CARBURETION SYSTEM FOR BIOMASS GAS FUELING OF SPARK IGNITION ENGINES

by

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A special note of praise goes to Pat Parke for his preliminary work on this project. Most of the test equipment was gathered or built by him. Also, some of his results for engine performance are included for comparison purposes. Since his results are used freely and concurrently throughout this paper, his work is not explicitly referenced.

Special thanks go to Bob Keller for his assistance in preparing the test setup and help in supervising the engine tests. Thanks also to Dan McAnarney and Larry Wagner for their technical assistance in use of the data acquisition system. Also Mike LaFebere and Ken Jackman for their operation of the gasifier and gas analysis equipment. Acknowledgement also goes to Farmland Industries' Oil Test Lab for their inspection and evaluation of all engine oil samples.

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INTRODUCTION

Agriculture is a somewhat unique industry in that it has the potential to supply a significant fraction of the energy it needs for its operation from readily available wastes or perhaps, more properly, non-marketable by-products of the industry. Currently researchers are investigating four primary methods of energy recovery: anaerobic digestion, gasification, fermentation, and direct combustion. All except the latter are capable of supplying fuel for internal combustion engines, either in liquid or gaseous form.

Each of these four methods have their advantages given the proper circumstances. Clark et al. (1978) proposed that gasification holds the greatest potential for irrigators in the Great Plains States. They suggest that about 50% of the available residue from a crop of irrigated corn, if converted to low Btu gas, could provide all of the energy required to pump the water for the season and to dry the grain after harvest.

Gasification can be accomplished with a variety of technical options. Fixed bed, moving bed, and fluidized bed are the most common. Fluidized bed technology was chosen for this work primarily because of its flexibility in regards to materials that can be processed. In addition to this, fluid bed technology has the following advantages.

1. It can follow a load curve.

2. It can adapt to large or small-scale applications.
3. Design is relatively simple.
4. Operation is simple and relatively stable.
5. It can retrofit with existing natural gas fired equipment such as internal combustion engines, driers, and boilers.

A spark ignition engine was chosen over a compression ignition engine because so many of the irrigation and drying power units are of the spark ignition type. This study then will focus on the fueling and performance of a spark ignition engine fueled by low Btu gas from a fluidized bed gasifier. Medium term engine tests were performed to evaluate what affects this fuel has on engine wear and performance.

LITERATURE REVIEW

Available Biomass

A conservative estimate of the energy that can be realized from converting readily collectable crop residues and animal manure into low Btu gas is about 0.75 quad or about 33% of the annual consumption of agriculture (Walawender, 1979). From the prospective of a local user, about 50% of the available residue from a crop of irrigated corn, if converted to low Btu gas, could provide all the energy necessary to pump the water for the irrigation season and to dry the grain after harvest (Clark et al, 1978). These estimates allow that adequate residues be left on the field to prevent water and wind erosion of the soil. However, they do not take into account the possibility of contributions from short rotation "energy crops". In spite of some variability in the estimates of available biomass, it is evident that agriculture does have the potential to supply a significant portion of its energy demand.

Gasification

Thermal gasification is an old technology that resurfaced over the past decade. The term is used to describe the composite of several phenomenon taking place in sucession. All involve pyrolysis, which is the thermal degradation of carbonaceous material to volatiles (gas and liquid) and char. The other phenomena involve cracking, reforming or combustion of the volatiles and steam gasification and/or combustion of char. These phenomena and their extent depend on the process configuration and the operating conditions.

Construction details, theory of operation, and performance data of the Kansas State University fluidized bed gasifier have been documented by Raman et al. (1980), Walawender et al. (1980), and Walawender and Fan (1978). Data are included for the gasification of feedlot manure, corn stover, cane, sewage sludge, and tire rubber. A complete history of early gasifiers is provided by Horsfield and Williams (1978), Nowakowska and Wiebe (1945), and the Solar Energy Research Institute (1979).

Gas Cleanup

All researchers agree that gas cleanup is a critical step when fueling an engine with biomass gas. The amount of particulates which can be tolerated in an internal combustion engine is not well established, however, high concentrations of particulates will increase engine wear. Datin et al. (1981) describe the use of two high efficiency cyclones for clean-up of low energy gas produced from a fluidized bed gasifier. Jacko and Barrett (1981a,b) describe procedures and equipment for taking gas samples and present results including energy content, total particulates, and size distributions for gas produced from biomass residues in an air blown gasifier.

Little work has been published on the removal of tars from producer gas. Parke suggests that they be removed with a high temperature condenser immediately after exiting the reactor.

After spraying the gas with water in the venturi scrubber, an electrostatic precipitator could be used to remove entrained droplets of tar and water.

Spark Ignition Timing

In work with an engine fueled by anaerobic digester gas Stahl et al. (1982) concluded that engine operation is insensitive to small changes in spark advance. They suggest that the optimum spark advance is not well defined for low energy density fuels that burn slowly. They also suggest that brake specific fuel consumption is a better measure of optimal spark advance since it is less sensitive than power output to small, inevitable variations in the air-fuel ratio. In addition to changing the timing, they experimented with increasing the spark plug gap, but to no avail. In work with an engine fueled by gas from a fixed bed gasifier, Spiers (1942) also found that there was a wide range of ignition timings for optimum results. A possible explanation given was variation in the hydrogen content of the reactor gas.

Power Output

Spiers found that the maximum power developed with producer gas was only 53% of gasoline power output, while Burstall and Woods (1939) report that engine power using a charcoal derived gas was 66% of gasoline power output. The power loss is due mainly to the low heating value of producer gas and to low volumetric efficiencies. The results reported by Parke (1981) support this statement.

Carburetion

Spiers agrees with Burstall and Woods on the importance of mixture strength in power output. Burstall and Woods conclude that a change in mixture strength has a much greater effect on power for biomass gas than a similar % change in a gasoline mixture. Therefore much more precise control of the mixture strength is necessary for biomass gas than for gasoline. Spiers reports that the mixture of biomass gas and air must be closely controlled to obtain optimum results. He also suggests that this may be difficult to do.

INVESTIGATION

Objectives

The objectives of this investigation were:

1. To develop a carburation system with optimum engine performance using biomass producer gas as fuel.
2. To study the effects of biomass producer gas on medium term engine wear and deposits.

Theory

Because the fuel has such a low heating value, the gas volume required was so large that available carburetors were unable to handle the necessary flow. Earlier work by Parke used a 5.08 cm pipe for the air and a 2.54 cm pipe for the fuel. Flow was controlled with a ball valve and a butterfly valve respectively. This worked for test purposes, but is not a practical solution because of the need to constantly monitor and adjust the mixture.

Carburetors, or gas mixers as they are often called, have basically two functions: 1) to control the flow of gas and air to maintain optimum fuel-air ratios under different loads and speeds and 2) to effect an intimate mixture of the gas and air. When dealing with gasoline the air-fuel ratios are about 16 to 1, and the mixing function is very important. If the gasoline and the air are not mixed properly then each cylinder recieves a different mixture, none of which are correct for best performance. When dealing with biomass producer gas the air-fuel ratios are about 2 to 1 or even 1 to 1. With such small ratios the mixing is accomplished quite easily and the mixing function is considered minor compared to the flow control function.

A second design criteria is the ability to adjust to changes in the quality of the fuel. The output from a fluidized bed is characterized by an unsteady, pulsating flow. This is caused by pockets of the fluidizing gas rising through and erupting at the surface of the bed. Other variables governing the behavior of the gasifier are bed temperature, air injection rate, and material heterogeneity. Figure 1 shows the variation in the average lower heating value of producer gas on a daily basis. It is clear that the output of the gasifier is hard to control and will vary from day to day.

Figure 2 shows the variation in the on-line lower heating value for the producer gas. The variation is smaller, but still large enough to create problems for the fueling system. These two figures tend to suggest that the problem is greater than it really is. Even though the fuel heating value jumps up and down 10 percent, the mixture heating value only changes about 5 percent.

Figure 3 presents a family of curves which illustrate the relationship between the fuel-air equivalence ratio and the fraction of the mixture that is occupied by fuel. Each curve

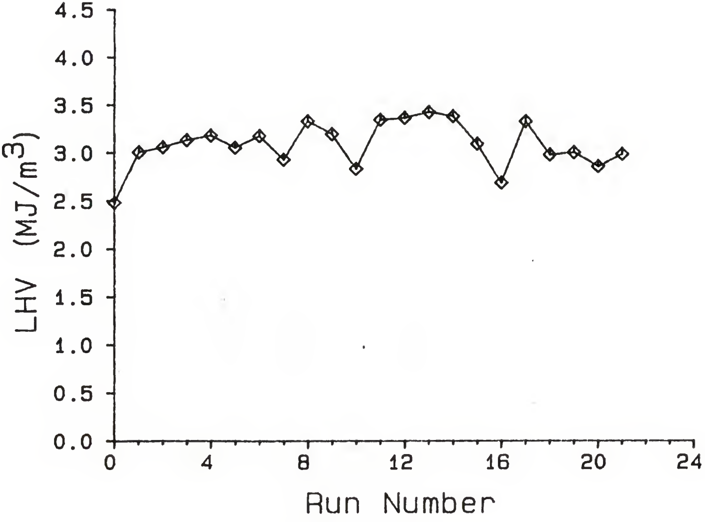


Figure 1. Calculated Lower Heating Value of Biomass Gas on a Daily Basis

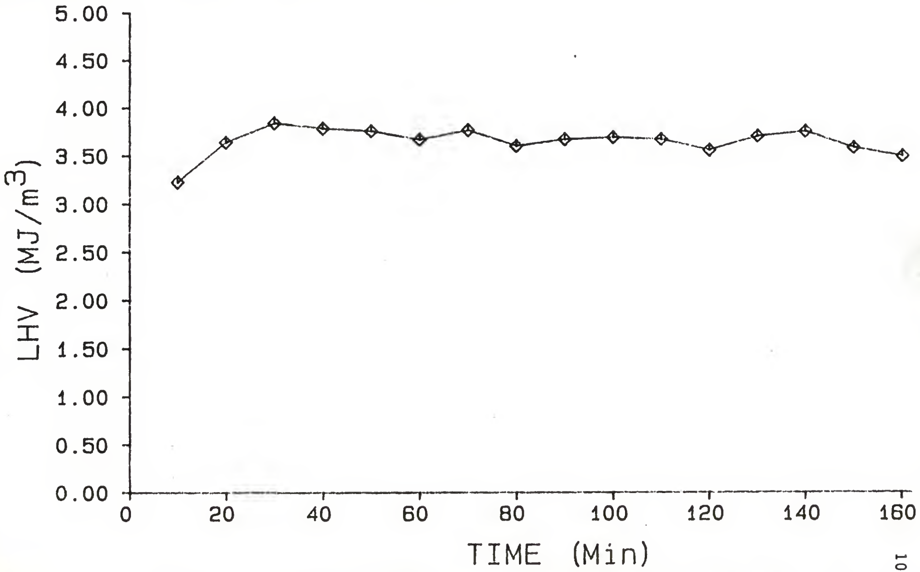


Figure 2. On-line Calculated Lower Heating Values of Biomass Gas

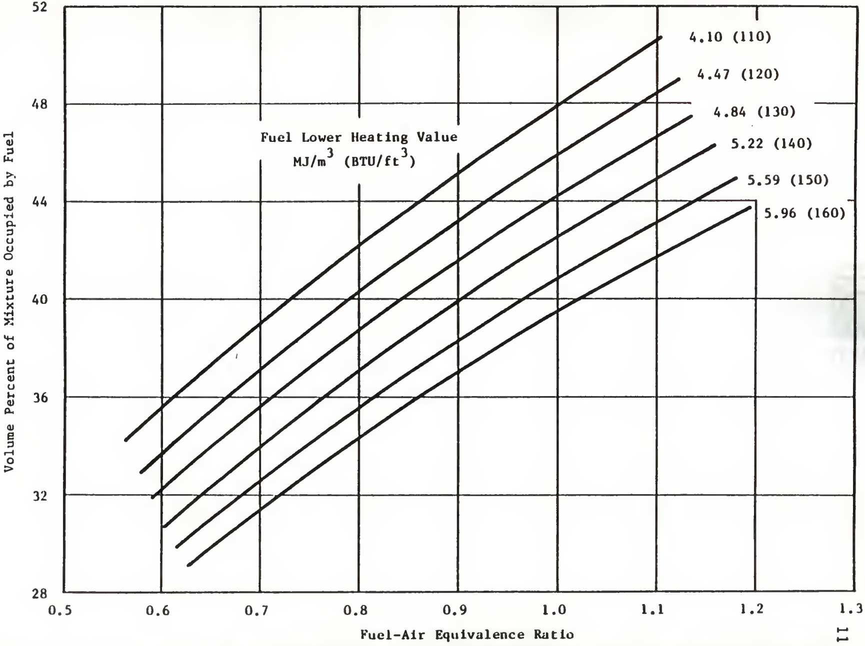


Figure 3. Amount of Mixture Occupied by Fuel for Fuels of Various Heating Values.

represents a fuel with a particular lower heating value. The fuel-air equivalence ratio is defined as the ratio of the actual fuel-air ratio to the chemically balanced fuel-air ratio on a mass basis. So relatively speaking, values greater than one represent rich mixtures, while values less than one represent lean mixtures. Referring to Figure 3, assume the engine is operating at an equivalence ratio of 0.9 with a fuel having a heating value of 5.59 MJ/m^3. About 38.4% of the total mixture is occupied by fuel. Now, suppose the heating value of the reactor gas quickly drops to 4.47 MJ/m^3 before another gas sample is taken. If the air and the fuel metering valves are left unchanged, the proportion of the fuel in the mixture is still the same. However, the engine is now operating at an equivalence ratio of 0.74. It is clear that the carburetion system must be able to make some adjustment due to the variability of the gas.

The carburetor developed for this work uses an idea suggested by Obert (1973). He suggests that the oxygen present in the exhaust gas is a good measure of performance. The lower the oxygen, the better the performance. For lean mixtures the excess air causes higher oxygen content in the exhaust, and for rich mixtures the reaction fails to go to completion and therefore leaves some excess oxygen. This proved true for both natural gas and biomass gas. The maximum power was found to be at the point of least oxygen in the exhaust, which was very near an equivalence ratio of one.

Materials and Equipment

Gasifier and Filters

A schematic of the gasifier used in this work is shown in Figure 4. The gasifier is divided into seven major components: 1) the reactor, 2) feed hopper and screw feeder, 3) high temperature cyclone for particulate removal, 4) venturi scrubber, 5) excess fuel afterburner, 6) controls, and 7) gas sampling equipment.

The reactor was a 0.23 m I.D. cylinder constructed of 310 stainless steel with a normal operating range of 800 to 1100 K. The combustion of propane in the plenum supplied the necessary heat for gasification and the fluidizing gas. A perforated plate acted as a gas distributor. Excess air was supplied to the bed so that the combustion of char in the bed provided additional heat to sustain the reaction.

The feedstock was fed to the fluidized bed by a horizontal auger located under the feed hopper. The auger moved the material to a vertical feedpipe. Gravity feed was used to deliver the feed from the auger to the bed surface. A nitrogen purge on the feed hopper was necessary to prevent reactor gases from rising into the feed system. If the seal on the hopper was inadequate, the feedpipe would plug due to the condensation of vapors in the pipe. A slide valve was installed in the vertical pipe to keep reactor gases from rising into the feed system during the heat up of the reactor.

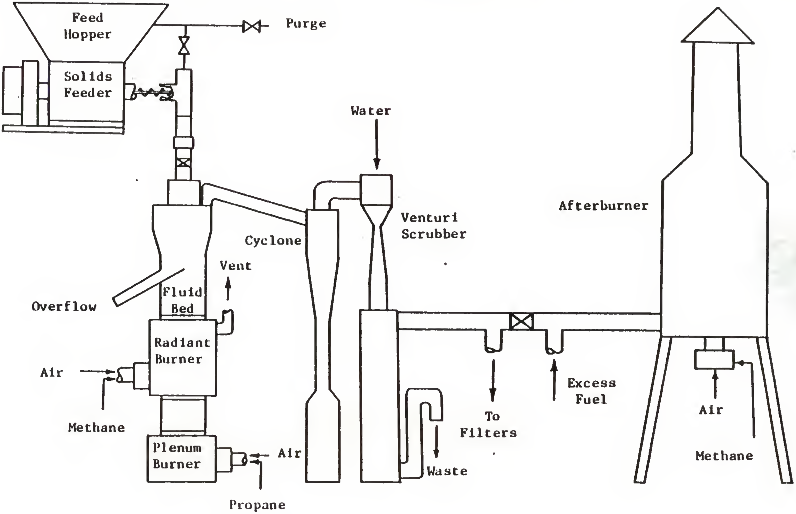


Figure 4. Schematic Diagram of Pilot Plant Gasifier.

The reactor bed contained about 46 kg of silica sand with a size range of -14 +50 mesh. When the feedstock entered the bed, char and volatiles were formed rapidly. Superficial velocities were maintained in the range of 27 to 46 cm/s so that the sand remained in the bed, but most of the ash was entrained in the off gas.

The volatiles produced in the reaction passed upward through a disengaging zone and then on to a cyclone which removed most of the particulates. From there, the volatiles passed through a venturi water scrubber, a ceramic balls impingement filter, and on to a roots blower. The scrubber rapidly quenched the gas and removed most of the tar from the gas stream. As the gas passed through the ceramic balls filter some of the heavy tar was removed by impingement on the balls. The blower provides the necessary pressure to overcome pressure drops across the packed column filters and to pump up the constant pressure tank. The first filter consisted of .6 m of ground corn stover followed by two layers of furnace filter. This combination proved very effective in removing tars from the gas, but the corn stover had to be replaced about every 5-6 hours. The thrid filter was very effective in removing residual tar from the gas. It consisted of very densely packed glass wool. After 160 hours of operation the pressure drop across this filter became so large that new glass wool had to be installed. Following this filter, the volatiles entered a variable volume, constant pressure fuel storage tank. This tank provided a steady flow of fuel to the engine at a constant pressure of 1.3 kPa. Before the gas reached the engine, it passed through a refrigeration unit which condensed out most of the remaining water. Table 1 shows the approximate composition of the gas used in the tests, along with data from Parke for comparison.

TABLE 1. Average Fuel Composition

Component	Natural Gas	Producer Gas	Producer Gas	Producer Gas
		New Stover	Corn Stover	Wheat Straw
	Vol. %	Vol. %	Vol. %	Vol. %
Hydrogen		10.5	6.7	5.6
Nitrogen	12.2	56.2	55.2	54.0
Methane	76.4	3.7	4.1	3.3
Carbon Monoxide		11.1	14.2	12.2
Carbon Dioxide		15.7	16.4	20.1
Ethylene		1.2	1.3	0.8
Ethane	7.4	0.2	0.3	0.4
Propylene		0.3	0.4	0.3
Propane	3.7			
LHV (MJ/scm)	29.550	3.266	3.798	3.035

Producer gas new stover refers to the gas that was used in earlier research, conducted by Parke. Corn stover was used as the feedstock for the first 50 hours of engine operation for the current tests. All tests after that were conducted with wheat straw as the the feedstock. The lower heating value of the gasified wheat straw was 8% lower than the heating value of new stover gas that Parke used.

Instrumentation on the gasifier included flow meters for air, propane, and a twelve point temperature recorder. An Applied Automation on-line process gas chromatagraph was used for gas analysis.

Engine and Carburetor

The engine used in this study was a Continental R800-46 four-stroke, four cylinder engine with a displacement of 0.846 L and a maximum rated speed of 5000 RPM. The engine was manufactured by Renault of France. The gasoline carburetor, fuel pump, governor and fan were removed for the tests. Cooling was provided by a water-to-water heat exchanger. This particular engine was selected because its power output matched the fuel output potential of the gasifier.

Figure 5 shows a picture of the carburetor. It was a simple mixing chamber with two butterfly valves to control air and fuel flow. The final design used valves with a 2.54 cm throat for the air and a 1.90 cm throat for the fuel. A cut-away view of the carburetor is shown in Appendix A. The throttle plate positions were measured with two-ten turn potentiometers connected to the valves by ten-to-one gear reductions. This is shown in Figure 6. The gear reductions allowed very acccurate control of the throttle plate positions. The potentiometer readings could be read mechanically or electrically.

Figure 5. Side-view of Carburetor Mixing Chamber. (Top)

Figure 6. Side-view of Carburetor Controls. (Bottom)

To provide feedback of the gas quality a Beckman OM-11 Oxygen Sensor was used to analyze the exhaust gas for oxygen content. The data acquisition system read the voltage output of the sensor and through the use of a software program determined if the mixture needed to be adjusted. If an adjustment was necessary, the acquisition system provided the voltage to drive a 1657 gm-cm (23 oz-in) Eastern Air Devices stepping motor which was attached to the fuel flow potentiometer. A flow chart for control of the carburetor is shown in Figure 7. The input sequence from the computer is shown in Figure 8. The stepping motor driving circuit, and a printout of the software are included in Appendix A. In effect, the butterfly valve on the air acted as the throttle of the engine. If it was adjusted, the fuel flow would be adjusted by the stepper motor until the equivalence ratio was near one again.

Dynamometer and Instrumentation

A 130 kW model Mid-West eddy current dynamometer was used throughout the tests. The dynamometer, equipped with a Control Engineering CE229 controller, allowed automatic control in either constant load or constant speed modes. For this work, it was operated in the constant speed mode and also acted as the governor for the engine. A dual bridge load cell, Transducers Inc. Model T63H-200, installed in the dynamometer scale linkage provided an electronic as well as a visual indication of torque.

FIGURE 7 CARBURETOR CONTROL FLOW CHART

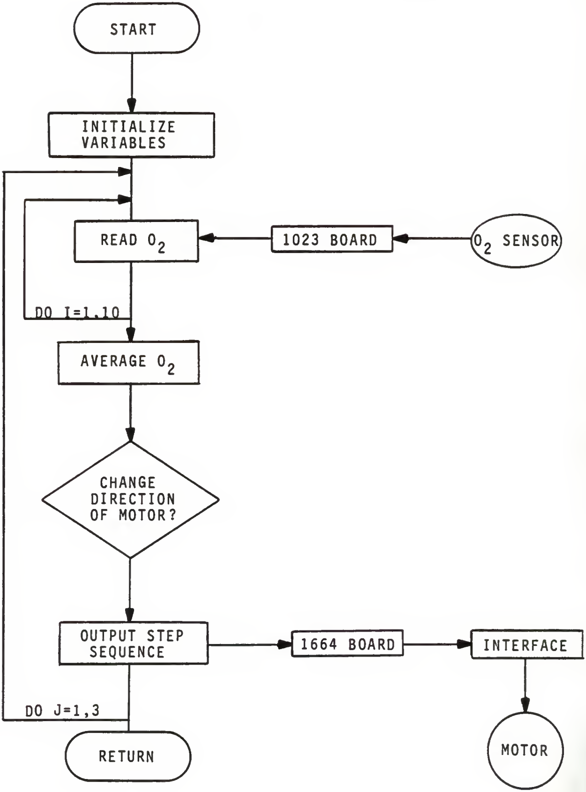


FIGURE 8. STEPPER MOTOR INPUT SEQUENCE

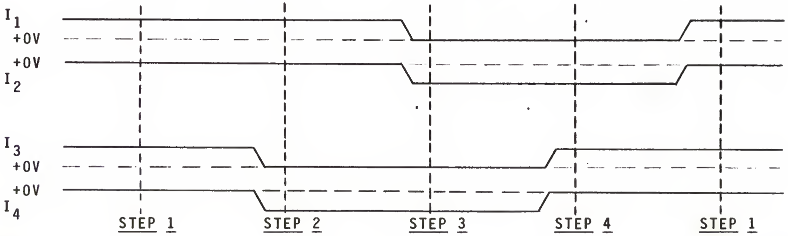
STEP INPUT SEQUENCE

STEP	INPUT1(I_1)	INPUT2(I_2)	INPUT3(I_3)	INPUT4(I_4)
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF

ON- INDICATES +5V OR HIGH LEVEL

OFF- INDICATES +0V OR LOW LEVEL

TIMING RELATIONSHIP BETWEEN TRANSISTOR INPUT SIGNALS



The load cell signal was received by a Daytronic 3270 strain gage conditioner and indicator. Engine speed was determined by a 60-tooth gear and an Electro 3010AN magnetic pickup, with the signal being received by a Daytronic 3240 frequency conditioner and indicator.

Copper-constantan thermocouples were used to measure fuel temperatures, inlet mixture temperature, water jacket temperatures, and the pan oil temperature. An iron-constantan thermocouple was used to measure the exhaust gas temperature.

Air and fuel flow measurements were performed with 25.4mm and 19.4mm diameter long radius ASME nozzles respectively. Both nozzles were mounted in 76.2mm diameter tubes and the pressure drops across them were measured using Setra Systems Inc. Model 239 variable capacitance differential pressure transducers. Because of reduced fuel demand when operating on natural gas, a 50.8mm diameter tube with 12.7mm ASME nozzle was used to obtain better readings while running the engine on natural gas. The same transducer was used for both fuels. The differential pressure transducers were calibrated against a Meriam Model 34FB2 micromonometer. A relationship proposed by Benedict (1966), relating the most probable discharge coefficient to the Reynold's number, was used to determine the discharge coefficients for the flow nozzles. Air filtering was done by an automotive type air filter located at the intake, just upstream from the nozzle.

Absolute gas pressure, intake manifold pressure, and atmospheric air pressure were measured by Setra Systems Inc. Model 204 variable capacitance absolute pressure transducers. The transducers were calibrated according to the daily barometric pressure.

An ADAC System 1000 Series data aquisition system incorporating a DEC LSI 11/23 computer and DEC VT100 terminal was used to collect, process, and store data on-line. The computer contained 256K of memory, a 5 megabyte Data Systems Winchester hard disk (Model 880), and an 8-inch floppy disk drive.

A 32 channel 12 bit resolution ADAC 1023AD and 1023EX analog to digital cards with programmable gain selection collected analog voltage signals from the dynamometer's Daytronic 3270 strain gage conditioner and Daytronic 3240 frequency conditioner, and the Setra Systems 239 and 204 pressure transducers. A 12 bit resolution ADAC 1113AD and 1113EX low level analog to digital cards were used to collect all the thermocouple voltages. A software programmable gain and cold junction compensation circuit allowed direct reading of the different thermocouple types. A 16 bit ADAC 1601GPT general purpose timer card was used as a software programmable clock that controlled the data collection timing process.

Software programs, written in Fortran, controlled the interrupts for data collection and performed the necessary calculations. Data could be sent to the terminal screen for immediate analysis or stored on disk files for permanent storage. Actual data collection was set to occur every 2 seconds and averaged over a period of 1 minute continuously. A sample of the output to the screen or disk is shown in Appendix B.

Exhaust Gas Analysis Equipment

Emissions measurements were conducted using the following instruments:

1. Beckman OM-11 polarographic oxygen analyzer with range 0-25%.

2. Beckman 402 flame ionization hydrocarbon analyzer with ranges 0-10, 0-50, 0-100, 0-500, 0-1000, 0-5000ppm, 0-1%, and 0-5%.

3. Beckman 864 infrared carbon dioxide analyzer with ranges 0-5% and 0-10%.

4. Beckman 865 infrared carbon monoxide analyzer with ranges 0-2% and 0-10%.

These instruments were mounted in a portable console according to Beckman specifications and were plumbed so that appropriate zero and span gases could be passed to their respective analyzers for calibration purposes. An oven and heated sampling hose were used to keep the exhaust gas temperature high enough so that it didn't condense in lines or in the analyzers before it was analyzed. This was especially important for accurate hydrocarbons measurement. The data acquisition system can be interfaced to read these instruments, but interfacing is not yet complete.

Test Procedure

Engine tests were performed at speeds of 2200 and 2600 RPM. The engine was run for 200 hours at 2600 RPM and full load over a period of about two months. Each run lasted 3 to 4 hours and was limited by the size of the biomass hopper. The engine was started directly with producer gas with no need for other fuels. It did have to be monitored closely until it was up to operating temperature. Other than the exhaust gas analysis, full data sets were taken approximately every 10 hours. All exhaust gas analysis work was done in the last 30 hours of engine operation. This was due to the analysis equipment not being operational during the first 200 hours of testing.

Every 15 hours the intake valves were inspected by removing the manifold. Every 25 hours oil samples were taken and sent in to be analyzed. The oil was changed after 100 hours. Due to water appearing in the oil, the oil change cycle was reduced to 50 hours. At the end of the 200 hour test the engine was torn down and inspected for wear and deposits. After the engine was rebuilt, a 25 hour test was done on producer gas with the engine operating at a higher temperature. Following this, the engine was run on natural gas for 25 hours, but the carburetor did not allow full power to be reached because of a limited air supply. In addition, a 6 hour test was conducted on producer gas with an engine speed of 2200 RPM. This last test was only to confirm that the carburetor would work on more than one engine speed.

RESULTS AND DISCUSSION

Carburetor Performance

The feedback controlled carburetor worked well, but not without some experimental adjustment. For these tests, the exhaust gas had to be run through a 10m heated hose before it reached the oxygen analyzer. This caused a 7 second delay in the sensing of any changes in the air-fuel ratio. Originally the software was set up to read the sensor voltage every two seconds and make necessary adjustments, but this resulted in an overadjustment because the sensor did not realize the first adjustment until two more had already taken place. Changes were made in the software so that sensor voltages were read and adjustments made only every 10 seconds. This allowed the voltage to reflect any changes that had been made earlier. About one minute after changes in the air-fuel ratio had been made, the carburetor adjusted the fuel intake so that the engine would be operating with a minimum amount of oxygen in the exhaust gas. This corresponded to equivalence ratios of 0.95 to 1.05. To establish the flexibility of the carburetor, severe adjustments were made to the air intake. The sensor was able to realize the adjustment and make necessary corrections within a matter of 3 to 4 minutes.

The carburetor was also able to respond just as well when the engine was operating at 2200 RPM. This indicates the ability of the carburetor to adapt to different levels of air intake. However, it did not operate well on natural gas. The carburetor throttle plates were not sized well for operation on natural gas. The fuel valve had to be almost closed while the air was wide open. When adjustment was made to the air, the fuel would be closed completely and the stepper motor would try to close it even further. More than enough natural gas passed around the closed butterfly valve to keep the engine running. When the fuel valve was opened to reach full power, the air valve could not supply enough air. Therefore, there were no results on natural gas at full power.

The ability of the carburetor to respond to changes in the air-fuel mixture allows the engine to operate on variable quality gas. This allows a change in the properties of the feedstock to the gasifier to be accomodated without making any adjustments to the engine or carburetion system. The feedback controlled carburetor is effective and should be used with low energy producer gas from a fluidized bed and other gasifiers.

Gas Production and Cleanup

Variable gas quality is inherent in biomass gasification. Fixed and moving bed gasifiers require fairly well defined feedstocks, but a fluidized bed gasifier has the flexibility to use almost any type of feedstock. Even though the feedstock is ground to pass through a 0.64 cm screen, there is considerable variability in the size and make-up of the pieces. This, coupled with the use of a horizontal auger to transfer feed from the hopper causes the feedrate to vary within a small range. Almost all of the tests conducted were with a feedrate of about 20 kg/hr and the size of the hopper limited the length of the runs to about 3 hours each.

The use of crop residues as a feedstock is known to produce tars in the volatiles. Increasing the bed temperature will reduce the amount of tars by cracking more of them before they leave the reactor bed. This can not be done without limit however, because these tars must eventually be used as a fuel to heat the bed so that the use of propane will no longer be necessary.

Filters are not the complete answer to the removal of the tars. High maintenence and short replacement interval appear to be too costly to be considered practical. The filters currently in use were effective in removing tars to such an extent that there was no appreciable build up on the intake valves. However, after 50 hours were completed, the butterfly valve on the fuel side became quite hard to turn. Upon inspection it was found that considerable tar was reaching the carburetor. Since impingement seemed to be effective in removing tars, another filter was added. This one consisted of iron filings and was followed by a trap and an automotive type air filter to prevent any removed tars from being blown on into the flow measuring nozzle. After this was installed the carburetor stayed considerably cleaner, although the butterfly valve did become sticky from time to time and had to be cleaned.

Research is being conducted to develop a condenser that will remove the tars immediately after the volitiles leave the reactor. The condenser should remove the bulk of the tars so the filters will last longer. Multiple filters seem to be necessary in order to remove enough of the tars so that build-up in the engine is not a problem.

Engine Oil

The oil used in the engine was Farmland Industries Diesel Multi-Grade Engine Oil, SAE 15W-40. The oil analysis was performed by Farmland Industries Oil Test Lab. The oil analysis measured viscosity,and the amounts of fuel dilution, water, and total solids in the oil. Metal concentrations in ppm were determined for iron, chromium, aluminum, copper, lead, tin, silver, nickel,silicon, sodium, boron, phosphorous, and zinc. A test for antifreeze, oil oxidation, and total acid number was also performed. Significant results are presented in Table 2.

Table 2. Results of Engine Oil Analysis

Hours on Engine	Hours on Oil	Water %	Vis centi stokes	Total Acid Number	Iron ppm	Chrom ppm	Alum ppm	Cop ppm	Lead ppm
50	25	3.3	10.7		27	0	2	5	3
75	50	4.4	10.7	10.7	265	3	5	15	5
100	75	5.8	10.6	14.7	998	15	12	25	7
125	25	1.4	10.8	8.3	394	4	3	22	8
150	50	4.9	10.3	12.1	460	7	11	37	11
175	25	2.2	11.4	8.4	201	3	7	16	7
200	50	>7.0	10.3	15.2	998	11	18	36	7
225	25	nil	13.2	4.0	111	0	11	16	7
*250	25	nil	12.4	2.3	77	0	5	14	6

*The last 25 hours were on natural gas.

Just before 25 hours of engine operation an oil pressure line broke and most of the oil was lost. Rather than adding oil to that remaining, the oil was changed. For this reason, the hours on the engine and the hours on the oil do not agree. A 50 hour oil change cycle was recommended after 100 hours of engine operation because water was appearing in the oil. The oil was changed at 25, 100, 150, 200, and 225 hours on the engine.

During the first 200 hours of engine operation it was thought that the water in the oil and the indication of high wear rate in the engine were due to water in the producer gas. At the 200-hour teardown it was discovered that the engine did not have a thermostat. Earlier work by Parke had been conducted without a thermostat by adjusting the cooling water flow until the desired operating temperature was reached. Examination of the data taken during the 200-hour test revealed that the operating temperature of the engine was around 30 C instead of the recommended 82 C. The water in the oil was caused by condensation because the engine was running too cool. This problem disappeared after a thermostat was installed.

Viscosities during the first 200 hours were lower than those for the 225 hour and for natural gas. This was caused by the presence of water in the oil. It is surpising to note that the viscosity for the 25 hours on natural gas is lower than for the 25 hours on producer gas at 82 C. No explanation is offered for this behavior. Longer tests should be run at the higher temperature on both producer gas and natural gas to evaluate differences and trends that might exist between these two.

The Total Acid Number was quite high throughout the whole test period. This would be expected during the first 200 hours when the engine was running too cold and water was condensing in the oil. After the 200-hour teardown a 12-hour cycle was run on natural gas to clean any impurities from the engine. Acid number tests for the 25 hours at high temperature indicate a significant reduction in the amount of acid present. An acid number of 4 is considered to be high for 100 hours of operation on an engine fueled by diesel. It is not known how much of this acidity remained in the engine block after the 12-hour cleaning cycle. The results from the 25 hours on natural gas are considered to be about normal, but the residual acidity may have had a chance to disappear by then. More tests need to be performed with the engine operating at recommended temperature in order to evaluate to what extent these acids exist and how harmful they might be.

Iron, aluminum, and copper indicate the most wear, and all are at unacceptable levels during the first 200 hours. The high iron content indicates excessive wear of the cylinder walls, while alumimum levels indicate piston wear. The copper is from wear in the bearings. The last 50 hours are also at a level that is higher than desirable. The reasons are the same as discussed in the last paragraph.

Engine Teardown

At the end of the first 200 hour test cycle the engine was torn down and examined for wear and deposits. None of the moving parts showed any unusual wear, but there was some scale appearing in the block. It appeared that the acid in the oil had worked its way into the porous metal and begun to corrode it. This was the reason for a 12-hour cleanup cycle, but there is no way of knowing what that accomplished. The engine was torn down for over a month while waiting on parts.

Figures 9 and 10 show the intake and exhaust valves after 200 hours of operation. The intake valves appeared to be wet and had some buildup, but not enough that it had begun to affect the output of the engine. Figure 11 shows the top of the combustion chamber; moderate deposits are visable around the intake valve. Some deposits also appeared on the top of the piston shown in Figure 12. There were moderate deposits in the first ring groove, but no stuck rings.

It is suggested that for future tests the engine be torn down and a complete set of measurements taken, both before and after the test. Similarly, the deposits should be quantified so that comparisons can be made with other tests. Farmland Industries has such a test that was developed for alternate fuel test evaluation.

Figure 9. Intake Valve after 200 hours Operation on Biomass Gas. (Top)

Figure 10. Exhaust Valve after 200 hours Operation on Biomass Gas. (Bottom)

Figure 11. Top of Combustion Chamber after 200 hours Operation on Biomass Gas. (Top)

Figure 12. Top of Piston after 200 hours Operation on Biomass Gas. (Bottom)

Spark Ignition Timing

Although the hydrogen content was lower during the current tests than in the work of Parke, the spark advance was greater for the previous tests. This is exactly opposite of what would be expected and is contrary to results reported by all experimenters. A possible explanation for this has to do with the quantity of tars being burned. In work by Parke, the tar content was high, but in this work the tar content was a minimum. If these tars were slow burning, it would account for the earlier fuel needing a larger spark advance. Previous results were about 39 BTDC while for this test the spark advance was about 23 BTDC. Peak power was used to determine the optimum advance. Experiments resulted in a range of advances being established for no noticeable decrease in power. However, once the advance was lowered below 17 BTDC or raised above 29 BTDC, there was a very rapid loss of power. The spark advance did not change appreciably for natural gas or for biogas operating at a lower temperature.

Power Output

The power output of the engine is a direct result of the quality of fuel input. Because of the changes in the gas quality, the power output would vary from day to day and even within the same day. Due to a calibration error, the power output data for the 200 hours at a low engine temperature had to be discarded. Figure 13 shows the peak power output of the engine on natural gas, producer gas new stover, and producer gas wheat straw at various equivalence ratios. The maximum power obtained on producer gas wheat straw was only 6.4 KW; Parke (1981) was able to obtain 8.1 KW on producer gas new stover. The exact quality of gas that he used to obtain this power level is unknown. Had he been operating on what he presented as his average fuel compositition it would indicate that power levels on wheat straw were about 15% lower than expected, based on the compared heating values of the fuel-air mixtures.. Since gas quality controls power output, only limited conclusions can be drawn without knowing the quality of gas he used for this power level.

This apparent loss of power is attributed to the cleanup of the gas. Parke was operating with higher tar levels, some of which provided useful energy to the engine. The removal of these tars is necessary for long-term engine operation, but it also means less power output. The balance between maximum power and minimum deposits may be difficult to establish due to changes in the amount of tar produced by the gasifier.

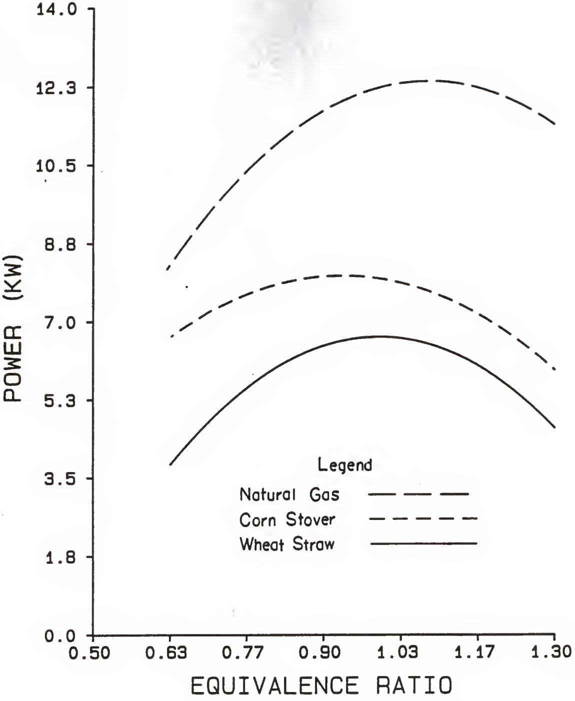


Figure 13. Peak Brake Power at 2600 RPM for Natural Gas and Biomass Gas

Brake Thermal Efficiency

Figure 14 shows the brake thermal efficiencies of natural gas, producer gas new stover and wheat straw for various equivalence ratios. The peak efficiency for Parke's data on producer gas new stover occurs with a lean mixture. The complete burning of excess tars would require more air. Since most of the tars were removed for the test on producer gas wheat straw, the peak efficiency is shifted to the right. The engine also exhibited a lower brake thermal efficiency during the wheat producer gas tests. This could be due to the lower heating value of the fuel. The removal of the tars again appears to have had a negative effect on engine performance by lowering the thermal efficiency, however, the loss of some efficiency is more acceptable than damage to the engine due to deposits. Efficiency and power output can be increased by supercharging the fuel-air mixture. Quadratic equations describing power and thermal efficiency as functions of equivalence ratio are included in Appendix C.

Exhaust Gas Analysis

Figures 15 through 19 show the specific emissions of the various constituents over a range of equivalence ratios. All emissions tests were performed with producer gas wheat straw as the fuel for the engine. The oxygen emissions shown in Figures 15 and 16 indicate that oxygen content in the exhaust is a good measure of extent of combustion. The lowest oxygen contents are at equivalence ratios of near one. Operating at a speed of 2200

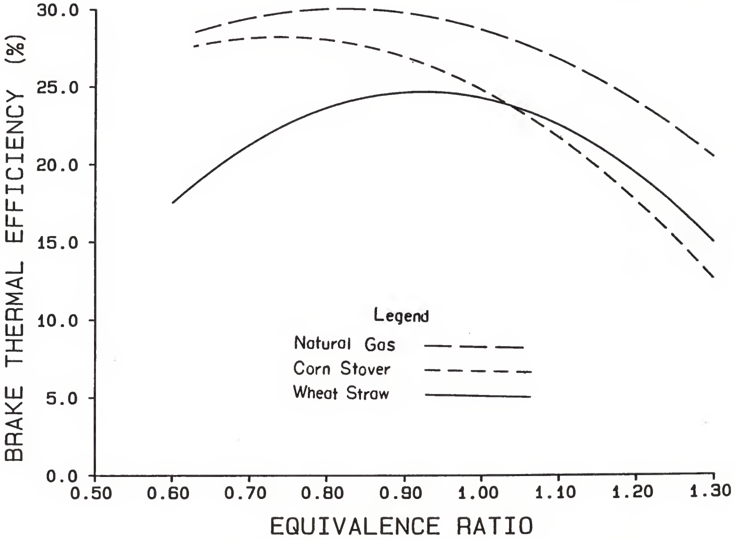


Figure 14. Brake Thermal Efficiency at 2600 RPM for Natural Gas and Biomass Gas

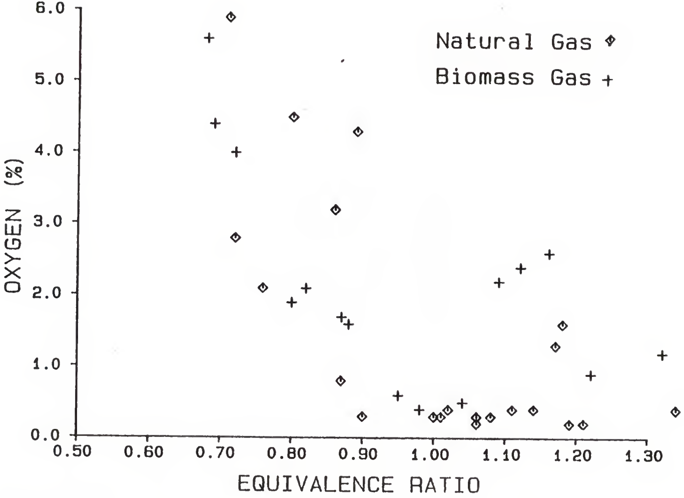


FIGURE 15. Oxygen Emissions at 2600 RPM for Natural Gas and Biomass

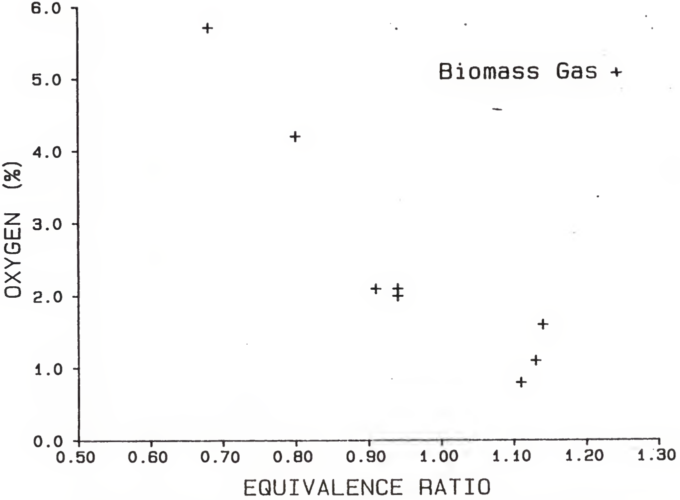


FIGURE 16. Oxygen Emissions at 2200 RPM

RPM produces the same results. This indicates that the carburetor can operate under different speed and load conditions.

The hydrocarbon emissions, shown in Figure 17, are lower for the biomass than for the natural gas. This is partially due to the absence of great quantities of hydrocarbons in the unburned biomass. Hydrocarbons could be used as an indicator of operating fuel rich. Once the equivalence ratio reaches one, the hydrocarbon emissions sharply increase.

Below an equivalence ratio of one the carbon monoxide emissions, shown in Figure 18, do not even appear on the scale. This is one of the useful constituents of the fuel, therefore most of it is burned, especially at lean air-fuel ratios.

The carbon dioxide levels shown in Figure 19, are quite high for producer gas compared to natural gas. This is due, in part, to the higher carbon dioxide levels in the inducted gas.

Nitrous oxides were to be measured, but that equipment was not functional during the test period. Few conclusions can be drawn from the emissions tests, but none of the values seem extraordinarily high.

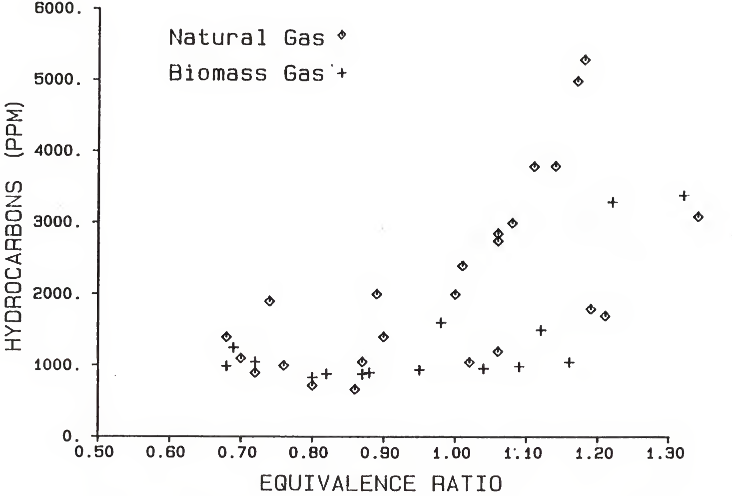


FIGURE 17. Hydrocarbon Emissions at 2600 RPM for Natural Gas and Biomass

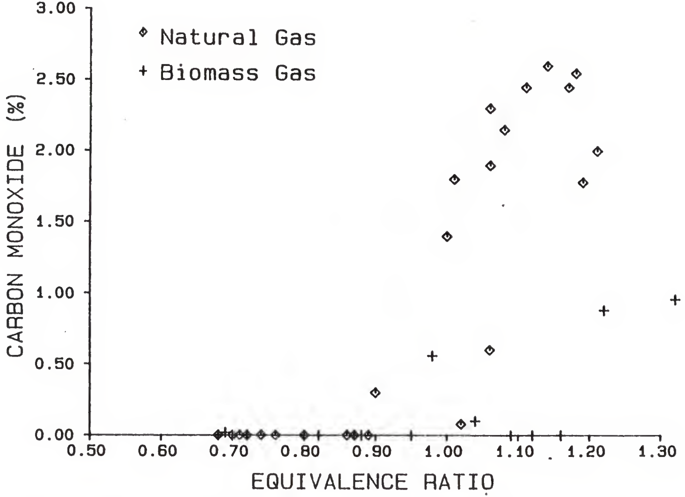


FIGURE 18. Carbon Monoxide Emissions at 2600 RPM for Natural Gas and Biomass

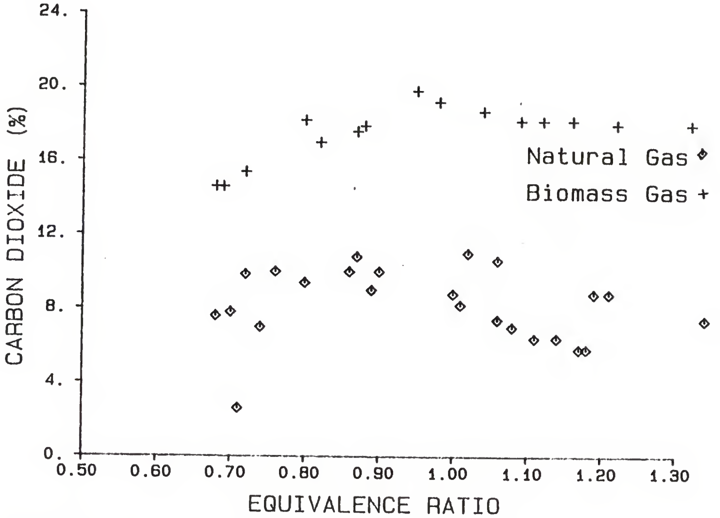


FIGURE 19. Carbon Dioxide Emissions at 2600 RPM for Natural Gas and Biomass

CONCLUSIONS

1. When using a fluidized bed gasifier for the production of low-energy gas from crop residues, the gas is not of a constant quality. This is due to inherant qualities in the fluidization process and adjustments must be made after the gas leaves the gasifier.

2. The use of crop residues as a feedstock produce tars in the reactor off-gas. These tars must be removed before the gas reaches the engine to prevent buildup internally and a subsequent loss of power.

3. The carburetor of a biomass gas engine must be able to supply a volume flow rate of fuel equal to 30-50% of the total air-fuel mixture.

4. When a gaseous fuel has a low volumetric energy density, small variations in the fuel quality will have a noticeable effect on engine performance.

5. The optimal spark advance for best power is hard to locate and in fact, the engine operates just as well over a range of spark advance values. There is a definite loss of power when operating outside of this range, and the decrease is rapid.

6. Internal combustion engines may be fueled with biomass gas produced in a fluidized bed if the gas is sufficiently clean. Medium term test results at 2600 RPM indicated

little buildup in the engine and no appreciable loss of power over the duration of the test.

7. The use of multiple filters by themselves to clean the gas is not very practical because of high maintence and replacement costs. The use of a condenser would greatly facilitate the clean-up of the gas by removing most of the tars before they reach the filters. This would add to the lifespan of the filters.

8. Oxygen content in the exhaust is a good indicator of engine performance. When oxygen content is a minimum, the engine is operating at an equivalence ratio of near one.

9. A carburetion system using feedback from an oxygen sensor in the exhaust is capable of sensing changes in engine performance due to gas quality and of making adjustments to the air-fuel mixture so that power output is optimum.

SUMMARY

The results of this investigation show that a spark ignition engine can be operated on low energy biomass gas if the fuel is cleaned adequately. Longer tests should be performed to better evaluate the appearance of an acid in the engine oil. Deposits and visable wear in the engine were a minimum. The oxygen content in the exhaust was used to control feedback to the carburetor gas flow which is driven by a stepper motor and the use of software in the data acquisition system. The feedback controlled carburetor proved effective in adjusting the air-fuel mixture to changes in the quality of the fuel gas.

Further work needs to be done in the area of gas cleaning so that an optimal system may be developed.

SUGGESTIONS FOR FURTHER RESEARCH

A prototype gasifier with tar recovery and recycling as fuel to replace propane should be constructed. Work should be done to determine the amount of tars produced with varying parameters such as bed temperature and gas residence time. Once this is done, gas clean-up requirements can be established. For maximum operating efficiency, only the amount of tar necessary to heat the bed should be produced.

Further tests should be run to establish the long term effects of producer gas on engine wear and deposits. The engine should be torn down both before and after the test and key wear areas should be physically measured. Likewise, the deposits on pistons and valves should be quantified for accurate comparison. Farmland Industries Petroleum Research Division has an established program of engine evaluation for wear and deposits. Further work is needed to establish optimum spark advance with changes in gas quality. Additional work should be done to recover power output and efficiency with the use of supercharging.

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APPENDIX A

CARBURETOR CONTROL

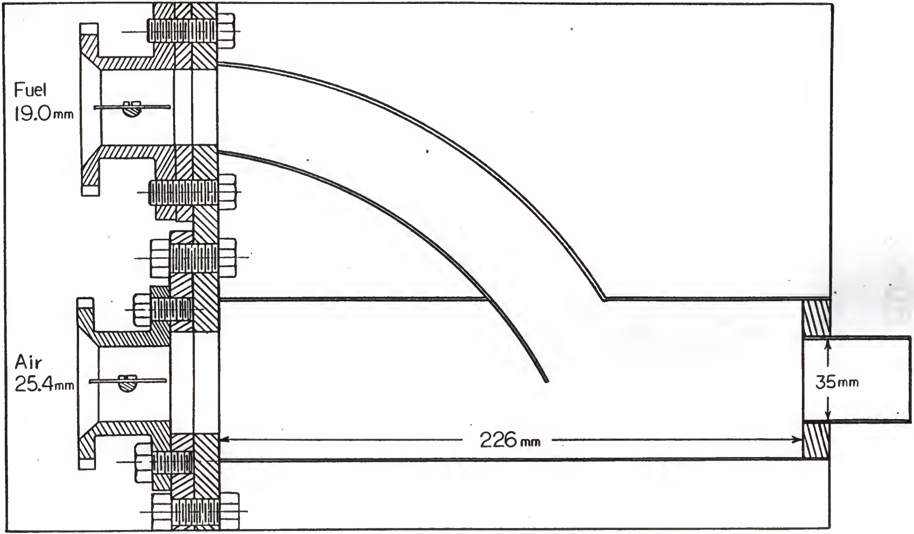
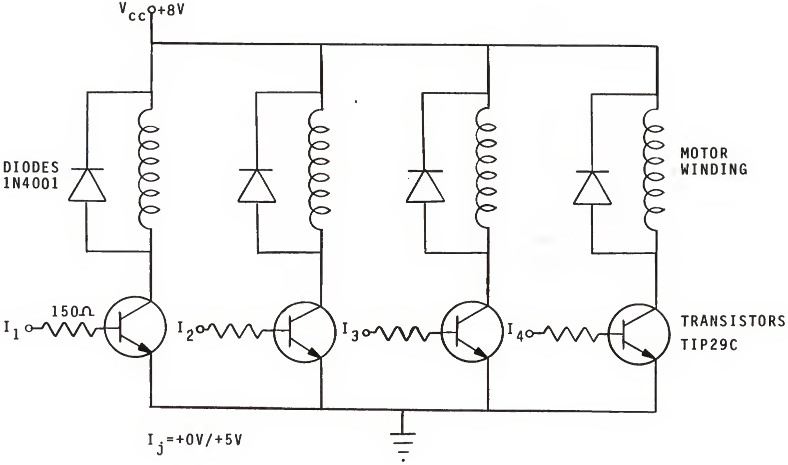


Figure 20. Cut-away View of Carburetor.

```
C***************************************************************************
C
      SUBROUTINE STEPSR
      INTEGER CLW(5),DIRMOV(5),WDATA
#include "ENG:COMMON.BLK"
C
C     FOUR STEP INPUT SEQUENCE (FULL STEP MODE)
C     BITS 7,6,5,4 OF BYTE ARE USED IN STEPPING THE MOTOR.
C
      CLW(1) ="001704
      CLW(2) ="001644
      CLW(3) ="000060
      CLW(4) ="000120
      CLW(5) ="001704
      WDATA  = -1         !WRITE DATA TO DEVICE.
      IDELAY=500          !DELAY TIME BETWEEN PARTS OF THE STEP
      IDIR=-1             !INITIAL DIRECTION CLOCKWISE
      ICOUNT=10           !NUMBER OF TIMES TO READ VOLTAGE TO AVERAGE
      ISUM=0              !SUM OF VOLTAGES
      ISTEPS=3            !NUMBER OF STEPS TO TAKE WHEN CALLED BY INTRTN
C
C     TAKE ISTEPS NUMBER OF STEPS.
C     EACH STEP IS TAKEN IN FOUR PARTS
C     THE VOLTAGE FROM THE EXHAUST GAS IS READ 10 TIMES AND
C     AVERAGED.  THIS AVERAGE IS COMPARED TO THE VOLTAGE AT THE START
C     OF THE LAST STEP. IF THE CURRENT VOLTAGE IS GREATER THAN THE
C     VOLTAGE AT THE LAST STEP, THE DIRECTION IS KEPT THE SAME.
C     IF THE CURRENT VOLTAGE IS LESS THAN THE LAST VOLTAGE, THE STEP
C     DIRECTION IS CHANGED.
C
      DO 250 N=1,ISTEPS                        !TAKE A STEP.
        DO 50 I=1,ICOUNT                       !READ CHAN 0 AT 5 VOLTS
          CALL AREADP(ISTAT,IBUFF,1,0,,2)      !  10 TIMES AND SUM.
          ISUM=ISUM+IBUFF
50      CONTINUE
        IBUFF=ISUM/ICOUNT                      !CALCULATE AVERAGE.
        IF (ILAST.LE.IBUFF) IDIR=-IDIR         !CHANGE DIRECTION IF
        ILAST=IBUFF                            !  NEW > OLD
        ISUM=0                                 !CLEAR FOR NEXT TIME.
C
C     SETUP STEPER TO GO CLOCKWISE
C
      DO 105 K=1,5
        DIRMOV(K)=CLW(K)
105   CONTINUE
C
C     CHANGE DIRECTION OF MOTOR MOTION IF NECESSARY
C
      IF (IDIR.EQ.-1) GOTO 120
      DO 110 K=1,5
        DIRMOV(K)=CLW(6-K)
110   CONTINUE
C
```

```
C       TAKE ONE STEP.
C
120       DO 200 J=1,5
            CALL DEVICE(WDATA,DIRMOV(J),"164100+2)         !OUTPUT STEP
            DO 190 K=1,IDELAY                               !WAIT A LITTLE
190         CONTINUE     !WAIT
200       CONTINUE       !NEXT PART OF THIS STEP
250     CONTINUE         !NEXT STEP
        RETURN
        END
```

FIGURE 21 STEPPER MOTOR DRIVING CIRCUIT



APPENDIX B

SAMPLE DATA

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*******************************************************************************

DATA TAKEN AT 15:56:10                  DATA TAKEN ON 06-MAR-84
FUEL TYPE: BIOGAS
LOWER HEATING VALUES                    Btu/lbm   MJ/kg   Btu/scf   MJ/scm
       Fuel:                             1926.5   4.478    102.0    3.803
       Mixture:                          1263.1   2.936     68.8    2.565
Percent O2 from exhaust gas analyzer    7.1%
                              FUEL CONSTITUENTS, PERCENTAGES
  H2       N2        CH4      CO        CO2        C2H4       C2H6      C3H6
 7.50     53.40      4.40    14.70      17.80      1.30       0.40      0.50

RPM = 2605.2                            CORR BRAKE POWER =  5.5HP( 4.1kW)
TORQUE =  11.3ft-lbs   ( 15.3N-m)       CORR BMEP =  32.4psi      ( 223.6kPa)
INDICATED POWER = 9.5HP( 7.1kW)         CORR IND. MEP =  55.4psi (   0.0kPa)
EQUIVALENCE RATIO =  2.52               CORR BSFC = 7.785lb/hr-hp(4.735kg/hr-kW)

FUEL FLOW RATES
FUEL FLOW =  42.86lb/hr( 19.44kg/hr)  VOLUME FLOW =  10.60cfm  (  5.00l/s)

AIR FLOW RATES
AIR FLOW =  22.51lb/hr ( 10.21kg/hr)  VOLUME FLOW =   5.12cfm  (  2.41l/s)

CORR. BRAKE THERMAL EFF. = 17.0%        VOLUMETRIC EFF. =  40.4%
CORR. IND. THERMAL EFF. = 29.0%         MECHANICAL EFF. =  58.9%
MASS AIR/FUEL RATIO =  0.53             MASS FUEL/AIR RATIO = 1.9040

TEMPERATURES   F          (C)           PRESSURES        psi        (kPa)
Ambient Air   60.1      ( 15.6)         Atmospheric     14.1       ( 97.3)
H2O inlet     83.9      ( 28.8)         Abs. Gas        13.5       ( 93.15)
H2O out      183.4      ( 84.1)         Intake manif.   ****       (183.32)
Oil           32.0      (  0.0)         P diff gas      0.024      ( 0.169)
Fuel          71.8      ( 22.1)         P diff gas  0.678in.H2O   (0.0172m.H2O)
Intake manif  81.3      ( 27.4)         P diff air      0.002      ( 0.015)
Exhaust gas 1164.4      (629.1)         P diff air  0.062in.H2O   (0.0016m.H2O)

Air density = 0.7332E-01lb/cu.ft    (1.1744kg/cu.m)
Air viscosity = 0.1205E-04lbm/ft-s  (0.1793E-04kg/m-s)
REYNOLD'S NO.(air) =   7929.8         NOZZLE COEF. OF DISCHARGE(air) = 0.930

Gas density = 0.6737E-01lb/cu.ft    (1.0791kg/cu.m)
Gas viscosity = 0.1097E-04lbm/ft-s  (0.1632E-04kg/m-s)
REYNOLD'S NO.(gas) =  21682.7         NOZZLE COEF. OF DISCHARGE(gas) = 0.954
*******************************************************************************
```

APPENDIX C

QUADRATIC EQUATIONS DESCRIBING ENGINE POWER AND EFFICIENCY

Predicted Value = $Ax^2 + Bx + C$, where

A = second order coefficient

B = first order coefficient

C = intercept

x = fuel-air equivalence ratio

Predicted Value = Power (kW), or

Brake Thermal Efficiency (%)

Table 3. Coefficients and Intercepts for Quadratic Equations

Fuel	A	B	C	R-square
		POWER		
Natural Gas	-20.53	44.42	-11.61	.995
New stover	-15.69	29.24	-5 57	.664
*Wheat straw	-21.99	43.76	-15.09	.922
		BRAKE THERMAL EFFICIENCY		
Natural Gas	-41.62	68.29	2.07	.977
New stover	-49.51	73.08	1.29	.663
*Wheat straw	-68.55	126.61	-33.74	.748

*Equation for wheat straw is for only one days data. Because of too much scatter due to variable gas quality, it was impossible to fit all the data to one curve.

CARBURETION SYSTEM FOR BIOMASS GAS FUELING OF SPARK IGNITION ENGINES

by

MARK A. GOODMAN

B. S. M. E., Kansas State University, 1982

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1984

ABSTRACT

Agriculture is a somewhat unique industry in that it has the potential to supply a significant portion of its energy demand from available , non-marketable, crop residues. Researchers estimate that 50% of the available residue from a crop of irrigated corn, if converted to low Btu gas, could provide all the energy required to pump the water for the season and to dry the grain after harvest.

A pilot plant fluidized bed gasifier, using corn stover and wheat straw as feedstocks, has been used to fuel a spark ignition engine. The most evident result of using the low energy gas was that engine power output dropped. The decrease in power output was almost entirely accounted for by the smaller amount of potential energy inducted in the air-fuel charge. The drop in the air-fuel mixture heating value was caused by a high levels of nitrogen and carbon dioxide delivered by the gasifier along with the useful fuel components.

Commercially available carburetors were unable to provide adequate fuel flow; 30-50% of the air-fuel mixture was occupied by fuel. Also, the quality of the producer gas was not constant. Because of this a carburetion system was developed that used oxygen content in the exhaust gas as a measure of complete combustion. This carburetor was successful in sensing changes in the extent of combustion due to a change in the quality of fuel and making adjustments to the mixture so that power output remained

at optimum levels.

Medium term tests indicated little buildup of tars in the engine and no visible wear on any of the moving parts. The oil analysis indicated a possibility of an acid being formed in the oil. Further tests are recommended before conclusions can be drawn.

Gas cleaning was performed by a series of packed column filters. They were effective for testing purposes, but do not appear to be a complete solution.