DEVELOPMENT OF A SOLID WASTE TO BIOCHAR REACTOR

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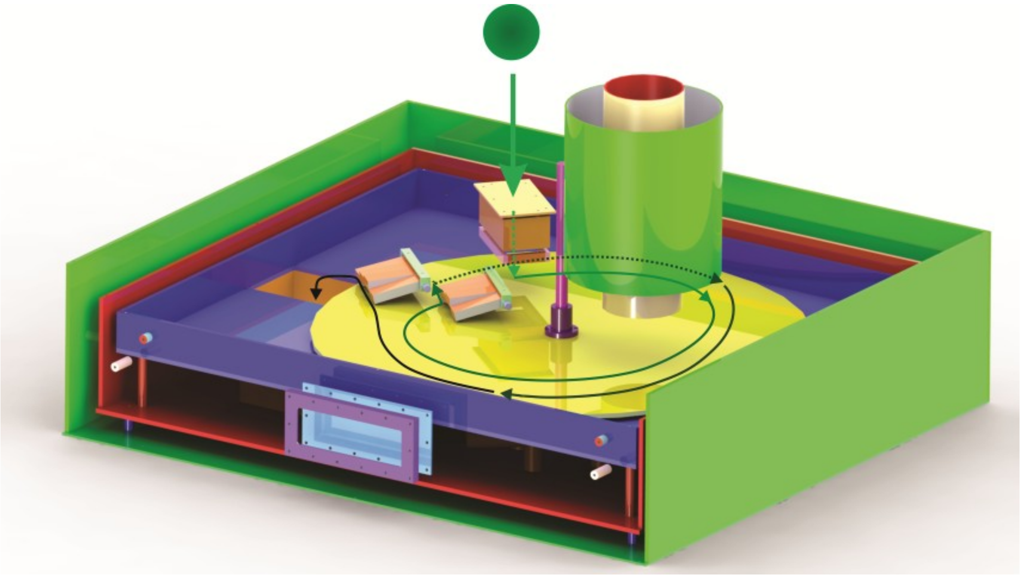

INTRODUCTION

Background

The Stanford / Climate Foundation Biochar Reactor effort began in 2011 to develop a prototype reactor to efficiently convert human solid waste to biochar without grid power or water. We have developed a small-scale pyrolyzer that utilizes high-moisture feedstock through a two-stage combustion process. In addition, a two-stage counterflow heat exchanger provides thermal recuperation of the incoming air while cooling the exhaust gases. We model the energy balance and essential components of the biochar reactor, describe the resulting system design, and report on the results.

The Stanford / Climate Foundation team has designed, fabricated, assembled, tested and refined a biochar reactor capable of serving up to 100 people per day. The reactor features a counterflow heat exchanger that recovers thermal energy in the exhaust by transferring it to the intake air, thus conserving energy and making the reactor more efficient. We developed a functional pyrolysis system earlier this year, including testing the system and demonstrating the prototype at the Reinvent the Toilet Fair at the Gates Foundation in August, 2012, with our partners Sanergy from Nairobi, Kenya.

Sanergy is developing a vertically integrated infrastructure in Nairobi, including sanitation units, processing centers and associated conveyance infrastructure, composting facilities, and ready fertilizer markets throughout Kenya. To this infrastructure our biochar reactor will add a biochar fertilizer substrate that renders nitrate insoluble, multiplying the efficacy of Sanergy's fertilizer amendment and facilitating long-lasting improvements to soils utilizing Sanergy's amendments.

Our system is designed with flexibility in mind, including using a range of startup fuels. It can be started with waste biogas from Sanergy's existing digester system, and can transition to syngas from the biochar pyrolyzer after startup. Alternatively, biochar can provide startup energy to reach operating temperature. The biochar produced comprises a high-quality form of charcoal with heating value as a smokeless fuel as well as a fertilizer substrate.

System demonstrations have validated biochar reactor operation at input rates of approximately 2 kg/hour in a semi-continuous process. Continuous operation improves the uniformity of syngas flows, which then enables smoother syngas combustion.

Objectives

Objective 1: *Sanitation of Human Solid Waste using High Temperatures and Long Residence Times*

Complete elimination of pathogens from Human Solid Waste (HSW) is a priority of our biochar reactor. By heating an appropriate flow of input material to high temperatures above 450 C for about 15 minutes, the material thoroughly chars, causing a 100% elimination of pathogens.

The HSW residence time is controlled by the rotation of the turntable carrying HSW and correspondingly adjusting an appropriate HSW feed rate. Higher moisture content HSW requires lower feed rates and slower rotations, which increase the exposure time of the feedstock to high temperature. Lower moisture content HSW enable higher feed rates and faster rotation to yield sterile biochar.

Objective 2: *High biochar reactor efficiency using Gas Flow Management and Counterflow Heat Exchange*

Prolonged operation of our apparatus in remote environments will be facilitated by minimizing required input energy. The core of the biochar reactor comprises a set of three nested shells that accommodate significant heat exchange between inflowing air and output gases. A counterflow heat exchanger further recovers heat to create a more efficient biochar reactor.

The main heat source for the reactor comes from complete combustion of the syngas produced from the HSW as it is pyrolyzed. The resulting enthalpy is conveyed from the lean-burn combustion chamber back to the pyrolysis chamber through a pair of heat exchangers. On reactor startup, an integrated biogas burner can bring the system up to operating temperature and provide a pilot flame for the lean-burn syngas combustor. Other fuel sources for startup include biochar, propane and natural gas. High system efficiency is achieved through the combination of counterflow heat exchange in the core reactor and in the exhaust heat recovery subsystem.

Objective 3: *Field Reliability*

Machines intended for field environments should be designed for robustness and maintainability. The biochar reactor described here comprises several stationary steel shells that do not require precise dimensional tolerance or alignment, with one primary moving component, which reduces complexity and reduces possible failure modes. The biochar reactor is relatively simple to understand and repair.

The biochar reactor uses simple materials, including low-carbon steel or alternatively cast iron. Welding is helpful but not required. A shaft inserted into a spindle seat supports the single primary moving part, a rotating steel turntable; as such, no bearing is required. The turntable is rotated either manually or automatically via a shaft exiting the system.

The prototype can be disassembled and repaired using commonly available hand tools. Future revisions may be even more robust and easy to maintain, based on lessons learned from the prototype.

Variations in feed rates and input material affect the composition and production of syngas. These variations can reduce the combustibility of the syngas and affect the complete burning of syngas in the lean burn combustion chamber. Controlling these variations is important to produce consistent results.

Pre-drying through the 50-60% moisture content “sticky zone” is an important requirement to operating under varying conditions. The turntable is robust to transitioning through the sticky zone. However, larger biochar reactors that may utilize conveyor belts or other mechanisms must manage rheology through the “sticky zone” to manage material buildup for consistent results.

Project Organization

The team has been organized as shown below in Fig.1, combining unique skill sets, experience and expertise at Stanford, Climate Foundation and Sanergy.

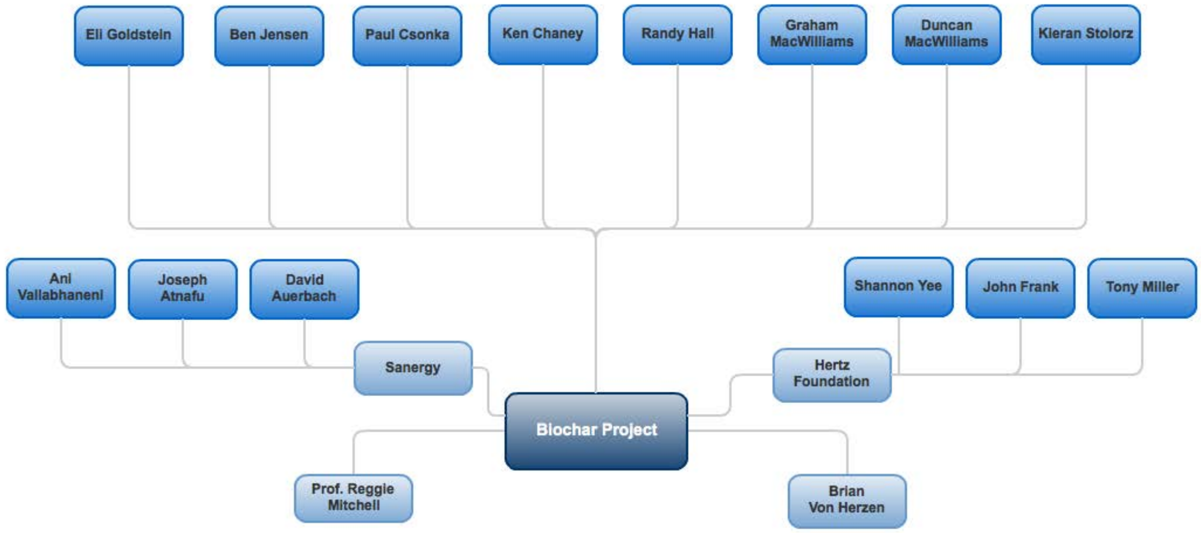

Figure 1. Team organizational structure.

MODELING AND SIMULATION

System Modeling Objectives

A thermodynamic analysis represents our reactor configuration with the purpose of guiding design work and gaining insight into system operating conditions (e.g. system temperatures, flows of human waste & supplemental fuel, air, etc...) and estimating biochar reactor performance metrics for the biochar system. From an energetic / thermodynamic perspective, we modeled the reactor with two objectives in mind. First, process human solid waste (HSW) for a community of 100 people with a minimum amount of a supplemental fuel. Second, maximize biochar production as a function of feedstock moisture level for HSW and combinations of HSW and greenwaste.

In the model, untreated greenwaste comprises an optional supplemental fuel. Greenwaste such as untreated sawdust is readily available for the proposed biochar reactor in Nairobi, Kenya.

To gauge system performance, the following questions were posed:

- What is the minimum amount of supplemental fuel needed to operate the biochar reactor?
  - How does the minimum supplemental fuel flow depend on the water content and heating value of the human waste?
  - How much excess energy is there to run supplemental processes (steam generation or electricity production)?
- How much air is needed to oxidize all of the fuel to combustion products ($CO2$ & $H2O$)?
- What performance gains are made by pre-heating the air with waste heat?
- How much heat exchanger surface area is needed?

The Model Biochar reactor

The biochar reactor model developed for the Gates program tracks streams of materials (e.g. the human waste, greenwaste, air, water, syngas, biochar, etc.) as they are chemically reacted through each process in the reactor. The biochar reactor is comprised of the following process components, including a dryer/dewatering, solid-gas separator, pyrolyzer, gasifier, combustor, biochar collector and heat exchanger / recuperator. These different subsystems are integrated to form a complete reactor that can process human solid waste to biochar. A brief description of each system can be found in Table 1 with example input and output streams:

Table 1. Reactor sub-processes.

Sub-Process	Purpose	Example Input	Example Output
Dryer / solids preheater / Dewater	Reduce moisture content of incoming material	Human waste at 75 % moisture & air at 105 ˚C	Partially dried human waste with 40% moisture, humidified air
Pyrolyzer	Establish chemical equilibrium at a given temperature, pressure	Partially dried human waste	Syngas, biochar, & ash
Gasifier	Establish chemical equilibrium at a given temperature, pressure	Partially dried human waste and a sub-stoichiometric volume of air	Syngas, biochar, & ash
Combustor	Establish chemical equilibrium at a given temperature, pressure	Syngas, raw greenwaste and excess air	Combustion products (CO_2 & H_2O)
Heat Exchanger	Transfer energy from hot exhaust stream to cold inflow stream	Ambient air and combustion exhaust	Hot air and cool combustion exhaust

Simple Analysis. With a lesser heating value of 20 kJ/g dry as an average heating value for the biosolid simulant, and a moisture content based on the NASA Ames value of 60%, we can infer the data in Table 2 (all values are in MJ/kg wet).

Table 2. Net process energy based on heating values.

8.00	MJ/kg	Heat generated from combustion
-1.35	MJ/kg	Heat of vaporization
-0.18	MJ/kg	Heat to warm the moisture from 30 to 100 C
-0.14	MJ/kg	Heat to warm dry fecal solids from 30 to 100 C
-0.52	MJ/kg	Heat to warm the steam and solids from 100 C to 350C
∑ = 5.81	**MJ/kg**	**Remaining thermal energy available including feedstock heating**

The thermochemical calculations performed within the pyrolyzer, gasifier and combustor process model assume full equilibrium for gas phase species and partial equilibrium between steam and biochar (carbon). At the temperature and time scales of our biochar reactor, 300-500 ˚C and characteristic flow times of tens of seconds, carbon-steam chemistry will effectively be frozen. From the numerous experiments performed in our biochar reactor, it is expected that 5 to 7% of the initial material will remain as biochar at our operation time scales and reactor conditions. The remaining biochar parameter is an input to the model. Thermodynamic equilibrium is calculated by minimizing the Gibbs function for the streams entering a given reactor at a specified temperature and pressure. Thermodynamic properties were determined from NASA property tables.

Model System. Based on the criteria above, the biochar reactor in Fig. 2 has been modeled and developed to convert human waste to biochar.

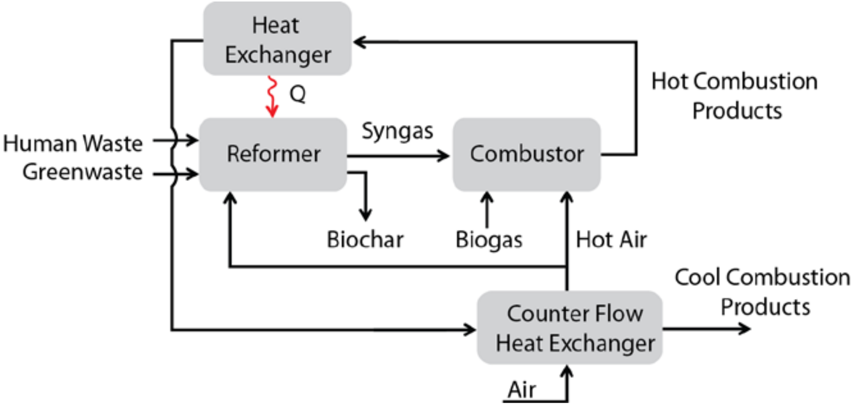

Figure 2. Block diagram of the model biochar reactor.

In the model, human waste and optional greenwaste can be gasified at a specified temperature in the reformer to produce biochar and a synthesis gas. The syngas and biochar exit the reformer and are separated; the syngas is transported to the combustor where it can be burned with additional greenwaste and the biochar is collected and used for agricultural purposes. The products of the combustion are hot and can be used to drive reformation reactions as well as pre-heat air for the biochar reactor.

Results. The model ran under the conditions listed below, and the resulting mass and energy flows were determined. One of the conditions is a pinch point of 10 ˚C, giving the minimum temperature difference between heat exchanger streams. Properties of the human solid waste (HSW) heating value and moisture content were varied to determine their impact on operation. By running the biochar reactor with zero greenwaste input, the minimum energy inputs to operate the biochar reactor can be determined. Results were calculated for the model conditions listed in Table 3.

Table 3. Model conditions.

Pyrolysis Temperature: 550 ˚C	GreenWaste Flow to Combustor: 0 kg/hr
Human Waste Flow: 10 kg/ hr	Weight Fraction of Biochar & Ash: 10 %
Heat Exchanger Effectiveness: 80%	Oxygen Concentration in Exhaust : 3 %
GreenWaste Flow to Pyrolyzer: 0 kg/hr	Pinch Point: 10 ˚C

Calculations were made of the operating region, excess energy at a given set of operating conditions, syngas heating values and airflow required for complete oxidation of the syngas. With heating values of 20-22 MJ/kg dry input and NASA HSW simulant moisture content of 60%, the operating point is feasible. In addition, with 75% moisture content of human waste can be mixed with up to 45% moisture content greenwaste. Based on the simulation, it appears to be feasible to operate with a majority of HSW and a minority of greenwaste at such moisture levels.

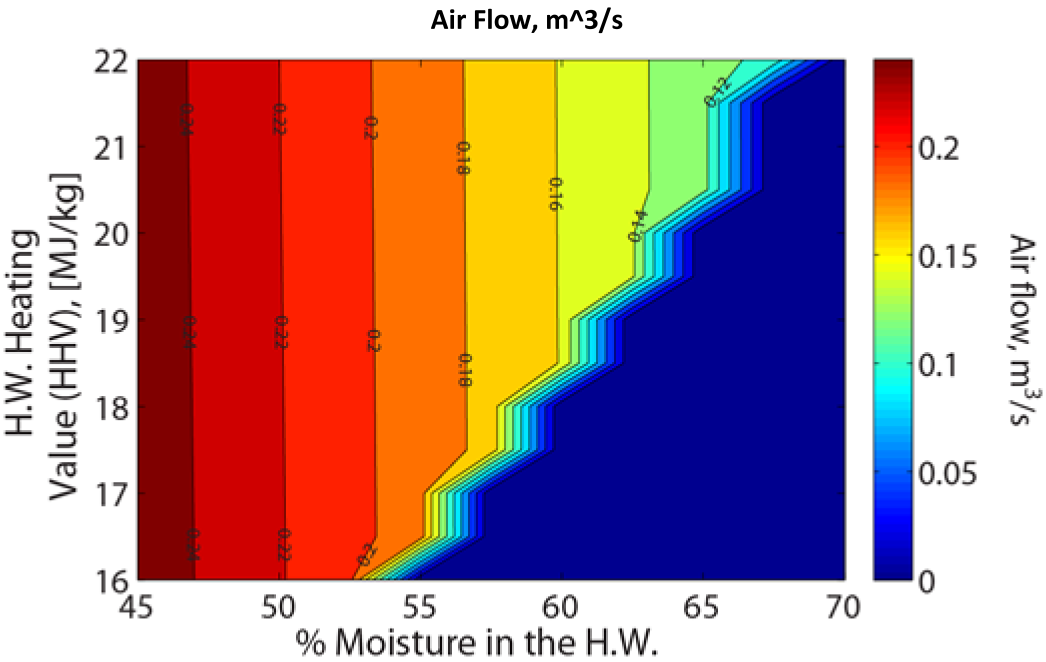

Figure 3. Plot of required air flow for given moisture level and heating values.

Discussion. By running the model with zero supplemental greenwaste, we calculated that the biochar reactor could operate using human waste with a higher heating value in the 20-22 MJ/kg range and with moisture content more than 60%. These limits on water content and heating value are greatly expanded when limited quantities of supplemental greenwaste are provided. For example, HSW at 75% moisture can be processed when a smaller amount of greenwaste at 35% moisture content is utilized, for an average moisture content of 55-60%.

Human Waste Simulant Recipe and Development. We used a human waste simulant to test the proposed biochar reactor. The simulant recipe was developed by Wignarajah et. al. and is documented in [1]. The composition of the simulant can be found in Table 4.

Table 4. Simulant composition.

Ingredient	Dry Composition	Wet Composition
Cellulose	37.50%	15 %
Yeast	37.50%	15 %
Peanut Oil	20%	8 %
Potassium Chloride (KCl)	4%	1.6 %
Calcium Monophosphate (Ca(H2PO4)2)	1%	0.4 %
Water	[-]	60 %

During initial testing, the simulant would rise upon heating, presumably due to the yeast reacting with the other components of the recipe. To approximate the rheology and density of human solid waste, the yeast is killed by heating prior to mixing the remaining ingredients together.

BIOCHAR REACTOR DESIGN

Design Philosophy

In keeping the target locations and users in mind, the primary design objective is a biochar reactor that can be manufactured with relatively low complexity, can be maintained using commonly available tools, and can be operated with minimal training. The first guiding principal is eliminating the need for many precision components or tight tolerances during fabrication, allowing for some loosely fitting parts that still work well with each other, leading to easier manufacturing and assembly of the main reactor core. A second guiding principle involves construction to facilitate energy-efficient operation, with gas flow routed between reactor sections in a path that provides minimal heat loss.

General Architecture and Operation

The architecture of the biochar reactor evolved from industrial gasifier architectures. Char-producing apparatus comprise combustion and pyrolysis zones, as well as exhaust cooling and air intake preheating.

These four regions are present in our reactor. Our energy efficiency objective led to conceptual evolution of vertical gasifier architecture to horizontally chained zones of drying, pyrolysis, and combustion. In the horizontal configuration, material moves via a conveyor belt. A further refinement is a vertically planar variant where drying occurred in the top of the reactor to which hot gases rise, with pyrolysis beginning near the column center, and combustion occurring near the bottom of the reactor. Under such an architecture, material moved via a series of horizontal conveyor belts one under the other, with HSW residence time determined by the number of belts and the speed of the belts, dropping to the next belt when the end is reached.

One difficulty of that architecture is the need for high temperature conveyor belts that can accommodate high levels of moisture, including flowing sludge that would otherwise leak or fall through most belt configurations. Several high temperature textile belt weaves exist, however their robustness is uncertain under prolonged use at elevated temperatures. Additionally, belts with tight metallic weaves require more maintenance and alignment when cycled through high temperatures, adding cost to reactor operations in parts, downtime, and skilled labor that might be required.

This robustness challenge calls for pre-drying the input material, but the long-term robustness of even coarse-weave high-temperature belts are suboptimal according to the industrial experts we have consulted with to date.

Nested Shell Architecture

We considered another approach as well: instead of using a complex moving system (belts, etc), we conceived of transporting material on a rigid substrate. A horizontal turntable came to mind, where the input matter is deposited near the perimeter. Since high moisture content HSW would not leak through a solid turntable, drying and pyrolysis could occur in the same chamber, and the HSW residence time in the pyrolysis zone is thus dictated by the time spent on the turntable before being scraped off into an exit chute (more on that in the sections below titled *Char Scrapers* and *Turntable Assembly*).

With the turntable being circular, a natural shape for the housing chamber could be cylindrical. However, for ease of construction and modification of the prototype, the turntable is housed in a rectangular housing. The upper chamber provides space for pyrolysis. The pyrolysis chamber is air tight, and includes a defined gas exit path for steam and synthesis gases, an airtight input chute for HSW, and an airtight exit hopper for the produced char or ash. Operation of the pyrolysis section is fairly straightforward: if the temperature inside the pyrolysis zone is raised above about 350 C, and the time the material is present inside is sufficiently long, the steam and syngas will first force any residing air from the pyrolysis chamber and create the desired oxygen-free environment needed for the generation of char.

The pyrolysis chamber is heated by the lean-burn combustion chamber immediately below the pyrolyzer. The combustion chamber is a rectangular shell, slightly wider and taller than the pyrolysis shell, and thus can completely enclose it. There is a sufficient height difference (about 6 cm) so that burners and injectors can be placed between the two chambers. Syngas burners route gases from the pyrolysis zone into the combustion zone, where the mixing with oxygen can allow the syngas to burn and further heat the pyrolysis chamber through its floor plate. These burners are optimized for our target HSW feed rates, with the appropriate number of holes and their diameters for laminar flow, to allow for relatively stable seated flames for the predicted syngas flow. The hole spacing and pattern also allows for mixing with air between each flame jet. The injectors keep the flames far enough away from the pyrolysis chamber floor that flame quenching is minimized. The injector port entrance lies near the center of the pyrolysis chamber floor to facilitate gas convection and thermal transfer between the two chambers (see Fig.4).

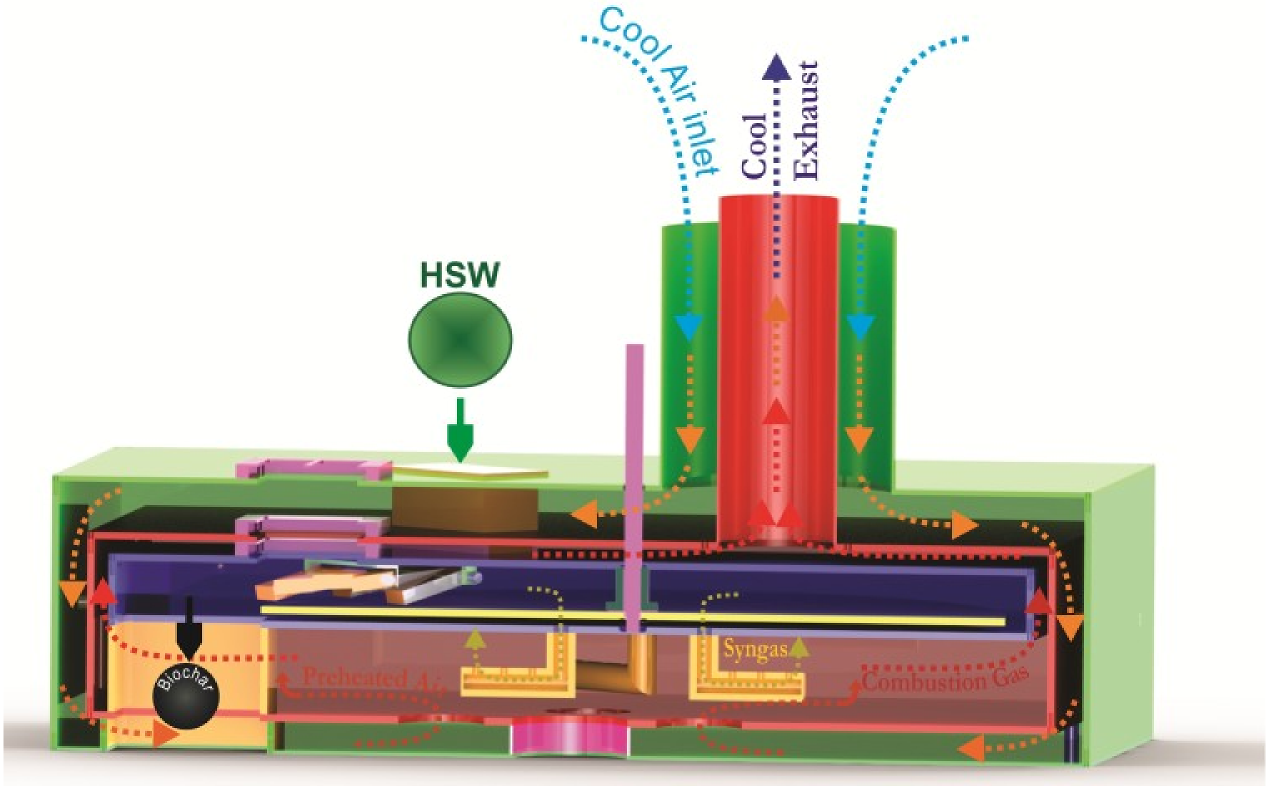

Figure 4. Gas flow paths inside the nested chamber shells.

Once mixed with warmed air, the syngas combusts in the combustion chamber, and heats the pyrolysis chamber. The latter heat exchange is made more efficient by the exit gas flow from the combustion chamber: the hot, buoyant gases flow up and around all walls of the pyrolysis chamber, and over the lid, before exiting through a stack connected to the top of the combustion chamber (more on the stack later). The combustion chamber also acts as an odor-controlling lean-burn stage, as discussed later.

To further raise system efficiency, the air for combustion is preheated using combustion waste heat in a counterflow strategy: a third shell encompasses the combustion chamber, with space for gas flow between the corresponding floor, lids, and walls. The air intake is located at the top of the third shell (Fig.5), so that incoming air is pulled around the outer walls of the combustion zone, under the combustion zone, and then up through the air intake holes in the floor of the combustion chamber (Fig.6). The outside walls of the air intake shell are insulated with silicon rockwool, which insulates the reactor on its outermost walls. The retained heat is redirected to air preheating. The air is thus preheated by several hundred K before entering the combustion region. High-temperature air entering the combustion zone improves reactor efficiency, since the reactor does not need to heat the incoming air as much as without pre-heating.

In summary, three nested shells route gases to maximize heat transfer, utilizing reaction heat efficiently. Ambient air enters through the top of the outside shell, is pulled around and heated by the combustion shell, whereupon the hot air combusts with syngas emerging from syngas injectors and heats the pyrolysis chamber. The resulting hot combustion gases exit via a shell that completely surrounds the pyrolysis chamber, heating the chamber. Figure 7 shows the combustion chamber and output port for the hot gasses.

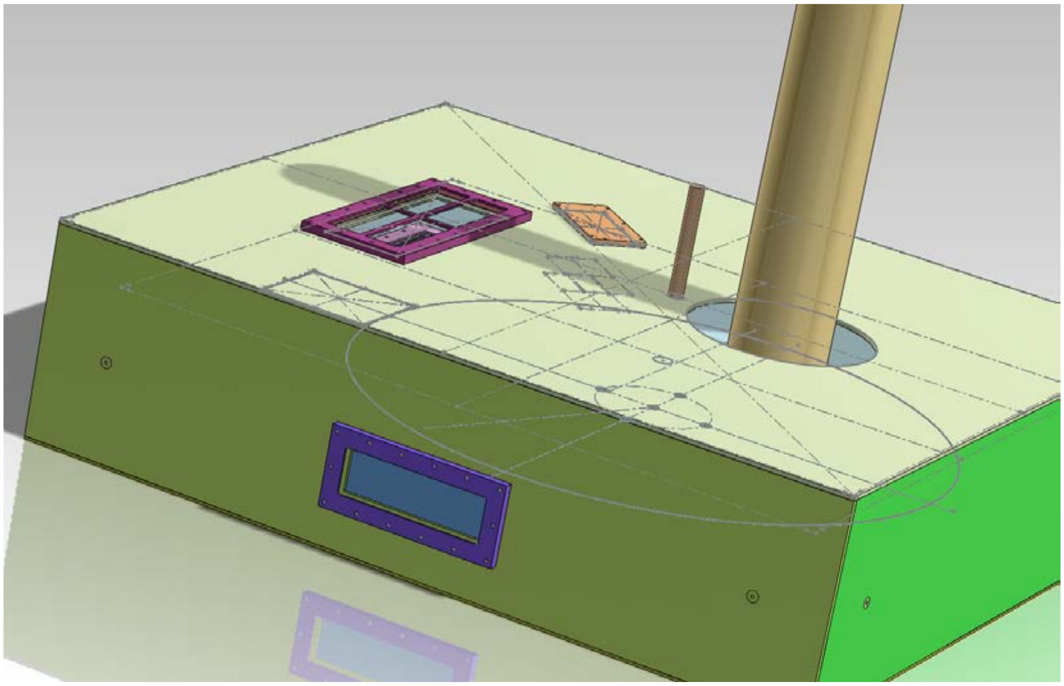

Figure 5. A view of the exhaust stack and the concentric input port for the counterflow heat exchange of incoming air.

Figure 6. The combustion region of the pyrolyzer featuring a central hole for injecting warmup gas, while the surrounding four holes provide warmed incoming air from the heat exchangers for the lean-burn combustion.

Figure 7. Gas exhaust and HSW input ports on top of the combustion (second) shell. The view is rotated from the view in Figure 5.

Specific Architecture

Syngas Injectors. The average velocity of a gas jet through a nozzle varies with the pressure differential across the opening as well as its area and shape. Syngas pressure depends on the HSW feed rate; the total area of the injector nozzles relates to the exit velocity. Other injector criteria include restricted gas flow before the nozzles, the shape of the nozzles and their spacing, the nozzle pattern, as well as the number of injectors.

Four injectors are mounted under the floor plate of the pyrolysis chamber (see Fig.8) to distribute the heat onto the floor plate in a distributed pattern, with each injector radiating out from the center. Air mixing considerations led the shape to assume a maple leaf pattern. The injectors were made from stainless steel, enabling them to withstand the 2100K temperatures of the flames, as well as the 2100K temperature of the startup burner configured immediately beneath them. Each L-shaped injector has the longer stem parallel to the ground; each is about 15 cm long. Each injector contains 30 holes, for a total of 120 holes. The 30 holes are distributed on two non-adjacent faces of the hexagonal nozzle, so that the holes face upwards in a “V” orientation. In this manner, the buoyancy of the gas increases the exit velocity. The holes are 2 mm in diameter, and are spaced about 1 cm apart; the 1 cm spacing allows thorough mixing with air on all sides of each flame jet. The injector geometry provides a flame velocity of ~2 m/s. Figure 9 shows typical syngas combustion taking place at the injectors.

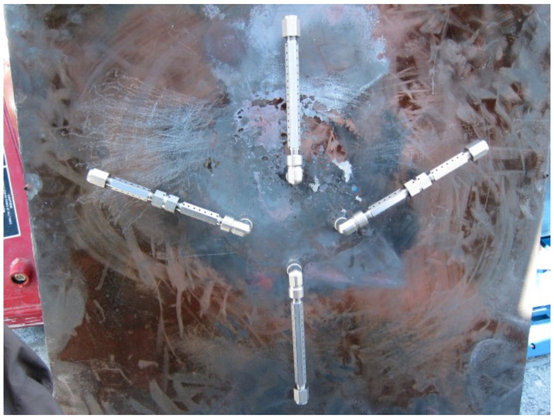

Figure 8. The four syngas injectors located under the pyrolysis chamber.

Five centimeters above the pyrolysis floor-plate, the main injector tube allows steady-state flames to reach a target height without quenching on the metal. Quenching creates soot, preventing complete combustion.

Figure 9. Syngas being combusted in the lean-burn chamber.

Pilot Light. The syngas injectors utilize a pilot light for semi-continuous operation. The biochar reactor is preheated with locally available biogas from the Sanergy biodigester. For our first prototype, we use propane as a proxy for the biogas, which presently also serves as a pilot light during normal operation. Several HSW simulant flows of 50 g/minute have been undertaken. Steady state combustor temperatures are achieved for approximately a half hour during which time drying and pyrolysis occur, and syngas is generated and combusted. Syngas combustion maintains the pyrolysis chamber temperature, and keeps the pyrolysis process going. Syngas thermal input is on the order of 5 kW while the pilot light contributes approximately 750 W, or less than 20% of the thermal input for the reactor.

Char Scrapers. In the turntable architecture, char must be transferred into the exit chute. The general principle is that once char is obtained, running the char into a barrier angled away from the direction of motion causes the material to displace along the barrier. If the scraper barrier were aligned with a certain angle, material residing on the turntable would be dislodged from the turntable and displaced towards the edge of the turntable as the turntable rotates. A scraper dislodges and displaces the biochar; one scraper assembly can be seen in Fig.10. Several scrapers may accelerate the scraping process in the reactor.

Figure 10. In the prototype, one scraper assembly consists of four leaves.

The simplest design for a scraper comprises a piece of metal bar-stock placed fixed to the chamber walls, with the ability to float and floating horizontally just above the surface of the turntable. However, in keeping with our design philosophy of loosely fitting parts that work together, the rotating disk is allowed to warp, which. Warping does not influence the operation of the biochar reactor given the flexible 6-D seals, but it does prohibit the use of a fixed, rigid scraper that would bind under turntable cause binding at the first hint of warping. Instead, the scraper is made articulated (see Fig. 10 above) and self-adjusting, comprised of two sets of four independently moving leaves. Other configurations can utilize more or thinner leaves, but the four leaves per scraper have successfully demonstrated the principle.

Early revisions of the articulated scraper included springs to press each (then-lightweight) steel leaf down onto the surface of the turntable. As the turntable warps, its vertical displacement changes. Each leaf compresses as needed, but always with a steady force between leaf and turntable. However, under the high temperatures of the chamber, the springs lost their effectiveness. Therefore we shifted our strategy to passive components.

The current approach uses heavy bars of steel, pivoting on one end on a shaft and separated from neighbor leaves with thin spacers, as shown above in Fig. 10. Gravity creates a large moment on the bars, and thus a large force at the end of the scraper that surpass the needed char dislodging forces. As a warped turntable rotates, the leaves independently follow the contour of the rotating turntable, and always provide a solid scraper-front on the turntable surface. The scrapers shift material off the turntable and into the char exit chute, as depicted by the arrows in Fig.11. A sample of the resulting biochar is provided in Fig.12.

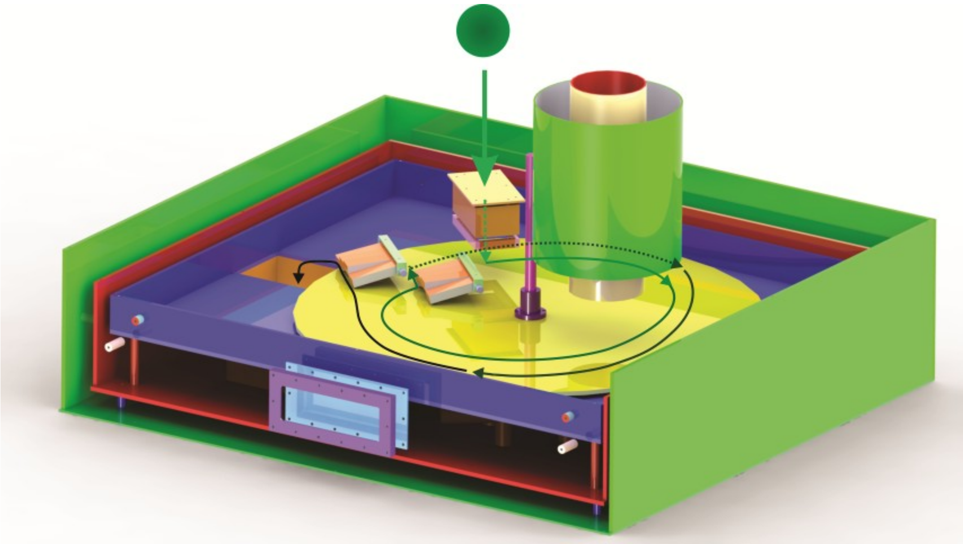

Figure 11. Rotating turntable and scraper assemblies in a cutaway reactor model.

Hardened steel (of different grades to prevent binding) on the shaft and scrapers resists rust. The pivot points are located above the expected material accumulation line, thus making it difficult for char to enter the pivot regions and contribute to binding.

Figure 12. A bucket of resulting char from our reactor.

Odor Management. The reduction and elimination of odors from our biochar reactor is a high priority. Several strategies contribute to the biochar reactor producing little odor.

The input hopper is sealed from the atmosphere; in future revisions, we plan to pull air through the hopper and into the system, lowering the pressure of the reactor relative to the open air. If any leaks occur, air goes in rather than vapors leaking out, thereby catching and containing any outgoing vapors.

Second, a blower on the output stack keeps the entire reactor below atmospheric pressure, so that air is pulled into the system everywhere rather than leaking out. In addition, the blower pulls the gases through the lean-burn stage (in the combustion zone) before exiting to the atmosphere. Gases escaping early through leaks in the system will, by design, be recycled through the lean-burn stage before exiting, thus ensuring odor control even during several types of malfunctions due to disrepair.

Third, the output of our biochar reactor is high-quality char, which is odorless when properly processed. In our experiments, the resulting char is indeed odorless. These three levels of protection are well suited to elimination of unwanted odors during thermal processing of HSW.

Heat Exchanger. One of our main considerations was making a reactor that is as efficient as reasonable given target objectives of capital cost and simplicity. Carefully routed gas flow through the nested shells comprise a portion of the system efficiency using heat exchange, but a second main portion exists in the heat exchange stack attached to the chamber.

On the top of the combustion chamber is the air exit tube, shown in Fig.13. A blower is attached to the other end of the stack that is open to atmosphere. The exhaust tubing comprises a pair of 10-cm diameter aluminum ducting. A 25-cm diameter rigid steel duct surrounds the tube pair, terminating on the concentric opening on the air intake shell. The outside of the outer tube is mostly insulated with cylindrical duct insulation. The heat exchanger stack is ten meters long, creating a high surface area for more efficient heat exchange.

The entire chamber is insulated as well using 5 cm thickness rockwool with r values of ~0.5. A final layer of insulation is a reflective welders blanket cut to size, as shown in Fig.14.

Figure 13. The heat exchanger attached to the top of the reactor.

Figure 14. Insulated reactor and heat exchanger, with HSW input feed (red tube).

The blower pulls gas directly from the exhaust tubes, resulting in the entire reactor operating below atmospheric pressure. The air intake draws incoming air and warms it as it nears the reactor core. As air exits the reactor, it pulls hot exhaust out of the reactor through the exhaust tubes, while concurrently pulling cool ambient air into the stack. By the time the air reaches the combustion zone, the combination of the counterflow heat exchange inside the reactor and the counterflow heat exchange in the stack preheats the incoming air several hundred K. Since the cold side flow and hot side flow are similar in the exchanger, and given the similar temperature change of hot side and cold side air, the heat exchange effectiveness *Eff* can be estimated using equation [1], with the result being *Eff* = 0.628.

$$Eff = (T_{out} - T_{in})_{cold\ side} / ((T_{in})_{hot} - (T_{in})_{cold}) \qquad [1]$$

We expect to significantly improve the tube heat exchanger effectiveness as the prototype is further refined and subsystem optimizations are identified.

Turntable Assembly. The rotating turntable is a solid plate of ¼” (6 mm) steel thickness 28” (71 cm) in diameter. A photograph of the turntable and shaft is in Fig.15. The turntable is coupled to a 5/8” (1.6 cm) diameter drive shaft using a strong coupling mechanism. The driveshaft exits the reactor through a series of holes and seals in the three shells.

Figure 15. A top view of the rotating turntable and turntable shaft placed inside the pyrolysis chamber.

In future revisions of a reactor of the same scale, the turntable can be made thinner and lighter. Its mass may be reduced by removing material from the middle sections, leaving spokes that support the important outer half of the turntable that holds the material.

As part of our strategy of robustness and loosely-fitting parts operating correctly, the turntable (and thus driveshaft) are allowed to tilt several degrees in the pitch and roll directions. As such, the bottom turntable support is a loose-tolerance spindle seat that does not require an active bearing. There is no similarly fixed upper shaft constraint, as the exit holes through the shells are oversized by up to a millimeter. The relatively free upper constraint allows the shells to expand and shift differently relative to one another without binding the shaft, which is especially important when the shells are not precisely aligned on construction.

To avoid gas leakage between shells, we use a specially created 6-degree-of-freedom (6-DOF) seal to hold the pyrolysis and combustion gases in their appropriate shells. The 6-DOF seal uses a set of conical springs, spacers, and silicon-weave gasket material to withstand displacement in three dimensions, as well as roll, pitch and yaw. Though the seal works very well for the prototype, future revisions will require an updated seal strategy to function robustly in the long-term.

Materials Selection

Because of the relatively high temperatures of the combustion and pyrolysis chambers, the dominant housing materials are 1020 mild steel. Several criteria drove selection of 1020 steel. First, with expected maximum temperatures around 1200 C, high melting points are required. While both refractory materials and metals have high melting points, metals have advantages due to the high capital cost and skilled labor associated with creating refractory-lined chambers.

In material downselection, we compiled a list of melting points, coefficient of expansion, heat capacity, thermal conductivity, and cost for various candidate metals and alloys. Since the biochar reactor is frequently thermally cycled, one requirement is a low expansion coefficient so that various components of the reactor experience sufficiently low strains. Thermal conductivity is a second consideration. The higher the conductivity the better the performance, keeping in mind that conductivity changes with temperature. Cost further reduced the list. Although certain alloys are good candidates, they are impractical due to very high costs of acquisition. Other discarded alloy options had poor machinability and poor ease of welding (tightly related to low ease of field repair).

The top choice is cast iron, followed by 1020 mild steel. Cast iron, however, is hard to obtain in the sheet sizes we were looking for on short lead times; and, many manufacturers call their low-carbon steels “cast iron”. For future revisions we now have sources for cast-iron construction, however we chose 1020 steel for the prototype.

We chose a ¼” (6.3 mm) plate thickness for the center two chambers to minimize warping and accommodate our fastener and sealing strategy, and 3/16” (4.7 mm) for the outer chamber. In future revisions the walls may be thinner for all the chambers, however certain sections (such as the pyrolysis chamber floor) have a minimum required thickness in a few regions.

All of the chamber edges in the three shells are welded air tight, with the exception of the top lid of each section. The lids are fixed with bolts and made airtight using high temperature silicon-fiber-weave gasket material. When assembled, the reactor appears as a single box as seen in Fig.16.

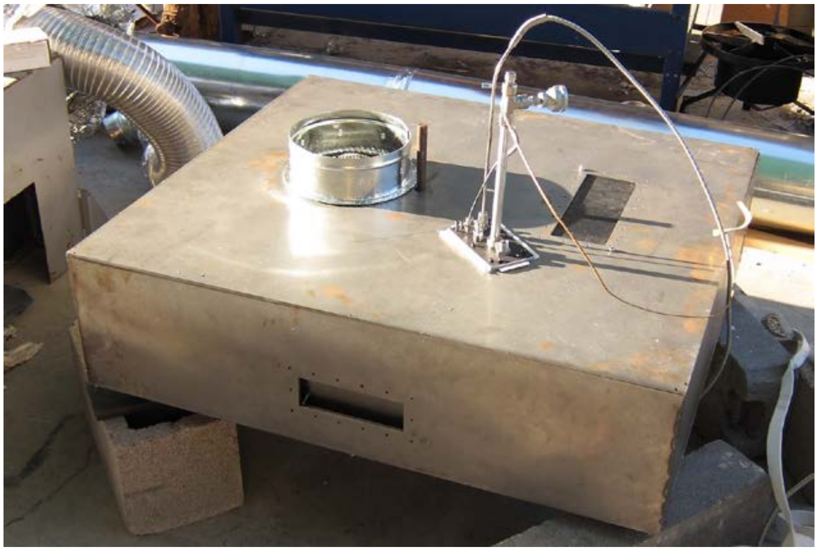

Figure 16. Assembled pyrolysis / combustion chambers.

The char scraper material required resistance to high-moisture and high-temperature environments. As such, rust and binding is a concern. Therefore the scrapers rely on no active driving components, but only gravity and their large mass. They were also made of hardened tool steel that resists rusting. Tool steel is also resistant to scratching or surface damage.

In our trials over the summer, the scrapers did not bind significantly. However, one leaf of one of the two scrapers did have difficulty moving after some tests. We determined this malfunction to be the result of an assembly problem. The scraper continued operating as desired after modification. Nonetheless, it is anticipated that occasionally a maintenance operator will have to clean the scrapers (in their current incarnation) of char (dust or otherwise), since these may accumulate between the holding shaft and leaves.

One strategy to minimize the maintenance needed from material buildup is to move to a semi-fixed part. For example, the force from a flexing thin leaf could maintain contact between the leaf and turntable, and it would be difficult for contamination to bind a leaf given that there is no part-on-part motion in the scraper mechanism. As long as any bending is limited to the elastic range at operating temperature, the scraper will remain robust to thermal cycling.

DISCUSSION

Gates Foundation Phase I

The Phase I project with the Gates Foundation was aimed for smaller biochar reactors that could address village needs and ultimately, extended family needs on a smaller scale. To that end, the prototype targets a biochar reactor designed to serve up to 100 people per day, an intermediate scale that could pave the way for smaller or larger systems in Phase II. Typical fecal sludge output of 135-400 g/day has been reported in the literature. Using the geometric mean of 232g/day per capita, 100 people/day implies 23.2 kg per day throughput, or just less than 1000 g/hr. Our biochar reactor demonstrates the ability to process more than 1000 g/hr of NASA simulant fecal sludge.

The Gates Foundation also requested that the demonstration be done with simulant material. We adopted the NASA Ames simulant formula published by Dr. Wignarajah. As a result, we have focused on meeting demonstration milestones at the Gates Foundation in advance of deployment in Kenya. Before deploying the biochar reactor in Kenya, we will need to qualify the biochar reactor with non-simulant sludge. This process is planned for Q4 of 2012, after which will be able to deploy a prototype in Nairobi, Kenya, at Sanergy’s facilities. Based on our timeline, we have targeted the RTTC demonstration at the RTT Fair in advance of the Kenya deployment milestone.

Risks

Complete combustion is a key aspect of energy efficiency and of minimizing partial combustion products and minimizing odor. To this end, we designed the lean-burn post combustor to operate with an excess of air. In addition, we designed the biochar reactor to operate below atmospheric pressure, so that any leaks will result in air going into the biochar reactor rather than odors leaving the system. The secondary combustion system fully oxidizes odors and partial combustion products. We also plan to use biochar as an activated charcoal filter to further reduce odor after cooling exhaust gases. This filtering process may also add nutrient content to the biochar product.

Pre-drying technology may enable higher moisture feedstock, in turn enabling much moisture to bypass the primary combustor and to be de-odorized in the lean-burn post combustor.

Sustainability

We applied for and received support from the North American Free Trade Association (NAFTA) Commission for Environmental Cooperation (CEC) to develop a similar biochar reactor for North America. We plan to demonstrate such a similar system in the second half of 2012 in Palo Alto and/or City of San Jose, California.

Scalability

With further support, we intend to scale the system to match the needs of Sanergy and other infrastructure partners in developing nations.

Lessons Learned

We have identified several key issues that can be remedied in future revisions of the system. These issues relate to both specific technical issues, and general understanding of practical char production, machine structure, and operation.

Architecture. To create a simpler biochar reactor, the chutes and ports that lead through all three shells could be updated from the prototype, allowing for more misalignment of the various shells while maintaining a gastight seal. The heat exchanger may be terminated differently, enabling efficiency improvements while concurrently enabling more accurate temperature measurement.

Serviceability. Agile prototyping relies upon accessible modification of reactor designs and implementations. The biochar reactor can be built with more elegant sealing, especially in the lids of the three nested shells, to allow faster disassembly. We are further investigating alternatives to our current airtight high temperature sealing strategy.

In addition, the biochar output chute could be easier to access in order to clear the biochar reactor of char during longer operational trials.

Combustion Subsection. Pilot lights in the combustor provide resilience to syngas variability across the fully anticipated range of operation of the reactor, especially with incomplete mixing or high moisture content.

On a more fundamental level, to insure complete combustion of the syngas, steam and syngas in the pyrolysis chamber should be thoroughly mixed, to keep a steady combustible syngas mixture emerging from the injectors during continuous feeding of input material. Mixing improvements will facilitate complete combustion in the lean-burn chamber.

Additionally, if a ring of flame with associated pilot lights is placed near the outer perimeter of the injectors, outgoing gas could be forced to exit through the flame ring, combusting unburned volatiles and increasing heat production of the reactor.

Scraper Subsection. The current scrapers have a narrow operating range of material width. We can easily change the width parameter in future revisions. Also, to assist in better scraping char off at the desired exit locations, the incoming feed should be segmented instead of being a continuous stream.

In the current reactor, we made the scraper leaves intentionally wide to validate the core elements. In future revisions, reducing the width of the leaves will allow the scrapers to more closely conform to the turntable surface.

Pre-drying. In the absence of a mixing mechanism in the pyrolysis chamber, there are issues maintaining continuous syngas flames from the injectors with high-moisture-content material. It seems as though steam is dominating the output.

However, one other method of reducing steam dominance (aside from mixing) is to reduce the input moisture level. Given the significant heat available from both the reactor body and heat exchanger, pre-drying the input material would most likely benefit efficiency and efficacy of the biochar reactor. In exchange, we would need to address other difficulties with lower moisture content HSW, including reduced handling via pumping.

CONCLUSION

Stanford University and the Climate Foundation designed a reactor to process human solid waste for Phase I of the Gates Foundation Reinvent The Toilet Challenge. We demonstrated an energy surplus at 60% moisture content when burning synthesis gas created by pyrolysis. The surplus energy should enable continuous reactor operation without external energy input.

We built a reactor to serve up to 100 people per day (2-kg per hour), comprising three nested steel shells, a material-carrying turntable, scrapers to remove the char, and counterflow heat exchangers in both the reactor and external heat exchanger stack.

In trials, the prototype operates with semi-continuous processing of simulant derived from a NASA formula. However, truly continuous self-sustaining operation is still in development.

The theoretical and experimental analyses have provided numerous insights on reactor optimization and improvement. We anticipate scaling the reactor to metric tons per day, capable of serving larger communities. We have validated the first biochar reactor capable of directly processing high-moisture feedstock.

Gates Foundation Reinvent the Toilet Fair (August, 2012)

US Biochar International Conference (July, 2012)