A TIRE GASIFICATION SENIOR DESIGN PROJECT

That Integrates Laboratory Experiments and Computer Simulation

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The Accreditation Board for Engineering and Technology (ABET) requires that students in accredited engineering programs complete certain requisites to graduate. One constituent is engineering design, "the process of devising a system, component, or process to meet desired needs,"[1] specifically Criterion 4–Professional Component, which is particularly focused on a major design project incorporating appropriate engineering standards and multiple realistic constraints. To fulfill the program, the Department of Earth and Environmental Engineering at Columbia University allows undergraduate seniors the opportunity to work independently under the supervision of a faculty advisor. The faculty advisor's purpose is to guide the student's activities and ensure progress.

The student typically decides on a topic area, such as waste to energy, in consultation with a faculty member. Once the overall project area is identified, a rigorous task plan and schedule are given to the student to begin the design effort. Clearly, this plan must be consistent with any guidelines outlined by the department (*e.g.*, midsemester report, final presentation). In this case, Figure 1 (next page) details the efforts to be undertaken by the student and that are aligned with the department's requirements of a fall and spring term presentation (not shown) and the final report.

One recent student's project involved the conversion of waste tires by thermal treatment to either energy generation or chemical synthesis. The field of study was selected based on the expertise of the mentoring professor and capabilities of the laboratory. Weekly meetings between the student and professor were arranged and a schedule of activities was drafted to facilitate progress toward the design. The first semester (fall) concentrated on researching the topic, creating a design, and justifying the initial feasibility of the design with eco-

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Plan for Fall Semester

0) Motivation **(September 22)**
    a. Market demand
    b. Environmental/Economic/ Global impacts/benfits
    c. Type of waste
1) Previous work **(October 15)**
    a. Patent office **(Next Week)** (www.USPTO.gov)
    b. Textbooks
    c. General literature (journals)
    d. Company info
2) Identify most promising processes (**November 15)**
    a. Product yields
    b. Feedstock accessed
    c. Prototype built
    d. Economics
    e. Energy balance
3) Understand **(December 10)**
    a. Flow diagram
    b. Chemistry and reactions
    c. Thermodynamics
    d. Pitfalls
    e. Lab work
4) Improve **(Ongoing)**
    a. Imagination
    b. Lab work

Plan for Spring semester (**Due dates in bold**):

0) Review of tire pyrolysis and combustion characteristics. **(Jan 14)**
    a. Literature search

1) Materials list for Prototype **(Jan 21)**

2) Lab Work **(Feb 25)**
    a. Combustion – TGA, micro GC **(Jan 28)**
        i. Test Plan **(Jan 14)**
        ii. Kinetics
        iii. volatile fraction; CO_2/CO; optimum atmosphere
    b. Gasification – Same apparatus **(Feb 25)**
        i. Test Plan **(Jan 28)**
        ii. w/ H_2O (g + l); CO_2, CO, air
        iii. GC/MS product analysis
        iv. Effect of Temperature; optimum atmosphere;

3) Computer simulation **(Apr 8)**
    a. Aspen Plus
    b. Use TGA data
    c. Team with Kimberly?

4) Prototype build **(Apr 29)**
    a. Wire and Cellophane
    b. Smoke experiments

5) Final Report **(May 2)**

Notes to plan:

The prototype build might run overtime depending on the complexity of the project. The priorities will be physically observing the design, i.e. the lab work and the prototype build. The main benefit of a computer simulation could be a comparison with the models from last semester so it need not be the focus.

Figure 1. *The student and professor drafted a schedule of activities at the beginning of each semester. The schedule followed the guidelines given by the academic department.*

nomic and thermodynamic calculations. The second semester (spring) focused on executing laboratory work necessary to provide data for input to a theoretical modeling of an overall system. Typically an industry-accepted modeling package is used to conduct simulation and analysis of an overall process. The package used during this project was Aspen Plus v. 12.1 by Aspen Technology, Inc.

Other design projects in which students combined experimental work and computer simulation have demonstrated positive results. In such projects, students can gain a profound understanding of industry in a more stimulating setting than a lecture class. In one project, students were instructed to use theory and experimentation to execute a boric acid dehydration process. The result won recognition from education competitions and Borax Europe, Ltd., an industry leader.[2] In another case, students were prompted to design, fabricate, and test single-component, mechanical products.[3] In both projects, an emphasis was made to complete the curriculum within one or two semesters. In the latter, computer aided design was necessary for compressing the work into the desired time frame. The success of each example project lay in the ability to organize a broad scope of activities into manageable blocks.

The first step of the present design project was for the student and professor to propose a schedule of activities ensuring the student gained exposure to all aspects of the design experience. Shown in Figure 1, this type of work plan allows the student to understand the usefulness of preliminary calculations in guiding subsequent work. All segments of the plan were executed. The prototype build was attempted but not completed, however, because unanticipated opportunities to present the work arose and demanded more effort be devoted to refining what was already accomplished. The remaining sections of this paper are taken from work done by the student during the two-semester design project.

This paper is an example of how to integrate environmental issues such as pollution prevention, reuse, and recovery into the design experience. While this particular project did not use life-cycle assessment methods and tools, it could be a very worthwhile effort to employ them to explore the outcomes for waste tire and other waste-to-energy processes.

BACKGROUND WORK

The project began with a literature survey of academic papers, government programs, and business efforts. Currently in the United States, 290 million waste tires are generated annually. Additionally, nearly 300 million tires (~ 6 million tons) reside in environmentally unsound stock piles. Accordingly, government impetus has created a market for waste tires that currently awards tipping fees to users between $50-100 per ton.[4] Discarded tires have applications as a co-combustion fuel and ground rubber fills in construction materials. Only 9% of the tires currently generated in the United States go to landfills. Current applications for tires are both economically practical and regulated by national standards, but initial research showed opportunities for improvement.[5] Most tires are used as supplementary feed in processes for which they were not explicitly designed. Since many advantages can be realized from a method specifically adapted to the feed, the purpose of the project became to design a system specific to scrap tires.

Since tires possess several distinct qualities as a fuel, thermal processing may offer a broad range of opportunities to improve existing practices. In the United States, three facilities have been established to convert exclusively scrap tires to electricity: Exeter Energy in Connecticut, Modesto Energy in California, and the Ford Heights facility in Illinois. Each facility was built in the early 1990s with a capacity to handle 8-10 million scrap tires per year on conventional equipment to produce 25-30 MW of electricity. Only one remains in business, however, indicating that their profitability is, in the current environment, only marginal.[6] It is anticipated that, with rising energy and landfill prices, an innovative approach may enable a more successful business.

PRELIMINARY DESIGN AND ECONOMICS

Before drafting a reactor design, the economics and thermodynamics of the process were investigated using information found in the literature. These steps were intended to provide a "first-cut" analysis and set the boundaries of feasibility and profitability. A process was proposed with unit operations including: a standard thermal reactor; an electricity-producing system with boiler, turbine, and generator; a gas clean-up system consisting of an electrostatic precipitator, a scrubber and a stack; and auxiliary capital (pipes, pumps, etc.). Costing estimates were obtained from a chemical engineering textbook; size, efficiency, and inflation were incorporated into the model.[7] Tires consist of a mixture of rubber polymer $(C_5H_8)_n$ and carbon black with added fillers such as light oils, fibers, trace metals (zinc), and a steel wire belt. A chemical and elemental analysis of tires was taken from a published source and showed a combustion enthalpy of 35 kJ/g.[8]

The economic model was created for a process scaled to 10 million tires per year (164 thousand tons). The results showed that 16.7% of the tire's enthalpy of combustion could be converted to an output of 28.6 MW of electricity. The revenue generated by the system included tipping fees from the tires ($100 per ton) and electricity sales ($0.05 per kWh). At an interest rate of 5%, the revenue after a 40% tax totaled to $21.5 million per year. The net present value was $201.5 million, which annualized to $8.4 million per year. The profits were $13.1 million per year indicating an internal rate of return of 19%. These results include all relevant parts such as working capital, debt servicing, permitting, and citing. The experiences of the other facilities combusting tires support the estimate.

Although the process proves profitable, the return is lower than most investors would prefer for new technology, indicating that a technological breakthrough is necessary to secure the business. Several reactors for converting waste-to-energy were researched including fixed beds, moving beds, fluidized beds, and rotary kilns.[9, 10] A fixed-bed type reactor was selected for its cost effectiveness, ease of use, and appropriateness to the feed. Additionally, it was proposed that the end product would be syngas (primarily CO and H_2), which was thought to enable more controllable conditions. Syngas can be created by reforming the tires with CO_2 and H_2O. Because these reactions are endothermic, a heat source is required. Thus it was proposed that the combustion of tires with air could provide that heat to drive the reactions. Using sewage sludge as the water source could minimize costs, extending the scope of the design to a truly novel integrated waste converter. The ideas behind the design evolved by employing the principles of process intensification to existing technologies. Process intensification basically is the reduction of process volumes by combining and consolidating multiple unit operations into one physical unit.[11]

DESIGNING THE REACTOR

The reactor was sketched in StudioTools (Alias). Anticipated flow patterns are shown in Figure 2. Scrap tires and stoichiometric air are fed separately into the combustor through an annular pipe. Tires fall and combust on a ceramic plate similar to a grate-type combustion system. The wall of the combustor has two layers: an outer impermeable steel barrier and an inner screen within which primary air emerges. This concept was adapted from the gas turbine industry to maintain moderate metal temperatures of the combustor. The purpose of the double wall is to maintain a unidirectional flow pattern that minimizes the amount of hot gases impinging on the wall. Secondary air actively cools the struts supporting the ceramic plate and assists the combustion. The combustion product leaves the combustor from below and enters the gasifier. The material to be gasified falls from the top in a counter-current flow to the hot gases. Heat transfers to the gasifier across the dividing wall of the combustor and via the enthalpy contained in the combustion product stream. The syngas produced is extracted through a pipe from the top or side. The ash falls to the bottom of the reactor where it is collected and removed using standard equipment. The reactor has similar attributes to a previously disclosed design for a combustion-gasification system of wood chips.[12] Nonetheless, because the system proposed for this project was conceived independently, there are considerable differences to make this design unique. The design possesses capabilities beyond existing technology because it is prepared to handle fuel with a large heating value and high ash content, such as tires, while beneficially using sludge material.

MATERIAL AND ENERGY BALANCES

Material and energy balances were performed for both the combustor and the gasifier. For a reactor that consumes 10 million tires per year (164 thousand tons), combusting 30% in stoichiometric air and gasifying the remainder with 87,600 m^3 of water per year, the results of the calculations showed the syngas to consist of 18.9% H_2, 16.6% CO, 6.0% H_2O, 8.4% CO_2, and 49.9% N_2. The total energy output is 37 MW of sensible heat and 103 MW of chemical energy. The temperatures of the combustor wall and gasifier are 1,040 °C, and 614 °C, respectively. A flame temperature for the combustion of the tires was calculated to be 1,469 °C. Based on a material residence time of one hour, a combustor size of 27 m^3 was calculated with a 2.8 m base diameter.

The gasifier was sized to allow a moderate flow rate of the syngas produced, while enabling most of the large ash particles to settle. This led to a unit of 77 m^3 that is 5.0 m diameter and 3.8 m in height.

The success of the process will be determined by the ability to control the material and heat flow. Because combustion temperatures can run higher than the limitations of most metals, the wall must be kept cool, which will be accomplished by air flow augmented by the fresh tire/sludge mixture entering the gasifier. The double wall will create a unidirectional air-flow pattern and minimize the impingement of hot combustion gases onto the wall. Both the temperature

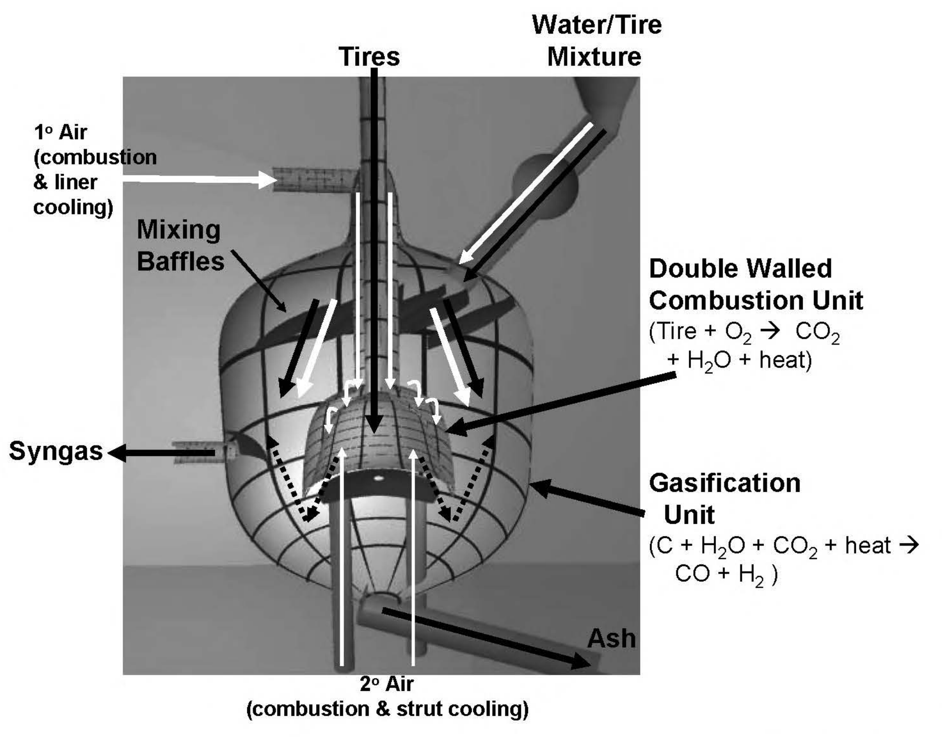

Figure 2. *A rendering of the proposed reactor. Tires and air flow in an annular pipe and combust on a ceramic plate in the center. The combustion product exits the inner chamber from below and mixes with additional water, sludge, and tires. The syngas is extracted from a pipe in the side or on top and the ash falls to the bottom. Baffles ensure the flow patterns run along the planned routes.*

and the syngas quality will be regulated by the composition of the feeds: adding more tires produces more energy and higher temperature whereas more water yields more hydrogen in the product stream.

LABORATORY WORK

While most, and probably all, parameters could be obtained from the literature, one of the advantages of having individual design projects is the ability for students to get hands-on experience working in a laboratory. This enables them to generate pertinent data needed for their design. It also forces students to think of the experimental outcomes before doing the work, thus preparing them to develop practical test methods for efficiently generating data. To enable realistic engineering, basic thermodynamic and kinetic parameters of tires were required. Some of these parameters were obtained from equipment readily available in the faculty advisor's combustion laboratory. An oxygen bomb calorimeter (Parr) yielded the heat of combustion of tires. The bomb calorimeter adiabatically combusted the tire sample at constant pressure. The temperature rise of a water bath correlated to the enthalpy of combustion of the tires. The enthalpy of combustion of tire was determined to range from -33.37 to -36.33 kJ/g which was consistent with established data.[13, 14] Kinetic information was obtained from thermogravimetric analysis (TGA). A Netzsch TG 409 PC instrument was used to record the mass loss of a sample as the temperature was increased at a constant rate. Constant flow rates (100 mL/min) of air (20% O_2; 80% N_2) and inert purge gas (20% CO_2; 80% N_2) flowed over the sample. The air enabled evaluation of combustion parameters while the inert atmosphere was selected to resemble the gasification zone. A plot of the fractional weight loss, α, versus temperature, T, showed that the sample mass decreased as temperature increased. A derivative plot of α showed reaction rates as peaks. At a constant temperature ramp, the reaction rate can be described by $d\alpha/dT$, which follows an Arrenhius rate law.

$$d\alpha / dT = A\beta e^{E_a/RT}\left(1-\alpha\right)^n \qquad (1)$$

where A, E_a, and n are the Arrenhius frequency, activation energy, and reaction order, respectively; R is the universal gas constant, and β is the heating rate.

A representative TGA analysis is shown in Figure 2 in which the student had to convert that raw data to usable data for input into a model for design simulations. Combustion of tires in air revealed five peaks in the derivative plot implying an equal number of reactions, which have been proposed to correspond to light oils, natural rubber, synthetic rubber, and tars.[15] Under inert atmospheres only the first three peaks were observed, implying that the tar only combusts in the presence of oxygen. At higher heating rates the peaks overlap but maintain recognizable reactions.

Because Eq. (1) cannot be solved explicitly, quantitative parameters were derived from a method from the literature.[16] Plotting 1/T versus

$$-\log\left[1-\left(1-\alpha\right)^{1-n}\right]\Big/T^2 \quad \left(1-n\right) \quad \text{for } n \neq 1 \qquad (2a)$$

$$-\log\left[-\log\left(1-\alpha\right)\right]\Big/T^2 \qquad \text{for } n = 1 \qquad (2b)$$

reveals a linear plot for the appropriately chosen reaction order. The Arrenhius rate parameters can be related to the slope, m, and the intercept, b, by

$$E_a = 2.3 \text{ m R} \qquad (3a)$$

$$A = 10^{b\beta E_a}\Big/R\left(1-2\text{ R T}/E_a\right) \qquad (3b)$$

By this method, rate parameters for air and 20/80 CO_2/N_2 atmospheres could be obtained as shown in Table 1.

TABLE 1
Parameters Derived from TGA Experiments
Ascertained by the Derivative Method of Fristky, *et al.*, (1994)
The "Weight" column refers to the amount of mass change that can be accounted for by the reaction. Under air, there was a 5% residual, whereas under an inert atmosphere there was a 38% residual.

Reaction under Air

Reaction	1	2	3	4	5
Weight	15%	13%	23%	20%	24%
E_a (kj/mol)	120	180	187	325	258
A (hz)	5.5×10^8	1.3×10^{13}	2.3×10^{11}	4.0×10^{19}	2.7×10^{13}

Reaction under 20% CO_2

Reaction	1	2	3
Weight	18%	12%	32%
E_a (kj/mol)	95	203	176
A (hz)	1.4×10^6	2.5×10^{14}	3.0×10^{10}

The outflow of the TGA was connected to an Agilent 3000 micro-GC gas chromatograph (GC). Figures 3 and 4 show a typical species analysis of the product gases by the GC, and allowed the student to conduct a material balance ensuring the integrity of the data generated. Combustion under air revealed that CO_2 was the main constituent of the exhaust. Pyrolysis of tires under CO_2 indicated that the amount of CO_2 in the product gas increased slightly during the reaction and no CO was detected. The GC proved useful for determining the product species and can be used in future work to identify important constituents.

SIMULATION

Following the laboratory work, the student then reduced the data and calculated the parameters needed to input into a simulation. There were two sets of simulations done, one was thermodynamic and the other used kinetics obtained from the laboratory experiments to more accurately simulate the combined combustor-gasifier reactor. This allowed the student to better understand the type of information thermodynamics can provide versus an actual operating system where the kinetics play an important role. Results are shown in Table 2.

Thermodynamic Simulation

The thermodynamic data obtained from literature and the student's experiments (bomb calorimeter) were input into Aspen. Tires were defined as a mixture of the rubber monomer (C_5H_8), graphite, iron, and zinc so that the final assay equaled the literature value.[8] Figure 5 shows the process flow diagram of the equilibrium simulation. The combustor and gasifier were represented as two Gibbs reactors connected by material and heat streams. The ideal "separators" surrounding the gasifier selectively remove solids from the streams. A calorimeter module was programmed to combust the syngas with stoichiometric amounts of oxygen only, to enable the student to conduct an energy balance and compare that with initial calculations. The model output of 170 MW total power from 18,700 kg per hour (5.2 kg per second) indicates an energy input for tires of -33 MJ/kg of tire, which is consistent with bomb calorimeter measurements. The product gas is composed of 24.0% H_2 and 10.8% CO. The temperature of the gasifier is 786 °C, which suggests that the temperature of the inner wall may be maintained at an acceptable level. The Aspen equilibrium simulation reflects the material and energy balance calculations from preliminary assessments.

Kinetic Simulations

Upon completion of the thermodynamic simulations, programming of the kinetic parameters began. For this task, the student used his own data generated from the TGA and compared them to literature values to ensure the integrity of the data. The TGA data from Table 1 was used for the Aspen kinetic simulations. The kinetic simulations first attempted to model the TGA experiments to ensure the results were consistent. The simulated TGA was a semi-batch reactor with a charge of the tire sample and a constant flow rate. Due to the kinetic parameters' sensitivity to the phase of the reactants, the tires were modeled as a mixture of coal and graphite—both present in the Aspen database. The Aspen-defined coal had many similar properties to tires. The mixture was modified so that the final analysis of the material would have an enthalpy of -33 MJ/kg

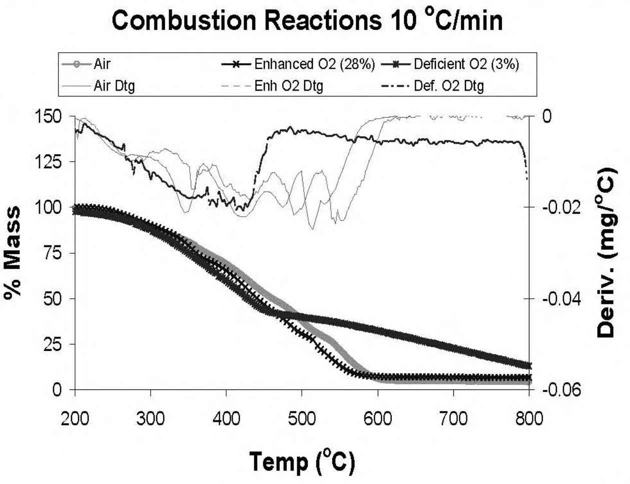

Figure 3. *The results of the TGA with derivative plots show the combustion reactions under O_2 and N_2 atmospheres (Air – 20% O_2; enhanced O_2 – 28% O_2; deficient O_2 – 3% O_2) heated at 10 °C/min.*

TABLE 2

The results of one Aspen equilibrium simulation show a system that handles 164,000 tons of tires (~10 million tires) per year. The power output is 170 MW for a syngas that consists of 34.8% by volume of useful material. The temperatures of each reactor have reasonable values.

Reactant Flow Rates		Product Flow Rates		
	ton/hr		Nm^3/hr x 10^3	%
Tires (total)	18.7	H_2	25.8	24.0
Combusted	5.6	CO	11.6	10.8
Gasified	13.1	CO_2	11.5	10.6
Water	18.0	H_2O	11.2	10.4
Air	97,490 Nm^3/hr	N_2	47.2	44.0

Temperature (°C)		Energy (MW)	
Combustor	1626	Chemical	**130 (eq)**
Gasifier	786	Sensible	**40**

and a total chemical assay of the literature.[8] For the combustion reactions, the tire was separated into six components based on the reactions determined by TGA in Table 1. The gasification simulation used four components. The simulation results of Figure 6 show that the simulation closely approximates the measured data. The correspondence suggest that the kinetic model can be developed further to simulate the combustion-gasification reactor. Although the ultimate plan was to simulate the design of the integrated gasifier and combustor, time did not permit this step. The exercise of conducting a thermodynamic simulation of the entire design and programming the kinetics to simulate the TGA experiments provided the student with sufficient experience to complete the project had time permitted. Upon completion of this task, the student was keenly aware of the many ways to arrive at designing a new technology or modifying an existing technology. Moreover, the student was now well prepared to understand the importance of experimental data generation and how to attack such a process in the future.

OUTCOMES

The undergraduate design project taught the student how to address engineering challenges. The literature research aided in the design of the combined combustion-gasification system, which was devised solely by the student. The professor's role was to provide insights into the merits and limitations of such a device. Using a more experienced knowledge base, the professor was able to recommend calculations and experiments that would prove the design.

The independence of the student allowed greater opportunities for learning about the business environment surrounding waste manage-

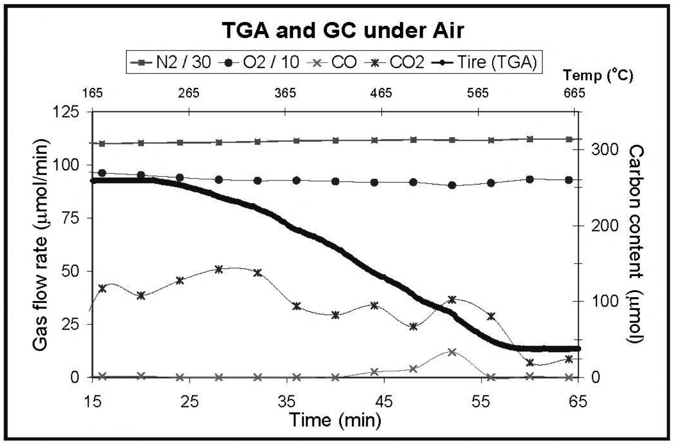

Figure 4. *GC flow rates (left axis) plotted with TGA mass loss (right axis) for flow under air. The O_2 and N_2 curves are scaled by 1/10 and 1/40, respectively. CO_2 is produced throughout combustion; CO increases in the tar region.*

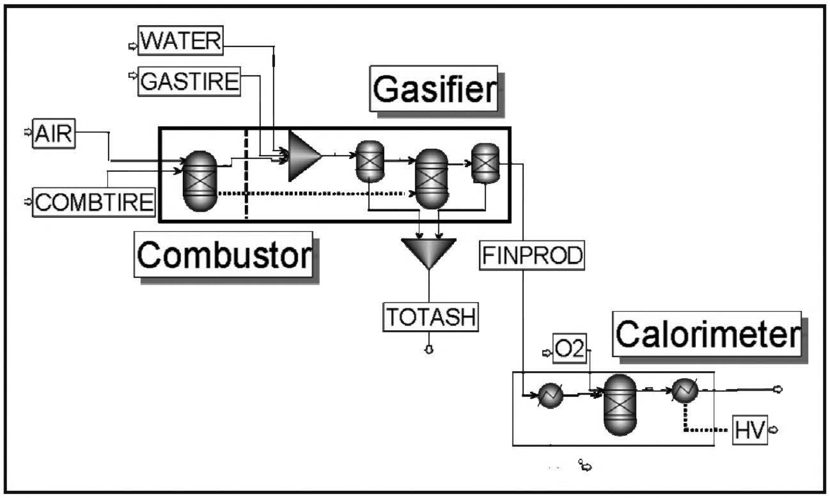

Figure 5. *Flow diagram of the primary reactor. All feeds began at room temperature (20 °C). The calorimeter was added to measure the heating value (HV) of the final product gas (FINPROD).*

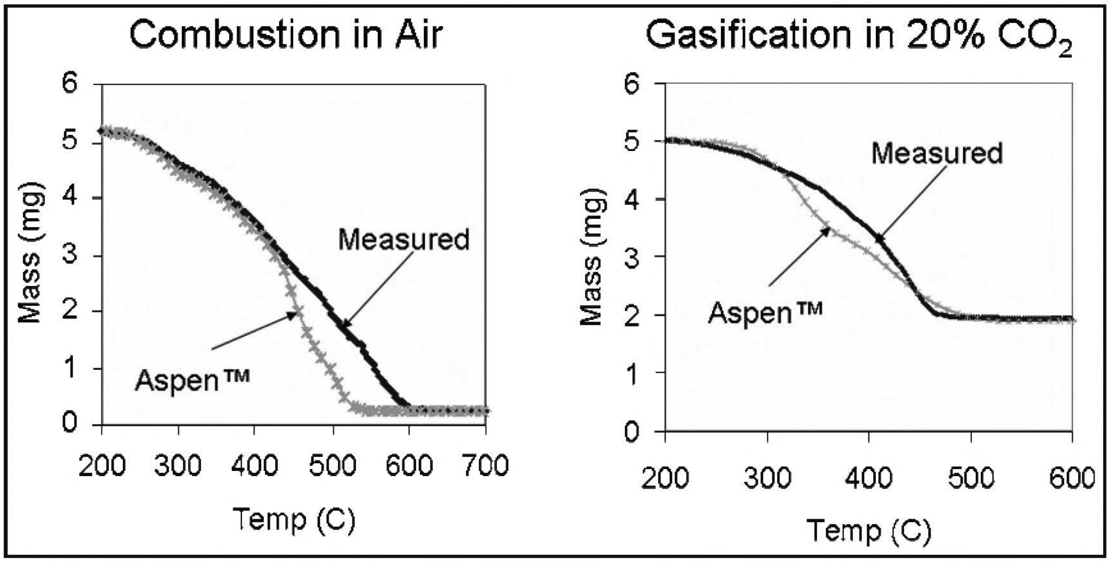

Figure 6. *The measured data (solid line) and the Aspen simulation (dashed line); the model shows potential for developing further investigations.*

ment, industrial thermal processes, reactor designs, and the engineering process. Performing the laboratory experiments helped the student comprehend the operation of standard analytical tools. Further, the student began to understand how to devise a test plan and allocate adequate time to attain a sufficient amount of data. The Aspen simulations were instructive in demonstrating the next level of design execution and evaluation. Finally, to expose the student to the experience of communicating the work, poster or lecture opportunities were pursued with presentations at two academic departments in Columbia University and Barnard College, at a university-wide undergraduate research symposium, and at an American Chemical Society meeting.[17]

The individual responsibility for the project encouraged a greater commitment from the student and allowed a wider platform for innovation. The development and successful implementation of the project, however, may have benefited from a larger undergraduate or graduate team. Nonetheless, the student was able to maintain the directives assigned in the predetermined schedule and provide a report at the end of each term. The time frame of the project allowed ample time to understand basic aspects of designing a reactor and carry out the preliminary steps. The student was able to identify future directions for the project in the final report. It is anticipated that the student will be better prepared for future work as a professional engineer and that the project described herein may be continued under other circumstances.

IMPLEMENTATION

A suggested implementation strategy is briefly presented for those who wish to augment a traditional chemical or environmental engineering capstone experience with a similar effort. Provided the scope of the project is contained and a schedule is put forth at the beginning of the semester, a project such as this becomes very manageable. As evidenced in Figure 1, all elements of engineering design are covered. An important aspect of this type of project is to have the course span two semesters to give students time to assimilate material, develop and design processes, and possibly build devices or conduct limited experiments.

So as not to risk skipping or eliminating any of the critical areas of the design process, the real task, for the student and faculty advisor, is not to spend extensive time on any one area. All components should be developed to the extent that the student can see a clear path to the outcome of each task. Most engineering departments maintain a software license to the common programs used in industry and typically have some level of laboratory capabilities. This leaves only the task plan and timing to be formulated and strictly followed. For reference, the hours spent by the student and faculty advisor on this project were no more than a typical design course and the cost of everything except for the software license was under $200. Typically, software licenses are heavily discounted for educational institutions.

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