Final Report

Title Page

Project Title: Testing a New Type of Fixed Bed Biomass Gasifier
DOE Award Number: DE-FG36-02GO12055
Date of Report: March 31, 2006
Recipient Name: Gazogen, Inc.
Recipient Address: 1915 East Hill Road, Marshfield, VT 05658
Project Director/Principal Investigator: Carl N. Bielenberg
Contact information: (802) 456-8993, gazogen@yahoo.com,
Working Partners: Terrianne Klein, Dennis Wilber, Mory Thiaw

Note on Patentable Material/Protected Data: The technology described in this report is subject to a U.S. Patent application filed on February 16, 2005.

Executive Summary

This report details work performed by Gazogen to develop a novel biomass gasifier for producing electricity from commercially available hardwood chips. The report begins with a summary of project activities, then details specific achievements, and ends with a discussion of the conclusions and recommendations for future work.

The research conducted by Gazogen under this grant was intended to demonstrate the technical and economic feasibility of a new means of producing electricity from wood chips and other biomass and carbonaceous fuels. The technical feasibility of this technology has been furthered as a result of this grant, and work will continue, whether or not further grant funding becomes available, to fully demonstrate the production of electricity with this technology. The economic feasibility can only be shown when all operational problems have been overcome. The technology could eventually provide a means of producing electricity on a decentralized basis from sustainably cultivated plants or plant by-products.

Project Description

Summary

The purpose of this project was to test the technical and economic feasibility of a new type of biomass gasifier, invented by the author, for generating electricity in a containerized 100 kW power plant. This purpose was not achieved. The containerized power plant, less controls and wiring, was built, but was not completed due to difficulties encountered in getting the gasifier itself to operate properly. In order to facilitate testing of the gasifier, without compromising the gas cleaning equipment or engine of the containerized power plant, a second gasifier was built and installed in a boiler firing test bed. All testing was performed with this device.

Testing of the gasifier focused on improvements to the gas collector, which is the device responsible for extracting gas by suction from the charcoal bed. Proper operation of the gas collector is challenging because the collector must maintain free gas flow not only through its own surface, but also through the charcoal bed that surrounds it. In addition, the gas collector should transmit as little particulate matter, mainly fine charcoal, but also ash and high ash content charcoal, into the gas produced by the gasifier. The gas collector must resist elevated temperatures. The effectiveness of the gas collector is influenced by the overall design of the gasifier, including its controls. Perfecting the system is made very difficult by the fact that its internal operation is not directly observable, and because internal temperatures are not homogenous, and therefore difficult to characterize. Despite these difficulties, progress was made, to the extent that several test runs produced sustainable gas production and controllable operation.

Technical Achievements

A. Assumptions

The design of the Two Stage Rotary Hearth Gasifier arose out of difficulties encountered while attempting to operate more conventional downdraft fixed bed gasifiers using commercially available woodchip fuel. This earlier work was done in collaboration with Jack Humphries, a citizen of New Zealand having more than twenty years experience in the design and construction of small downdraft gasifiers. Our collaboration was based upon the development of so-called linear hearth gasifiers. While most downdraft biomass gasifiers have historically been circular in format, and limited to fairly small diameter in order to achieve good performance, the linear hearth gasifier is rectangular. The width dimensions of the linear hearth gasifier are similar to the diameter dimensions used in traditional downdraft gasifiers, while the length dimension may be increased in order to produce gasifiers having larger capacity. The motivation behind this work was to be able to offer gasifiers having different capacities, but without changing the dimensions that are critical to good performance. In addition, different sized gasifiers would utilize many of the same components, reducing the cost and complexity of manufacture.

Gazogen conducted four months of intensive testing of its linear hearth gasifier, observing a number of operational problems that we were unable to solve with this design:

1. The gasifier would typically start quickly with a good carbon monoxide/hydrogen flame. The size and/or quality of the flame would rapidly decrease, being barely sustainable after fifteen to thirty minutes of operation. We attribute this to a phenomenon that is rarely reported in the literature on fixed bed gasifiers and which we call char bed aggregation. In effect, the char bed becomes impermeable to gas flow due to the filling of all voids in the bed with progressively smaller char particles. At least a dozen different grate designs were tested in order to attempt to overcome this problem, but none were effective. Stirring of the char bed, reverse pulsing of the char bed, alternately increasing and decreasing the grate openings and other strategies showed no observable reduction in char bed resistance to gas flow. This little reported problem is, in our experience, the most fundamental and intractable problem with conventional fixed bed downdraft gasifiers.

2. The above problem is exacerbated by the fact that the temperature of the char bed drops with distance from the hearth or char production zone, such that there is no means to control the depth of the charcoal bed or reduction zone, except by discharging char through the grates. A portion of the finer particulate material, including ash, is entrained by the gas, while the larger portion must be removed from the gasifier, disposed of or returned to the fuel stream.
3. Fixed bed downdraft gasifiers are susceptible to bridging above the hearth and channeling below the hearth, both phenomena causing poor gas quality and therefore unreliable engine operation. Bridging causes an interruption in the supply of raw fuel to the carbonization zone, causing a rapid depletion of the gas producing charcoal bed (reduction zone). Channeling causes the charcoal bed to be bypassed by non-combustible, tar laden combustion gas and the entrainment of large amounts of particulate matter.
4. Fixed bed downdraft gasifiers having refractory lined insulated walls or hearths are susceptible to gas ignition due to gas and air leakage through the insulation behind the refractory, and through cracks in the refractory.

Due to these problems, we were forced to suspend work on the linear hearth gasifier in the spring of 2002. By the end of 2002, frequent contemplation led to the concept of the rotary hearth mixed flow gasifier, which we now call the two stage rotary hearth gasifier, the essential features of which are:

1. A rotating hearth, which provides some movement of the fuel as it passes through the carbonization zone. The hearth is mounted on a centrally located vertical spindle, supported from the top of the gasifier, and rotated slowly by a drive mechanism located above the gasifier. The spindle may also have air nozzles located above the hearth and stirring fingers to prevent fuel bridging.
2. A second combustion zone, located at the bottom of the gasifier, enables complete combustion of char that has passed through the char bed/reduction zone.
3. A gas collector, located below the rotary hearth and attached to the rotating spindle is immersed in the char bed/reduction zone, and is responsible for removing gas from the gasifier.
4. Multiple spindle assemblies may be mounted in a common gasification chamber to increase the gas production capacity of the gasifier, potentially into the multi-megawatt size range.

The two stage rotary hearth gasifier attempts to address the problems encountered with the fixed bed downdraft gasifier. The problem of char bed aggregation is an inherent characteristic of particle matrixes having a large diversity of particle size and a flow through the matrix capable of particle entrainment. Char bed aggregation is not eliminated in the rotary hearth two stage gasifier, but is controlled by causing the char bed to move from the rotary hearth, past the surface of the gas collector, to the second combustion zone, where the residual char is completely burned. The second combustion zone provides much of the heat required for gas production in the charcoal bed/reduction zone. A helix which surrounds the gas collector and rotates with the spindle assists in char transport toward the second combustion zone. The location of the gas collector between the first combustion zone, where the char is produced, and the second zone, where residual char is fully combusted, eliminates the problem of residual char accumulation in a place where temperatures are too low for further char gasification, and where gas flow is progressively obstructed by char bed aggregation. While fine char necessarily migrates with gas flow toward the gas collector, the entire char matrix is in continuous motion toward the secondary combustion zone, where temperatures are sufficient for further char gasification.

The problems of fuel bridging and channeling are solved or solvable by rotation of the hearth, gas collector helix, and other features of the rotating spindle. The problem of gas combustion behind or within the ceramic walls of the gasifier is eliminated by locating the gas collector in the center of the char bed, away from the walls. We assumed therefore that the basic features of the rotary hearth two stage gasifier would largely overcome the problems that we had encountered with the fixed bed downdraft linear hearth gasifier previously tested.

Since the spindle assembly is responsible for most of the functions of the gasifier, its design details are critical to proper gasifier operation. These details, and related features and dimensions of the gasifier chamber, were the focus of much of the effort expended under this grant.

B. Equipment Designed and Constructed

The 100 kilowatt containerized power plant to be tested under this grant was substantially built but has not yet been tested. It is shown in the attached photographs and schematic diagram (figure 1). Essentially, the power plant consists of a woodchip fuel dryer, an auger for metering fuel from the dryer to the gasifier, the gasifier, gas cooling and cleaning equipment, an engine-generator set. It also includes a gas burner and boiler for burning gas and operating the fuel dryer when the gas is not of suitable quality for engine operation, typically when the fuel is too wet. Air within the container is used by the dryer so that all waste heat produced by the equipment contributes to fuel drying, and there is no risk of carbon monoxide inhalation within the container so long as the dryer fans are operating. The control panel for the power plant was not built during the grant period due to delays in getting the gasifier operating properly.

The power plant gasifier has not yet been tested, all testing to date having been performed with a second identical gasifier located inside the workshop. This gasifier is connected to a 90 hp firetube boiler, so that the gas can be burned within the combustion chamber of this boiler during testing. The boiler is piped to a 1000 gallon water tank, providing increased thermal storage for absorbing the thermal output of the gasifier, and also to a large truck radiator, which provides hot air for the fuel dryer. The water tank is fitted with eight 10kW electric immersion heaters, which may be connected individually to the generator of the containerized power plant as a means of providing controlled electric load. During testing of either the boiler firing gasifier or the 100 kW power plant, a pump provides rapid circulation of water between the 1000 gallon water tank and the boiler, and also to the truck radiator, enabling the heat produced to be dissipated. All of this equipment was assembled as part of this grant.

C. Tests Conducted

All of the testing performed during this grant was undertaken so as to improve the performance of the gasifier, both with respect to gas quality and power. As a result of these tests, the design of the gas collector went through several iterations. Finally the design of the gasification chambers of the two gasifiers was also modified. Most of the parts of the gas collector and spindle were made of stainless steel to better resist the high temperature conditions in the gasifier.

Early versions of the gas collector were relatively small, being a cylinder 5.5" in diameter and 6" long, therefore providing a total surface area of about 100 square inches. The first gas collector had longitudinal slots .06" wide spaced every .5" around the circumference. Gas is drawn into the gas collector by a gas suction fan located outside of the gasifier and connected to the gas collector via a 5 inch diameter gas pipe passing down the center of the rotating spindle. The gas pipe and gas collector do not rotate, although the latter is surrounded by a double helix that is attached to and rotates with the spindle (see figure 2).

The first gas collector quickly clogged with coked tar and carbon, which filled the slots, preventing any further gas flow. This problem was addressed by designing and constructing a new collector, consisting of a stack of alternating fixed and rotating rings. Motion is imparted to the rotating rings by the double helix, which is attached to the rotating rings as well as the rotating spindle. In this design it is impossible for the gaps between adjacent rings through which the gas passes to become completely clogged because the rings are in relative motion. The first of these gas collectors had 16 rings, measuring 0.5 inch square in cross section, between which the average gap width was .02". Although the total area of the collector is about 130 square inches, the area open to gas flow, or the total area of the gaps, is only about 5 square inches. Since the total anticipated gas flow is about 6 acfs, the required gas velocity is above 150 ft/sec.

While these gas collectors were somewhat resistive to gas flow when no charcoal was present, they became highly resistive with the collector immersed in randomly sized charcoal. While this resistance is partly attributable to char particles filling the gaps, it also appears to be caused by char aggregation around the gas collector. After several trials in which the gas production was very weak, and not at all reduced by spindle rotation, we became convinced that the charcoal mass was actually rotating with the double helix, which was therefore not effective in transporting char downward toward the secondary combustion zone. This problem is exacerbated by high levels of suction, which cause the char bed to become more firmly compacted against the gas collector.

In designing the rotary hearth gasifier, I was concerned about the possibility that char might rotate with the spindle in the vicinity of the gas collector, and made the gasifier square rather than circular in cross section in an effort to prevent this. The idea was that a square cross section would tend to restrain the charcoal mass against rotating, while a circular section would allow it to rotate as a solid body. When the problem of char rotation appeared to occur even with the square format, the only possible solution seemed to be to increase the diameter of the gas collector, thereby decreasing its distance from the gasifier walls. Doing so would increase the surface area of the collector, thereby reducing the suction required to achieve required gas flow. Reducing the suction reduces the density of the char bed which, from our previous experience gives a net increase in gas production.

Gas collectors were subsequently built with an outside diameter twice as large as the earlier gas collector. This nearly doubles the surface area and, assuming the same total gap width, also doubles the total gap area of the gas collector. Since the average gas velocity at the gaps is reduced by 50%, the pressure drop across the collector itself is reduced by 75%. The minimum clearance between the gas collector surface and the walls of the gasifier is reduced from over 6 inches to about 3.5 inches. It was with this gas collector, having 1/4 inch square section rings, having an outside diameter of 10.75 inches, a length of 9 inches, and a double helix made of 5/8 inch stainless steel square bar, that we first achieved sustainable operation of the gasifier at close to the required output.

Before starting the gasifier in this and preceding tests, we used a pitot tube to measure the velocity of air pulled through the gas suction pipe at the normal operating suction of 2 to 6 inches of water. The calculated airflow at 4.5 inch suction was slightly more than the 6 acfs required. The gasifier was ignited and the gas burner of the boiler firing test bed kept lit for approximately 1.5 hours. During this time, the temperatures in the first and second combustion zones were measured with thermocouple probes inserted through the refractory walls of the gasifier. The temperature in the first zone averaged 800 degrees F, while the temperature in the second zone was 1100 to 1400 degrees F. The temperatures in both zones were controllable by controlling the amount of air supplied to each zone. Gasifier operation was halted after 1.5 hours due to overheating of the top cover of the gasifier, which I feared would damage the spindle rotation and feed auger motors.

This test was repeated about one week later, on September 2, 2006, whereupon similar results were achieved, except that the temperature of the second combustion zone was increased, reaching 1940 degrees F. Overheating of the top cover of the gasifier was observed as in the first test, and problems were encountered with the fuel feed regulator, which often caused the woodchip supply to the gasifier to be interrupted, and spindle rotation, to become less reliable during the course of the test. Following this test, the gasifier was disassembled, whereupon the gas collector was found to have been partially melted at its lower end, just above the ceramic heat shield. The gas collector was replaced with a new gas collector of the same length, but having much more substantial ½" square section stainless steel rings, and two tests conducted specifically to measure the rate of temperature rise in the boiler and thermal storage tank. This enabled us to estimate the heat recovered from the gas flame at 1.28 MMBtu/hr. Factoring in the counterbalancing effects of the temperature of the gas and the heat loss from the boiler stack, the amount of chemical energy available is approximately that needed to produce 100 kW of electricity with an internal combustion engine.

Several more test runs were performed before again disassembling and inspecting the gas collector. During these runs, the temperatures of the first combustion zone were in the range of 500 to 750 degrees F, temperatures of the second zone were in the range of 1400 to 2000 degrees F, while the gas temperature, measured at the outlet of the gas pipe from the gasifier, was typically 750 degrees. The gasifier had provisions for adjusting the distribution of air to the first and second combustion zones, in the first case being admitted through a ring of nozzles mounted on the spindle just above the rotary hearth, and in the second case through nozzles mounted in the sloping walls of the hopper bottom of the gasifier. In addition, we provided a duct leading from the top of the gasifier to a fan intended to inject water vapor and other gasses produced in the first zone into the second zone. Operating this fan increases temperatures in the first combustion zone, both by increasing the suction, and therefore the amount of air admitted to this zone, and also by tending to move the flame upward into the raw fuel, therefore accelerating char production. We have observed that this “combustion gas recirculation” tends to extinguish combustion in the second zone and frequently to reduce or stop the production of combustible gas by the gasifier. Controlling the admission of air to the two zones has proven to have some influence on the temperature of the first zone and a very strong influence on the temperature of the second zone. As in the previous series of tests, the lower end of the gasifier was overheated, causing disintegration of the 3000 degree F rated ceramic heat shield, and partial melting of the steel plate at the bottom of the gas collector to which the heat shield was attached. We were happily surprised to see that the stainless steel rings of the gas collector had not suffered any visible damage.

The failure of two gas collectors led us to the conclusion that the design of the lower end of the gasifier, enclosing the second combustion zone, needed to be changed to increase the distance between the air entry location and the gas collector. Since we were constrained as to overall height by the design of the containerized power plant, already substantially built, and because we had experienced trouble extracting ash from the gasifier with its hopper bottom and single bottom auger, I opted to replace the hopper bottom with parallel sides extending to horizontal movable grates at the bottom of the gasifier. This approach would facilitate the downward movement of char within the gasifier, provide a more diffuse source of air to the second combustion zone, and provide the means to verify, either visually or with a free temperature probe, the uniform distribution of temperature within the second combustion zone. The vertical distance between the air source and the lower heat shield of the gas collector was increased from about 8 inches to12 inches. This gasifier design is shown as figure 3.

Two new gasifier chambers on the above design were built during 2005. Three test runs were performed with one of these gasifiers on the boiler firing test bed. We were unable to repeat the level of performance achieved in 2004, apparently because of an inadvertent reduction in the total gap area of the new gas collector. The new collector is still 10.75 inches in diameter, but only 6 inches long. The length is reduced by using rings having a thickness of 0.25 inches, but a width of 0.5 inches to resist radial deformation. The rings were too tightly spaced on the gas collector used in these tests, which allowed an air flow from the gas pipe of only 3 acfs before startup of the gasifier. Rotation of the rings of the gas collector was very difficult because of the tight ring spacing, preventing continuous rotation of the spindle. Gas color was nonetheless good, gasifier startup easy, with spontaneous reignition of both combustion zones after a 48 hour shutdown.

Conclusions and Recommendations

Conclusions

The project grant enabled Gazogen to make progress in developing the two stage rotary hearth gasifier toward a workable technology. It also enabled us to build a containerized power plant and boiler firing test bed in which the gasifier can be tested. We were unable to demonstrate complete technical viability not to mention economic viability of the technology. We were sufficiently encouraged by the test results that we proceeded with a U.S. patent application in February, 2005, covering the general concept of the gasifier and the design details of the gas collector.

Recommendations:

1. Continue testing the current gasifier. The current gasifier, which has a square cross section of uniform size from top to bottom, and rocking grates to support the char mass and admit air to the second combustion zone, has not been adequately tested. Further testing is needed to refine the gas collector and verify its longer term durability. Such testing may indicate the need to increase the height or vertical length of the gasifier chamber, in order to increase distances from the combustion zones to the gas collector, and to increase the reservoir of char present at all times in the gasifier. If an increase in the height of the gasifier is needed, this will require changes to the 100 kW power plant.
2. Develop and automated control panel. We are beginning to achieve enough familiarity through manual operation of the gasifier to be able to attempt to automate its operation. Automation should enable the temperatures of the top and bottom of the gasifier to be stabilized regardless of the gas flow demand. Temperatures may either be measured directly, or imputed from the temperature of the gas leaving the gasifier, and the temperature of the recirculated combustion gas. Total air admission to the gasifier will be controlled to maintain negative pressure in the gasifier relative to the outside air.
3. Demonstrate electric power generation. Generating electricity is the principal purpose and market for the technology and this needs to be demonstrated as soon as possible, pending accomplishment of the two preceding steps.

Appendices

Supplemental Information

Appendix A

Final Task Schedule

Final Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Build Integrated RHMF Gasifier Generating Plant	02/28/03	03/30/05		85%	.
2	Build Shop Test Bed for RHMF Gasifier Generating Plant	03/31/03	06/31/03		100%	Completed.
3	Shop Test RHMF Gasifier Generating Plant	09/30/03	06/30/05		50%	
4	Field Test RHMF Gasifier Generating Plant	09/30/04	--		0%	.
5	Semi-Annual Reporting	04/30/04	06/30/05		100%	Completed.
6	Final Report	12/31/04	12/31/05	03/31/06	100%	Completed.

Appendix B

Final Spending Schedule

Project Period: 07/01/02-12/31/05

Current Semi-Annual Period:10/01/05-12/31/05

Spending Schedule

		Project Expenditures	
Task	**Approved Budget**	**This Period**	**Cumulative to Date**
Task 1 Build Integrated RHMF Gasifier Generating Plant	65,000	0	87,169.93
Task 2 Build Shop Test Bed for RHMF Gasifier Generating Plant	25,000	0	11,959.55
Task 3 Shop Test RHMF Gasifier Generating Plant	40,000	19,887.51	73,527.38
Task 4 Field Test RHMF Gasifier Generating Plant	88,000	0	0
Task 5 Semi-Annual Reporting	30,000	0	4962.50
Task 6 Final Report	10,000	7100.00	7100.00
Total	288,000	26,987.51	184,719.36
DOE Share	175,000	21,887.00	96,119.36
Cost Share	113,000	5100.00	88,600.00

Appendix C

Final Cost Share Contributions

Final Cost Share Contributions

Funding Source	Approved Cost Share		This Period		Cumulative To Date	
	Cash	In-Kind	Cash	In-Kind	Cash	In-Kind
Gazogen, Inc.	0	113,000	0	5100	0	88,600
Total	0	113,000		5100		88,600

Cumulative Cost Share Contributions	88,600

Gazogen Inc.
List of Photographs

1-Gazogen - Woodchip dryer for gasifier testbed (foreground) Containerized powerplant behind

2-Gaztest - Tested gasifier

3-Gazrothearth - Rotary hearth and gas collector

4-Gazflame- Gas combustion in boiler

5-Gazint - Interior of 100kw containerized power plant showing fuel dryer (behind) gas cooler and generatorset

6-Gaschamber - Refractory lined gasifier chamber