Control of Biodiesel Generator Set in Biomass Gasification Emulation for Use in Emergency Energy Module (EEM)

Caroline Ayanian and Samip Desai

Supervisor: Anders Malmquist

Internship Report

June 29th, 2016

Department of Energy Technology, Royal Institute of Sweden

Duke Smart Home Program, Department of Mechanical Engineering and Materials Science, Duke University

Stockholm, Sweden

1 Abstract

This objective of this project is to model the dynamics of the PowerPallet20 gasifier (PP20) and the MDG6000CLE generator set using transfer functions. Simplified models of the dynamics of gasification and generator set were constructed using Simulink. The dynamics of the generator set can reasonably be described by a 0.34 second time delay and 0.10 second time constant. The PP20 has a time delay when starting up of approximately 600 seconds. Other characteristics of the PP20 cannot be presently defined given their great variability based on an array of environmental and systematic factors. The constructed model provides a starting point for the implementation of hardware, as well as a framework for a model of digestion.

2 Acknowledgements

This research was supported by KTH Royal Institute of Technology in Stockholm, Sweden and Duke University in Durham, North Carolina. We thank Dr. Anders Malmquist for his expertise and advisement throughout the duration of the project. His knowledge of control system design was critical to the development of this project.

We thank Moksadur Rahman for his assistance and continual guidance in all aspects of the project. He provided constant feedback and an understanding polygeneration technology.

We are grateful to all those who have helped and provided feedback in all capacities: Leif Pettersson for his help fixing and running the gasifier, Christer Rosén for describing the dynamics of gasification, Austin Liu from All Power Labs for his constant correspondence and level of detail in explaining the PP20 gasifier technology, and all those who have conducted research in this field to make a substantial literature review possible.

Lastly, we are grateful to Dean Jim Gaston and the Duke Smart Home Program for making this research possible and the KTH Royal Institute of Technology for its access to numerous resources and faculty. This was a truly unique and eye-opening opportunity that has shed light on clean energy technologies and control system design.

Table of Contents

3 Introduction

According to the UNHCR, in 2015, 34 thousand people were forcibly displaced from their homes each day, adding to the already 42.5 million displaced persons worldwide. The same conflicts or natural disasters causing their displacement often damage or impede access to the local electrical grid and water infrastructure. In such cases, these populations' energy and water needs are either not met or met with dirty, intermittently available sources. Additionally, access to clean water can also be insufficient for the aforementioned conditions. KTH Department of Energy Technology is developing the Emergency Energy Module (EEM) to simultaneously address the need for reliable, clean energy and water. The EEM is a mobile, flexible polygeneration unit with energy inputs of wind, solar, and biomass energy, and outputs of electricity and purified water. The unit is intended for use in refugee camps during intermediate (2 weeks to 2 years) stages of relief. Hybridized, renewable energy devices have been produced with limited success. However, the EEM is novel in its potential independence from the grid, its use of exclusively locally available, renewable energy sources and its coordinated production electricity and purified water. Major challenges facing its implementation include minimizing costs and improving the reliability.

Research is currently underway for the biomass module of the EEM to determine whether gasification or digestion are better suited for integration with solar and wind power in its intended use. However, using a simple, low maintenance system such as a generator to emulate more complex ones in the lab environment is ideal for both economic and operation factors. The generator behavior can be modified using control mechanisms. A model of the dynamics of each system is produced based on testing, literature, and supplier data. The model in turn informs the design of the controller. Ultimately, the use of the generator decreases the cost and operational demands of the prototype while improving its versatility.

3.1 Solar Energy

The EEM includes 22 statically mounted monocrystalline photovoltaic panels. Connected with three bypass diodes, this module has a maximum output of 5.5 kW. In addition to the panels and support system, the module includes a solar inverter and battery charger to enable integration with the micro grid.

3.2 Wind Energy

In addition to the array of solar panels, a 2.4 kW wind turbine is installed on the container of the EEM. The turbine has its own battery bank as well as controller and inverter, thereby converting the output voltage from 3-phase AC to 48V DC and finally 24V DC. The specifications of the turbine are particularly subject to change given the wind conditions of the installation location. The EEM prototype used a 1 kW turbine given it was previously purchased by KTH and therefore free of charge.

3.3 Biomass Energy

In accessing the biomass energy, either a gasifier or a digester will be used. As further research needs to be performed to select the proper energy conversion device, a diesel generator set will be used to match the electricity production of each device, emulating in particular the transient output of each.

With the variability of solar and wind power, biomass energy is intended to add redundancy to the system, providing in times of limited solar and wind output as well as low battery storage.

3.3.1 Gasification

The goal of gasification is to control discrete thermal processes that are normally mixed, as in the case of lighting a match. Gasification is the thermochemical conversion of a carbon source, such as wood or coal, into syngas, a mixture of carbon dioxide and hydrogen. While these products are made when directly burning biomass, the abundance of oxygen results in syngas being consumed in combustion. It is necessary to consume some of the produced gases in gasification as well as combustion is the only exothermic process. However, by controlling the temperatures at various locations in the gasifier and the air available for combustion, only about ¼ of the produced gases are consumed. The remaining syngas can then be used in a variety of applications. In the case of the PP20, the produced syngas is used to power a generator, which produces electricity. This process can be thought of as a controlled burn, as shown in Figure 1.

Figure 1: While complete combustion Gasifiers, shown on right, separate discrete thermal processes by controlling air intake and temperatures that otherwise

Gasifiers come in a variety of forms, such as updraft, downdraft, cross draft and fluidized bed. In each case, the device separates the processes in burning biomass that normally occur more or less concurrently, such as when a match burns. These discrete processes are summarized in Figure 2.

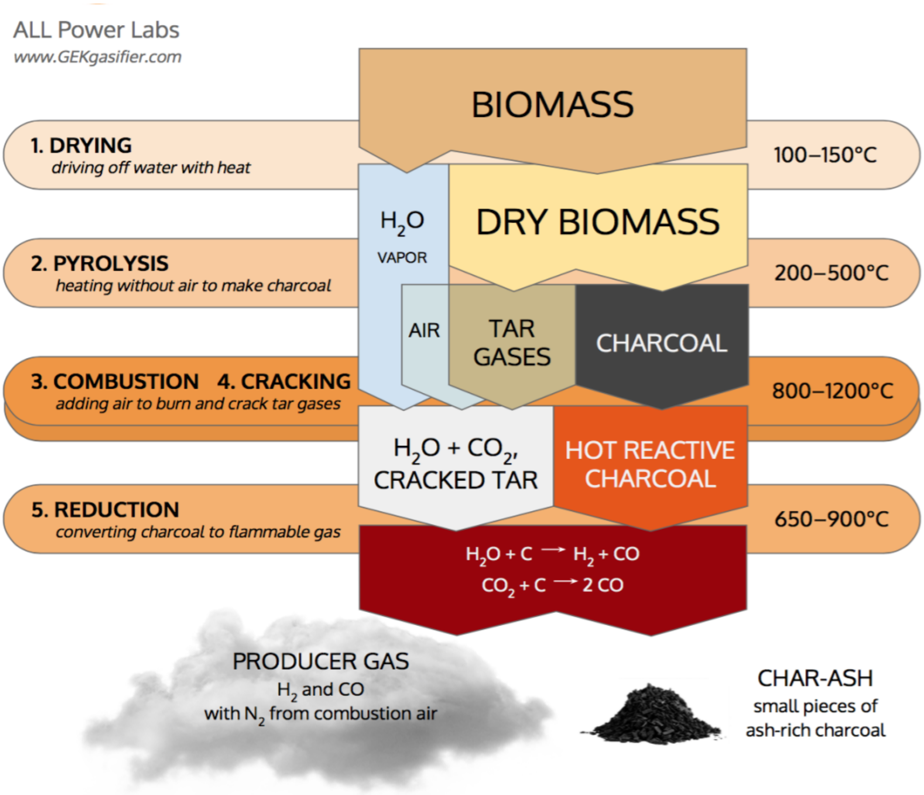


Figure 2: Summary of the characteristics of the main processes of gasification

Gasification utilizes the differences in temperatures at which each process occurs to isolate each, as shown in Figure 2. First, the biomass is dried at relatively low temperatures to remove water vapor. Next, the dried biomass enters the hotter pyroreactor of the gasifier, and the process of pyrolysis commences. Volatile tar gases separate from the fixed carbon of charcoal. The intake of air combusts with the tar gases to produce additional H_2O vapor, CO_2 and cracked tar.

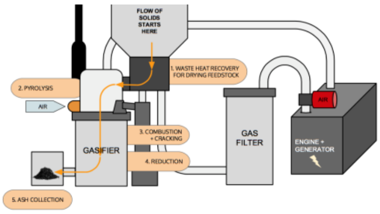
$$C_xH_y + N * O_2 \rightarrow X * CO_2 + {}^{Y}\!/_{2} * H_2O + heat \qquad (1)$$

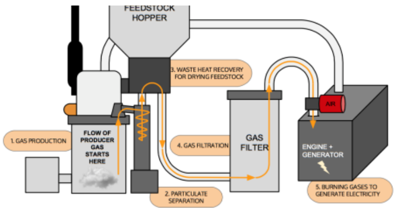
The final process, reduction, can be thought of as reverse combustion. As combustion is the only exothermic reaction in gasification, it is the heat from this process that drives the final conversion deoxygenate the combustion products as H_2O vapor and CO_2 pass over the hot charcoal bed, reducing to syngas.

$$heat + H_2O + C \rightarrow H_2 + CO \qquad (2)$$

$$heat + CO_2 + C \rightarrow 2CO \qquad (3)$$

The waste heat from the produced syngas and the attached internal combustion engine (ICE) exhaust is used to drive drying and pyrolysis, as shows in Figures 4 and 5 respectively.





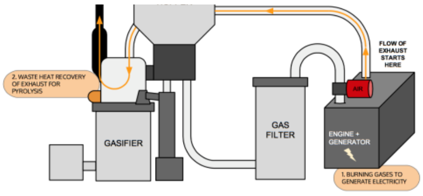


Figure 3: Flow of solids Figures 4 & 5: Flow of gases

The figures above summarize the flow of solid and gases in the PP20. The solid waste is primarily ash, the majority of which exits directly after the reduction zone. Gaseous waste is the product of the ICE, which as shown in the combustion reaction in equation 1, is primarily CO_2 and H_2O vapor.

In creating a model of the power output of the gasifier, the output in transient periods such as start-up and load changes were of particular interest, as these periods are crucial to control when attempting to harmonize the entire EEM. Start-up is defined as the period during which the reduction zone has not yet reached 700 ^oC. In start-up, the gasifier consumes electricity supplied by a car battery onboard to power blowers, but does not yet produce useful syngas. During normal operation, the ICE's consumption of gases causes a pressure gradient. This causes the intake of air, which drives the exothermic combustion, in turn propelling the reduced gases produced to the ICE . However, during start-up, the reactor is not hot enough to break down tar gases to CO_2 and H_2O vapor. Instead of clogging the ICE with tar gases, this produced gas is flared off, and blowers are used to create this pressure gradient. Once the reduction zone reaches 700 ^oC, however, the engine is turned on. Waste heat from the engine's exhaust causes the temperature to sharply rise.

At this point, steady state function is achieved. The generator set is an electric generator driven by an ICE. The power stroke of the ICE produces a torque on the crankshaft, which turns the rotor of the generator. The turning of the rotor causes an AC current to be produced in the stator via electromagnetism. However, this concurrently produces a Back Electromotive Force. At steady state, the sum of the ICE torque, the Back EMF, and internal losses (friction) sum to zero. A governor, a type of control mechanism, ensures that it runs at a constant frequency. If the frequency is too low, the governor opens the throttle, increasing fuel rate and ICE torque. If it is too high, the fuel rate is decreased.

$$T_{eng} - T_{gen} - T_{friction} = \sum I \frac{dw}{dt} \qquad (4)$$

In equation 4, I is the system moment of inertia, and w is the angular frequency. As the load demand changes, the generator torque changes, and causes a change in frequency. The governor will adjust the throttle to either increase or decrease the engine torque, returning to the desired frequency. This is particularly important as frequency is proportional to voltage, and the voltage must be kept constant. When the ICE fuel rate is changed, so is the pressure gradient within the system. A larger difference in pressure results in an increased flow of gases and intake of air. As more air enter the system, more oxygen is available for combustion, and more heat is then available for the three other processes. Consequently, syngas production increases.

While gasification can be an efficient, renewable method of electricity production, a buffer tank for storing syngas has thus far proven impractical due to the large size of the tank that would be needed to be effective. As a result, the gasifier must complete the start-up sequence each time it is turned on, resulting in a delay of 5-20 minutes.

3.3.2 Digestion

Digestion is the anaerobic conversion of biomass to biogas using bacteria. Biogas is approximately 60% CH_4. Similar to gasification, an anaerobic digester produces gas which can be consumed by an ICE to turn a generator. However, unlike syngas from gasification, biogas can be stored effectively in a buffer tank. Therefore, once the digester reaches steady state, the dynamics of the system is equal to that of just the generator set in both restarting and changing loads. The major drawbacks of digestion are the initial time for start-up, which is on the order of magnitude of hours to days, and the extra space required for the digestion equipment. This may be impractical for deployment purposes, as the biomass generator is expected to correct for unpredicted variations in solar and wind output.

3.4 Main Energy Storage 15 min

The main energy storage is a lead-acid battery bank, with a voltage of 24 V and capacity of 1200Ah. The battery pack is comprised of 6 cells, each rated at 200Ah. Two groups of three cells are connected in parallel, with the two groups of cell connected in series. In addition to the cells, the subsystem includes electrical cable, a support structure for the batteries, a fan heater and insulation. The latter two are valuable in temperature control, which is necessary as the range of optimal operation of the battery is quite narrow, at 15 ^{o}C to 20 ^{o}C. Even a drop in temperature to 0 ^{o}C incurs a decrease in capacity to 85%. Ultimately, the losses of running the heater are less than losses from operating at low temperatures.

3.5 Electrical and Control System

A robust control system is required for the integration and harmonizing of a diverse mix of energy sources and for implementing a hierarchy of power sources used. The hierarchy is summarized in Figure 6. The integration is crucial as wind systems and solar PV produce direct current whereas loads typically use alternating current.

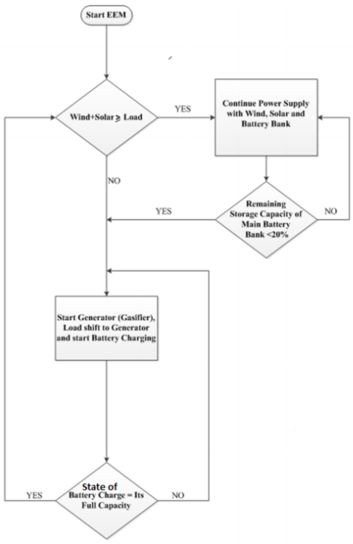


Figure 6: Decision matrix in control module for implementation of source hierarchy during start-up. This matrix ensures that the load demand is met, use of renewable sources is maximized, and the charge of the battery bank does not fall below 20%

The control module used is a Power Router. This device meets the system requirements, and is also capable of grid connection.

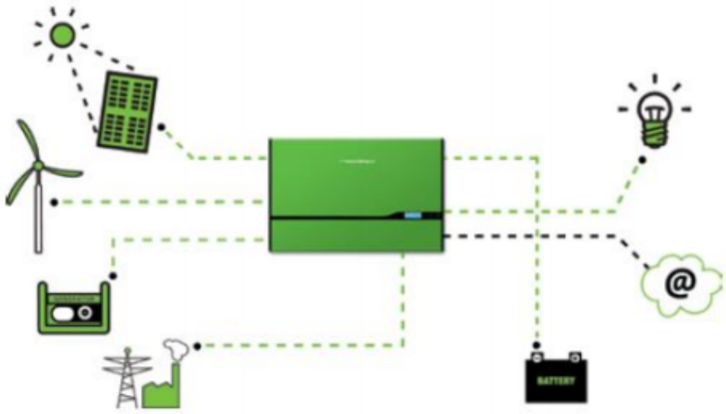


Figure 7: Schematic of linkage of possible power sources and sinks

3.6 Water Purification

The aims of the water purification module are to produce a sufficient volume of water with an acceptable purity level with minimal auxiliary energy usage. In addition, the selected appliance should require minimal upkeep and repairs, fit within a portion of a shipping container, and of course be economically viable. It is estimated that a person would require a minimum of 3.7 L of clean water per day. Therefore, if the EEM is to support a camp of 5000 individuals, the apparatus must be capable of supplying at least 18,500 L of purified water per day. Additionally, the total dissolved solid (TDS) in the produced water must be less than 1,200 ppm, though ideally less than 600 ppm. Originally, the Reverse Osmosis system from Pure Aqua was selected. However, in testing, it was decided that this device exceeded the maximum level of required repairs. Additionally, repairs were found to be overly involved as the broken subsystems could not be easily replaced.

Research is currently underway in studying the feasibility of Membrane Distillation technology. This technology is particularly attractive because it can utilize waste heat from the Biomass system. However, no conclusions can be made at this time as to whether this technology will ultimately meet all of the aforementioned system requirements as feasibility research is still in its preliminary stages.

3.7 System Representations

In modelling, transfer functions can be used to mimic a system's response to a range of inputs. A transfer function is a relationship between an input and an output, and is often represented as a fraction. Additionally, this relationship is described in the frequency domain.

Functions can be described in one of two domains: the frequency domain and the time domain. Time domain systems are functions time, whereas frequency domains are functions of 's', where s is an imaginary value with a magnitude of the frequency. The complex plane is used to present functions in the frequency domain. Functions can be converted from one form to another via the Laplace Transform operation.

A system in the frequency domain is characterized as first order when only it only contains one root. It should be noted that for a system to be stable, no roots should exist in the right half plane. First order systems are of the following form.

$$\frac{Y(s)}{U(s)} = \frac{K}{\tau_C s+1} \tag{5}$$

In equation 5, U is the signal, or input, and Y is the system response, or output. K is the gain of the system and τ_c is the time constant. This parameter is equal to the response time of a system to a unit step input to reach the value of $1 - {}^{1}/_{e}$, approximately 0.63. In the time domain, equation 5 is as follows.

$$y(t) = Ke^{-t/\tau_c} * u(t) \tag{6}$$

Additionally, a system may have a time delay. This is the amount of time it takes for a signal to initiate a response in a system. A system with purely a time delay is represented in the frequency domain as an exponential function.

$$\frac{Y(s)}{U(s)} = e^{-\tau_d s} \tag{7}$$

In equation 7, τ_d is the time delay. Alternatively, this can be thought of as a shift of the system response along the time axis.

$$y(t) = u(t - \tau_d) \tag{8}$$

More generally speaking, a time delay can be added to any response as follows.

$$f(t - \tau_d) \rightleftarrows e^{-\tau_d s} * F(s) \tag{9}$$

Transfer functions may also be characterized by a state space representation or block diagram. The software used in modelling in this project symbolizes systems as block diagrams.

4 Materials and Method

In the course of the project, a combination of a thorough literature study, interviews with experts and suppliers, and experimentation were performed to explore the theory and characteristics of gasification and diesel generator sets. Much of the findings of the literature study are presented in the Introduction, and the correspondence with the All Power Labs sales representative is included in the Appendix.

In constructing the model, several parameters needed to be determined to set the transfer function emulating the system characteristics. Tests were performed to ascertain values for no-load fuel consumption, the load demand range for linearity, and load change dynamic response. The range of load demand for linearity was performed to determine the range of load demands over which the mass of fuel consumed each stroke was linearly related to the power output. This was necessary for the dynamic testing, as the results from such testing could only be modelled by a first order system if all load changes occurred within the range of linearity as defined above. The materials and method for each of the three tests are presented in Table 1.

Table 1: Materials and methods for three experiments of the diesel generator set

	No-Load Fuel Consumption	Load Demand Range of for Linearity	Dynamic Response Testing
Materials	• Diesel generator set • Diesel of B20 fuel • Ammeter • Voltmeter • Graduated cylinder fuel tank • Load equal to rated capacity of genset • Carbon monoxide detector • Stopwatch	• Diesel generator set • Diesel of B20 fuel • Ammeter • Voltmeter • Graduated cylinder fuel tank • Variable load equal to rated capacity of genset • Carbon monoxide detector • Stopwatch • A good podcast	• Diesel generator set • Diesel of B20 fuel • Ammeter • Voltmeter • Graduated cylinder fuel tank • Variable load equal to rated capacity of genset • Carbon monoxide detector • Stopwatch • Camera • Patience
Method	1. Add at least 500 mL of fuel to the graduated cylinder fuel tank 2. Start the genset 3. Switch the breaker to “on” and run for 3 min 4. Record voltage and fuel level and start timer 5. When 150 mL have been consumed, stop timer and record time 6. Connect loads and ammeter 7. Increase loads to rated capacity and run for 30 sec 8. Record voltage, amperage and fuel level and start timer 9. When 150 mL have been consumed, stop timer and record time	1. Add at least 500 mL of fuel to the graduated cylinder fuel tank 2. Start the genset 3. Switch the breaker to “on” and run for 3 min 4. Connect loads and ammeter 5. This test will repeated with **no load and five other load values** spaced between no load and full load 6. Adjust load and run for 30 sec 7. Record voltage, amperage and fuel level and start timer 8. When 100 mL have been consumed, stop timer and record time 9. Turn off genset for 10 minutes 10. Listen to good podcast 11. If the fuel level has dropped below 200mL, add fuel 12. Repeat steps 2-11 for each load value	1. Add at least 300 mL of fuel to the graduated cylinder fuel tank 2. Start the genset 3. Switch the breaker to “on” and run for 3 min Connect loads and ammeter 4. Increase load to at least 50% of rated capacity and run for 30 sec 5. Set up camera to record the genset voltage and amperage 6. Begin recording 7. At a set time stamp in the recording, increase the load in one step 8. Run for at least ten sec 9. Return to the lower load in one step 10. Run for at least ten sec 11. Repeat steps 7-10 several times 12. Transfer data from video to spreadsheet. When output is steady, one data point per second is sufficient. In transient periods, record the voltage and amperage at each frame (30-40 per sec)

5 Results

First, a skeleton of a first order model was designed. For each of the gasifier start-up, gasifier load change, and genset load change, an associated time delay and time constant needed to be determined. This was accomplished using information from literature, suppliers, and experimentation, and an exact value or a range of values for each parameter was ultimately specified.

Results from the three experiments performed are presented below.

5.1 No-load Fuel Consumption Results

Table 2: Results of No-load Fuel Consumption Testing

	Test 1	Test 2
Date	09-jun	14-jun
Ambient Temperature	59F (15C)	66F (19C)
Start Fuel Volume (mL)	225	200
End Fuel Volume (mL)	75	50
Net Fuel Volume (mL)	150	150
Time (sec)	892	248
Actual Output (kW)	0	4,614
Actual Voltage (V)	234	224
Actual Current (A)	0	20,60
Theoretical Output (kW)	0	4,5/5
Fuel consumption (mg/stroke)	2,843E+00	1,068E+01
Conversions:		
L/mL		1,000E-03
kg/L		8,600E-01
mg/kg		1,000E+06
strokes/second (Hz)	5,087E+01	4,870E+01
No-Load Fuel Consumption	**26,615%**	

Ultimately, it was determined that the no-load fuel consumption of the diesel generator is 26.6% that at the rated capacity of 4.5 kW.

5.2 Linearity Results

Table 3: Results of Linearity Testing

	Test 0(1st)	**Test 2(3rd)**	**Test 3(5th)**	**Test 4(4th)**	**Test 5(6th)**	**Test 6 (2th)**
Load Level	0	2(1,0;1,0)	3(1,1;1,0)	4(1,1;1,1)	5(2,1;1,1)	6(2,1;2,1)
Voltage (V)	235	232	230	227	225	224
Current (A)	0.00	3.31+2.99	6.10+2.94	6.11+5.93	8.87+5.97	8.81+8.75
Time (sec)	601	413	352	293	259	227
Fuel Volume (L)	0.150	0.150	0.150	0.150	0.150	0.150
Power Output (kW)	0.00	1.4198	2.074	2.726	3.339	3.933
Fuel Power (kW)	6.5058	9.4673	11.1080	13,3447	15.0965	17.2247
Efficiency (%)	0	15.00	18.68	20.48	22.03	22.84
Fuel Rate (mg/st)	2.801	4.129	4.886	5.948	6.815	7.780

Calculations

Fuel Power: $$\frac{\text{Fuel Volume}}{\text{Time}} * \frac{39100\ \text{kJ}}{\text{Fuel Volume}} = \text{kW}$$

Efficiency: $$\eta = \frac{\text{Power Output}}{\text{Fuel Power}} * 100 = \%$$

Fuel Rate: $$\frac{\text{Fuel Volume}}{\text{Time}} * \frac{0.86\ \text{kg}}{\text{L}} * \frac{10^6\ \text{mg}}{\text{kg}} * \frac{1\ \text{sec}}{50\ \text{cycles}} * \frac{\text{Voltage @50Hz}}{\text{Actual Voltage}} = \frac{\text{mg}}{\text{cycle}}$$

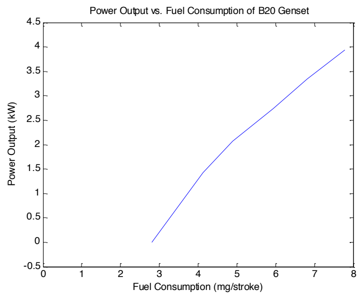


Figure 8: Power Output vs. Fuel Consumption of B20 Genset

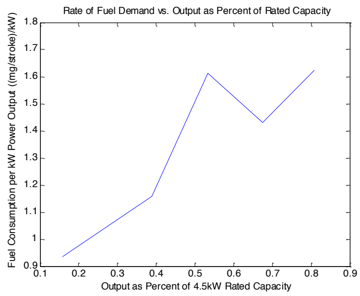


Figure 9: Rate of Fuel Demand vs. Output as Percent of Rated Capacity

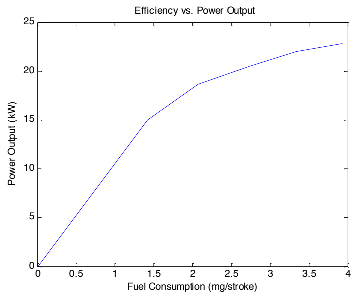


Figure 10: Efficiency vs. Power Output

As depicted in Figure 9, the fuel rate in mass/stroke is approximately linearly related to the power generated within the range of 46.09 to 87.4% of the rated load capacity. This correlates to approximately 2 to 4 kW power generation.

5.3 Dynamic Response

The results were used to approximate parameters for a first order model with a time delay. A time delay of 0.34 seconds and time constant of 0.10 seconds were used.

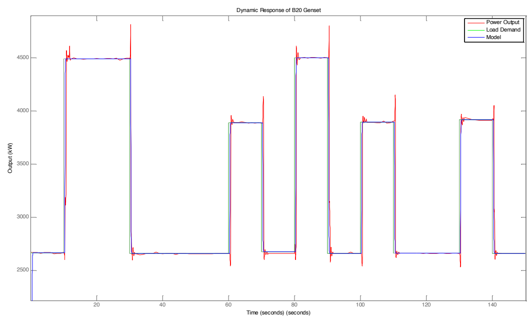


Figure 11: A series of five load steps were performed in testing

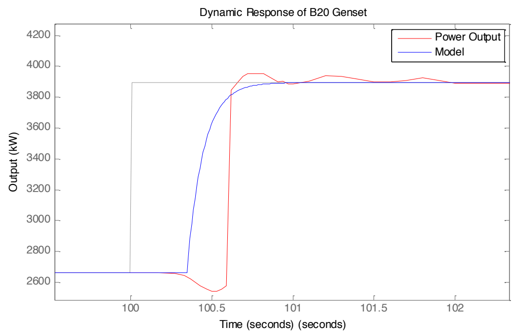


Figure 12: A zoomed in view of the experimental results and model response to a load increase

5.4 Transfer Function and Simulink Model

The overall model constructed consists of two pathways: start-up and load change. Start-up is defined as the period of time before the power output is within 2% of the first non-zero power reference value. The load change transfer function describes the dynamics from this point onward. Note that the gain is one as the transfer function relates power demand to power generated, which at steady state should be equal.

Start-up

$$\frac{Y(s)}{U(s)} = \frac{e^{-(\tau_{d\_g1}+\tau_{d\_gs})s}}{(\tau_{c\_g1}s+1)(\tau_{c\_gs}s+1)} \tag{10}$$

Load Change

$$\frac{Y(s)}{U(s)} = \frac{e^{-(\tau_{d\_g2}+\tau_{d\_gs})s}}{(\tau_{c\_g2}s+1)(\tau_{c\_gs}s+1)} \quad (11)$$

g1 refers to the gasifier in start-up, g2 to the gasifier in load change, and gs to the genset. τ_d refers to time delay, and τ_c to time constant. For example, τ_{d_g2} is the time delay associated with the gasifier in load change. Approximate values for each parameter are presented in Table 4.

Table 4: A summary of values for each parameter

	Parameter	**Variable**	**Recommended Value (seconds)**
Gasifier	Time Delay – start up	τ_{d_g1}	660
	Time Constant – start up	τ_{c_g1}	Less than 10
	Time Delay – running	τ_{d_g2}	1 – 2
	Time Constant – running	τ_{c_g2}	Less than 10
Diesel GenSet	Time Delay	τ_{d_gs}	0.34
	Time Constant	τ_{c_gs}	0.10

Additionally, the Simulink model includes logic to limit any single operation to 12 hours per the specifications of the gasifier. A model of the gasifier and genset was constructed using Simulink.

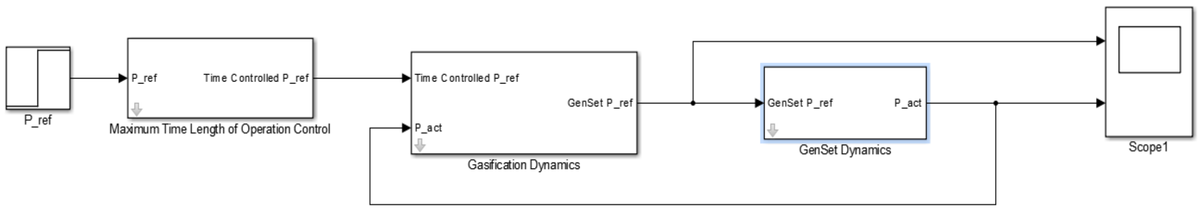


Figure 13: Simulink model

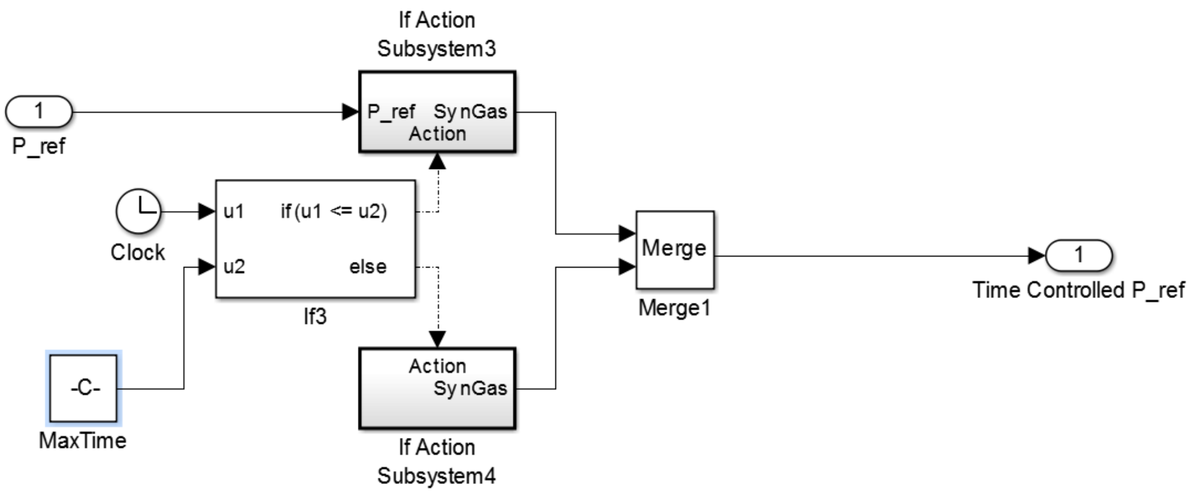


Figure 14: Maximum Time Length of Operation Control Subsystem. MaxTime is set to 43200 seconds, or 12 hours

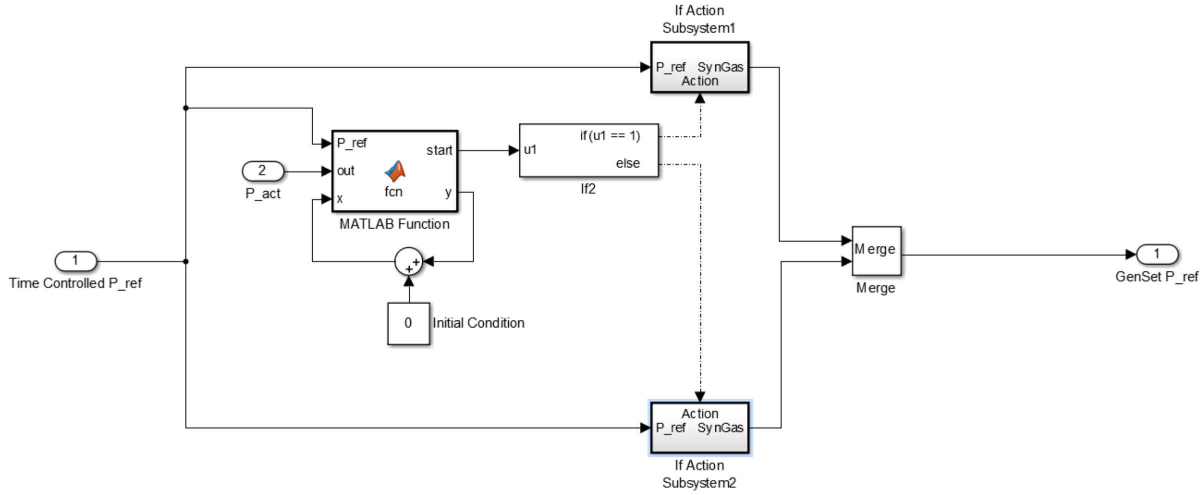


Figure 15: Gasification Dynamics Subsystem. The MATLAB Function block contents are included in the Appendix

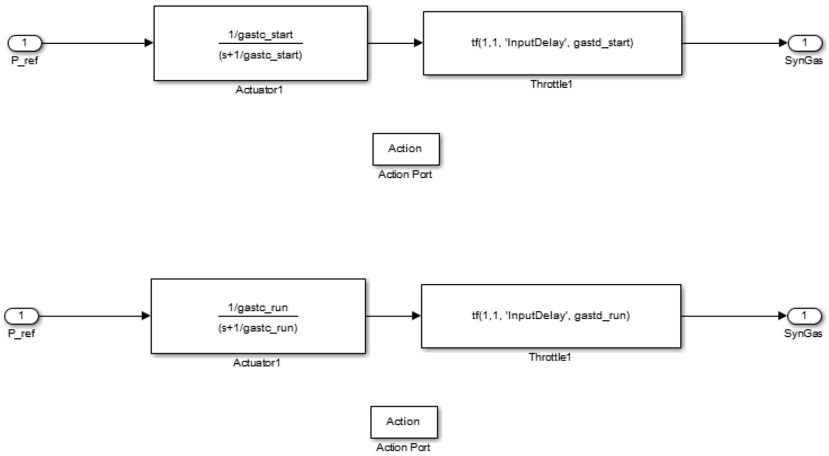


Figure 16 & 17: If Action Subsystem1 and If Action Subsystem2 respectively

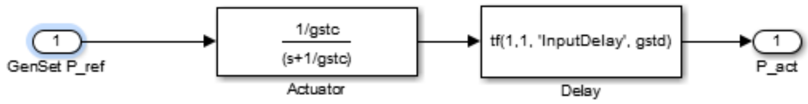


Figure 18: GenSet Dynamics Subsystem

The quality and practicality of the model represented above as a transfer function and a Simulink block diagram will be considered in later sections.

6 Discussions

The results presented above provide insight as to the ability of the model to predict the response of the studied generator to load shifts. It also outlines the extent to which the dynamics of the gasifier is understood under various circumstances. The model was based on a series of fitting parameters, many of which at least partly relied on assumptions. To start, the genset portion of the model was relied more heavily on theoretical understanding. However, this would inevitably involve the neglect of several factors and the approximation of the influence of other factors. Therefore, it was elected to rely on experimental data, and use a simple first order transfer function with a time delay. It was ensured that only data from a linear load range was used in the dynamic testing because this would result in a model time constant and time delay that could more reliably represent load changes within at least this range. Additionally, given the applications of the model, the genset is likely to be run at half-load or greater. This model was then also used for mimicking gasification as it helped frame the research process to have two set parameters to determine.

6.1 Modelling a Genset

When creating the genset portion of the model, once the dynamic portion of the data was collected, an appropriate time delay and time constant were determined for each load change, of which there were five load increases and five load decreases. The criteria for selecting the time delay was the amount of time after the reference power step to change from the starting load by at least 10 watts. After this, the amount of time to complete at least 63% of the load shift was recorded as the time constant. When disregarding outliers, an average value for each the time delay and time constant were calculated. As shown in Figure 11 & 12, the model does approximately follow the experimental data.

In terms of the quality of the genset portion of the model, primarily the discrete nature of the ammeter, the error incurred by recording methodology, and the simplicity of the model limited the ability of the model to accurately predict the genset dynamic characteristics. In recording data, only one data point was recorded per second during steady state operation, and up to 40 leading up to, during, and just after transient operation (load changes). The voltmeter is an analogue instrument. Therefore, while human error in approximating the position of the needle exists, its measurement was essentially continuous. However, the ammeter is only able to record 3 to 5 data points per second, and thus measured current changes had some inherent delay. As the load increases for example, the current output is input, causing an increase in the Back EMF in the generator, an increase in the generator torque, and finally according to Equation 4, a decrease in the generator frequency. As voltage and frequency are proportional, the dip in the measured power output shown in Figure 12 prior to the power is the result of this momentary slowing of the generator. Therefore, as a current change preempts any voltage change, the power measurements within the "dip" are likely artificially low is load increases and high in load decreases.

Second, the data was recorded using an iPhone camera that included both the digital ammeter and analogue voltmeter reading in the frame. However, the load was changed with an off-screen dial on the attached heater. It was found to be more effective to always change the loads at some multiple of ten seconds into the recording. It was assumed that the load change occurred on the exact second. While being able to see the time stamp during recording aided in accomplishing this, the load change actually occurred with a window of +/- 0.05 seconds of the desired time due to human error. The heaters may have had a small time delay and/or constant in the change in the load demand they place on the generator.

Finally, a first-order model was chosen for ease of parameter evaluation. As depicted in Figure 12, the genset does have a small overshoot, and is an underdamped system as shown by the oscillations. These two are characteristic of second-order systems. A general form of a characteristic second-order equation is shown below.

$$F(s) = \frac{K*w_n^2}{s^2+2\zeta w_n s+w_n^2} \qquad (12)$$

where ζ is the damping coefficient. A system with a damping coefficient of 0.707 is considered critically damped (those with greater than 0.707 are overdamped, and less than 0.707 underdamped). w_n is the natural frequency, and is the logarithmic average of the two poles. This system is likely not a first-order system based on the experimental data. However, the resolution of the model required did not necessitate an improved fit, and therefore it was elected to continue with a simpler model.

6.2 Modelling Gasification

In the gasification portion of the model, correspondence with a sales representative of All Power Labs informed parameter choices for the time constant and time delay during both start-up and running. As the investigation continued, the wide variability of gasification dynamics became apparent. These variables can generally be thought of as either intrinsic to the gasifier itself, the fuel selection, and external conditions. A sampling of these considerations are presented in Tables 5 through 7.

Table 5: Gasifier Characteristics

Gasifier geometry	Fixed bed: feedstock flexibility Downdraft: solid fuel must be pelletized before use Updraft: "high equipment efficiency", feedstock flexibility • Fixed in a given gasifier
Time since last run	Less time since last run = shorter startup time • Newton's law of cooling T(t) = T_a(aka ambient temp) + (T-T_a)*e^-kt
Moisture content of gasifier	Less moisture = shorter startup time
How long has it been running	PP20 can run for a maximum of 12 continuous hours

Table 6: Fuel characteristics

Fuel Moisture • Intrinsic = independent of weather effects • Extrinsic = influence of weather conditions during harvest on moisture content	Less moisture = shorter startup time Moisture content of 15%wb recognized as optimal efficient thermochemical gasification of biomass • Wood = intrinsic moisture of 20% • Wheat straw = intrinsic moisture of 16% • Barley straw = intrinsic moisture of 30% Gasification is a thermal conversion, so moisture content quite important (must be <50% moisture by weight)
Fuel Size	Must be at least ½ inch diameter
Bulk Density	B.D. = weight/volume. High B.D. = high energy/volume = shorter startup time

$\frac{\text{Void space}}{Surface\ Area}$	Higher ratio = shorter startup time • Void space is required for combustion, as it is a gaseous reaction • Surface area required for reduction, as it is a reaction between gaseous and solid reactants As combustion produces heat and reduction consumes heat, increasing this ratio increases the net heat produced, decreasing the time for start-up
$\frac{Surface\ Area}{SolidFuel\ Volume}$	Higher ratio = shorter startup time • Higher ratio means more of fuel volume near a surface, so more of moisture can vaporize & exit fuel in drying
Fuel/atomic composition	Solid fuel = 1 to 1 ratio hydrogen & carbon Liquid fuel = 2 to 1 ratio hydrogen & carbon Higher ratio of fixed carbon to volatiles = longer startup time

Table 7: External Condition

Ambient temperature	Higher temperature = shorter startup time • Relative to target temp of 700C, small range
Air Humidity	Less moisture = shorter startup time • Issues could arise at higher humidity
Air pressure/elevation	Higher elevation = longer startup time

In estimating the startup time for the gasifier, each variable should be considered. However, their relative impacts vary. In general, gasifier qualities either are constant between applications, such as gasifier geometer, or are impractical to quantify. External conditions are easily measured but have a small impact on the startup duration. For example, the range of ambient temperatures is inconsequential when compared with the required temperature of 700^{o}C of the reduction zone. However, the characteristics of fuel are both practical to quantify and impactful. Fuel moisture content is perhaps the most measureable yet impactful of this category. Intrinsic moisture content can be thought of as the theoretical moisture content of a fuel based solely on the type of fuel. Extrinsic moisture content levels include the conditions in which the fuel was grown and harvested. It is then recommended to consider at least the intrinsic moisture content of a fuel, for which a literature value can easily be obtained.

According to supplier information, the range for startup is 5-20 minutes. 5-10 minutes is considered average, with closer to 15 minutes in moderately retarding conditions, and 20 minutes in cases where most or all conditions are not optimal. The project team recommends assuming a ten-minute startup time as a default, and adjusting if more information regarding the listed variables is known. Additionally, the team recommends including an additional minute in the model for safety checks to be completed prior to startup. In all, an 11-minute startup time delay is recommended as the default time.

For the time constant, given the small size of the gasifier, it is nimble is meeting load demand. Once the reduction zone reaches 700^{o}C and the genset is turned on, the rated capacity can be reached in a matter of seconds. It is dependent on the time for suction of the genset to cause a pressure gradient within the combustion zone where air is drawn in. The increase in air flow causes an increase in the rate of oxygen entering the system, which ultimately impacts the reaction rates of each process in a cascaded manner. Therefore, the recommended time constant is on the order of seconds.

Similarly, load changes post-startup occurs over the course of seconds. The recommended time delay is then 1-2 seconds in load changes, and several seconds for time constant.

7 Conclusions

The objective of this project was to develop a model of a gasifier's dynamic responses. It was originally also desired to create an outline on how best to use the model transfer function in designing a control mechanism to have a genset mimic the gasifier. A model was constructed and defined using Simulink, but research into its implementation could not be performed in the allotted time frame. The developed model was a simplification of the actual system dynamics. These simplifications prove minimally important given the greater lack of precision inherent in the gasification portion of the model. For the resolution of the model to be increased, testing on the PP20 would need to be performed given the lack of consistency in dynamics between gasifiers. If this were possible, then it would be possible to also replace the simplified first-order genset model with a second-order transfer function. Additionally, if greater resolution is desired, the impact of the time since the last run could be included included in the model.

Currently, a parallel project is investigating the dynamics of digestion. Future projects can implement the genset control mechanism to emulate each of gasification and digestion. This will enable the exploration of each technology and its capability to meet the requirements of the EEM biomass module.

Alternatively, a project could investigate whether gasification or digestion is more suitable to the EEM using the information presented by each this project and its parallel project without implementation. This would shorten the time frame of the development of EEM and be less costly.

Continuation of this project may investigate hardware implementations for the genset and using the PP20 to conduct on-site testing if such a biomass gasifier is desired in the final EEM.

8 Works Cited

2006, Espoo, and Faisal Mohamed. "Microgrid Modeling and Simulation." *Helsinki University of Technology Control Engineering Laboratory* (n.d.): n. pag. Web.

"All Power Labs." N.p., n.d. Web.

Bruno, Giacomo. "Pressure Influence on Potassium Catalysed Char Steam Gasification." *Fuel* 65.10 (1986): 1368-370. Web.

Cheong, Kai Loon, Perry Y. Li, and Jicheng Xia. "Control Oriented Modeling and System Identification of a Diesel Generator Set (genset)." *Proceedings of the 2010 American Control Conference* (2010): n. pag. Web.

"Diesel Engine Controls and Governing." *Emergency Diesel Generator* (n.d.): n. pag. Web.

"Diesel Generator Set MDG6000CL." Mellga, n.d. Web.

Feng, Yu, Bo Xiao, Klaus Goerner, Gong Cheng, and Jingbo Wang. "Influence of Particle Size and Temperature on Gasification Performance in Externally Heated Gasifier." *Smart Grid and Renewable Energy SGRE* 02.02 (2011): 158-64. Web.

"Gasifipedia - NETL Coal Gasification Systems." U.S. Department of Energy, n.d. Web. 02 June 2016.

Jr., Amado Latayan Maglinao, and Sergio Canzana Capareda. "Operation of the TAMU Fluidized Bed Gasifier Using Different Biomass Feedstock." *2008 Providence, Rhode Island, June 29 - July 2, 2008* (2008): n. pag. Web.

Madadian, E., Lefsrud, M., Lee, C., Roy, Y., and Orsat, V. (2016). "Gasification of Pelletized Woody Biomass Using a Downdraft Reactor and Impact of Material Bridging." J. Energy Eng. , 10.1061/(ASCE)EY.1943-7897.0000336 , 04016001.

Olsson, Johan. "Automatic Tuning of Control Parameters." *Advances in Industrial Control Precision Motion Control* (n.d.): 83-100. KTH Royal Institute of Technology, 22 Nov. 2004. Web.

Wellstead, Peter. "Engine Speed Control." (n.d.): n. pag. *Control Systems Principles*. Web.

Zainal, Z.A. "Experimental Investigation of a Downdraft Biomass Gasifier." *Experimental Investigation of a Downdraft Biomass Gasifier*. Volume 23, Issue 4, October 2002, Pages 283–289, n.d. Web.

Zhiquan, Hu. "Influence of Particle Size on Pyrolysis and Gasification Performance of Municipal Solid Waste in a Fixed Bed Reactor." *Bioresource Technology*. Elsevier, 14 July 2009. Web.

9 Appendix

9.1 Email Correspondence with APL Sales Representative

<u>From 6/13:</u>

Hello Ms. Ayanian,

Sorry about the delay; most of last week I was reassigned off of my normal duties to deal with an emergency; I'm back now.

That would be great if you knew of any places with your gasification equipment in the area!

We have a recent model gasifier genset unit at Clemson U. I'm going to email you and our contact there for you to continue discussions with them, whether it is to get data from them or to borrow or rent their unit. I'll send that email separately.

With the load change question: if the load were to be doubled at a given instant, how long would it take the syngas production rate to double?

I can give you a quick estimate on the load change problem. The engine governor responds to a sudden spike in load as quickly as the RPM detector can detect it and send the measurement through the PID controls to get the throttle to open up. The restoration of the engine RPM then happens as fast as power can be produced at the engine's RPM, which, at 1800, is fairly fast, but detectable; you can generally hear the shift in power output occur over the period of a second or less. The gas for the engine response is the gas that is already in the gas circuit, which has considerable volume The increase in suction results in an increase in the reaction rate a fraction of a second after the suction reaches the gasifier, which is roughly at the speed of sound through the gas circuit. The impulse of the suction is initially dampened by the volume of the gas circuit and the expansion of hot gases from the combustion and reduction zones of the reactor, but two things drive the reaction rate up:

- The increased burn rate in the engine from the opened throttle increases the heat available from the exhaust. This heat goes through the space in the hollow walls of the pyroreactor to assist in pyrolysis. There will be a bit of a time lag between the initial onset of additional exhaust and when the pyroreactor gets hot and results in more pyrolysis and tar gas production. We have no data for how much/how long the temperature inside the pyroreactor lags behind the temperature and quantity of exhaust.
- The increased air intake when the suction finally gets to the reactor will result in more combustion, but since the suction likely comes to the combustion zone before the heat propagates through, the rate of gas production may not necessarily rise as quickly because a sudden increase in air without an increase in the tar gasses from reduction means the air ends up burning the charcoal in the immediate surrounding of the nozzle. The resulting gas may then have a bit more CO, and less H2 for a brief moment. However, the impact of this on the power output is not entirely clear, since humidity in the gas circuit driven off during the drying stage could also get sucked downstream from a sharp increase in suction, and when the humidity goes through the hot charcoal, the reduction reactions produce hydrogen by reducing the water vapor. The back-propagating heat from the increased combustion also increases pyrolysis, but in a narrower vicinity above the combustion zone; the pyrolysis gasses then contribute to the combustion so that less char is consumed by the incoming air.
- Eventually, the increased pyrolysis from increased exhaust heat catches up to the increased air intake, and a new equilibrium is reached.

Unfortunately, the dynamics of this process have not been measured in high temporal resolution, so I can't really tell you anything quantifiable.

I hope this helps somewhat.

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

From: *Austin Liu <austin@allpowerlabs.com>*
Sent: *Tuesday, June 7, 2016 2:19:53 PM*
To: *Caroline Ayanian*
Cc: *Samip Desai; salesmgmt@allpowerlabs.com*
Subject: *Re: [New Lead] PP20 Power Pallet Inquiry*

Hello Ms. Ayanian,

After speaking with a couple of our own engineers, it has become apparent that due to the complexity and great number of variables involved in the gasification process, it is best to rely on experimentation rather than theory to predict a gasifier´s behavior. I therefore wanted to follow up with you to see if you had had a chance to speak with the engineers in your team regarding experimentation of the PowerPallet's dynamics. Any test results would be much appreciated!

I am in a sales role, and I have not been able to get data on these matters. The only other thing I could do is to ask if we have any connections to academic institutions near you that have one of our gasifiers, and see if you could discuss with them the possibility of leasing their unit for the duration of your research. I'll ask and see if there's any near you.

We were hoping to better understand also the dynamics in changing loads. After speaking with our supervisors, they were a bit unsure about the time to change loads. As the demand on the generator increases, the torque on the generator increases(from increase in current drawn --> increase in back emf, as I understand it). This causes the system to draw more air/fuel into the ICE, which causes an increase in the intake air flow rate. However, at this point, would the increase in the oxygen present cause more of the syngas produced to be combusted, thereby decreasing the fuel output to the engine?

The air intake rate is determined by a feedback loop control system as well; an oxygen sensor at the exhaust of the engine detects the fuel-air ratio, and regulates the air intake using a butterfly valve. The system maintains the lambda ratio at 1.05 for a lean burn, regardless of what the load is. The only thing that varies with load is the amount of combustible mixture being taken into the engine; even the RPM is maintained at a constant pace, with the power needed to maintain that RPM being the only thing that changes.

(Lambda is defined as the measured air-fuel ratio divided by the stoichiometric air-fuel ratio. Lambda = 1 is stoichiometric, > 1 is lean, < 1 is rich.)

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

From: *Austin Liu <austin@allpowerlabs.com>*
Sent: *Tuesday, June 7, 2016 2:19:53 PM*
To: *Caroline Ayanian*
Cc: *Samip Desai; salesmgmt@allpowerlabs.com*
Subject: *Re: [New Lead] PP20 Power Pallet Inquiry*

Hello Ms. Ayanian,

After speaking with a couple of our own engineers, it has become apparent that due to the complexity and great number of variables involved in the gasification process, it is best to rely on experimentation rather than theory to predict a gasifier´s behavior. I therefore wanted to follow up with you to see if you had had a chance to speak with the engineers in your team regarding experimentation of the PowerPallet's dynamics. Any test results would be much appreciated!

I am in a sales role, and I have not been able to get data on these matters. The only other thing I could do is to ask if we have any connections to academic institutions near you that have one of our gasifiers, and see if you could discuss with them the possibility of leasing their unit for the duration of your research. I'll ask and see if there's any near you.

We were hoping to better understand also the dynamics in changing loads. After speaking with our supervisors, they were a bit unsure about the time to change loads. As the demand on the generator increases, the torque on the generator increases(from increase in current drawn --> increase in back emf, as I understand it). This causes the system to draw more air/fuel into the ICE, which causes an increase in the intake air flow rate. However, at this point, would the increase in the oxygen present cause more of the syngas produced to be combusted, thereby decreasing the fuel output to the engine?

The air intake rate is determined by a feedback loop control system as well; an oxygen sensor at the exhaust of the engine detects the fuel-air ratio, and regulates the air intake using a butterfly valve. The system maintains the lambda ratio at 1.05 for a lean burn, regardless of what the load is. The only thing that varies with load is the amount of combustible mixture being taken into the engine; even the RPM is maintained at a constant pace, with the power needed to maintain that RPM being the only thing that changes.

(Lambda is defined as the measured air-fuel ratio divided by the stoichiometric air-fuel ratio. Lambda = 1 is stoichiometric, > 1 is lean, < 1 is rich.)

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

From: *Austin Liu <austin@allpowerlabs.com>*
Sent: *Monday, May 23, 2016 5:48:10 PM*
To: *Caroline Ayanian*
Cc: *Samip Desai*
Subject: *Re: [New Lead] PP20 Power Pallet Inquiry*

The engineer of ours who is most familiar with this topic says that the simulation of our machine using another internal combustion engine largely depends on the level of resolution you need. If your simulation needs to have resolution down to fractions of a second, you should know that a diesel engine's response to changes in load will be faster than the PP20's response to an increase in load, but that the difference in response rate is on the order of a second or two down to a fraction of a second. If you need to simulate longer-term operation, you should account for the fact that the PP20 needs to be shut down daily for emptying of the ash cans and draining of condensate; longer than that, you would need to account for the downtime needed to refresh the filter media, do oil changes, and clean the engine governor, and things like that.

He also confirmed to me that once the machine's engine is started, it can pretty handle a high load immediately; it doesn't need to warm up. In this sense, you can simply simulate the PP20 by using any internal combustion engine powered generator of equivalent capacity once you account for the start-up time.

Lastly, if you stop the machine's engine, the conventional shut-down operation is to switch it to the flare and turn the flare down so the reactor can coast down to a lower temperature before being shut off; this usually takes 5-10 minutes. Suddenly shutting down the machine while the reaction is still going hot will cause pressure to build up from continued gas production if you seal it, and additional tar will be produced, both of which could be bad for the machine. If you don't seal it by shutting all the valves all the places where gas can come out will emit smoke and a great deal of carbon monoxide, which could be hazardous. However, if you begin to shut down the machine, and find that you need to re-start it, restarting a hot machine is much faster; you can usually get the reactor back up to operational temperatures in a matter of a few minutes vs. a cold start—for example, going from a couple hundred degrees up to 700˚C vs. from ambient temperature up to 700˚C.

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

On Mon, May 23, 2016 at 1:53 PM, Austin Liu <austin@allpowerlabs.com> wrote:

The start-up period is very rarely as long as 20 minutes. It appears to me that 5-10 minutes is typical, 10-15 is for difficult cases, and 20 minutes indicates something is amiss.

I will see what I can get you on engine dynamics.

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

From: *Austin Liu <austin@allpowerlabs.com>*
Sent: *Friday, May 20, 2016 2:30 PM*
To: *Caroline Ayanian*
Cc: *Samip Desai; salesmgmt@allpowerlabs.com*
Subject: *Re: [New Lead] PP20 Power Pallet Inquiry*

I'm waiting to hear back from our engineers with details.
As far as I understand, once the machine is running on the gas that is produced, the combined effect of the buffer of gas in the volume of the connecting tubes, the filter, and other spaces, and the effect of the feedback loop engine governor (under PID control) keep the machine operating at a steady load match. The only period of concern is the 5 minutes or so after the engine is started on the gas.

One more thing: the machine must not run a load under 3kW for any significant period of time; when the load is low, the reactor won't run hot enough to crack tar gases, and the gas filter subsequently gets fouled very rapidly, and everything downstream of that is also at risk of rapid fouling, including the engine governor and the engine. Ideally the low-end load is over 4kW, or even 5kW if the feedstock is higher in volatiles and lower in fixed carbon. Running a load bank may help if the load you need to power is too low, but of course, the load bank is wasting the energy for the sake of not fouling the machine with tar.

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

From: *Austin Liu <austin@allpowerlabs.com>*
Sent: *Thursday, May 19, 2016 2:12:35 PM*
To: *Caroline Ayanian*
Cc: *Samip Desai; salesmgmt@allpowerlabs.com*
Subject: *Re: [New Lead] PP20 Power Pallet Inquiry*

Thank you very much for that additional detail. That definitely helps clarify the startup process. Is the period in which the tarry producer gases are sent to flare the entire 5-20 period cited on PP20 specifications sheet?

The start-up period varies with temperature, moisture levels, and size and shape of the feedstock in your reactor. Anything that hinders the spread of the combustion will slow the start-up process. Densely packed small feedstock pieces that have absorbed moisture during the prior shut-down slow the process down.

Also, once the reduction zone has been heated to 800 degrees and the is started, is the gasifier producing its maximum output rate (modeled at a step input), or does it ramp up over some additional time period?

The video play-list recommended starting the engine on the gasifier's output when the reactor is over 700˚C, not 800˚. That was my mistake. Starting the engine sends hot exhaust to the pyroreactor, and the heat of the exhaust accelerates pyrolysis while taking the burden of providing this heat away from the combustion zone. This causes the temperature around the combustion zone to rise. The gas output does ramp up between 700˚C and 800˚C and above; tar cracking becomes more efficient as the reactor gets hotter, as does reduction. The reactor operates at its best when the engine is running near its rated capacity.

The engine's RPM is kept constant by the engine governor because the engine cranks an AC generator, and the AC frequency must remain constant. The power output is varied by throttling how much gas the engine can suck in during its intake. If the governor system detects that the engine's flywheel is speeding up, it throttles the gas suction and lets the flywheel slow down to match the target RPM. If it detects that the flywheel is slowing down, it opens up the throttle and lets the engine suck in more gas and accelerate to match the target RPM. The entire correction cycle happens in less than a second.

Since this suction is what ends up driving the reaction in the gasifier, and since the reaction rate is highest and hottest when the suction is strong, the gas production is best when the machine has run near its rated output long enough for the high temperatures to spread to a large portion of the reduction zone, where most of the gas is produced.

The only time this breaks down is where the suction is so strong that the combustion zone gets drawn down into the reduction zone. Under this condition of excessive load, the combustion would outpace the reduction, and the combustible fraction of the gas would diminish as more unreduced gases dilute the final mixture.

~Austin Liu
Sales Engineer

All Power Labs
1010 Murray St.
Berkeley, CA 94710

From: *Austin Liu <austin@allpowerlabs.com>*
Sent: *Thursday, May 12, 2016 1:53 PM*
To: *Samip Desai; salesmgmt@allpowerlabs.com*
Subject: *Re: [New Lead] PP20 Power Pallet Inquiry*

Hello Mr. Desai,

I've attached some info sheets on the PP20 and the continuous feed air lock.

I'd like to clarify a potential point of confusion. The continuous feed "air lock" is not really an air lock. It is an airtight lid. The entire PP20 gas circuit is under vacuum pressure, with the only air coming into the system being the air from the air inlet, which enters the combustion zone through the air nozzles. Opening the lid breaks the vacuum pressure, and lets the combustion zone start to rise as it chases the air percolating through the feedstock. Hopper refilling operations can be done in spite of this, but they must be done quickly so the loss of vacuum is not for long enough to interrupt the operation of the machine.

The continuous feed hopper lid is activated by a pair of rotating paddles that can detect what the level of feedstock is inside. The level detectors bungs on the hopper look likey are spaced quite close together, but this is to account for two things:

- Feedstock tends to form a heap with a peak when it is being loaded
- Feedstock tends to empty to form a V-shaped pit as it is being emptied.
- Frequent, smaller refills are safer than letting the hopper become nearly entirely empty before refilling.

Let me know if you have any additional questions.

I also attached a graphical process explanation that may be useful to you.

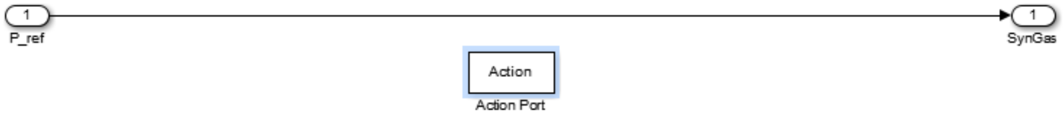
~Austin Liu
Sales Engineer

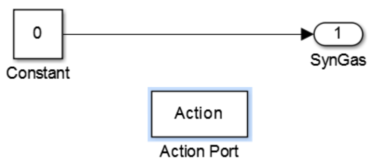
All Power Labs
1010 Murray St.
Berkeley, CA 94710

9.2 MATLAB Function block contents

```
function [start, y] = fcn(P_ref, out, x)
%#codegen

% x holds either 0, 1st nonzero P_ref val or "run" value (10,000)
if(x<=0)
   x = P_ref;
end

% Once out is within range of first input, set to running
   % Concern: what if input not step
if((out>=0.98*x && out<=1.02*x)&&(x~=0))
   x = 10000;
end

% Unless x hold "run", use start sequence
if(x==10000)
   start = 0;
else
   start = 1;
end
y = x;
```

9.3 Additional Subsystem Blocks: If Action Subsystem3 and If Action Subsystem4 respectively





9.4 Data from Dynamic Testing

[Click here to open file]

9.5 MatLab Code for 5.2

```
Voltage = [235 232 230 227 225 224];       % V
Current = [0 6.12 9.02 12.04 14.84 17.56];  % A
Power = Voltage.*Current./1000;             % kW

Time = [601 413 352 293 258 227];           % sec

n = Power./(3910./Time)
FuelRate = 86000*230./(50.*Time.*Voltage);  % mg/str

figure(1)
plot(FuelRate, Power)
xlabel('Fuel Consumption (mg/stroke)')
ylabel('Power Output (kW)')
title('Power Output vs. Fuel Consumption of B20 Genset')
axis([0 8 -.5 4.5]) ;

%% Rate calc
for i = 1:5
  dP(i) = (Power(i+1)+Power(i))/2;
  deriv(i) = (FuelRate(i+1) - FuelRate(i))./(Power(i+1)-Power(i));
end

figure(2)
plot(dP/4.5, deriv)
ylabel('Fuel Consumption per kW Power Output ((mg/stroke)/kW)')
xlabel('Output as Percent of 4.5kW Rated Capacity')
title('Rate of Fuel Demand vs. Output as Percent of Rated Capacity')
% linear from (3) -> (6) aka 2.0746 -> 3.9334 kW (46% -> 89%)

%%
Kp = 1/((FuelRate(6)-FuelRate(3))/(Power(6)-Power(3)))

%% Efficiency

figure(3)
plot(Power, n*100)
xlabel('Fuel Consumption (mg/stroke)')
ylabel('Power Output (kW)')
title('Efficiency vs. Power Output')
```

9.6 MatLab Code for 5.3

```
%% Load Data
X = xlsread('DynamicsResults2.xlsx');
t = X(2:end, 1);
V = X(2:end, 2);
I = X(2:end, 3);

%% Initial Data Visualization
P = V.*I+8.69.*V;
time = linspace(0, 150, 15000);
u = 2666.5+(4490.6-2666.5)*(time>10)-(4490.6-2659.4)*(time>30)+(3889.3-2659.4)*(time>60)-(3889.3-2675.1)*(time>70)+(4500.1-2675.1)*(time>80)-(4500.1-2661.3)*(time>90)+(3895.4-2661.3)*(time>100)-(3895.4-2662.1)*(time>110)+(3917.4-2662.1)*(time>130)-(3917.4-2660.7)*(time>140);
figure(1)
plot(t,P, time, u)

%% First Order Model Construction (NO PID ATM)
s = tf('s');
td = .34;
tc = .1;
G1 = (1/(s*tc+1))*exp(-td*s)

%% First Order Analysis
figure(2)
plot(t,P, 'r')
hold on
lsim(G1,u, time);
hold off
legend('Power Output', 'Model')
xlabel('Time (seconds)')
ylabel('Output (kW)')
title('Dynamic Response of B20 Genset')

%% Second Order Analysis
% wn
% zeta
% num = [wn^2];
% den = [1 2*wn*zeta wn^2];
% G2 = tf(num, den);
% H2 = G2/(1+G2);
% lsim(H2,u, time);
```

9.7 Highly Pertinent Images