



An Inexpensive Inverted Downdraft Biomass Gasifier for Experimental Energy-Thermal-Fluids Demonstrations

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Kyle Pace

Jeremy R Anderson, EASENET

Jeremy is a retired Navy Diver, sustainable energy engineer, and social entrepreneur. Growing up in a rural Texas community Jeremy endured great hardships, forming the unmatched resiliency that drives his continued successes. Out of high school, Jeremy joined the Navy and quickly ascended the ranks to First Class Petty Officer in only six years. Starting out as a Hull Maintenance Technician, Jeremy found an affinity for design and fabrication; this led to his acquiring the rates coveted title "Super Welder" in only three years. Having reached this apex so quickly, and fearing stagnation, Jeremy sought more challenging opportunities to expand his skill sets. The search ended when Jeremy decided to become a Navy Diver and thus a member of one of the militaries most elite communities. His aptitude for leadership shown true as he directed many high-risk/high-stress diving operations resulting in numerous awards and accolades. After eight years of honorable service, he was no longer able to dive and was medically retired from the Navy.

Jeremy's current path started with an acceptance into the Mechanical and Energy Engineering program at the University of North Texas. In the spring of 2010, Jeremy began performing renewable energy research. Soon after, he was leading a team of researchers and collaborating with a green energy start-up. He was the first and only UNT engineering student to be selected as a McNair Scholar, a competitive scholarship offered to top juniors and seniors at select schools around the country. In the summer of 2011, Jeremy accepted a research assistantship at the Milwaukee School of Engineering. This move allowed Jeremy to focus on his passion for innovation, leading to a grant in aid of research from Sigma Xi. This grant funded his development of a novel pyrolysis biomass processor that extracts energy from biomass waste streams. Now, Jeremy is leveraging all of these experiences to lead EASENET in transforming the world of energy.

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Abstract

To facilitate experimental introduction of biomass-to-energy technologies in an upper-division undergraduate thermodynamics course, a small, inexpensive wood chip gasifier was designed, constructed, and tested. This device was built from a metal vacuum-flask-style thermos bottle, and it was constructed for less than \$50. The design is both simple and economical. In the reported experiments, the gasifier processed pine wood chips (rabbit cage litter – available from any pet store), but it could also accommodate a variety of other dry, solid biomass feedstock including other wood types, grass, shredded paper, or leaves.

Oriented in an ‘inverted downdraft’ configuration, the gasifier motivates teaching opportunities through experiments in heat transfer, fluid mechanics, thermodynamics, and combustion. The apparatus provides both enriching outdoor demonstrations for lecture classes and serves as a laboratory exercise (as reported here) viable for any energy-thermal-fluids course. Within a single charge of wood chips, there are two reaction zones. The bottom wood layer smolders, converting chemical energy to heat. This heat conducts upward through the chips into the pyrolysis layer. Here the wood is converted to syngas composed of flammable hydrogen, carbon monoxide, and methane as well as inert nitrogen and carbon dioxide. Natural convection drives the syngas through the gasifier’s burner (the thermos bottle’s neck). In parallel, ambient air is drawn up the space between the thermos inner flask and outer wall. At the burner, combustible fuel combines with oxygen in the air to support a flame.

To juxtapose biomass gasification and subsequent syngas combustion against directly burning wood chips, students also burned identical masses of pine wood chips placed in an open-air container. Students logged mass depletion as a function of time and measured the initial and final wood chip masses for both combustion techniques to quantify energy conversion efficacy through ash generation. They found gasification converted more than 97.8% of the biomass to syngas while direct burning left more than 5% of the initial fuel mass as ash. In some cases direct combustion even left behind substantial unburned wood. Students also took temperature measurements inside the flames for both combustion techniques. Experimental results compared qualitatively to adiabatic flame temperature predicted for syngas versus cellulose and lignin fuels. Despite similar predicted adiabatic flame temperatures, syngas produced by the gasifier yielded a hotter flame than did direct wood chip combustion because the gasifier’s fuel consumption rate was higher and neither system adiabatically contained the flames.

Introduction

According to DeWaters and Powers [1] and to Condoor [2] lack of energy-related knowledge among American students and the general public is endemic. As the world transitions toward a renewable energy future, familiarity with energy and sustainability concepts will become increasingly important. For example the U.S. Bureau of Labor Statistics projects 505,000 engineering positions across all disciplines opening by 2016, a 10.6% increase over 2006 levels. Notably, Environmental Engineering, a field that readily combines energy and sustainability

studies, leads all other engineering fields in percent growth. Environmental Engineering job openings are projected to increase by 25.4% from 2006 to 2016. [3]

While the technical knowledge gap in energy is being effectively addressed in the engineering education literature for solar and wind energy through a variety of innovations, the literature remains surprisingly sparse for bio-renewable energy. In their seminal paper on the need for bio-renewable curricula at U.S. universities, Rosentrater and Balamuralikrishna quantified the dearth of relevant manuscripts appearing between 1997 and 2007 in the proceedings of American Society for Engineering Education conferences: 0 papers on bio-products; 2 papers on bio-energy, 6 papers on bio-fuels, 3 papers on bio-mass, 4 papers on bio-processes, and 10 papers on bio-chemicals. [4] Only 25 total papers on bio-renewable topics at ASEE conferences in 10 years accentuates an unrealized opportunity to improve STEM education and best practices dissemination in this topical area.

At the Milwaukee School of Engineering, we capitalized on an opportunity to teach a bio-renewable energy module within an existing required mechanical engineering class. ‘Thermodynamics Applications’ is a senior-level hybrid lecture/laboratory course in which two weeks are set aside for instructors to teach customized energy-focused modules of their own choosing and design. To help address the lack of bio-renewables coverage illuminated by Rosentrater and Balamuralikrishna, a bio-energy module has been taught in this class for the past two years. In this unit, students experiment with two biomass energy conversion methods, gasification and direct combustion, and they synthesize their results with classroom theory to evaluate the efficacy of both techniques.

Background

Increasing green-energy-focused education is important to meet the growing demand for sustainability-conscious technical professionals. However, the practical need remains to keep technical training in energy balanced with classical engineering and science fundamentals. New energy content must be carefully evaluated and integrated so as not to overburden existing STEM curricula. One solution is to create a broadly-accessible introductory-level elective course in energy engineering. UC Santa Cruz, for example, created “Renewable Energy Sources,” a prerequisite-free class that attracts students from all STEM fields as well as humanities, art, and social sciences. [5] The course is built around seven simple renewable energy experiments including a flywheel; sun tracker; fuel cell; and power conversion through photovoltaic, hydroelectric, thermoelectric systems. While laudable both for its ubiquitous and accessible student engagement and its seamless insertion of hands-on energy activities into STEM and general curricula, the UC Santa Cruz class omits bio-renewable energy as a topic. To alleviate this gap, the experimental unit described in the current paper could be added to Renewable Energy Sources.

To meet energy and sustainability training needs, other engineering programs integrate hands-on energy content into their engineering curricula via energy-focused design-and-build and capstone senior projects. For example, Sam Houston State University recently reported completion of seven energy and sustainability student projects on topics including A) a renewable energy trainer, B) an environmentally friendly electric boat, C) a solar-thermal space and water heater,

D) design of a self-sufficient residential home, and E) a hybrid wind and solar system. [6] As with the UC Santa Cruz example, no projects containing bio-renewable energy systems were reported by Sam Houston State.

As indicated by Rosentrater and Balamuralikrishna, bio-renewable energy content in STEM curricula is rare. However, use of biomass reactors for education has been reported in some recent literature examples. For example, an anaerobic digester test-bench was designed by students at Saint Louis University but not reduced to practice. [2] In another example, reported by Manhattan College, senior chemical engineering students designed and built a biomass gasifier to consume brewing waste and measure the chemical components of the resulting syngas via gas chromatography. [7]

In addition to bemoaning lack of bio-renewable teaching, Rosentrater and Balamuralikrishna also implore engineering educators adopting bio-renewable topics to expose students both to theory as well as provide meaningful hands-on experiences working with bio-renewable experiments and equipment. Since engineering students typically enjoy very limited bio-processing experience from foundational STEM laboratory classes like physics and chemistry, hands-on learning is critical to provide essential background experience in energy and sustainability. [4]

To integrate energy topics, particularly bio-renewable systems, into STEM curricula, we propose an alternative to creating new classes or concentrating content into senior projects. Instead, an archive of “Energy Engineering Laboratory Modules” (EELMs) is being developed by collaborating faculty and students at MSOE, accumulated, and disseminated to facilitate spiral insertion of energy engineering concepts into college and high school courses across STEM curricula. For example, a series of building energy audit exercises was recently created and described that harvests existing buildings as living laboratories suitable for quantitative evaluation using an inexpensive audit tool kit. [8] EELMs are envisioned as economical, hands-on, “turn-key” activities that can be incorporated into any STEM curricula to introduce energy studies without the need for specific standalone energy engineering courses. This paper introduces a biomass gasifier EELM with the goal of increasing access to bio-renewable energy technical training.

While coverage of bio-renewable systems appears sparse in the engineering education literature, this technology has been extensively studied and reported in the technical literature. Technical inspiration for the biomass gasifier EELM reported here is drawn from this substantial literature body. For example, a recent review by Rasul and Jahirul nicely describes the state of the art for biomass pyrolysis, [9] which is the feedstock processing technique used by the gasifier described in this paper. Pyrolysis exposes biomass to elevated temperature ($\sim 700^{\circ}\text{C}$) in an oxygen-poor environment that prevents combustion. The resulting thermo-chemical breakdown of biomass feedstock produces syngas, which is made of hydrogen, carbon monoxide, methane, nitrogen, carbon dioxide, and trace gasses. Owing to the first three components, syngas burns in air, producing useful thermal energy for heating and other thermodynamic applications.

Equipment and Methods

This bio-renewable EELM presents a comparative study between wood gasification and conventional direct wood combustion. The gasifier, which is pictured and shown schematically in Figure 1, was constructed from a commercially-available stainless steel vacuum-flask-style thermos bottle. To better retain heat, the gasifier was thermally shrouded with batting held in place with stove ducting and hose clamps. No special tools were required for fabrication; the thermos bottom was cut off with a hack saw and holes were drilled into the metal with a hand drill. The entire apparatus was constructed for less than \$50.

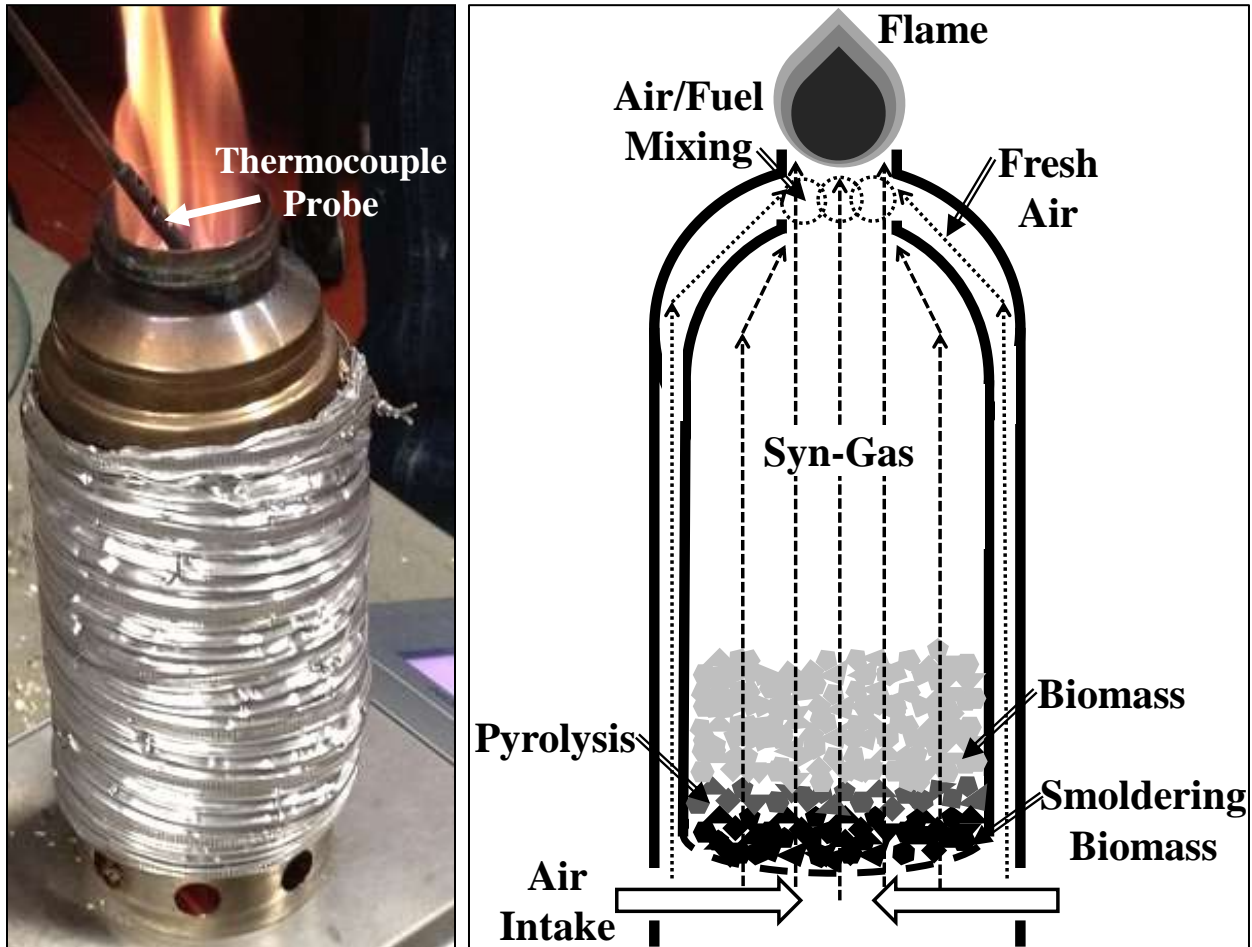


Figure 1: (Left) A simple, inexpensive wood gasifier built using hand tools for less than \$50 from a stainless steel vacuum thermos forms the central experimental apparatus for the bio-renewable energy EELM. (Right) A schematic representation of this inverted downdraft gasifier shows locations for biomass fuel, airflow paths, air-fuel mixing, and combustion.

The gasifier is self-heating, using a smoldering wood layer to provide thermal energy for pyrolysis. It is oriented in an ‘inverted downdraft’ configuration, which means ambient air enters from the bottom to arrive at the biomass and sustain a smoldering layer sitting on the bottom of the fuel supply. This stationary heat source converts the biomass layer above to syngas by pyrolysis. As the biomass is consumed, fresh fuel replaces it from above until the entire supply is

exhausted. A convenient feature of this gasifier is once the smoldering layer is established, the biomass can be replenished through the thermos top while the gasifier is still running.

The produced syngas travels unburned through the remaining biomass fuel layer up to the throat of the thermos carried by buoyant natural convection. Simultaneously, some air entrained at the gasifier's bottom and heated by the warm thermos walls is carried by buoyancy past the fuel to the thermos throat. It is critical that the gasifier be made from a vacuum thermos because the vacuum space provides a clear pathway for fresh air to traverse upward without being consumed by the smoldering layer (see Figure 1 schematic for air flow paths). At the thermos throat, the fresh air and syngas meet and mix; if ignited this air-fuel combination will burn steadily for the experiment's duration until the fuel supply is exhausted.

The entire gasifier was placed on a digital scale, providing instantaneous mass measurement during the process. A Cen-Tech Digital Scale with 5000 g capacity and 0.1 g precision (less than \$30) yielded adequate mass data. Using a stopwatch, students read and recorded instantaneous mass from the scale at 30-second intervals. As the syngas combustion process proceeded, students carefully interrogated the temperature of the gasifier walls, the flame itself, and the wood gas upstream of the combustion front using an Omega thermocouple probe with insulated handle (less than \$40).

To experimentally juxtapose biomass gasification and subsequent syngas combustion against direct biomass combustion in air with no gasification, students burned an identical mass of pine wood chip biomass in a metal mesh open-air container (shown in Figure 2).

To keep the wood chips from falling through the open mesh, they were placed atop a finer screen at the bottom of the container. One of the challenges with this direct biomass combustor was getting all the fuel to burn without agitating the pyre once lit. Once ash formed around the outside surface of the fuel, it prevented adequate amounts of air from penetrating deeper, quenching combustion. Students running this experiment devised two solutions to prevent premature extinguishing. First, they packed the wood chips very loosely to promote air flow, and second, they stood the metal mesh basket up off the scale stage with a hollow metal stand to promote air flow through the basket's bottom.

As with the gasifier, the entire metal mesh basket was placed on a digital scale, for instantaneous mass measurement during the process. Students keeping time with a stopwatch, read and recorded instantaneous mass from the scale at 30-second intervals. Students used the thermocouple probe to carefully interrogate the temperature of the burning wood chips and the flame itself.

A Kestrel 4500 pocket weather station was set up in the laboratory to log temperature, humidity, and barometric pressure data. While these data streams were not essential to the experiment, they proved helpful in explaining performance differences between observed between different days. It was sometimes difficult to get all the fuel to completely burn in the direct combustor experiment. Since the wood chips were stored in an open-air container in the laboratory, they were free to absorb moisture from the air, and combustion performance was generally poorer on more humid days. Moisture content is known to significantly impact biomass combustion

because absorbed water consumes energy by flashing to steam. We hypothesize that poorer performance observed on humid days arose from the wood chips containing higher moisture content during those experiments. While not done for these EELM experiments, the day-to-day biomass moisture content could be quantified by placing a fixed biomass volume open to the laboratory on a scale and correlating its apparent mass change to lab humidity.

As described in Future Work, the experiment will be improved in upcoming years by baking select feedstock to drive off and modulate moisture. A control sample of well-dried feedstock will be created via long baking at warm temperature to drive off all moisture. Moisture content of other samples will then be quantified by density comparison to the dried control sample. Combustion performance of various samples will then be tied to moisture content to illuminate for the students moisture's critical role in this biomass-to-energy conversion processes.

While running the two different biomass combustion experiments, students measured the initial and final biomass masses for both techniques, they monitored the rate of combustion by



Figure 2: (Top) An open basket made from scavenged metal mesh holds wood chips undergoing conventional combustion. (Bottom) A schematic representation of the direct combustion burner shows locations of biomass fuel, airflow paths, and the ash formed at the combustion front.

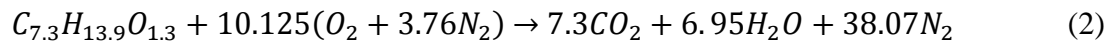
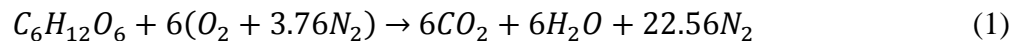
recording mass at 30-second intervals, and they also recorded the temperature of the hottest part of the flame at 30-second intervals. These measurements enabled quantitative analysis and comparison of 1) combustion efficacy [how much of the available fuel is actually burned], 2) fuel consumption rate, and 3) flame temperature. Observed results were then be quantitatively justified using arguments from chemistry, physics, fluid mechanics, heat transfer, and thermodynamics.

Theory and Experimental Results

We report results from two experiments with the gasifier and two with the direct combustor. Students were free to use any initial mass of wood chips they wanted, provided they did not overload the apparatuses with fuel. If time remained at the end of the first set of experiments, student were encouraged to re-run tests with different masses to observe and evaluate any differences. Here results for initial biomass masses of 30 g and 40 g are reported, and it was found that the behavior of each apparatus generally did not depend on the mass of the initial fuel charge.

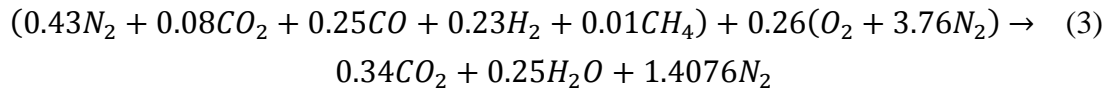
Combustion Chemistry

By mass, pine consists of about 40% cellulose ($C_6H_{10}O_5$) [$\Delta\bar{h}_f^o = -976,362 \text{ kJ/kmol}$], [10] about 28% lignin ($C_{7.3}H_{13.9}O_{1.3}$) [$\Delta\bar{h}_f^o = -1,592,659 \text{ kJ/kmol}$], [11] and the remainder of organic molecules that mostly resemble cellulose and lignin. [12] For the bio-renewable EELM, chemical analysis of direct combustion applied an engineering estimate in which wood was first assumed to be made completely of cellulose and then completely of lignin. For both analyses the fuel was treated as if stoichiometric air were available for reaction. However, as shown later, evaluation of remaining ash indicated incomplete combustion suggesting that oxygen in the air was the limiting reagent. Students making this important connection demonstrated their ability to juxtapose theoretical chemical analysis against experimental results. They realized that engineering models may not always match real experimental outcomes, but these models are nonetheless critical to understanding function of engineering systems and predicting their performance. The two balanced chemical equations for direct stoichiometric combustion of cellulose and lignin in air are, respectively:



Direct analysis of syngas chemical composition requires mass spectroscopy, which was not available at our institution. So, an approximate composition was used, drawing on a literature source, [13] as outlined in Table 1. Syngas produced by the gasifier was thus treated as having the following volumetric chemical composition: 43% nitrogen (inert), 8% carbon dioxide (inert), 25% carbon monoxide (combustible), 23% hydrogen (combustible), and 1% methane (combustible). These gaseous components were produced at atmospheric pressure and were far from their critical temperatures. Thus, their kinetic behavior is well-approximated by the ideal gas model. So, the given volume percentages can be treated as mole fractions. Combustion

analysis on this syngas was performed as if it was burned with stoichiometric air at the throat of the gasifier thermos. The balanced chemical equation for stoichiometric syngas combustion in air is the following:



Direct observation of the combustion pattern in the thermos throat, shown in Figure 3, proves it is the produced syngas that is burning in the throat of the thermos and not the wood chips below.

Table 1: Experimentally-measured syngas chemical composition ranges by percent volume from a downdraft wood chip gasifier with an 800 °C pyrolysis layer reported as a function of feedstock moisture. [13] Since molecular mass spectroscopy was unavailable at our university, the wood gas composition used for our analysis assumed values for 10% feedstock moisture content. While this approach is an engineering approximation, the tight range of syngas composition values ensures minimal deviation from the actual composition.

Molecular Species	N₂	CO₂	CO	H₂	CH₄
Units	[% Vol.]	[% Vol.]	[% Vol.]	[% Vol.]	[% Vol.]
Range from 0% - 40% Feedstock Moisture	44% - 40%	5% - 15%	15% - 28%	20% - 25%	0.9% - 1.4%
Value at 10% Feedstock Moisture	43%	8%	25%	23%	1%

Flame Temperature and Fuel Consumption Rate

Flame temperature for both the gasifier and the direct wood combustor were interrogated by placing a hand-held thermocouple probe directly into the flame and locating the spatial maximum temperature (see Figures 1 and 2). This technique was inexact, and students found large spatial and temporal variations in the measured flame temperature during the combustion process. They commented that even once they located the hottest part of the flame both slight hand movements and evolution of the flame with time led to lower flame temperature readings. Nonetheless, this method gave students qualitative insight into the structure of a flame – that the hottest spot is coincident with the combustion front. Students recorded the maximum measured flame temperature during each experiment to provide



Figure 3: A top-down view of the gasifier reveals a star-shaped combustion pattern aligning with holes drilled in the thermos throat to enable mixing of air and syngas. This pattern proves the syngas (and not the wood chips in the thermos) is burning.

an experimental comparison against calculations for adiabatic flame temperature.

In general, the adiabatic flame temperature for any system undergoing combustion is determined by applying the First Law of Thermodynamics to a steady-state control volume where the reactants enter, react inside the control volume, and the products are then exhausted:

$$\frac{dE}{dt} = \dot{Q}_{net,in} - \dot{W}_{net,out} + \sum_i^{n_r} \dot{n}_{r,i} (\bar{h}_f^o - \bar{h} - \bar{h}^o)_{r,i} - \sum_i^{n_p} \dot{n}_{p,i} (\bar{h}_f^o - \bar{h} - \bar{h}^o)_{p,i} \quad (4)$$

At steady state, the control volume energy is fixed ($dE/dt = 0$), the flame performs no mechanical work ($\dot{W}_{net,out} = 0$), and maximum temperature is attained if the control volume boundary is assumed adiabatic ($\dot{Q}_{net,in} = 0$). Applying these assumptions, this general energy balance equation becomes the following:

$$\sum_i^{n_r} \dot{n}_{r,i} (\bar{h}_f^o - \bar{h} - \bar{h}^o)_{r,i} = \sum_i^{n_p} \dot{n}_{p,i} (\bar{h}_f^o - \bar{h} - \bar{h}^o)_{p,i} \quad (5)$$

where $\dot{n}_{r,i}$ and $\dot{n}_{p,i}$ are the molar flow rates of reactants and products, \bar{h}_f^o is the enthalpy of formation, and $(\bar{h} - \bar{h}^o)$ is the thermodynamic enthalpy referenced to standard conditions. Provided the reactant inlet conditions are known, this equation can be solved for the temperature of the products, which is embedded in the product enthalpies. Students compared the idealized flame temperature equation to experimental results to confirm the resulting calculated flame temperature represents an absolute upper bound. It was assumed for both syngas and direct wood combustion that the reactants entered at standard conditions, which gives a lower bound on adiabatic flame temperature.

Adiabatic flame temperature represents a maximum bound on the experimentally-measured value because the real flame does not have an adiabatic boundary; it radiates and convects heat to the environment. Moreover, the stoichiometric treatment of the combustion processes maximizes the release of chemical energy from the fuel while minimizing the amount of nitrogen carried through the system. Nitrogen molecules are inert and do not release chemical energy as heat during the reaction (excepting trace amounts that do decompose to form NO_x , but this proportion is tiny and can be ignored). However, nitrogen does absorb thermal energy to attain the temperature of the product stream. So, provided combustion is complete, the less nitrogen present, the hotter the flame becomes.

Table 2 compares the calculated adiabatic flame temperature to the maximum measured gasifier flame temperature both from the 30 g and 40 g wood mass experiments.

Table 2: Comparison between the maximum theoretical syngas flame temperature versus measured flame temperature from two gasifier experiments.

Adiabatic Flame Temp. Syngas	Max. Temp. (30 g) Gasifier	Max. Temp. (40 g) Gasifier
2071 K	952 K	952 K

Table 3 gives calculated adiabatic flame temperatures assuming 1) wood is made entirely of cellulose or 2) entirely of lignin. These temperatures are compared to the maximum measured

direct wood combustion flame temperatures from both the 30 g and 40 g wood mass experiments.

Table 3: Comparison between the maximum theoretical direct combustion flame temperature for pure cellulose and pure lignin versus measured flame temperature from two direct combustion experiments.

Adiabatic Flame Temp. Cellulose	Adiabatic Flame Temp. Lignin	Max. Temp. (30 g) Direct Combustor	Max. Temp. (40 g) Direct Combustor
2286 K	1837 K	673 K	691 K

As expected, the experimentally-measured temperatures were significantly lower than the calculated theoretical adiabatic flame temperatures as a result of the assumptions described in Equation 5, derived from Equation 4 above. Moreover, the overall initial fuel mass had little impact on the maximum measured temperature. So, the deviation in measured temperatures between 30 g and 40 g in the direct combustor likely reflects the inaccuracy of the experimental flame temperature interrogation technique.

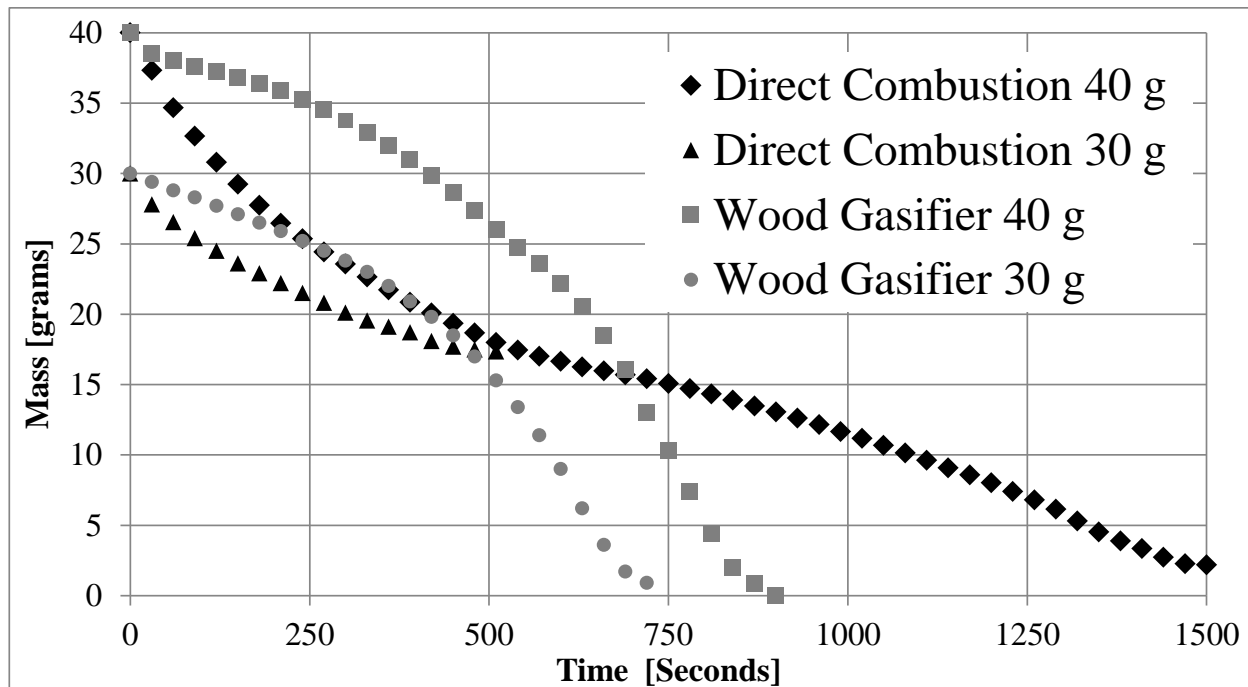


Figure 4: Biomass consumption versus time for four experiments shows wood gasifier behavior is independent of starting fuel mass. The direct combustor loaded with only 30 grams of fuel extinguished prematurely. Maximum measured flame temperatures corresponded to the highest fuel consumption rates (steepest negative slopes) near the end of gasifier combustion cycles and at the beginning of the direct combustor cycle.

Based on the calculated adiabatic flame temperatures, no significant difference was expected between experimental values for direct combustor versus gasification. However, students observed that the maximum gasifier flame temperature was consistently about 270 K hotter than

the maximum direct combustor flame. We hypothesize several reasons to explain this temperature difference. The key quantifiable reason was that the maximum rate at which fuel was being consumed was generally greater for the gasifier, as is shown in Figure 4. Moreover, the gasifier reached maximum fuel consumption rate toward the end of the burn sequence whereas maximum burn rate was achieved near the beginning of the direct combustion process. For the gasifier running with 30 g and 40 g initial fuel mass, the maximum fuel consumption rate was 0.093 g/s and 0.100 g/s respectively, and these maximum rates occurred after the entire system had time to warm to operating temperature. By contrast, the direct combustor running with 40 g of fuel achieved a maximum fuel consumption rate of 0.067 g/s, which occurred near the beginning of the process before the system had warmed up. For the direct combustor running 30 g of fuel, the wood chips likely had higher moisture content and were too tightly packed to fully burn. So, the flame extinguished prematurely, and the maximum fuel consumption rate, 0.042 g/s, was achieved in the first minute of the process. Since the actual flame was not surrounded by an adiabatic boundary, higher fuel consumption rate correlated to higher flame temperature. More rapid chemical energy release compensated more substantially for heat lost to radiation and convection.

Qualitative reasons for higher gasifier flame temperature included 1) the thermos throat concentrated the fuel over a smaller area than the direct combustion pyre and 2) syngas provided a more uniform and well-mixed fuel-air mixture than the direct combustor, which likely promoted more complete combustion and released more of the available chemical energy as heat. Unfortunately, basic geometrical differences between the gasifier and the direct combustion burners used were significant. These differences presented many uncontrolled variables that detracted from quantitative comparison of the two processes. As described below in Future Work, direct combustion experiments planned in upcoming classes will use a second vacuum bottle to eliminate geometric dissimilarities between the two systems.

Wood Ash and Unburned Fuel

The ash and unburned fuel remaining at the end of the combustion processes provided additional comparisons and efficacy measures between the gasifier and direct combustor. For complete combustion, biomass leaves trace amounts of ash, made up mostly of non-organic chemicals that do not burn. However, if inadequate oxygen was available to facilitate complete combustion, ash made up of partially-burnt organic chemicals will also form. So, significant ash remaining after a combustion process indicates whether adequate oxygen was available during combustion.

Biomass combustion processes that extinguish prematurely and/or produce excessive ash leave behind unburned fuel that is not participating in releasing all available stored chemical energy as heat. Pine is known to be made up of 0.2% to 0.7% unburnable ash. [14] The gasifier, when loaded with 40 g of pine, left 0.87 g of residual ash; when it was loaded with 30 g of fuel, it left 0.63 g (respectively 2.2% and 2.1% of the original mass). Figure 5 shows the amount of material remaining in the gasifier after combustion.

The direct combustor loaded with 40 g of fuel managed to blacken the entire fuel volume, signifying some level of combustion – at least on the wood chip surfaces – occurred through all the fuel. In that case, 2.2 g remained after combustion extinguished (5.5% of the original fuel mass). When loaded with 30 g of biomass, the direct combustor extinguished early, leaving fuel

internal to the pyre un-blackened. This remaining fuel did not participate at all in the combustion process (see Figure 4). Of the 30 g initial fuel, 17.4 grams of material (58%) remained after combustion extinguished.

Discussion and Conclusions

While no quantitative data were taken to measure impacts of the bio-renewable energy EELM on student learning, qualitative and anecdotal observations indicate that it was 1) positively received, 2) it successfully impacted students' perceptions of biomass energy, and 3) it increased their curiosity to learn more about this topic.

For example, the summer after the bio-renewable energy EELM was first run, a recent program graduate sent the following e-mail to the instructor: *"I want to show my younger brother and his friend how to make a Thermos gasifier like we did in the Fall term of last year. Would you happen to have the plans for the one that was used in our experiment or any pictures showing the Thermos we used? I primarily forgot what to do near the bottom of the Thermos."* [15]

After sending this alumnus pictures of the thermos gasifier and a description of how it was constructed, the instructor received the following response: *"Thank you, this is very helpful! I made a mistake of drilling [one large] hole at the bottom of the central chamber where the wood is... We did get a few good runs, but nothing like we saw in lab. I will try again and let you know how it goes. Thanks again!"* [15] Happily, this former student was captivated enough by the wood gasifier laboratory to build and test his own device and to share his acquired knowledge with family and friends.

An additional metric of success is that after working with the thermos gasifier, two student groups spontaneously self organized to form senior design projects focused on creating commercial biomass energy projects. One team is building a self-propelled and autonomous lawnmower for landscape grooming, which is powered by syngas produced by gasifying lawn clippings. [16] The second team built a pyrolysis biomass processor to convert residential waste into syngas, [17] and it is now building a syngas-fired Brayton cycle for residential-scale combined heat and power generation. Both teams are commercializing their technologies, and the later team has already secured \$20,000 in start-up seed funding from VETransfer, a start-up incubator for U.S. Military Veteran-initiated businesses. [18]

As described in the Future Work section, a student survey instrument is planned for deployment in upcoming classes that use this bio-renewable energy EELM. The survey will quantify how



Figure 5: The gasifier's inner container, where fuel is retained, was imaged after a burn sequence to show the trace amount of ash remaining.

well the topic is received by students, how it impacts their perceptions of biomass energy, and whether it increases their curiosity to learn more about this topic. Synthesized with anecdotal observations like those described above, these survey data will quantify whether this bio-renewable energy EELM merits investment of valuable class time that might otherwise be used to teach other material.

Several key experimental observations and conclusions arose from this EELM comparing a wood gasifier to a direct wood combustor.

1. Initial biomass charge had little impact on gasifier or direct combustor performance, but high initial fuel moisture content made it difficult to burn all the fuel in the direct combustor without stirring the pyre.
2. Once lit, the gasifier required no mechanical mixing or stoking to maintain operation, and it was insensitive to initial fuel packing or moisture content. By contrast, the direct combustor was very sensitive to initial fuel packing and moisture content, and more complete combustion could have been achieved through mechanical mixing or stoking the pyre.
3. Maximum flame temperature was difficult to experimentally measure owing to temporal and spatial variations in the flame. Maximum measured flame temperature was always below the calculated adiabatic flame temperature (as expected from thermodynamic theory).
4. Maximum measured flame temperature occurred during the experimental period of highest fuel consumption.
5. Maximum gasifier temperature was consistently higher than direct combustion temperature owing to higher fuel consumption rate, a fuel-air ratio more favorable to complete combustion, and concentration of the fuel-air mixture at the throat of the gasifier.
6. Ash resulting from the gasifier cycle was about 2.1% – 2.2% of the initial fuel mass while ash from the direct combustor was 5.5% of the initial fuel mass. Premature combustion extinction in the direct combustor resulted in 58% of the original fuel mass being unburned.

Future Work

Biomass feedstock moisture content proved to be an important and yet uncontrolled variable in the experiments described here with poor direct combustion performance loosely attributable to more humid days. In upcoming classes, a control sample of well-dried feedstock will be created via long baking at warm temperature to drive off all moisture. Moisture content of other samples will then be quantified by density comparison to the dried control sample. Observed combustion performance variations between samples can then be linked to their moisture content.

Geometric differences between the gasifier and direct combustor presented several uncontrolled experimental variables that confounded quantitative comparison of the two techniques. In upcoming classes, a second vacuum bottle, configured to support direct combustion only will be used instead of an open basket to eliminate geometric dissimilarities between the two systems.

More similar combustor geometries will facilitate better, clearer quantitative comparisons between gasification versus direction combustion.

While anecdotal evidence suggests that this bio-renewable energy EELM positively impacts students' curiosity and perceptions about biomass energy, a more quantitative data gathering instrument is needed to verify that conclusion. In upcoming classes, a student survey instrument combined with direct assessments will be used to quantify whether this bio-renewable energy EELM merits investment of valuable class time that might otherwise be used to teach other material.

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