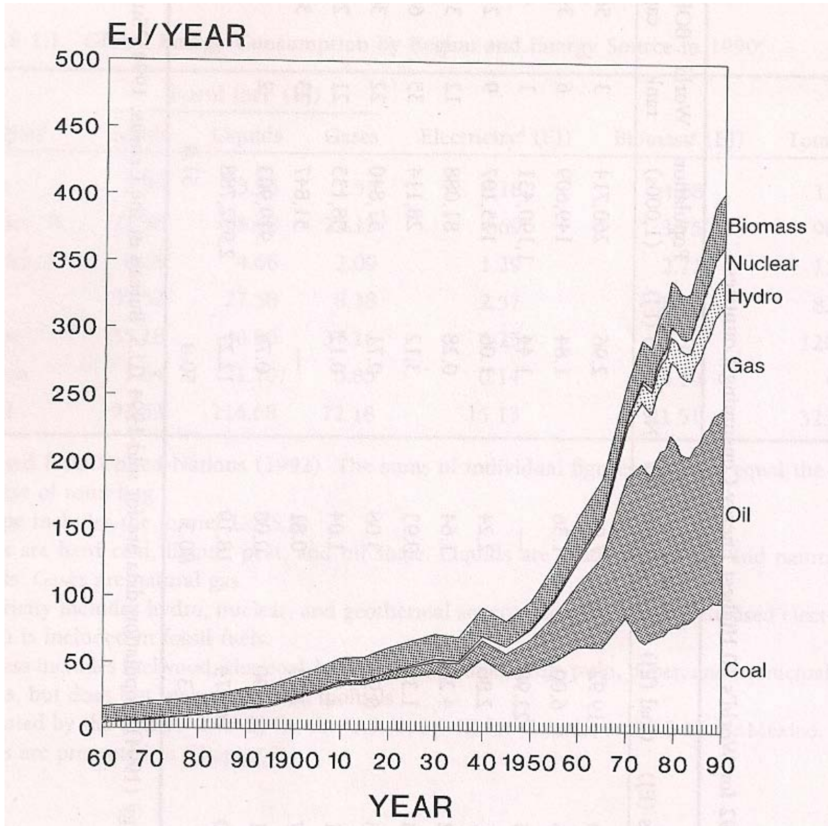

Figure 1. World energy Consumption by resource, 1860 – 1990 [1]

To this end, there has to be a decrease in the contribution of coal and oil, and an increase in contribution of the renewable energy. This trade off is necessary because one can predict from the trend in the past, energy consumption will still increase. There will be a need for renewable energy sources assuming that new sources of oil and coal aren't discovered

In engineering curriculums across the U.S. and specifically Manhattan College, emphasis on green engineering is on the rise. The ideas and methodology of green technology and design should be embedded in each graduating class of engineers.

Background:

As a widely dispersed, naturally occurring carbon source, biomass is a logical choice as a raw material for the production of a broad range of fossil fuels [1]. Biomass is a biological waste that is derived from living or previously living material, such as wood and municipal solid waste. "Biomass can be converted to fuels or energy using biochemical, thermochemical or [traditional] chemical methods [2]." Some of these methods include direct firing, co-firing, pyrolysis, liquefaction and gasification. "Biomass is the only indigenous renewable energy source capable of displacing large amounts of solid, liquid and gaseous fossil fuels [1]." Compared to methods of biomass conversion, other renewable energy sources such as thermal, wind and hydro energy are expensive and produce insufficient quantities of energy in relation to the cost to produce it [3]. "Biomass fuels are divided into three groups: wastes, standing forests and energy crops, which include trees and herbaceous plants [2]." Gasification is a common process utilized to convert this biomass fuels into energy.

Gasification is the conversion of a solid or liquid into a gas [4]. More specifically, carbonaceous materials, such as biomass, are converted into carbon monoxide and hydrogen. This conversion occurs in a high temperature and high pressure environment with a low presence of oxygen [5]. "Biomass gasification is generally designed to produce low to medium-energy fuels gases, and synthetic gases for the manufacture of chemicals or hydrogen [1]." Possible products obtained from the biomass gasification process are seen in Figure 2 [6]:

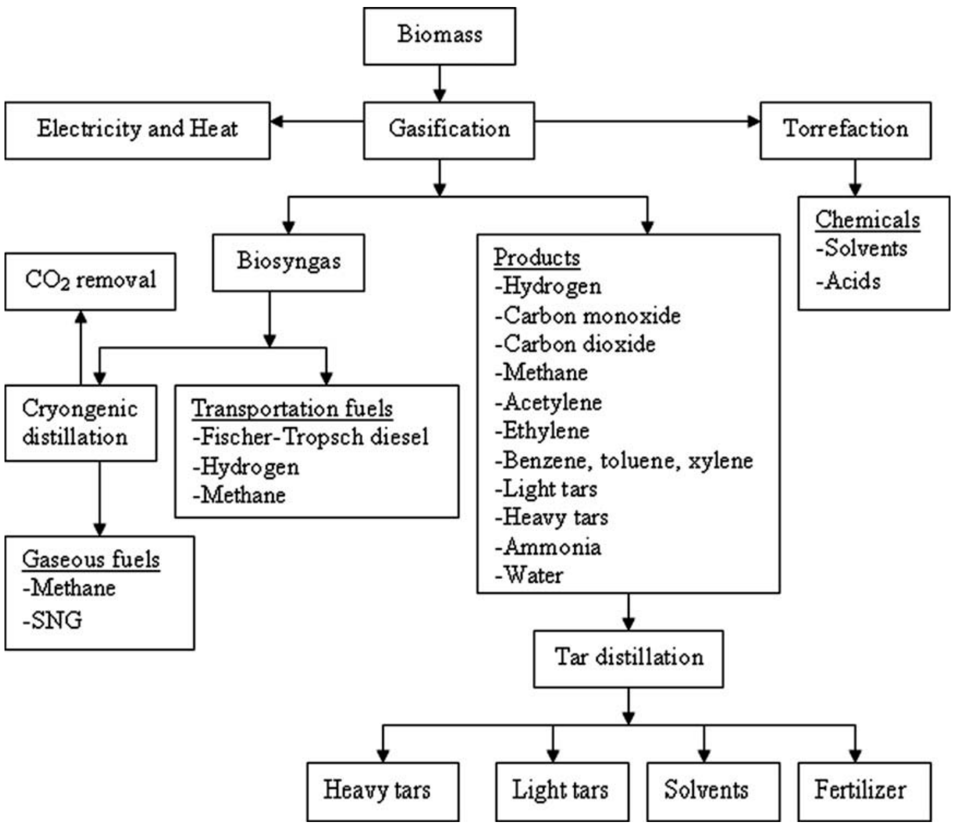

Figure 2. Products of the Biomass Gasification Process [6]

The main product of the gasification process are purified and separated from the aforementioned syngas (i.e., Hydrogen, Methane, additional Natural Gases). There are three main reactions in the Gasification Process [4]:

1. *Oxygenolysis*, or a reaction with oxygen to form carbon monoxide and carbon dioxide. This is actually controlled combustion in an oxygen depleted atmosphere. Much of the oxygen fed to the gasifier, either as pure oxygen or air, is used up in the initial combustion zone that provides the heat necessary for conversion:

$$C + O_2 \rightarrow CO_2 \qquad \Delta H^o_{298} = -393.5\, kJ/mol$$

   In the oxygen-depleted gasification zone, the material may burn in the CO_2 atmosphere according to the Boudouard Reaction:

$$C + CO_2 \rightarrow 2CO \qquad \Delta H^o_{298} = +172.5\, kJ/mol$$

Although the heat of reaction is dependent on the temperature, this dependence is not large and the heat of reaction is represented at 298K for comparison purposes.

2. *Hydrogenolysis*, or reaction with hydrogen to form methane:

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H^o_{298} = -74.8\, kJ/mol$$

Hydrogen also reacts with the nitrogen and other compounds in the material being gasified to yield ammonia. Hydrogen must be added to the system to ensure that the major reaction in hydrogenolysis goes to completion. Hydrogen is most often added in the form of water, i.e., steam.

3. Hydrolysis, or the reaction with water. A typical hydrolysis reaction under gasifier conditions is the endothermic formation of carbon monoxide and hydrogen:

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H^o_{298} = +131.3\, kJ/mol$$

The water,or more specifically the steam fed to the gasifier provides oxygen as well as hydrogen and under some conditions may react to form carbon dioxide directly:

$$C + 2H_2O \leftrightarrow CO_2 + 2H_2 \qquad \Delta H^o_{298} = +90.1\, kJ/mol$$

Or

$$C + H_2O \rightarrow \frac{1}{2}CO_2 + \frac{1}{2}CH_4 \qquad \Delta H^o_{298} = +7.7\, kJ/mol$$

While both of these reactions oxidize carbon to carbon dioxide, they are endothermic and require a heat input. Consequently, oxygen added to the gasifier to provide energy for the conversion should not be combined as water.

The process mentioned above represents the pure reactions of the carbon in the biomass material. It doesn't take into account the other compounds present in the biomass material Present in the biomass fuel are a multitude of various byproducts such as particulates, alkali and heavy metals, oils, tars and aqueous condensates must be taken into consideration. These various metals and tars can cause the major reactions in the energy conversion to become inefficient. The average compositions of the syngases from the biomass gasification process is seen in Table 1 [6]:

Table 1. Composition of syngas from biomass gasification

Constituents	**% by Volume (dry and nitrogen free)**
Carbon monoxide (CO)	28 – 36
Hydrogen (H2)	22 – 32
Carbon dioxide (CO2)	21 – 30
Methane (CH4)	8 – 11
Ethene (C2H4)	2 – 4
Benzene-Toluene-Xylene (BTX)	0.84 – 0.96
Ethane (C2H5)	0.16 – 0.22
Tar	0.15 – 0.24
Others (NH3, H2S, HCl, dust, ash, etc.)	<0.021

After the reaction has come to completion, the desired products, carbon monoxide, carbon dioxide and hydrogen are available for the ultimate goal: synthesis. The primary synthesized product is methanol. The simplest synthesis reaction is the combination of one mole of carbon monoxide with two moles of hydrogen to form methanol; the reaction is seen below [4]:

$$CO + 2H_2 \leftrightarrow CH_3OH(l) \qquad \Delta H^o_{298} = -128.2\, kJ / mol$$

This methanol produced can be stored in liquid form and used as a source of direct energy.

There are two concerns when it comes to the environmental impact of biomass gasification. One concern is that to acquire an adequate quantity of biomass to produce these syngases, it will alter the balance of the environment. The second concern is that during the process to convert biomass to energy it will pollute the surrounding environment.

Environmental Degradation. “Any activity taken on the scale necessary to contribute significantly to U.S. energy needs has the potential for profound upsets of climates, ecological balances, and other factors in the environment [3].” The mass cultivation and harvesting of biomass will upset the surrounding areas. There is no such thing as free land, especially when it comes to the eco-system. A company/organization would be able to purchase a plot of land to set up a standing forest or an energy crop system, but by clearing the land and setting up an artificial and most likely closed system, it would alter the surrounding ecosystem. For instance, if a pond were turned into an energy crop, whoever sets it up would close it off so the algae or plant life wouldn’t be disturbed during growth. This would take away a water source for the surrounding wildlife and would also alter the living organisms in the pond itself. This is also the case for energy crops or standing forests in vacant plots of land or ocean areas. It isn’t just the creation of the biomass that affects the surrounding environments; it’s also the implementation of the facilities to carry out the process of gasification to these environments. A biomass gasification facility of any size will affect the quality of living for both humans and animals [7].

Environmental Pollution. Gasification facilities share the same environmental problems associated with mass burn incinerators including [7]:

- Air pollution
- Water pollution
- Disposal of ash and other by-products
- Large amounts of water for cooling purposes
- Disincentives for waste reduction
- Diversion of waste from composting and recycling

Gasification of biomass might be a feasible option for decreasing the U.S. reliance on coal and oil, but it is just adding to our global warming problem. The gasification process yields carbon dioxide, one of the major green house gases, and if not contained properly will just add to the problem. To counter this issue, if the biomass used in the gasification process is obtained using standing forests or any other organism that utilizes photosynthesis, the carbon dioxide produced in the gasification reaction equals the carbon dioxide consumed in the photosynthesis reaction. Another environmental issue is the disposal of the undesired byproducts from the gasification process;, this material, including tar, ash and heavy metals, is brought to landfills where it will affect the surrounding water and air systems [7]. This increases the toxicity of the landfills.

Integration into Engineering Education: Unit Operations Lab – Gasification of Biomass:

The implementation of a new unit operation lab is a unique way to integrate green technology and design into the curriculum of an undergraduate chemical engineer. Utilizing this idea as a lab experiment lets the students get a hands-on perspective of the process rather than just applying the idea on the blackboard or on paper.

The students will have access to the gasifying apparatus and the GC (Gas Chromatograph), to analyze their product gas. They will be instructed on how to properly set up the apparatus and use the GC through the experiment's lab protocol and the assistance of the lab instructor and teaching assistant. The biomass materials the students will use during their experimental trials are waste grains that had been used during the freshman course, Intro to Engineering. These were used during the beer making process; they are a low quality grain used during the sugar extraction step. The grains will then be dried after the sugar is extracted, so the students in the unit operations lab will obtain a dry basis to start their experiments.

During the lab period, the students need to complete multiple experimental trials with the ultimate goal of determining the relationship between water content of the biomass and the quality and quantity of syngases produced. The students will come to lab prepared with a data sheet for their planned experimental trials; they will need to determine which water contents they will utilize during their procedure. It will be recommended that the students perform four runs at three different water contents and a dry run.

During each experimental trial the students will collect product gas at different time intervals. The gas will be collected in air sampling bags and be tested in the GC during start up of the next trial to be more time efficient. In each trial, the gasifier needs to reach steady state before gas is to be collected, so this would be a good time to analyze the samples from the previous trial. Each experimental trial should take on average one hour, including GC analysis.

During the students lab report write-up, they will perform material balances around their system utilizing initial data and composition data measured in the GC. The students will also discuss and prove the relationship between water content and syngas quality from their experimental data. The ultimate goal of the implementation will come when the students write the methods and background and theory section of the lab report. It is in these sections where the student will research the gasification process along with the viability of biomass as a renewable energy source.

Acknowledgment

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