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Syngas Use in Internal Combustion Engines - A Review

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Authors' contributions

This work was carried out in collaboration between both authors. Author RPB wrote the first draft of the manuscript. Author KD wrote the final draft and approved the final manuscript. Both authors read and approved the final manuscript.

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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.

Keywords: Syngas; internal combustion engine; diesel; spark ignition; gasifier.

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1. INTRODUCTION

Independence from fossil sources of energy is of great interest to many nations. The increasing costs of energy and material resources are directing industrial, commercial, farm-based and municipal enterprises to develop more sustainable modes of operation.

The most significant challenge facing our world in the future pertains to energy. Fossil fuels, the primary sources of energy on earth, are finite [1]. The development and conversion of sustainably produced biomass as a feedstock for bio refineries, biofuels, bio products and bioenergy is of critical priority due to concerns in achieving energy security, environmental and human health, rural economic development, and the need to diversify products and markets for the forest and agricultural industries. Many studies suggest that the costs of fossil fuel exploration and extraction will continue to rise, perhaps to unprecedented levels [1-4]. Finding ways to utilize appropriate technologies for alternative energy systems will be among the solutions that will remediate the impacts of fossil fuel utilization [5].

In both the United States and the developing world there is an increasing need for low-tech, low-cost solutions to our energy, resource, and waste management challenges.

Today, the U.S. forest industry produces approximately 67 million dry tons of Forest Residual Biomass (FRB) from harvesting and converting wood into consumer products, which equals approximately 3.4 million Barrels of Oil Equivalent (BOE). Currently FRB is partially used to produce mulch or is left unused in the forest by the harvesting operations and cannot be utilized for biofuel and /or value added product production [6,7].

The present cost of forest biomass ranges from \$12 to \$24 per barrel of oil equivalent [8]. High capital costs for the pretreatment and conversion processes used for the biochemical route typically raise production costs for biofuels to \$60–\$120 per BOE. Therefore, only high fuel prices, above \$50-\$75 per oil barrel (bbl), justify the higher production cost of bioenergy from biomass [9].

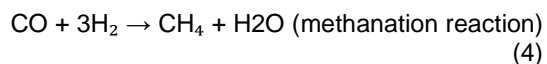
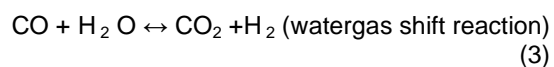
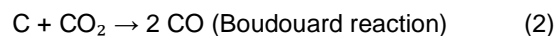
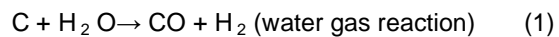
The present review focuses on the utilization of syngas product from wood that can enhance such activities and avoid the high investment costs that are typically associated with large

systems and provide site specific solutions for the entity. Gasification can effectively use FRB and other FB byproducts currently little utilized to reduce dependence on fossil fuel without requiring more forest to be cut for fuel.

2. TECHNOLOGY REVIEW FOR SYNGAS UTILIZATION

The two main technologies presently used to convert biomass into energy are thermochemical and biochemical. The production of syngas is one of the four main processes of thermochemical conversion of biomass to energy, the others being combustion, pyrolysis and liquefaction [10]. Brusca et al. [11] propose using gasification to generate energy from glycerol, a major byproduct of the production of biodiesel, a biochemical process. The glycerol first undergoes steam reformation and then is gasified in this thermo-chemical process.

Syngas, or synthesis gas, is the end-product of heating carbonaceous material with a limited amount of a gasifying agent, typically oxygen, air or steam in a process called gasification. It is a thermochemical process that increases the hydrogen to carbon content of the feedstock [12]. Most of the fuel energy in syngas is derived from its CO and H₂ content. Syngas also usually contains lesser amounts of CO₂, CH₄, and approximately 50% N₂ if air is the gasifying agent. Syngas heating values range from 10–28 MJ/Nm³ if oxygen or steam is the gasifying agent, 4 to 7 MJ/Nm³ if air is the gasifying agent [12]. Other names for syngas depending on the feedstock, gasifying agent or time and place of production include producer gas, wood gas, town gas, water gas and blast furnace gas. Gasification has four stages; drying, pyrolysis, oxidation and reduction [13]. Heat generated in the oxidation stage drives the other three stages, it dries the fuel out in the drying stage, drives out the combustible gases from the fuel in the pyrolysis stage and produces syngas in the reduction stage. Syngas is mainly formed by the following chemical reactions 1 to 4 shown below:



Temperature and residence time of the reactants determine the fractions of the products. Temperature and residence time are affected by the amount of gasifying agent introduced and gasifier design. By breaking down all the biomass to mostly simple gases gasification avoids complex treatments and conditions typical of fuels derived from pyrolysis, liquefaction and biochemical processes. However, syngas often contains contaminants such as ash, sand, char and tar. Internal Combustion Engines (ICEs) are more tolerant of contaminants than turbines and hence are well suited for use with syngas, particularly for smaller systems where equipment cost is a major concern as they do not require an extensive clean up train [12,14,15]. Tar is a major problem as a contaminant in syngas used in any engine as it tends to stick and plug pores in filters and engine components it comes in contact with [16]. In small engines using a downdraft gasifier using appropriately sized fuel with a low moisture content and operating it at an appropriately high combustion temperature is a good way to avoid tar problems [13,17]. The Imbert gasifier is a downdraft gasifier that incorporates a restriction below the air intake in the combustion zone and above the reaction or gasification zone. Imbert gasifiers were used extensively during petroleum fuel shortages in World War II (WWII) to power motor vehicles. Downdraft gasifiers including

Imbert and variations on the Imbert designs are currently used to successfully power ICEs today and are the only gasifiers considered in this paper. Fig. 1. is a diagram of an Imbert gasifier. Fig. 2. shows a block diagram for producing syngas and utilizing it in an ICE. Most of the energy in syngas usable in an ICE is provided by its hydrogen and carbon monoxide content.

Syngas composition varies widely due to biomass type and gasifier conditions. Typical composition of syngas produced by a gasifier using air as the oxidizer is by volume 18–20% H₂, 18–20% CO, 2% CH₄, 11–13% CO₂, traces of H₂O and balance N₂ [19]. The lower heating Value (LHV) of carbon monoxide is 10 MJ/kg, the LHV of hydrogen is 120 MJ/kg [20]. Thus, any process that generates syngas aims at maximizing the amount of carbon monoxide and hydrogen expressed in % by volume and the molar ratio of hydrogen to carbon monoxide in order to achieve a gas with as high as possible energy content. Typical LHV values of syngas produced in a gasifier using air or air/steam as the oxidizing agent are 4-6 MJ/kg [21,22,19,12]. Typical LHV values for gasoline and diesel fuel are 31.9 MJ/kg [23] and 43 MJ/kg, respectively [24]. Table 1 shows some properties of syngas versus other fuel gases.

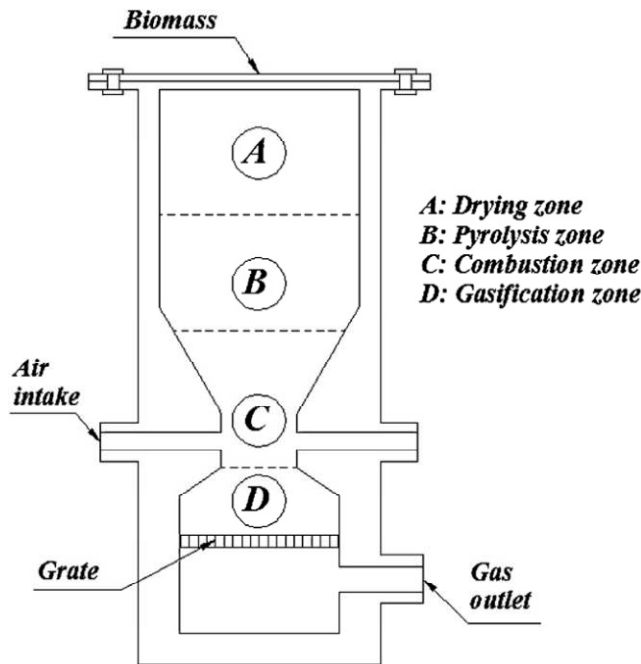


Fig. 1. Imbert gasifier diagram per Martinez et al. [18]

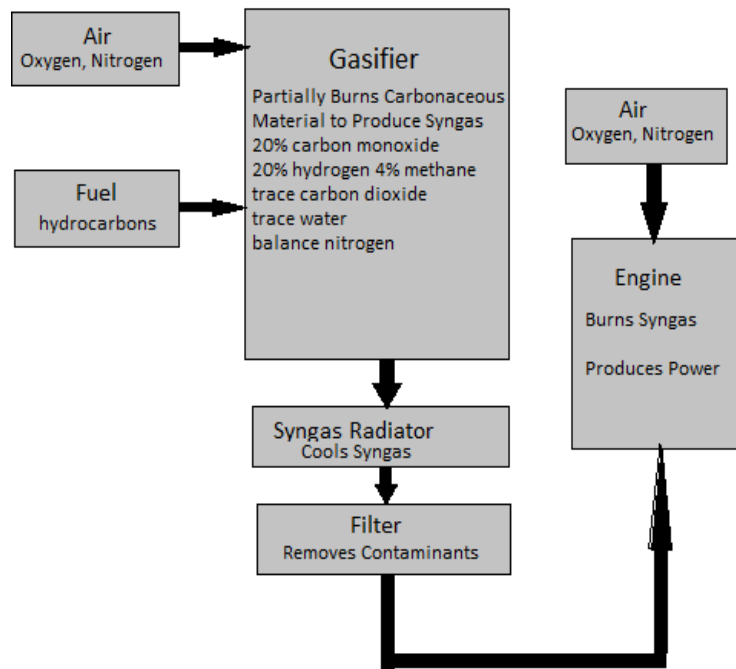


Fig. 2. Gasification and syngas utilization in engine process diagram

Table 1. Properties of producer Gas (PG) compared with pure combustible fuel gases + air, from [25]

Gas	Fuel LCV, lower calorific value, MJ/kg (MJ/Nm ³)	Air/ fuel @ $\Phi=1$ mass (mole)	Mixture, MJ/kg (MJ/Nm ³)	Fuel-air equivalence ratio (Φ), limit		Laminar burning velocity (S_L), (limit) cm/s		Peak flame temp, [K]	Product/ reactant mole ratio	
				Lean	Rich	Lean	Rich			
H ₂	121 (10.8)	34.4 (2.38)	3.41 (3.2)	0.01	7.17	65	75	270	2400	0.67
CO	10.2 (12.7)	2.46 (2.38)	2.92 (3.8)	0.34	6.80	12	23	45	2400	0.67
CH ₄	50.2 (35.8)	17.2 (9.52)	2.76 (3.4)	0.54	1.69	2.5	14	35	2210	1.00
C ₃ H ₈	46.5 (91.3)	15.6 (23.8)	2.80 (3.7)	0.52	2.26	-	-	44	2250	1.17
C ₄ H ₁₀	45.5 (117.7)	15.4 (30.9)	2.77 (3.7)	0.59	2.63	-	-	44	2250	1.20
PG	5.0 (5.6)	1.35 (1.12)	2.12 (2.6)	0.47a	1.60b	10.3	12	50c	1800d	0.87

At first glance it would appear that power derating for a gasoline or diesel engine operating on syngas would be severe given the disparity of the fuel's LHV values. However, the derating is mitigated by the disparity of stoichiometric air/fuel ratios for the two fuels, 1.2 for syngas and 14.9 for gasoline or 14.5 for diesel fuel [26,27,19]. Thus, the amount of energy burned in the engine per revolution is not as different when operating on syngas or petroleum fuel as the difference in LHV would imply. Typically, ICEs are derated by approximately 15% to 40% (15% to 20% dual fuel diesel, 30% to 40% spark ignition) when operated on syngas rather than petroleum fuels [28,20,13]. Compared to combustion of the same biomass, gasification generally results in lower emissions of carbon monoxide, sulfur and nitrogen compounds such as NO [15]. Trading off

nitrogen compound emissions with exhaust gas recirculation and retarding of the injection/ignition timing may lead to an optimal condition where nitrogen compound emissions, engine power and operation are acceptable [29]. Because wood derived fuel is generally low in sulfur content sulfur compound emissions from wood derived syngas powered engines are generally lower than from petroleum powered engines [7]. Integrated gasification combined cycle (IGCC) systems for power production have been shown to offer better energy efficiency and environmental performance than conventional combustion-based technology [15]. IGCC systems extract power from surplus heat generated by the gasification and burning of fuel via steam powered turbines.

3. SYNGAS USE IN DIESEL ENGINES

The quality of ignition of compression ignition (CI) engines is determined with the cetane number (CN). [30]. ASTM 613-08 describes the testing regime using a single cylinder engine with variable compression ratio [31]. The diesel fuel quality is not only determined by the CN. Other factors such as density, energy content, cold flow properties and Sulphur content are additional important factors [32].

Syngas is used as fuel in diesel or compression ignition engines in the dual fuel mode in which diesel fuel is used as the pilot fuel and syngas is introduced through the engine intake air and provides the bulk of the fuel charge. The properties of the diesel fuel are not changed, but the fuel mixture of diesel and syngas has different properties. Based on our knowledge dual fuel properties of diesel and syngas have not been tested in accordance with ASTM 613-08.

The pilot fuel is necessary to ignite the syngas as the syngas auto-ignition temperature (500°C) is higher than is achieved by the fuel charge in the diesel engine on the compression stroke [33,34], although Reed reports that a slow speed, single cylinder, direct injection diesel engine was able to run on 100% syngas for extended periods when operating conditions allowed [17]. Dual fueling diesel engines with a compression ratio greater than 17:1 may not be practical [22]. The amount of diesel fuel necessary as the pilot fuel is variable and largely depends on the quality and energy content of the syngas [35]. Syngas is able to substitute 60%- 90% of the diesel fuel required to run a diesel engine at a specific power level [18,35]. Dual fueling a diesel engine allows use of a lower energy syngas or one that varies more in energy content [35] than would be practical in a spark ignition engine. The diesel engine governor in dual fuel mode increases or decreases the amount of diesel fuel injected as necessary to maintain engine output in the face of decreasing or increasing syngas energy content.

Raman and Ram report that diesel engine dual fuel energy efficiency is generally about 20% using syngas but stipulate that this efficiency is only achieved when the engine is run at full power and that efficiency falls off rapidly at partial load and throttle settings [36]. They state that at full load diesel engine power generation efficiency is about 28%, this falls off to about

17% when the diesel engine is operated at 20% load. Producer gas (syngas) power generation efficiency is reported as 21% at full load and only 9% at 20% load [36], a much steeper drop in efficiency than for the diesel engine power generation efficiency going from full to partial load.

Emissions from dual fueled (syngas and diesel) Compression Ignition (CI) engines are generally less than when running on diesel alone. Greenhouse CO₂ is reduced by the degree of substitution of biomass-based syngas for diesel as biomass is considered carbon neutral [18]. SO₂ and SO₃ are considered culprits in acid rain production [18] and are reduced from levels emitted from a diesel engine running on 100% diesel when the engine is dual fueled with syngas [15]. Per Whitty et al. [15] syngas has a much wider ignition range than conventional hydrocarbon fuels so it can be burned leaner, reducing CO emissions over levels obtained from burning diesel. Particulate Matter (PM) emission levels are also reduced from diesel levels when the engine is dual fueled with syngas [12,37]. In a well-tuned dual fuel system Volatile Organic Compound (VOC) emission levels are reduced from those obtained from a CI engine running on 100% diesel [15].

CO emissions have been found to be greater in dual fueled engines than in engines fueled by diesel alone but hydrocarbon emissions to be lower in dual fueled engines than in diesel engines [7]. Sridhar et al. [38] found CO levels emitted by a dual fueled engine to be at 0.55 – 1.2 g/MJ at full load, noting that the India Central Pollution Board limit for CO is 1.25 g/MJ.

Nitrogen oxide (NO_x) compounds are considered the major cause of ecosystem acidification [37]. They are generated from the oxidation of N₂ which can happen in engines at combustion temperatures greater than 2500 F [15]. NO_x emissions increase with increasing flame temperatures, also with the amount of excess air and with the degree of fuel-air mixing [15]. NO_x emissions increase with higher ratios of nitrogen containing fuel and sulfur containing fuel [15]. Thermal effects dominate during operation, however, [37,39,15] control strategies that lower combustion temperatures that were developed for other gas fired technologies such as water injection and exhaust recirculation can be effective for engines operating with syngas [15]. Some balancing of emission controls may be necessary to achieve acceptable emission

levels for different pollutants. For example, higher compression ratios raise combustion temperatures increasing NO_x and SO_x emissions but decreasing CO emissions. Reducing the residence time of the fuel in the combustion chamber by retarding the engine timing as well as lowering the engine compression are thought to lower the temperature of the fuel charge and hence its NO_x emission. Sridhar et al. [38] found NO_x levels emitted by a dual fueled engine to be at 0.2 – 0.7 g/MJ, with higher levels resulting from higher compression and advanced timing and lower levels resulting from lower compression and retarded timing, noting that the India Central Pollution Board limit for NO_x is 2.22 g/MJ.

4. SYNGAS USE IN SPARK IGNITION ENGINES

Electrical generation using a syngas powered engine is applicable to the developed world as a means of reducing greenhouse emissions and the developing world as a means of providing electricity in rural areas which typically have available biomass [18]. A big advantage of syngas use in Spark Ignition (SI) engines as opposed to Compression Ignition (CI) or diesel engines is the ability to run on syngas fuel alone rather than in the dual fuel mode necessary in CI engines operating with syngas, thus eliminating the need for any petroleum fuel. High thermal efficiency is possible with syngas fueled SI engines resulting from higher compression ratios allowed by the high antiknock characteristics (low flame speed) of CO and CH_4 and diluents N_2 and CO_2 in syngas compared to those possible in gasoline powered SI engines [18]. These counteract the knocking tendencies (high flame speed) of the hydrogen in syngas and also decrease the cylinder temperatures and pressures and lower NO_x emissions [18]. It should be noted that much of the energy in syngas comes from its hydrogen content. Without increasing the compression ratio a SI gasoline engine running on syngas is estimated to have a thermal efficiency of 10% to 15% as opposed to 15% - 20% running on gasoline due to the lower energy content of the syngas – air mixture [39]. However, milling of the engine block and/or cylinder head and/or changing the engine pistons is necessary to increase the compression ratio of a gasoline SI engine.

In practice, operating an ICE coupled to a gasifier producing syngas resembles an art. Many factors influence the quality and quantity of

the syngas let alone the varying demands and ability of the ICE in utilizing the syngas.

5. CONCLUSIONS

Syngas can provide a possible energy source for the operation of diesel and spark ignition engines by utilizing carbonaceous material including many forms of biomass as a source for future fuel and energy production. Syngas has the potential to reduce the fuel requirement for internal combustion engines that are manufactured to operate on gasoline or diesel fuel, but require modifications to operate efficiently. Engine power derating when operating with syngas is typically 15% - 40%, less than the difference in energy content between producer gas and petroleum fuel. Syngas compared to combustion of the same biomass, gasification generally results in lower air emissions. In addition, operation of syngas engines require a good understanding of operational parameters and how the biomass used effect the operation of the syngas process. Dual fuel properties of diesel and syngas should be tested in accordance with ASTM 613-08 using a single cylinder engine with variable compression ratio [31].

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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