SYNGAS USE IN INTERNAL COMBUSTION ENGINES: A PRACTICAL APPROACH

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Abstract: *Syngas is a comparatively low energy fuel gas that can be utilized in spark ignition and compression ignition (diesel) internal combustion engines manufactured to run on gasoline or diesel fuels to reduce or eliminate the petroleum fuel requirement for the engine. Syngas can be produced from any carbonaceous material including many forms of biomass. Engine power derating when operating with syngas is typically 15% - 40%, less than the difference in energy content between producer gas and petroleum fuel would indicate largely because of the disparity of stoichiometric air-fuel requirements of producer gas and gasoline or diesel fuel. A wood gasifier powered pickup truck equipped with a spark ignition engine was operated over 69 runs from 4 miles to 320 miles, data collected showed fuel chunk size was most critical to engine performance followed by fuel moisture content, absence of leaks in the hearth or reaction zone and heat reclamation, respectively*.

Key Words: *Downdraft Iimbert style gasifier, gasification, wood chips, temperature, particle size.*

1. INTRODUCTION:

Worldwide energy demand is increasing, estimated to be five times current demand by 2100 [1]. Upward energy prices and a need to curb greenhouse emissions make biomass an attractive alternative to fossil fuels [2]. Biomass is unique among alternatives to fossil fuels in that it is carbon based, carbon neutral, can be converted to fuels comparable to fossil fuels and is relatively evenly distributed across the globe [3, 1]. It can increase fuel security as it is produced locally (3). Biomass currently supplies 75% of the world's renewable energy, 13% - 14% of the world's primary energy supply and could supply 25% to 33% by 2050 [1, 4]. Currently 1.3 billion people worldwide do not have access to electricity, 84% of these are rural. Biomass gasification can provide a renewable fuel to generate electricity in these rural areas while generating local employment and helping the local economy [4]. In addition, generating fuel from biomass can reduce environmental and waste disposal issues [5]. Gasification of biomass as well as fossil based fuels has been increasing dramatically recently. A 2005 US Department of Energy survey indicated that syngas use worldwide will increase approximately 8 % per year in the near term [6]. In addition, burning syngas for energy production has a better environmental sustainability than burning fossil fuels such as diesel and coal [7].

Today thermochemical and biochemical are the two main technologies presently used for the conversion biomass into energy. Syngas production by gasification is beside combustion, pyrolysis and liquefaction, one of the four main processes of thermochemical conversion of biomass to energy [8]. The gasification process has been known since the early 1800 [9]. The main process steps involved in gasification principles are drying, heating, and partially oxidizing the carbon containing materials by converting them into a synthesis gas, also called syngas, which contains the primary fuel sources carbon monoxide and hydrogen. The produced syngas can then be transformed into electricity, heat, or liquid fuel, using engines, boilers and turbines. The syngas is produced by pyrolysis at temperatures of 400 - 700ºC that produces water vapor, CO_2, combustible gases CO, H_2, CH_4 and a mixture of organic vapors from the biopolymers cellulose hemicelluloses and lignin [10]. The syngas has a reported heating value of approximate 4-18 MJ/m^3 [11], (3791 to 17060 btu/m^3) depending on the process set up. The syngas can be used to power, for example, a microturbine or a gas or diesel engine. In addition, syngas may be fermented or converted biologically by anaerobic micro-organisms into acetic, propionic, butyric, formic, and lactic acids as well as into methanol, ethanol, propanol, and butanol [12]. Syngas use in Internal combustion engines (ICEs) such as diesel and spark ignition engines is feasible [13]. Syngas produced with gasification most times contains unwanted impurities such as sand, tar, ash and char. Therefore, syngas is only suited for turbines if the produced syngas is extensively cleaned. ICEs do not require an extensive clean up processing equipment [13, 14, 15, 16]. ICEs typically use air as the oxidizing agent which results in a heating value of the syngas between 4 to 7 MJ/ [17]. However, tar contained in syngas can be considered a major problem for ICE engines, because it can plug pores in filters and cause deposits on engine components such as valves as the syngas comes in contact with if not cleaned up [18]. A good way to avoid tar problems is to produce syngas at high combustion temperature and use fuel with a low moisture content [19, 20].

The gasifier selected for this project is an Imbert style downdraft gasifier as shown in Fig. 1. The gasifier was built from carbon steel. The top cylindrical section of the gasifier contains the drying and conversion zone. The lower section contains a conical area were the combustion occurs, followed by a restricted conical area that contains the air intake. The gasification zone is located below the air intake. A grate located below the gasification zone holds the biomass char back till the biomass is fully gasified. The produced syngas exits below the grate to the cooling system. After the syngas is cooled it passes through a hay filter before entering the engine intake manifold of the 1969 GMC pick-up truck Engine Fig 2.

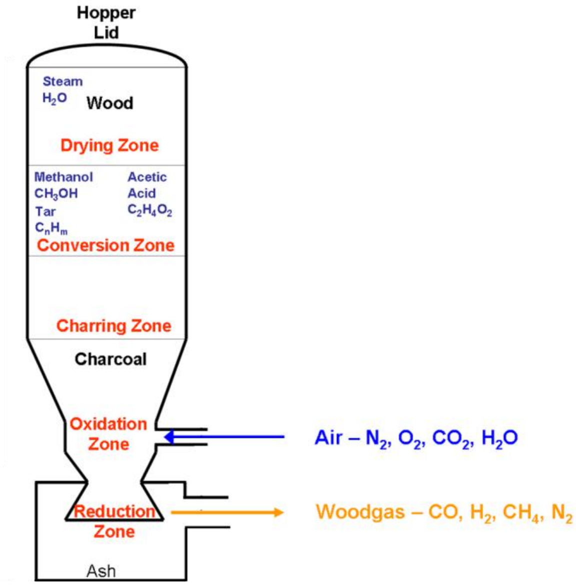

Fig. 1: Imbert Style Gasifie [21]

2. METHODOLOGY:

The methodology section describes the equipment, procedures and materials used to produce syngas and its application in spark ignition engines.

2.1 Gasifier and Engine

A home built downdraft gasifier was used. The gasifier was built from recycled materials for less than $100 and installed in the bed of a F150 1969 GMC pick-up truck Fig. 2, with a carbureted gasoline SI 250 cubic inch (4.1 liter)

Figure 2. 1969 GMC Truck Powered by a Downdraft Gasifier [22]

straight six-cylinder engine. The gasifier was operated with different wood materials specified in section 2.2. The engine vacuum generated by the truck engine moved air and syngas through the gasifier and into the engine through the carburetor. The carburetor throttle controlled the amount of syngas-air mixture into the engine by modulating the engine vacuum available to the gasifier. Gasifier nozzle dimensions and throat diameter controlled the air equivalence ratio and hence gasifier combustion temperature and syngas quality and quantity. The gasifier was a monorater design with hopper water collection just below the lid. After the syngas left the gasifier it passed through a cyclone filter, hay filter and the engine air cleaner before entering the engine. Air vacuum was monitored just past the cyclone (gasifier vacuum) and just before entering the engine air cleaner (engine vacuum). Gasifier temperatures were measured just after the gasifier but before the cyclone and sometimes at the gasifier grate.

2.2 Material

As feedstock for the gasifier hardwood was used. The hardwood was cut into wood chunks Fig. 3. Generally, sections of branches 25 mm to 75 mm (1" – 3") in diameter were cut in 25 mm to 75 mm (1" – 3") long sections. The hardwood generally was American beech, sugar maple, white ash, ironwood, black cherry or elm and was used for runs 1 – 21, 23 – 25, 27- 31 and 51 – 69. All hardwood material used was kept at a maximum of 15% moisture content (dry basis) unless otherwise noted in Table 1. Moisture content was measured using a drying oven set at a temperature of 105°C ± 2°C with free access to air. The samples were dried using a dry Kiln at the College of Environmental Science and Forestry (ESF) at Syracuse.

Figure 2. Wood Chunks used to power the Downdraft Gasifier [23]

For run 22 hardwood pellets approximately 1/4" in diameter 3/4" long with a moisture content up to 10% were used. Compressed wood cylinders 3" in diameter 1.5" long were used for run 26. Runs 32 – 36 were done using variably sized sugar maple chunks including up to 50% shredded stringy pieces approximately 1" x 3/8" x up to 6" long. Runs 37 – 51 were done using white ash chips approximately 1-1/4" wide, 1" long and 1/4" thick.

3. TESTING OF SPARK IGNTION SYNGAS ENGINES:

3.1 Syngas Engine Operation

The modified GMC truck, shown in Fig. 2 typically was started on gasoline and switched over to syngas after getting up to speed. Engine power on syngas was noticeably reduced but the engine ran quieter and had the ability to operate under load at very low rpms. My truck gasifier operating experience has shown that wood fuel block size was most important in determining syngas quantity and quality, too small and air would not penetrate the wood charge adequately and the syngas, although produced in adequate quantity, became tar laden, too large and there was not enough fuel surface area to produce an adequate quantity of syngas. Wood chunk moisture content was the next most influential fuel factor, if the wood was too wet, gasification temperatures became too low for good syngas production and quality. Recycling of gasifier heat through insulating and warming the gasifier incoming air increased the gasifier turndown ratio, the ability of the gasifier to provide adequate syngas for partial throttle operation, and enabled the gasifier to utilize wetter wood than without insulation or warming the incoming air. Below Table 1 shows various gasifier, truck and atmospheric conditions for 69 runs over a period of almost 4 years with the truck operating on syngas (woodgas).

Table 1. Truck Trials on Syngas Parameters

Run #	Ease of Switching to Syngas Operation	Engine Vacuum ("water column")	Gasifer Vacuum ("water column"))	Gasifer Outlet Temperature (°F)	Length of Run (miles)	Truck cruising speed (mph)	Comments
1	Difficult	13	10	425	8	60	48°F dry, bridging in hopper. Oily tar in air cleaner.
2	Difficult	13	11	400 estimated	12	65	Oily tar in air cleaner. Once switched over ran great
3	Easy	10	8	450	8	65	Started on bigger blower. Stalled when turning around. 40°F and sunny
4	Difficult	8	5	450 – 500	8	60 - 65	Once on syngas, ran very well, even slow speed in driveway. 60°F sunny weather
5	Difficult	10	7	700	8	60	Ran well once on syngas, made it up steep hill twice. 45°F cloudy
6	Difficult	n/a	n/a	650	40	60	Ran well once on syngas, stalled at stops. Gas radiator drain open but little difference noted. 40°F drizzly
7	Didn't happen	n/a	n/a	580		60	Would not run on syngas leak in hearth suspected.
8	Easy	n/a	n/a	450	8	60	Installed new grate and industrial startup blower. Ran smoothly once on syngas
9	OK	10	5	450	8	60	Ran well, climbed steep hill on syngas, good turndown ratio
10	Easy	7	5	600 – 640	8	60	Ran well, new piping, gasifier heated to 390°F on blower before driving. Good turndown 70°F
11	Easy	n/a	n/a	n/a	8	60	Insulated gasifier bottom. Forgot to change valves from startup but still ran well except for turnarounds. 55°F
12	Difficult	10	5	400 – 450	12	60	Did not run well on syngas except for idle. Maybe wood was wet.
13	Didn't happen	5	3	n/a	8	60	Wouldn't run on syngas, maybe a big leak, maybe char bad
14	OK	10	7	550	8	60	Fixed leak, ran well on syngas one leg but wouldn't run on syngas on second.
15	Difficult	10	7	780	8	60	New brake rotor hearth, great power on syngas, bad turndown, however. 1080°F combustion temp.
16	OK	n/a	n/a	950	8	60	Sealed leaks, great power, combustion temp 1275°F outside 40°F.
17	Easy	n/a	n/a	750 – 850	8	60	Poor turndown but good power. Violent shaking of wheels. Added secondary air control
18	Easy	n/a	n/a	850 -950	8	60	Added syngas shutoff – had little effect. Good power. Combustion temp 1450 -1550°F. Good turndown. Timing rod has a sweet spot

19	Easy	n/a	n/a	850	8	60	Good run. Good turndown. Good low speed performance.
20	Easy	n/a	n/a	800 – 1200	40	60	Great run. Great turndown. Combustion temp. 1000 – 2000°F
21	Easy – OK	10 -15	7 – 12	n/a	320	60 – 70	Generally good performance. Had to remove ashes once. Battery died halfway.
22	Easy	25	20	650	16	60	Run was done on hardwood pellets. Good all-round performance BUT lots of tar, stuck all intake valves
23	Difficult	+5	2	n/a	8	60	Poor power on gasoline and wood. Suspect valves not in adjustment. Combustion temp 1250°F
24	Easy	n/a	n/a	n/a	16	60	Engine repaired, front vacuum line disconnected, low power. Combustion 1800°F
25	Easy	15	8	1250	29	75	1st tried plugging 8 out of 17 nozzles, low power, restored
26	Easy	n/a	n/a	n/a	15	60	Tried to run on 1.5” long 3” dia. Pressed wood log. After old char exhausted, would not run.
Run #	**Ease of Switching to Syngas Operation**	**Engine Vacuum (“ water column”)**	**Gasifer Vacuum (“water column”))**	**Gasifer Outlet Temperature (°F)**	**Length of Run (miles)**	**Truck cruising speed (mph)**	**Comments**
27	Easy	n/a	n/a	n/a	40	45 max.	Wood char and chunks restored. Did not run well on wood, maybe char bed needs to be re-established
28	Easy	n/a	n/a	n/a	16	65	8 new copper nozzles installed, new char. Ran well but sluggish after turnaround. Did not make steep hill.
29	Easy	n/a	n/a	1150	16	55	Added exhaust stove to dry out air filter. Still sluggish, may be due to large chunks of wood
30	Easy	30	25	800	8	70+ max.	At first great performance, 65 mph uphill but stalled on turnaround, then would not run on syngas.
31	Easy	n/a	n/a	800	4	60	Dissected fire, nothing seen. Ran again, great performance, a few muffled pops on deceleration, air leak?
32	Easy	22	15	700	26	70+	Used shredded maple fuel, bridging noted. Added lime, no definite effect.
33	Difficult	n/a	n/a	250	8	60	No power, much popping in back, surging.
34	OK	n/a	n/a	550	12	60	New hopper gasket. Surging, popping, low power.
35	OK	n/a	n/a	800 – 1350	13	60	Balky on gasoline, low power on syngas.
36	n/a	n/a	n/a	750 – 1200	12	n/a	Shredded maple fuel, only ran 1 minute at a time on wood .
37	OK	n/a	n/a	640	13	65+	Ash chips 6% MC. Ran great at first, stalled at turnaround, not so great after.
38	OK	15	10	n/a	20	50	Ash chips. Came up to temp slowly. Ran well for 1 mile initially, stalled, not so great after. Ran out of fuel.

39	Easy	+5	n/a	680	9	55	Ash chips. Resealed hearth. Ran great but roughly. Possible stuck valve, filter somewhat tarry.
40	Difficult	30+	30+	415	8		Chips. Only a few sputters on wood, probably plugged.
41	Easy	n/a	n/a	455	4	65	Chips. Ran great initially, stalled on turnaround, vacuum gauges pegged, probably grate plugged again.
42	No	10	2	680 -1800	18	50	Chips. Restricted grate area, resealed hearth. Would not run on wood. Plugged hay filter?
43	No	10	2	680 – 1800	12	n/a	Chips. Changed hay in filter, still would not run on wood.
44	Easy	7 – 10	5 -7	800	12	70	Chips. Plugged vents in bottom rotor with furnace cement. Ran great, climbed hills, good turndown. Ran out of fuel on return.
45	Difficult	20 – 25	17 – 22	800 – 850	60	70	Chips. Not enough char to start with, mixed with chips. Balky in city traffic, carb gummed up on return, had to clean and finish return on gasoline.
46	Easy	10 out, 15 return	8 out, 12 return	900	12	60	Chips. New char bed, ran well. Broke trailing arm on truck on return.
47	Easy	30+	27	850 – 890	12	60	Raised grate 1.5”, ran well but had to keep engine revved to prevent stalling. Good power, made it up steep hill. Started on wood gas.
48	Easy	30+	30+	850	17	60	Ran well, good power but no idle on wood. Cooled down, did not restart return.
49	Difficult	30+	30+	850 – 900	40	60 - 70	Chips. Finally switched to wood after 8 miles on gasoline, then ran well, made steep hill but would not then run on gasoline. Carb dirty.
50	Easy	30+	30+	570	40	60	Chips. Stalled 5 miles into trip, would only run on wood intermittently afterwards. Probably plugged.
51	No	30+	30+	433	8	60	Chips, last run's material. Would only sputter on wood. Definitely plugged.
52	Difficult	15	10	1100	12	45	Chunks. Char bed replaced with charcoal, minimal power.
53	Easy	20	20	1300	22	65 – 75	Chunks. Added insulated sheet metal enclosure to bottom of gasifier and cyclone area, incoming air now hot. Ran great, made all stops and hills.
54	Easy	15-20	15-20	1250 max	22	65 -75	Chunks at 15% MC. Flawless run. Silicone inside enclosure burned.
55	Easy	10 – 15	10 – 15	1280 max	22	50	Undried dead wood. Great performance, made steep hill.
Run #	**Ease of Switching to Syngas Operation**	**Engine Vacuum (“ water column”)**	**Gasifer Vacuum (“water column”))**	**Gasifer Outlet Temperature (°F)**	**Length of Run (miles)**	**Truck cruising speed (mph)**	**Comments**
56	Easy	10 – 15	10-15	1175 max	40	60	Chunks ran well on wood but engine skipping. Did all but the steepest hills. Ran well in traffic.

57	No	10 – 20	10-20	1430	34	60	Chunks. Would not run on wood. Probably hearth air leak.
58	Easy	10-15	10-15	1150 max	14	60	Chunks recemented hearth, relocated blower to front, started easily. Good performance.
59	Easy	10-15	10-15	1100 max	12	55	Chunks. Good performance, good idle, made steep hill.
60	Easy	10-15	10-15	1170 max	12	55	Chunks. Mediocre performance, wood 25% MC.
61	Easy	10-15	10-15	1145 max	13	50	Chunks. Welded hearth, resealed. Ran great, lots of power, made steep hill easily.
61	Easy	10-15	10-15	1145 max	13	50	Chunks. Welded hearth, resealed. Ran great, lots of power, made steep hill easily.
62	Easy	5-10	5-10	1115 max	12	50	Chunks. Ran well, made steep hill easily.
63	Easy	10-15	10-15	1100 – 2000	60	60	Chunks. Wetter wood. Pretty good performance, balky at times. Sometimes good power on hills.
64	Easy	7-12	7-12	1100, erratic	40	60	Chunks, wetter wood again, sometimes balky, sometimes good power on hills, in city.
65	Easy	n/a	n/a	n/a	8	50	Chunks from previous season, balky, little power, idled well.
66	Easy	10-15	10-15	1450	40	50-65	Chunks, pretty good power, went up all hills on wood, poor idle.
67	Difficult	10-15	10-15	1350 max	40	50	Chunks, balky, not much power, ran well in traffic, idled well.
68	OK	10	10	1400	45	50-55	Chunks, recemented hearth, balky until warmed up. Ran OK in traffic, idled, made all hills.
69	OK	5-7	5-7	1280	45	50	Chunks, balky, not much power, hearth probably leaking again. Return half on gasoline.

4. DISCUSSION OF RESULTS:

As mentioned previously, truck performance was degraded when the truck was running on syngas. Generally, the truck was operated with a wide open throttle (WOT) on the open road. Truck cruising speed was usually maximum speed at 65 mph, at least on level or uphill grades. Truck performance during the runs described in Table 2 was highly variable in part due to differences in fuel chunk size and shape. Runs 1 – 21, 23 – 25, 27- 31 and 51 – 69 were done using hardwood chunks, generally sections of branches 1" – 3" in diameter 1" – 3" long. The hardwood generally was American beech, sugar maple, white ash, ironwood, black cherry or American elm. Run 22 was done using hardwood pellets approximately 1/4" in diameter 3/4" long. Run 26 was done using compressed wood cylinders 3" in diameter 1.5" long. Runs 32 – 36 were done using variably sized sugar maple chunks including up to 50% shredded stringy pieces approximately 1" x 3/8" x up to 6" long. Runs 37 – 51 were done using white ash chips approximately 1-1/4" wide, 1" long and 1/4" thick. All fuel used was at 15% or less moisture content (dry basis) unless otherwise noted.
Overall performance was generally best and more consistent on chunks averaging 1.5" on diameter, 1.5" long. Runs 28 and 29 were fueled with chunks that were larger and the truck's power was less once the larger chunks worked into the char bed, consistent with the rationale of larger chunks having less surface area and hence generated less woodgas. Run 22 was fueled with pellets which had a large total surface area and hence generated an adequate amount of woodgas but because the smaller sized pellets fit closely together they blocked penetration of the combustion air into the oxidation zone and allowed production of much tar which passed through the hay filter and air cleaner into the engine, sticking the intake valves and necessitating a teardown and cleaning of the engine. Runs 37 – 51 were fueled with white ash chips which were bigger than the pellets but smaller than the optimal chunks. Performance sometimes was good but in general was more erratic and the more tightly packed chips tended to plug the hearth as evidenced by the high gasifier vacuum readings. The plugged hearth restricted generation and movement of the woodgas through the gasifier.

Leaks that developed in the gasifier, especially those in the hearth area, degraded the quantity and quality of the woodgas and the truck's performance. The hearth area was sealed with fire cement which could withstand the high hearth temperatures but was brittle and tended to flake off over time leading to very debilitating leaks. Leaks in other parts of the gasifier system did not degrade performance as much as those in the hearth. Oxygen entering the hot hearth area immediately reacted with the carbon monoxide forming carbon dioxide and hydrogen forming water hence reducing the chemical energy of the woodgas. Poor truck performance in runs with no irregularities noted in the fuel was probably due to leaks degrading the woodgas.

Fuel moisture content was another big factor in truck performance. If the fuel was too moist, combustion energy necessary to generate high quality woodgas instead was used to boil off excess moisture. When more gasifier heat reclamation was used, more heat was available to boil off fuel moisture while still generating adequate quantities of high quality woodgas. Wood used in runs 1 – 53 generally was below 15 % MC (dry basis), runs 20 and 21 were done with fuel at 5 – 10 % MC (dry basis). The gasifier hearth, air inlet and cyclone filter areas were enclosed with insulated sheet metal before run 53 resulting in better heat reclamation and higher combustion temperatures because of 200F – 300F incoming combustion air temperatures. The higher combustion zone temperatures allowed the use of wetter wood and allowed higher turndown ratios. Runs 55, 60, 63 – 65 were done with wood at 25% or wetter MC (dry basis). Performance was good on run 55 but somewhat degraded on the other runs with wet wood.

Fuel wood species did not directly impact truck performance. Wood with a lower density would produce woodgas at the same rate as higher density wood as long as chunk size and moisture content was equal. A charge of lower density wood fuel would not power the truck for as long a distance as a charge of higher density wood, however. In other words, a pound of low density wood will produce the same amount of woodgas as a pound of high density wood all other factors being equal but will take up more volume in the gasifier. Some of the truck runs included chunks of lower density wood such as basswood or hemlock with no noticeable effect on truck performance.

Changes in gasifier hearth design such as changing the number of nozzles from 17 to 8, air nozzle length, or changing the height of the restriction from the bottom of the grate from 6 inches to 4 inches likewise did not change truck performance noticeably as long as no air leaks were introduced. As mentioned before, adding heat reclamation features dramatically improved the turndown ratio allowed by the gasifier and made the gasifier more able to utilize wetter wood.

5. CONCLUSIONS:

The syngas operated truck performance was degraded when the truck was running on syngas compared to truck performance when fueled with gasoline. Generally, the truck was operated with a wide-open throttle (WOT) on the open road where on a level road a cruising speed of 65 mph could be achieved. Truck performance during the different runs was highly variable and dependent on the biomass fuel used. Overall performance was generally best and more consistent when biomass in form of wood chunks averaging 1.5" on diameter, 1.5" long were used.

Pellets generated an adequate amount of woodgas, but because the smaller sized pellets fit closely together they blocked penetration of the combustion air into the oxidation zone and allowed production of much tar. Leaks can cause a degradation of performance especially in the hearth area of the gasifier. However, leaks in other parts of the gasifier system did not degrade performance as much as those in the hearth.

Performance sometimes was good but in general was more erratic. More tightly packed chips tended to plug the hearth as evidenced by the high gasifier vacuum readings. The plugged hearth restricted generation and movement of the woodgas through the gasifier.

Fuel moisture content was another big factor in truck performance. If the fuel was too moist, combustion energy necessary to generate high quality woodgas instead was used to boil off excess moisture. When more gasifier heat reclamation was used more heat was available to boil off fuel moisture while still generating adequate quantities of high quality syngas as well as allowing a higher turndown ratio.

Higher combustion zone temperatures allowed the use of wetter wood and allowed higher turndown ratios.

Fuel wood species did not directly impact truck performance. Wood with a lower density would produce woodgas at the same rate as higher density wood, as long as chunk size and moisture content was equal.

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21. Photo by K. Dölle, 1969 GMC Truck powered by a downdraft gasifier, jpg-file.
22. Photo by K. Dölle, wood chunks fuel for gasifier, jpg-file.