Operating a Diesel Irrigation Pump on Citrus-Wood Producer Gas

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Abstract

A 5.8L (354 in^3) displacement diesel engine was converted and operated on producer gas with fuel oil as a pilot fuel. Fuel gas, produced from air-dried, chipped citrus wood in a downdraft suction gasifier, was introduced along with air into the intake manifold of the engine and ignited when the pilot fuel oil auto-ignited. In the dual-fuel mode, the engine produced about 78% of the rated power produced on fuel oil. Nearly 75% of the energy came from the wood and the remainder from the pilot fuel. Wood fuel consumption was 0.95 kg/kWh (1.56 lb/hp-h). A ram fuel injector on the gasifier made refueling possible while the system was in operation.

Introduction

Agriculture in the last two decades of the 20th Century is facing increased costs, shortages of fuel supplies, and environmental concerns. For citrus growers in Florida, nearly 76 million liters (20 million gallons) (Stanley et al., 1980) of petroleum fuel are required annually for pumping irrigation water. Between 1974 and 1983, fossil fuel costs increased almost five-fold and at times the supply was critically short. In addition to this shortage and the expense of petroleum, citrus producers have an annual waste disposal problem of over half a million tons of citrus wood; this wood has to go into land fills or be incinerated. Thus, in looking for ways to decrease irrigation costs and to lessen the threat of petroleum shortages, it seemed that a logical solution would be to use the waste citrus wood for producing a fuel gas for the diesel engines operating irrigation pumps.

Gasification of solid fuel to produce internal combustion engine fuel was first accomplished by Dawson in England, in 1878 (National Research Council, 1983). Although the technology was largely forgotten when gasoline, fuel oil, and natural gas became plentiful and cheap about the turn of the century, it received great attention in Europe before and during World War II. In Sweden during World War II, nearly 70,000 vehicles were operated on wood and charcoal fuel – the principal source of motor fuel for the civilian population (Solar Energy Research Institute, 1979). In 1957, Sweden activated a national preparedness program for converting essential civilian vehicles to operation on producer gas, in case of an oil supply interruption.

Three studies in the United States of producer gas included that of Goss (1980) who operated a diesel engine on producer gas made from wood chips in a down-draft gasifier, of Williams et al. (1978) who fueled a turbocharged diesel engine with producer gas made from corn cobs, and of Park and Clark (1981) who tested a spark-ignition engine using producer gas made from corn stover in a fluidized-bed gasifier.

Thus, producer gas can be a viable alternative fuel for operating spark and compression ignition engines used in agriculture because it can be utilized in most existing engines without major modifications. Futhermore, it is possible to switch from liquid or gaseous fuel to producer gas and vice versa, depending upon the availability of each and upon the respective costs of wood and liquid or gaseous petroleum fuels.

In order to investigate the feasibility of using this alternative fuel source in citrus operations during fuel shortages, methods of processing, drying, and gasifying the citrus wood had to be developed and tested. It was anticipated that Florida's extremely high humidity would complicate the gasification process because air-drying the wood would be difficult and excess moisture would degrade the gasification process in a downdraft gasifier. But difficulties did not diminish the logic of using waste citrus wood from groves to produce gas that would power irrigation pumps for the same groves.

Because most irrigation pumps in Florida are powered with electric motors or diesel engines, the direction of this study was towards utilizing producer gas in compression ignition engines that operated under constant speed and constant load conditions. Unlike vehicle engines, which operate under varying speed and load conditions, pump engines must operate for long periods at a set speed. Because of the long time spans required in operating an irrigation pump, these investigations also evaluated a fuel-feeding system which would replenish the fuel supply while the engine was in operation.

Equipment and Procedure

Engine

The engine selected for conversion to producer gas operation was a model 6.354 Perkins, naturally aspirated,

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direct-injection compression ignition engine with a displacement of 5.8 L (354 in^3) and a compression ratio of 16:1. The fuel system was a CAV rotary distributor injection pump with a mechanical governor. This engine is widely used in agriculture and typical of those used on irrigation pumps. For break-in, this new engine was installed on an irrigation well pump in a citrus grove and was operated for approximately 25 hours on diesel fuel.

GASIFIER

The down-draft gasifier, specially built from mild steel for these tests, was based on a Swedish design (Johansson 1981a). Designed to produce about 190 m^3/h (6700 ft^3/h) of producer gas from wood chips, it had a 17.8 cm (7 in.) hearth diameter and seven 12.7 mm (0.5 in.) diameter stainless-steel tuyeres (figs. 1 and 2).

A truncated cone hearth was used instead of a flat hearth plate to avoid plate warping and cracking that could result from the intense heat in the combustion zone. To make the hearth cone more durable, its upper surface was built up by arc welding with stainless steel. In addition, the space around the hearth cone was filled with vermiculite insulation to concentrate the heat in the combustion zone. The grate, supported on rollers, was horizontally oscillated with a crank that was driven by a hydraulic motor. Under the grate was a receptacle for the ash.

The 350 L (12.4 ft^3) fuel hopper had a perforated liner that allowed vaporized moisture from the wood chips to escape and condense on the outer shell. A condensate trap collected the moisture from around the bottom of the fuel hopper and then this condensate accumulated in a receptacle. A slider-crank agitator was built into the fuel hopper section of the gasifier to prevent bridging of the fuel. Although this agitator was only occasionally operated, it was considered necessary because the stationary gasifier was not vibrated which does occur in a motor vehicle mounted gasifier.

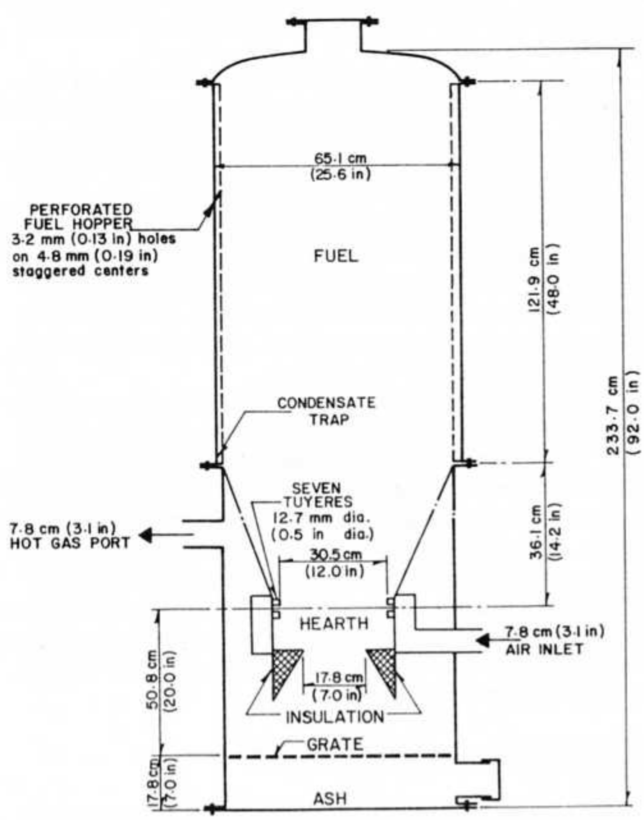

Figure 1–Cross-sectional view of downdraft gasifier.

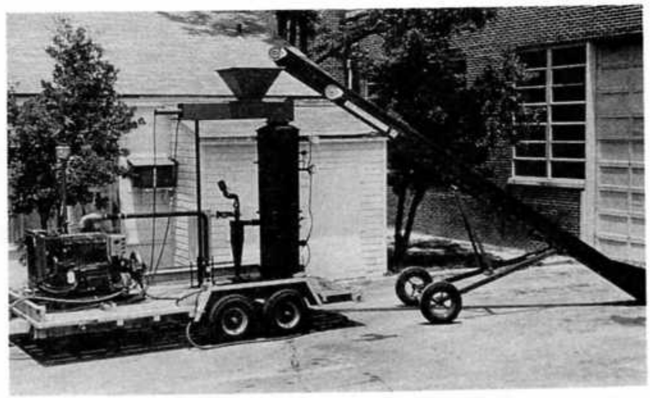

Figure 2–Dual-fueled engine and gasifier system.

FUEL FEEDER

For continuous operation of an irrigation pump engine, a gasifier must be refueled while in operation. Thus, a fuel-feeding system was developed which would not alter the production of gas while the refueling operation was underway.

Two systems were initially considered; the first possibility, a screwfeeder, was eliminated because a gas-tight seal could not be effected in the auger. Next, a rotary air-lock feeder with flexible blades on the rotor, guaranteed by the manufacturer to withstand 4.2 kPa (17 in H_20) of pressure or vacuum, was evaluated, but it would not feed chips without frequently jamming.

The system that worked satisfactorily with no decrease in power while the engine was being refueled was a reciprocating fuel feeder (figs. 2 and 3) that was specifically designed for this study. It consisted of a hollow, rectangular ram with a chamber for approximately 11.5 L (700 in^3) of fuel. On each side of the chamber were rubber seals to prevent leakage of air into the gasifier, and a knife on the feeder-housing entrance cut off the fuel charge in the chamber to prevent jamming. The reciprocating ram was actuated by a double-acting hydraulic cylinder that could be automated for the fuel-feed cycle. An integral hydraulic pump, installed on the engine, operated the gasifier feeder, the fuel agitator and the grate shaker.

About 16 strokes of the feeder were required to refill the gasifier when the low level fuel indicator called for refueling. Two level indicators that are commercially

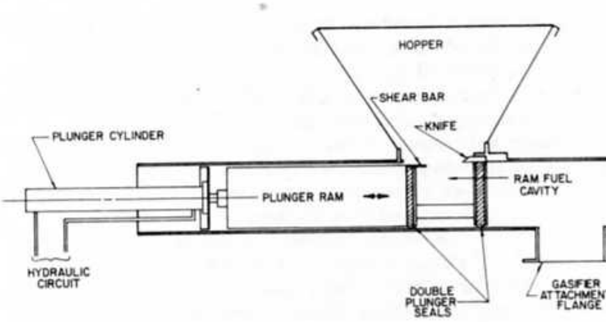

Figure 3–Reciprocating fuel feeder.

available for bulk material were used to indicate the fuel level in the gasifier; one indicated the maximum level of the fuel charge and the other indicated the need for refueling. A 12 VDC to 120 VAC converter furnished power from the engine electrical system for these fuel-level indicators.

Gas Cleaning System

The cleanup train for the producer gas consisted of a cyclone cleaner followed by a glass-fiber filter. The cyclone cleaner, fabricated from mild steel and attached directly to the gasifier, had an inlet velocity of about 13 m/s (43 ft/s) and was designed to operate at the temperature of the exit gas of 288-315° C (550-600° F). The final cleaning of the gas was accomplished by Endustra Model 3809110135 glass-cartridge filters rated at 7.9 m^3/min (280 ft^3/min) per element. A mild steel housing was fabricated to hold two of these elements in a parallel arrangement. The rating of these filter elements on gas, specified by the manufacturer, was an efficiency of 98% on particles of 3 µm (3 microns) and larger; the maximum temperature rating for the media was 370° C (700° F). Later these cartridge filters were replaced with a baghouse filter because they required frequent cleaning and maintenance.

Engine Adaptation

In Sweden and in the United States, various methods of utilizing producer gas in compression ignition engines have been used (Johansson, 1981a; Williams et al., 1978) these have included converting the engines to Otto cycle by adding spark ignition and lowering the compression ratio as well as dual-fueling them with producer gas and a pilot amount of fuel oil. For this research, the engine was dual-fueled.

To use producer gas in the compression ignition engine for this study, three minor changes to the engine were made: a producer gas carburetor was added, the output of the injection pump was restricted, and a centrifugal governor was installed. Because no other engine modifications were needed, this engine could be easily switched from operating in a dual-fuel mode with producer gas and diesel fuel to operating on only diesel fuel when desired. The fuel pump timing was not changed from the original factory setting.

A producer gas carburetor, connected to the inlet of the intake manifold of the engine, was designed to mix approximately equal volumes of gas and air (fig. 4). The unit consisted of welded pipe fittings that formed an expanded section in the gas piping where the air could be introduced into the gas stream. The air, drawn in through an air filter, was regulated with a manually controlled valve. With constant speed and constant load operation of the engine, the manual adjustment of the air-fuel mixture was satisfactory, but the automatic system developed by Shaw (1988) would have eliminated this task for the operator. A similar method of introducing producer gas into diesel engines was used by the Swedish National Machinery Testing Institute (Johansson, 1981b). On the outlet port of the carburetor, a throttle butterfly valve was connected to the centrifugal governor with an adjustable linkage.

The injection pump output was regulated by installing a vernier control on the fuel shut-off control. The amount of pilot fuel was adjusted to that amount required to operate the engine with no load on diesel at 1000 r/min. This adjustment was made after the engine was warmed up and before producer gas was introduced to the engine.

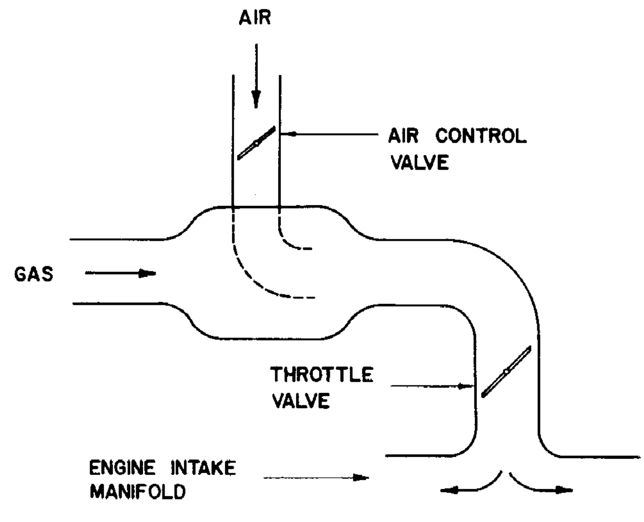

Figure 4–Producer gas carburetor for diesel engine.

When the output of the injection pump was restricted, the built-in governor deactivated; thus another engine governor had to be substituted. A centrifugal governor, installed on the engine and driven by a V-belt from the front of the crankshaft, was connected to the throttle valve on the producer gas carburetor to control the engine speed.

Fuel

The fuel used during the engine tests – citrus wood – is specified in Table 1. This wood from dead or diseased trees and trimmings from producing trees was processed though a flywheel wood chipper (Churchill, 1986). The chips were cut approximately 45° with the grain, and the theoretical length was 1.58 cm (0.625 in.). To remove overly large pieces, the chips were screened though a 5 cm (2 in.) square mesh screen. For drying, the chips were stored for several months in mesh baskets in an open building; they dried to a 14% (w.b.) or lower moisture level without significant mold.

System Operation

During the tests on gasifying citrus wood, the downdraft gasifier, operating under average conditions, produced good quality gas in 5-10 min from the initial lighting of the fuel in the hearth.

After the fuel in the hearth was ignited with a small blow torch, i.e., a small blower connected to the air inlet ventilated the gasifier. The first gas produced was mostly white smoke that was vented through a branch in the hot gas outlet. After two or three minutes, the vented gas was ignited; and in a similar interval, it burned with a very clear flame. When this stage was reached, the gas was ready for use in the engine.

For dual fueling the compression-ignition engine with producer gas and fuel oil, the engine was started and warmed up on diesel fuel before the producer gas was introduced. With this particular system, the vernier adjustment on the fuel injection pump shutoff was set to

TABLE 1. Fuel specifications

	Sample A	Sample B
Wood		
Species	*citrus sinesis* (L. Osbeck)	*citrus sinesis* (L. Osbeck)
Moisture (%, w.b.)	6.83	21.45
Length of cut	1.58 cm (0.625 in.)@ 45° to grain	1.58 cm (0.625 in.)@ 45° to grain
Chip density		
kg/m^3 (lb/ft^3)	240.3 (15.0)	331.61 (20.7)
High heat value,		
MJ/kg (BTU/lb, w.b.)	18.3 (7867)	18.3 (7867)
Sulfur (%)	0.03	0.04
Volatile Matter (%)	85.36	83.77
Ash (%)	0.59	1.81
Fixed carbon (%)	14.05	14.42

Analysis performed by Thornton Laboratories, Inc., Tampa, FL

Producer Gas Components	Dry Gas Analysis (% Volume)	Higher Heating Value (Goss, 1986) (MJ/n_s†)	(BTU/ft^3)
H_2	16.8	1.96	49.3
CO	21.7	2.51	63.0
CxHy*	2.2	0.80	20.1
CO_2	10.8	---	
O_2	0.6	---	
N_2	47.3		
	99.4	5.27	132.4

* Mostly CH_4

† N_s = cubic meter @ 1 atm, 25° C

Diesel Fuel (No. 2)
Higher Heating Value (Obert, 1973):
35 600 kJ / L (127,700 BTU/gal)

give a pilot fuel injection rate sufficient for the engine to idle at 1000 r/min with no load.

Once the idle speed was set, a valve was opened, introducing the producer gas to the carburetor while a valve on the vent pipe was simultaneously closed. At this time, the valve on the air inlet of the carburetor had to be fine turned for smooth engine operation. Fine tuning the air-fuel mixture took a minimum amount of time when the engine was running under a steady load, though the operator was generally occupied with refueling the gasifier or agitating the grate to maintain steady gas production. The engine speed during operation was regulated by the governor controlled throttle valve.

Refueling the gasifier was possible with the gasifier in full operation because the small amount of air introduced with the fuel had no noticeable effect on the producer gas quality.

Shutting the gasifier and engine system down was quite simple. When the gas supply to the engine was closed off, the engine returned to full diesel operation. The gasifier could be quickly closed down by closing the air inlet, thus extinguishing the fire.

Experimental Procedure

The engine power measurements were made by using a calibrated waterbrake dynamometer, installed on the flywheel housing of the engine. This data was recorded manually. Producer gas samples were taken during the dynamometer tests and were analyzed on a gas chromatograph, while the diesel fuel consumption was determined by timing the volume used from a graduated cylinder. During each refueling, the wood fuel was weighed before it was conveyed to the feeder. Manometers and thermometers, installed in the gas cleanup train, indicated the pressure drops across the gasifier and filter assembly plus the gas temperatures at the gasifier and filter outlet.

Results and Discussion

Engine Performance

To establish a performance base line, the engine was first tested with diesel; the maximum power and torque curves are shown in figures 5 and 6, respectively. The power output was less than rated by the engine manufacturer because this power unit was equipped with an alternator, hydraulic pump, and cooling fan.

The engine was next operated in the dual-fuel mode between 1300 and 2100 r/min; the maximum power and torque curves are also shown in figures 5 and 6. The engine was operated only within this speed range on the dual fuels because smooth operation could not be maintained below 1300 r/min and because the centrifugal governor was set to limit the speed at 2100 r/min to avoid overspeeding the engine. For continuous operation, the manufacturer recommends a maximum speed of about 2250 r/min. At 2000 r/min the power output in the dual-fuel mode was 78% of the power on full diesel operation. At this speed, the pilot fuel consumption was 70 to 75 mL/min (1.1 to 1.2 gal/h) or 28 to 31% of the fuel consumption on full diesel. Maximum torque was developed at the lowest engine speed in the dual-fuel mode, and the comparison peak torque occurred at a lower engine speed when the engine was operating on dual fuels than when operating on full diesel. Previous research with duel fueling a compression ignition engine had also shown that peak torque occurred at a lower speed for dual fuels than for fuel oil alone (Shaw, 1988). This shift in the peak torque may be due to the slower combustion of producer gas as compared to that of diesel.

After the tests at varied speed in the dual-fuel mode, the engine was operated as close to a constant 2000 r/min as possible to measure the fuel consumption at the speed selected for pumping water. A summary of this 4.5 h constant speed test is given in Table 2. The average power output, 45.1 kW (60.5 hp), was nearly the same as the 46.4 kW (62.2 hp) output at the same speed in the variable speed test. The average power derived from the fuel oil, 11.3 kW (15.2 hp), was determined by assuming that the BSVFC (Brake Specific Volumetric Fuel Consumption) of

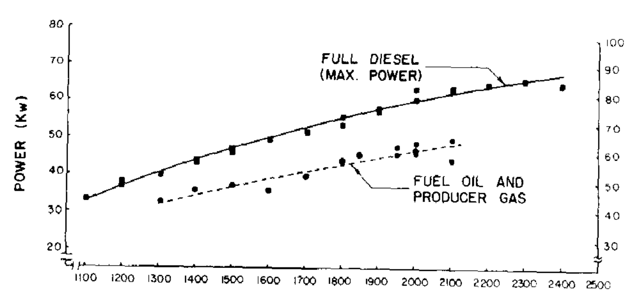

Figure 5–Compression ignition engine power.

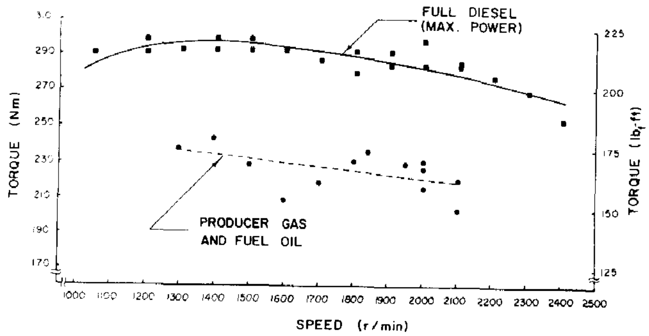

Figure 6–Compression ignition engine torque.

the engine during the dual-fuel mode was the same as that during full diesel operation.

The power derived from the producer gas was the difference between the total power and that produced from the pilot fuel. It was rather difficult to duplicate the fuel output of the rotary injection pump for each test. In this constant speed test the pilot fuel made up nearly 25% of the total fuel to the engine, whereas in the variable test it had made up 28 to 31%, and the 67 to 70 mL/min (1.0 to 1.1 gal/h), pilot fuel consumption was less than that consumed in the variable speed test at 2000 r/min. Later when the engine was driving the pump, a pilot fuel rate of 41 to 51 mL/min (0.6 to 0.8 gal/h), gave good performance, but the engine was not loaded quite as much as during the constant speed dynamometer test.

Table 2 shows that the specific fuel consumption of wood during the constant speed test was 0.95 kg/kWh (1.56 lbs/hp-h). This was a more efficient use of the wood fuel than was reported by Johansson (1981b) for spark-ignition engines under full load, but not as efficient as the estimated 0.67 kg/ kWh (1.1 lbs/hp-h), that he reported for a 3.5 L (214 in^3) diesel tractor engine. The overall thermal efficiency, enthalpy efficiency as defined by Obert (1973), for the gas producer and engine system increased from about 19.5 to 23.5% during the duration of this 4.5 h test.

Long Term Performance

The gasifier and engine power unit were installed at an irrigation well in a 16 ha (40 acre) citrus grove in central Florida for long-term evaluation. The unit pumped 2800 L/min (740 gal/min) of water at 276 kPa (40 psi) pressure to supply the grove through a microjet sprinkler system. A summary of the performance of the gasifier and engine system covering nearly 100 h of operation is given in Table 3. The gasifier, fuel supply system, and engine performed satisfactorily, but the gas filter initially used required frequent service.

With new cartridge filters, the maximum service period was 16 h before cleaning was necessary; after the filters had been in use, the average service interval was 5.9 h. The filters had to be washed in a water and detergent solution and then completely dried each time they were serviced.

Various other filter arrangements were examined, and a large baghouse system was selected. An insulated baghouse assembly, holding four glass fabric bags for a total filter area of over 6m^2 (65 ft^2) was designed and fabricated. The filter bag material selected was 915 g/m^2 (27 oz/yd^2) needled fiberglass, capable of operating at temperatures to 260° C (500° F). The first service on this filter was performed after 52 hours, and all of the cleaning was done with a vacuum cleaner. It seemed that the service interval on this filter assembly, after its initial use, would be about 40 hours, and the cleaning efficiency was as good as that of the cartridge filters. No specific filter tests were made on this filter material, but the manufacturer (Huyck Felt) reported it to be 99.98% efficient in removing Arizona road dust and 99.99% efficient in filtering Detroit Edison flyash.

The average wood fuel used while the engine pumped water was 25.9 kg/h (57 lb/h) with 1.3 kg/h (2.8 lb/h) of ash and 1.1 L/h (0.3 gal/h) of condensate being produced by the gasifier.

After approximately 100 h of total running time in the dual-fuel mode, the engine developed a serious knock. Engine disassembly revealed breakage of the cylinder sleeve in number one cylinder and cracks in the sleeves of the second and fourth cylinders. The engine manufacturer supplied repair parts at no cost to rebuild the engine, including new connecting rods with bearings, valves, pistons, sleeves, and rings. In reassembling the engine, it was discovered that the timing marks on the engine front sheave were 7° early; thus, the engine had been operating with incorrect valve timing. And this was the probable cause of the engine failure. Adjustment of the timing made the engine start much easier, but a dynamometer test on full diesel did not reveal any significant charge in power output. Since being rebuilt, the engine has operated nearly 120 h in the dual-fuel mode without any further difficulty and remains in service as a standby power unit for an electric pump.

Summary

This irrigation power unit remains in operation and its performance continues to be monitored. In other liquid cooled engines used in our research, there were occasional

TABLE 2. Summary of dual fuel engine performance for 4.5 h at constant speed (200 r/min)

	Wood	Diesel	Total
Power output (avg)			
(kw)	33.8	11.3	45.1
		1.07*	2.21*
(hp)	45.3	15.2	60.5
		1.43*	2.96*
BSFC	0.95 kg/kWh	2.73 kWh/L	
	1.56 lb/hp-h	13.86 hp-h/gal	
Fuel consumption	32.2 kg/h	4.13 L/h	
	(70.9 lb/h)	(1.1 gal/h)	
Ash, char under grate			1.9 kg (4.2 lb)
Dust in cyclone			0.6 kg (1.3 lb)
Dust in filter			240.0 g (0.5 lb)

* Standard deviation

TABLE 3. Gasifier and engine performance while pumping water

	Average for 100 h
Pumping rate	2800 l/min @ 276 kPa (740 gpm @ 40 psi)
Wood consumption	25.85 kg/h (57 lb/h)
Diesel fuel consumption	3.06 L/h (0.81 gal/h)
Frequency of filter change	5.9 h +
Ash from grate	1.3 kg/h (2.8 lb/h)
Condensate	1.1 L/h (0.3 gal/h)
Ash from cyclone cleaner	0.18 kg/h (0.4 lb/h)

problems in both CI and SI engines with sticking valves caused by tar accumulation on the valve stems. But during the entire operation of this engine, the valves did not stick. No serious problems occurred that could be attributed to the fuel system.

Because this dual-fueled engine produced 78% of the full diesel power at 2000 r/min, its performance was nearly equal to the continuous-duty power rating on full diesel, which is usually 85 to 90% of maximum power. Tests with other dual-fueled compression ignition engines (Shaw, 1988) resulted in over 80% of the maximum diesel performance; thus for continuous-duty service, dual-fueled engines probably do not need to be derated. If more power is needed for short periods such as in a tractor or motor vehicle, more fuel oil can be used.

The 4.5 h constant speed test demonstrated that the power output can be held to a fairly uniform level, but this achievement requires constant attention by the operator. Producer gas fuel systems at the present stage of development are not as convenient to operate as liquid-fuel systems, but they could be made more convenient with further development of automatic mixture adjustment (Shaw, 1988) and automatic fueling systems.

It appears that the use of producer gas as a substitute fuel and the operation of a diesel engine in a dual-fuel mode are practical when fuel oil is in short supply. The operation of this unit has also demonstrated that waste wood can be air dried and utilized as a substitute for liquid engine fuel in a humid, semi-tropical climate.

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