# Biomass Gasification System for Use In Off-Grid Irrigation

Greenpeace Energy [R]evolution Challenge 2013

Group Members:

Devin Chandler, Takuya Curtis, Stephen Moore

# Table of Contents


Executive Summary
I. Introduction to Gasification
- Historical Precedents
- The Chemistry

II. Our Design
- The Gasifier
- Safety Hatch
- Cyclone Separator
- Gas Cooler
- Substrate Filter
- Blower
- Water Pump
- Rice Husks as Biomass Fuel

III. Cost Analysis
IV. Operation
- Startup
- Use
- After use
- Maintenance
- Safety

V. Analysis of Other Power Generation Methods
- Diesel
- Gasoline
- Solar Photovoltaic
- Human Powered

VI. Conclusion
VII. Works Cited

## Executive Summary

This report details the design of our prototype gasifier unit for the 2013 Greenpeace Energy [R]evolution challenge. The challenge was to develop a green and affordable method of powering water pumps for Indian farmers who do not have access to advanced infrastructure. The main requirements of the design were that it would be affordable, portable, user friendly and provide adequate amounts of renewable energy.

We are a team of three mechanical engineering students from the University of Washington in Seattle. In this submission of our design, we will be writing a semi-formal technical report to describe our system and how it will provide adequate irrigation to farmers in the Bihar province of India.

We considered many different initial ideas, considering the more mainstream renewable energies such as solar and wind power. In the end our group decided to use renewable biomass fuels. Why we came to this conclusion can be seen in our comparison with other methods of power generation further in our report, along with the key idea (and advantage) of using biomass waste that results from farming, eliminating the issue of fuel availability.

The base of our design is a gasifier, which is a device that utilizes pyrolysis to extract fuel. Or, in other words, it uses a controlled application of heat and combustion to break down biomass into usable fuel. This usable fuel is a combination of carbon monoxide and hydrogen gas, or syngas. Syngas can readily be fed into gasoline or diesel engines with minor modifications. Gasification as a transportation fuel source is a proven process ever the Second World War, when its large scale implementation proved a reliable alternative to the rationed petroleum fuels. As the syngas is produced from rice husks and other agricultural waste products, the renewable requirement for the challenge is fulfilled. Our prototype is specifically designed with the user friendly and affordable requirements in mind, avoiding more complicated parts and control units that would be unnecessary for our design.

Our design would cost an estimated $1,496.97 in material and labor cost. We believe that our design will reinvigorate this overlooked and forgotten technology to help bring the energy revolution needed by farmers around the world with limited access to more modern infrastructure.

Special thanks to Professors John Kramlich and Phillip Malte of the University of Washington for their advice and guidance and to Dr. Robert Baldwin of the National Renewable Energy Laboratory. Also special thanks to Dr. Thomas Reed for his continuing research into biomass gasification and his publishing of the *Handbook of Biomass Downdraft Gasifier Engine Systems*. Finally, special thanks to those who looked over this document and offered their expert advice.

## I. Introduction to Gasification

### Historical Precedents

Gasification has been around since the early 19$^{th}$ century, originally known as "town gas", which was used for light and heating. It largely became supplanted by natural gas and oil. Use as a transportation fuel spiked during the Second World War, when over 1 million vehicles were being run on biomass (largely due to lack of availability of petroleum). Gasifiers are currently used for many purposes running on many different fuels (largely coal and wood), most notably for drying spices in India. Our design is a downdraft gasifier, chosen due to it producing the least tar of known gasifier designs and the most successful for power generation.

### The Chemistry

A gasifier is a device which burns biomass with less than stoichiometric air to produce a mixture mostly comprised of carbon monoxide and hydrogen gas. This is called synthesis gas, or syngas. Syngas can be ignited with a spark in an engine much like gasoline. Therefore, it can be used with any gasoline engine with minor modifications to the existing gasoline engine (more on this later). The main challenge of gasification is the cleanup process. Ash and tar will degrade and clog the intakes of any combustion engine. Are process for creating syngas and cleaning it up is explained below.

## II. Our Design:

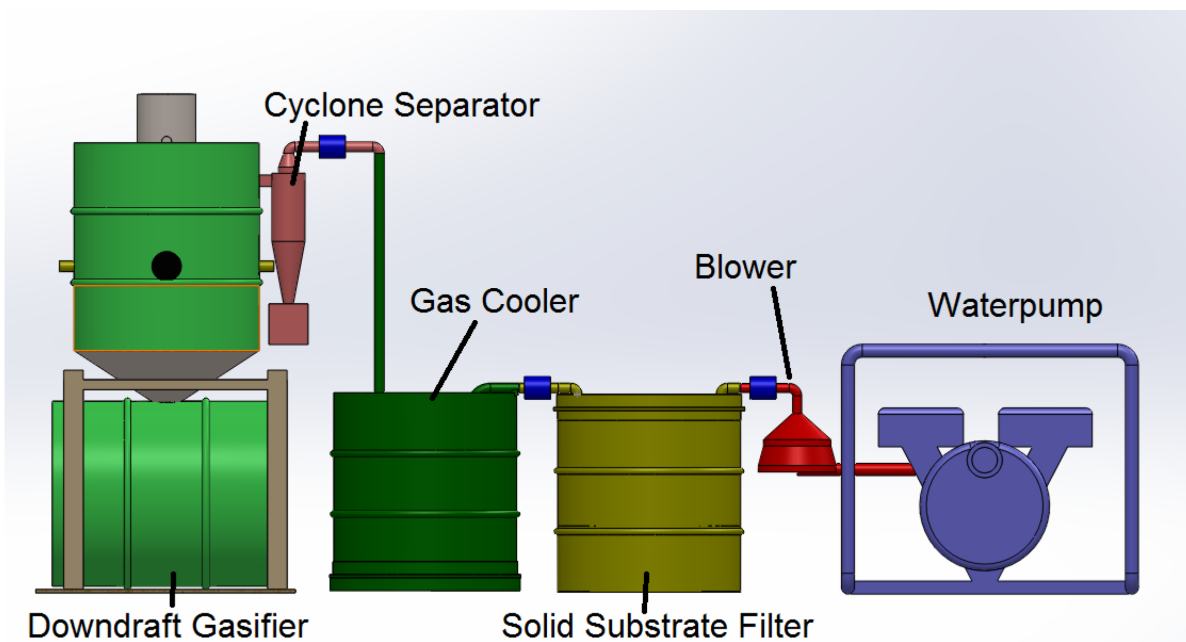


**Figure 1.** System Components

Our system comprised of a gasifier, filtration system, and gasoline powered water pump (Figure 1). Biomass is put into the gasifier, which combusts and pyrolyzes the fuel producing syngas. Before the syngas can be put into the water pump, it is first put through our filtration system, consisting of a cyclone separator, gas cooler, and solid substrate filter. A blower is included for initial startup of the system. How each component operates in greater detail is explained further.

**The Gasifier**

The gasifier chamber is made of a 10 gallon steel drum. Inside is a 4" steel tube combustion chamber (or fire tube) supported by ¾" steel bars. ½" steel pipes allow air to enter the system and a 2" pipe with an air tight cap serves as an entry point for a lighter when the gasifier is started. A shaker comprised of a steel mixing bowl with holes drilled in is hung from the top by steel chains.

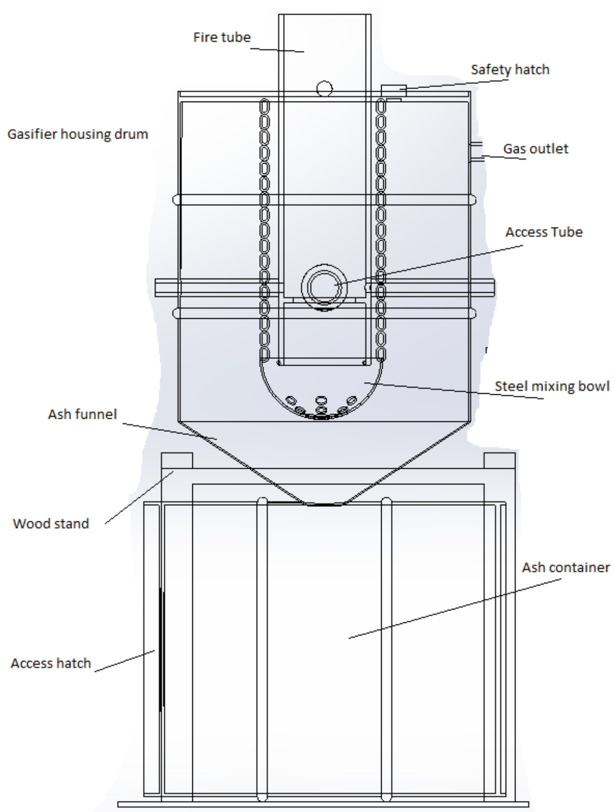


**Figure 2.** Gasifier

In our design, the biomass – either pieces of raw rice husks or rice husk pellets – is placed in the combustion chamber. The air inlets provide air to one part of the system so that combustion occurs. Also, an ignition pipe is aligned with the air inlets to allow the user to insert a lighter into the system, starting the fire that begins the process. When the biomass is near the air inlets, it will combust with air. As it burns, it will fall further down the chamber into the shaker grate. Here, it will pyrolyze into syngas. This syngas is pulled through the outlet (at first by the blower, then by the pressure of the water pump). Finally, the biomass will burn entirely into ash, which will fall through the mixing-bowl shaker or be shaken through by means of rotating the handle on the outside of the gasifier. The ash will mostly go into the ash chamber and remain there to be cleaned out later through an access hatch on the side of the ash house. Some will float through the outlet of the gasifier and be cleaned out later in the process.

**Safety Hatch**

Syngas is explosive, especially in high pressures. To avoid explosions in the gasifier, we have designed a weighted lid on the top of the gasifier so that when pressure starts to build, the hatch will open and relieve the pressure. When the hatch is closed, it is held down by weight and sealed with high-temperature seals much like gaskets in automobile engines.

**Cyclone Separator**

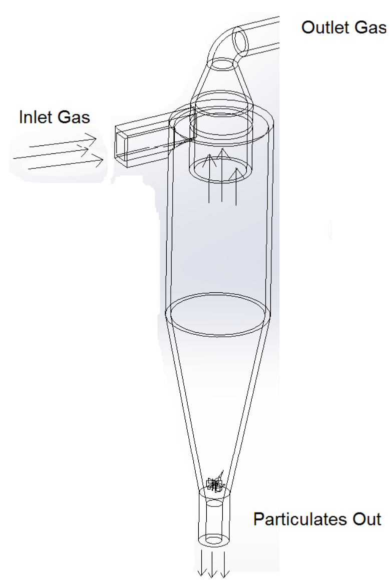


**Figure 3.** Cyclone Separator

The cyclone separator begins the process of filtration by removing particulates in the fuel stream in our system by inducing cyclonic separation, as seen in Figure 3. The fuel stream enters at a velocity of 15 m/s, and the shape of the container induces rotation. This, coupled with gravitational effects result in particulates in the stream to circle down. The now filtered air is brought up through the outlet tube by the pressure of the system. The advantage of the cyclone separator it requires no resources to operate; save for cleaning cost. The cyclone separator we have designed however can simply be taken apart by unscrewing at the middle, and cleaned for continued use.

**Gas Cooler**

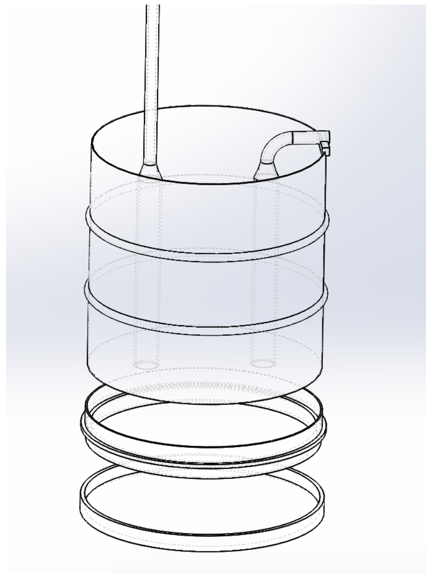

**Figure 4.** Gas Cooler

Before the hot syngas can enter the engine, it must be cooled. To achieve this, the syngas then continues on through our simple gas cooler, which is essentially another steel drum filled with water with expanded piping and a small chamber at the bottom. The expanding piping is a cost efficient method of increasing the surface area of the pipe, which along with the water contact with the piping allowing increased convective heat transfer. The gas cooler doubles as a filtration unit, with tar in the syngas condensing once it reaches 200°C at the bottom plate and tubes. To allow for easy cleaning and maintenance, the bottom chamber can be screwed on and off, exposing all areas which would require cleaning (notice the straight pipes).

**Substrate Filter**

One of the largest challenges surrounding gasification is the buildup of tar in the system. When the biomass fuel is broken down, tar is formed which can cause issues in the engine by affecting the flow rates in the system and by increasing the possibility of misguided combustion. To deal with this we added a filtering unit after the gas cooler to remove as much tar as possible before sending the syngas to the engine.

The design of the filter creates two separate air tight spaces which force the gas to travel through the filter unit twice. By doing this we help increase the amount of tar collected and have an alternating design to insure that both sides of the filter can be evenly used to collect tar until the substrate needs to be replaced.

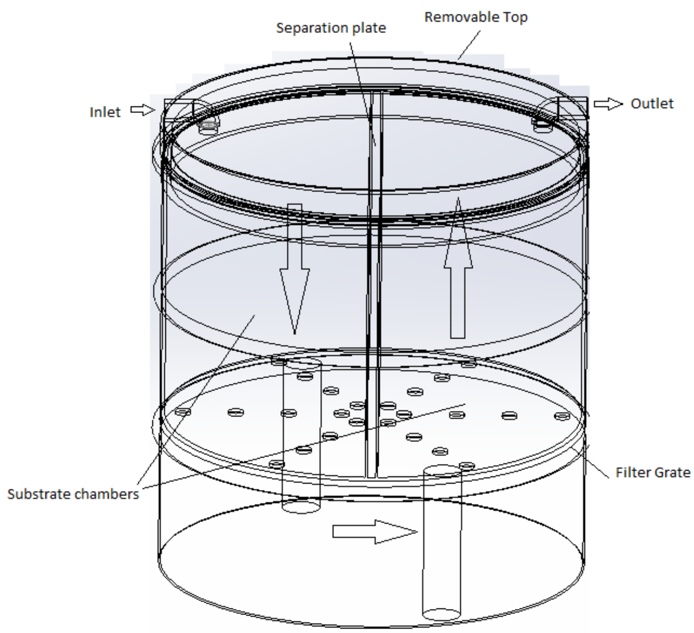


**Figure 5.** Substrate filter

To keep costs low we decided to use the fuel as the filter substrate. By doing this the tar would build up on the fuel inside of the filter. The fuel is then eventually placed into the fire tube and the process is repeated until the tar eventually breaks down from the pyrolization. The amount of filter substrate needed was calculated based on the surface area of each fuel type (husk or pellets) and with an assumed nucleation rate. The filter unit would successfully lower the tar to acceptable levels in the gas after testing is done to calculate the volume of the filter substrate needed.

**Blower**

In order for our system to begin running, it requires the use of a low powered blower to begin the process. Once the fuel stream becomes consistent, and the engine begins running on this stream, the blower is throttled down and shut off, as the pressure from the running engine is sufficient to pull the syngas through our system.

**Water Pump**

Finally, the syngas is then fed into the water pump to run the engine. We designed our gasifier to run a gasoline powered Honda WP-2065 engine, due to the relative simplicity of converting a gasoline powered engine to run on syngas. All that is required is the air to fuel ratio must be changed by adjusting the carburetor attached to the engine. For syngas, a ratio of 1:1 is generally desired, though that is one thing that requires further testing.


**Figure 6.** Honda WP-2065 Water Pump

If we were to run a diesel water pump on our gasifier, more extensive modification is required. A spark ignition system must be installed and the compression ratio in the engine must be modified. It is possible to run a diesel water pump on a mixture of diesel and syngas, roughly with 90% savings on diesel use, but our group opted to focus on a solution which required no fossil fuels to operate, and simpler engine modification.

**Rice Husks as Biomass Fuel**

Our design meets one of the main criteria for this design problem is the integral use of rice husks as the biomass fuel for our gasifier. Our fuel, unlike many others, fulfills the needs of a rice farmer in India, who has affordable access to fuel for their water pump. Rice husks are largely a byproduct of rice farming, typically burned, sold, or simply thrown away. Rice husks comprise 20% by weight of rice. Rice husks previously unused by farmers in Bihar can be directly fed in to our gasifier, along with rice husk pellets. The advantage to using pellets is the gasifier can more easily combust and pyrolyze the denser pellets. The disadvantage of rice husk pellets however is that they must be bought from a supplier (or self-processed). Again, our gasifier is designed to accept both rice husks and rice husk pellets, so this issue is moot.

The gasification process leaves behind ash, which can be used as a soil amendment or sold for cement board construction. It features one form of unusable waste, in the form of tar. However, it is collected in the filtration system, which has been designed to be easy to clean and to maintain. Some of the tar is collected in the substrate filter, which can then be re-fed into the gasifier. Tar cleaned out of the system requires waste disposal and storage.

## III.Cost Analysis

Once we had decided on our design, a bill of materials was drafted including all parts required. Price estimates on these parts were then conducted, resulting in a cost of materials (including the Honda WP-2065 water pump) of $1064.97 based on quotes from numerous sources. Time required for welding, brazing, machining, casting and assembly of our design were also considered, resulting in a total cost of $1496.97 for the complete system.

## IV. Operation

The operation of the gasifier is a fairly simple process of regulating the air intake and outtake throughout the system along with maintaining an appropriate amount of fuel.

**Start up**

1. The first step in the operation of the gasifier is to prepare the system by placing an adequate amount of filter substrate (biomass) into the filter unit along with placing enough water into the gas cooler.

2. The next step is to ground the system within the wooden gasifier stand to make sure that no static sparks can cause unwanted combustion of the syngas. The user must also at this time observe for any possible tar blockages in the system.

3. At some point before starting the gasifier, be sure to empty both ash catchers of all ash.

4. The next step in operating the gasifier is to load the biomass into the fire tube as shown. The desired running time should determine the amount of fuel to be placed into the tube as shown in our calculation as seen in appendix. Gasification of rice husks requires approximately 3.12 kg of fuel for each hour of use.

5. The next step in the operation of the gasifier is to start the combustion of the fuel in the fire tube. This is done by carefully opening the valve on the main body of the gasifier and lighting the fuel at the bottom of the firetube. The valve is then closed and then the air intakes on the side of the gasifier are adjusted to reach the desired amount of air for pyrolization.

6. The final step to start the gasification is to turn on the air blower to create the pressure necessary to reach the desired flow rate of the gas in the system. Once the system reaches equilibrium with the engine running the blower should be turned off as the engine will create the pressure difference needed to drive the gas.

### During Use

- Every hour or so, the shaker needs to be shaken and the fuel replenished. Using hot pads, cautiously and slowly open the fuel lid. Replenish the fuel as needed. Then, slowly lift the shaker handle and shake it thoroughly. Replace both and allow the system to resume operation.
- Always keep an eye on the water levels of the cooling unit. If too much water evaporates, the gas will not be cooled enough before entering the engine and could cause damage.
- Use of hot pads is recommended for touching any part of the system. Never touch the gasifier housing drum during use as it will be the hottest.

### After Use

Stop the engine and allow the process to die. Then, cautiously open all air inlets. Allow the system to cool before handling it and storing it. Ash clean out and tar cleaning should be done when the system is totally cooled.

### Maintenance

The maintenance of the gasifier system requires little training to comprehend. The main points to be careful of during the maintenance are the amount of tar build up and checking the integrity of the gasifier system. The gasifier will have to occasionally be opened and cleaned out manually due to the nature of tar build up. The system should also be checked during cleaning to insure that no other leaks or blockages in the system exist.

### Safety

As the gasifier does deal with gas, there are several things the user must be cautious about.

1. The grounding of the system is crucial to prevented unwanted sparks from igniting the syngas

2. Caution must be used when working around the running gasifier due to the production of carbon monoxide; this can be dealt with by having an air-filtering mask while opening the gasifier at the start of operation and especially when using the shaker or replenishing the fuel.

3. The gasifier should not be touched by bare hands while running as the internal temperature will reach very high temperatures (upwards of 700 degrees Celsius).

4. The air intake must be maintained throughout operation to prevent unwanted fires and combustions inside the main gasifier chamber.

5. The gasifier should not be run without the engine attached as the buildup of gas could lead to combustion.

## V. Analysis of Other Power Generation Methods

### Diesel

Currently, diesel is used to power water pumps in India. Diesel is a product of crude oil found in deep in the Earth. The main component of diesel is cetane, with a chemical formula $C_{16}H_{34}$. Let's do some combustion chemistry. The equation for the combustion of cetane with stoichiometric air (sufficient air to burn all of the cetane) is shown here.

$$C_{16}H_{34} + [24.5]O_2 + [92.12]N_2 \dashrightarrow [16]CO_2 + [17]H_2O + [19.12]N_2$$

So for every kilomole of cetane burned, 16 kilomoles of carbon dioxide is formed. Doing some quick calculations, it can be shown that 3.39 kg $CO_2$ is emitted from the combustion of each kilogram of cetane. This is $CO_2$ which was taken in by biomass thousands of years ago which were decomposed and left preserved deep in the Earth. That $CO_2$ is being put back into the atmosphere by mankind at the expense of the atmospheric balance necessary for the safety of life on Earth.

Using rice husks with an average chemical formula $C_{13}H_{23}O_{10}$ produces syngas which is burned with stoichiometric air to produce 13 kilomoles of $CO_2$ for each kilomoles of rice husk, or 1.84 kg $CO_2$ per kilogram of rice husk. However, this $CO_2$ was part of the atmosphere just in the previous year and was absorbed by the rice plant as it was growing. That same $CO_2$ would have been re-emitted by the plant after it died as part of the natural balance of life. This is why biofuels are considered carbon-neutral. There is a net zero production of carbon dioxide.

### Gasoline

The gasifier will be running on a previously gasoline running engine, about the size of a lawnmower engine (5 HP). It is reasonable then to consider whether our design use of biomass is an improvement. Small engines of this size are generally known to run at 1.25 gallons an hour, which translated in to Bihar's local gas price means an operating cost of 354.28 rupees an hour. Gasoline is of course a fossil fuel, and actually results in more carbon emission than Diesel. Compare this to our gasification system which runs on 3.12 kg of rice husk pellets an hour, resulting in an operating cost of 19.49 rupees per hour (based on the price of these pellets on alibaba.com), if any assuming a farmer uses his own rice husks.

**Solar Photovoltaic**

Photovoltaic solar power is another carbon neutral power source. However, it is expensive, and in a place where every meter of land is necessary for cultivation, expansive. Grainger currently markets 100W solar panels for $250. By my calculations, the power requirement needed to pump water given the typical efficiency of fossil fuel pumps is about 3.75kW, so we would need 37.5 of these solar panels for a price of $9375. These panels are 7.5 square feet each. So we would need 282.9 square feet.

This amount is based on rated power, which neglects the capacity factor of solar. The capacity factor comes from the fact that there will not always be total, uninterrupted sun aimed directly at the panel. Sometimes the panel is at an angle from the sun, sometimes there are clouds. Most of the energy for pumping water will be needed during the flooding of the fields. The United States capacity for solar power throughout a 24-hour period is 20% (Malte, 2013), so 40% when the Sun is up. India is approximately the same (NREL). The flooding of the fields happens during the rainy season however, so this figure should at least fall to an optimistic level of 20%. Therefore, we would need five times as much solar power to get 100% of the energy we need, for a price of $46,875. This would take 1,414.5 square feet.

There may be better solar panels out there, but not as cost effective or efficient. The Boeing Spectrolab recently designed a solar panel with an efficiency of 41.5% (Malte, 2013), but this is not on the market, and if it were, it would be enormously more expensive than the typical solar panel on the market. The maximum efficiency on the market right now for solar PV is about 24% (Malte, 2013), such as the Grainger panel aforementioned. This option greatly exceeds the maximum price for our gasifier system and also exceeds the systems footprint. Our system will cost $1496.97 and will take less than 5 square feet of room. It weighs very little so as to be more portable than solar panels.

**Human Powered**

Indian farmers gave up the idea of human powered pumps when they switched to diesel pumps. While human power can be considered free in the sense of fuel cost, the amount of power output capable of a human is only roughly 75 Watts over the course of an eight hour day, minus any harvesting inefficiencies, which when compared to an engine of 5 horsepower or 3,728 Watts means to accomplish the same task it takes 50 times longer based on human power. This costs quite a bit to an Indian farmer or farm-hand who could be using their time in more productive ways. In order to go back to using human power for crop irrigation, the farmer would have to give up labor in another aspect of their crops, costing them time and money, making them less competitive with other markets. In the year 2013, the only cost-effective way to farm is automatic irrigation.

## VI. Conclusion

Testing is paramount in the designing of a reliable gasification system. While the Solar Energy Research Institute's *Handbook of Downdraft Gasification* has given us much data on similar designs, little information is available about such a specific design. Therefore, testing is required in order to fully understand an exact volumetric airflow of syngas is necessary, how to set our blower, what kind of blower we need, and which diameter of our air inlets is optimal. The nature of cleaning our system, while designed to be easy, cannot be known until testing is done. Beyond this, there is more optimization that could be done to further reduce the cost, footprint and weight of the system. Testing would also be needed to be done to figure out the modifications necessary for the pump. If we win this challenge (and potentially even if we don't), we will continue forward building a prototype to test, and improve our design.

As can be seen from our design section of the report, our gasifier design fulfills all the requirements presented by the Greenpeace organization. Our design would provide adequate renewable energy that is also available conveniently to the farmers in the form of crop waste like rice husks or other agricultural biomass products. The simple mechanics of the system also allow it to be user friendly and maintain a compact design that can be scaled to match the needed power output for any small engine. We also intend on making the design very robust to limit the concerns of difficult maintenance and performance issues.  Even with all this it is still a preliminary design, testing on a prototype would allow us to test the unknown factors in our design and provide a mass producible power source for farmers all throughout India.

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**Appendix A: Calculations**

Calculating fuel consumption

First, taking the Ultimate Analysis of Rice husks given by the Reed Handbook, the molecular composition of rice husks is $C_{13}H_{23}O_{10}$. When combusted with stoichiometric air

$$C_{13}H_{23}O_{10} + w(O_2 + 3.76N_2) \rightarrow [A]CO_2 + [B]H_2O + 3.76wN_2 \quad (1)$$

When balanced, w become 13.75. The Handbook recommends a reduction in air of 25%. So

$$C_{13}H_{23}O_{10} + 0.25(13.75)(O_2 + 3.76N_2) \rightarrow [A]CO + [B]H_2 + [C]CO_2 + [D]H_2O + 12.925N_2 \quad (2)$$

again, running a balance knowing the concentration of CO to be ⅓ of the total products by mole

[A] = 12.475, B=8.15, C=0.525, D=3.350

Now going to the Colorado State University Equilibrium calculator, inputting the products of equation (2) as the reactants, the initial temperature of 373 K (the safe temperature for gas going into the engine) and pressure to 1 atm, with a constant temperature and pressure, the enthalpy is found to be -3019 KJ/kg syngas. This engine needs 5hp, or 3.75 KJ/s.

However, the typical efficiency of a stationary pump engine can be assumed to be about 25%. So the engine needs 15 KJ/s.

The combustion in the engine goes as follows

$$12.475CO + 8.15H_2 + 0.525CO_2 + 3.35H_2O + 12.925N_2 + w(O_2 + 3.76N_2) \rightarrow [A]CO_2 + [B]H_2O + (12.925+3.76w)N_2 \quad (3)$$

Balancing shows w to be 10.3035. [A] = 12.982, [B] = 11.5

Putting the products of (3) into the CSU calculator with initial conditions of T = 298K and P = 1atm (the ideal exhaust conditions. Any lack thereof is handled by the engine efficiency assumption) yields the exhaust enthalpy to be -3544 KJ/kg products, or -9723.6 KJ/kg syngas.

The enthalpy of the air into the engine is 298.18KJ/kg air = 520.12 KJ/kg syngas.

So the enthalpy in is -2499 KJ/kg syngas. The enthalpy out is -9723.6 KJ/kg syngas. So the change in enthalpy is 7224.7 KJ/kg syngas. This is equal to the 15kW/(mass flow rate of syngas). Turns out, the mass flow rate of syngas is 0.0020762 kg syngas per second.

The fuel consumption is just the mass ratio of syngas to fuel divided by this number. So, the fuel consumption rate is 0.868 g/s, or 3.125 kg/hr.

Calculating area into cyclone separator

So we know the syngas needs to move at 0.0020762 kg/s. At the gasifier exit temperature (estimated at 700K), it can be calculated (by the CSU calculator) the specific volume is 2.6496 $m^3/kg$. Therefore, there is a volumetric flow rate of 0.0055011 $m^3/s$. For the cyclone separator to work, the inlet velocity needs to be 15m/s.

So the area of the inlet is 0.0055011 ($m^3/s$)/15 (m/s) = 0.00036674 $m^2$. Or, 0.568 $in^2$.

Calculating the speed of the blower

The blower is blowing the syngas at 0.0020762 kg/s. The temperature at the blower is 373 K, so the volumetric flow rate according to the CSU calculator is 1.4118 $m^3/kg$. So the blower is blowing a volume of 0.002931179 $m^3/s$ or 6.21 CFM. This is really slow, so the blower does not require a great amount of power.