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Syngas as An Alternative Fuel Used in Internal Combustion Engines: A Review

Anushka Pradhan[1], Prashant Baredar[2], Anil Kumar[3,*]
[1]Research Scholar, Energy Centre, Maulana Azad National Institute of Technology, Bhopal, India.
[2]Associate Professor, Energy Centre, Maulana Azad National Institute of Technology, Bhopal, India.
[3,*]Post Doctoral Fellow, Energy Tech., Research Center, Dept. of Mech. Engg.,
Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, Thailand.

Among the various renewable energy sources, synthesis gas (syngas) offers a promising opportunity for sustainable development in the energy and transportation sectors. Syngas can provide an economically viable solution, in the areas where the price of petroleum and diesel fuels are high, or where supplies are unreliable. This paper contains the information regarding the effect of particle size, and the moisture content of feedstock on the quality of producer gas. Coupling of syngas to the internal combustion engines (ICEs) is a feasible technology for the generation of heat and power on a small scale. Here, effect of syngas addition on performance of a spark ignition (SI) engine and compression ignition (CI) engine is also studied. This review also presents combustion features like calorific value, laminar flame velocity and flammability limits of syngas and its effects on the combustion in an internal combustion engines.

Keywords: Synthesis Gas (Syngas), Internal combustion engine, Calorific value, Laminar flame speed, Flammability limits.

1. INTRODUCTION

One of the most effective means of reducing diesel engine emissions is the use of alternative gaseous fuels in place of fossil diesel. This is because, combustion of gaseous fuel produces almost no oxides of sulphur (SO_x) and relatively little oxides of nitrogen (NO_x), the main constituents of acid rain, and substantially less carbon dioxide CO_2, a key culprit in the greenhouse debate, than most oil products and coal [1]. The most commonly used alternative gaseous fuels for compression ignition (CI) engines that can substitute diesel are: natural gas, liquefied petroleum gas, hydrogen (H_2), biogas, landfill gas, sewage gas, digester gas, syngas etc. In its simplest form, syngas is composed of two diatomic molecules, carbon monoxide CO and H_2, that provide the building blocks upon which an entire field of fuel science and technology is based. Over the years, syngas has had many names depending on how it was formed; producer gas, town gas, blue water gas, synthesis gas, and syngas, to name a few. In principle, syngas can be produced from any hydrocarbon feedstock. These include: natural gas, naphtha, residual oil, petroleum coke, coal, and biomass [2].

Syngas is produced by gasifying a solid fuel feedstock, such as coal or biomass. For example, a biomass can be gasified by incomplete combustion, resulting in the production of combustible gases. It consists of about 40% combustible gases, mainly carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), the remainder is made up of

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non-combustible gases, primarily nitrogen (N_2), and carbon dioxide (CO_2). Varying proportions of CO_2, H_2O, H_2, and CH_4 may be present [3].

The major components of syngas is H_2, which has very clean burning characteristics, high flame propagation speed wide flammability limits. H_2 has a laminar combustion speed roughly eight times that of natural gas. Thus increased H_2 content in a gaseous fuel reduces the combustion duration and thereby increases the efficiency of internal combustion (IC) engines. It is of great interest that the addition of H_2 to a gaseous fuel extends the lean limit of gas operation without entering the lean misfire region. Lean mixture combustion has great potential for attaining higher thermal efficiency and low NO_x emission levels with only an insignificant increase in hydrocarbon emissions [4].

Gas composition of syngas varies with the feedstock, particle size, gas and feedstock flow rate, chemical reactor configurations, operating conditions or the gasification process, gasifying agent and catalyst and gas residence time. This gas can be used as a standalone or dual fuel for power production. The energy density of syngas is very low in comparison to natural gas with Lower heating value (LHV) ranging from 4-6 MJ-Nm^{-3}. The LHV of syngas can be increased in the range of 9-13 MJ/Nm^3 by using pure oxygen for the gasification process [5].This paper relates to the detail study of syngas as a single fuel in SI engine and as a dual fuel in CI engine, diesel as a pilot fuel. The SI ignition engine with syngas is very promising and even cost competitive with that of natural gas. Mixtures of H_2 and CO could serve as an alternative spark ignition (SI) fuel due to their high anti-knock behavior. However, the addition of H_2 to CO tends to increase combustion temperature which increases nitric oxide (NO) emissions under stoichiometric SI combustion. Hence, the use of H_2 and CO mixtures is more appropriate in lean burn conditions where combustion temperatures are moderated by excess air like in a CI diesel engine. The dual fuel engine is an ideal multi-fuel engine that operates effectively on a wide range of fuels including the flexibility of operating as a conventional diesel engine [6]. In dual fuel operation, a carburetted mixture of air and high octane index gaseous fuel is sucked and compressed like in a conventional diesel engine. The compressed mixture of air and fuel-gas does not auto-ignite due to poor ignition quality of the gaseous fuel. Hence, it is fired by a small liquid fuel injection, known as pilot, which ignites spontaneously at the end of compression phase [7].

This communication emphasised on review of syngas as an alternative fuel used in internal combustion engines.

2. SYNGAS PRODUCTION THROUGH GASIFICATION

Gasification is a process of conversion of any solid or liquid carbon-based material (feedstock) into gaseous fuel through its partial oxidation with air, oxygen, water vapour or their mixture. It could also be defined as the thermo-chemical process limited to a partial combustion and pyrolysis [8]. This process can be considered as a thermo-chemical treatment which unlike the full combustion uses air/fuel ratios noticeably below the stoichiometric value. Such a deficiency in the supply of the oxidation agent prevents the complete conversion of the carbon and the hydrogen present in feedstock into CO_2 and H_2O, respectively, and results in the formation of combustible components such as CO, $H_2$and CH_4. In addition to those components, the producer gas also contains typical products of combustion, namely CO_2, N_2, O_2 and H_2O. Although the process takes place with a sub-stoichiometric amount of air, it is usual to find a low concentration of oxygen in the gasification products. Finally, hydrocarbons such as ethylene (C_2H_4) and ethane (C_2H_6) are also present in very small quantities in the producer gas [9,10].

The gasifier is basically a chemical reactor where various complex physical and chemical processes take place that include drying, heating, pyrolysing, partial oxidation and finally reduction as it flows through it. Pyrolysis is the heating process, which produces both charcoal and tar and combustion is complete oxidation of fuel. Gasification process is in between pyrolysis and combustion. Gasifier can be broadly classified into three categories according to the gas flow direction, that is, up draft, down draft and cross draft gasifier. A typical composition of producer gas obtained from updraft and downdraft gasifier is as follows Table1.

Table.1: Composition of producer gas.

Composition	**Updraft Gasifier (% by Volume)**	**Downdraft Gasifier (% by Volume)**
Carbon monoxide	24	21
Hydrogen	11	17
Methane	3	2
Hydrocarbon	0.2	0.3
Nitrogen	53	48
Water vapor	3	4

2.1. Major Properties of Syngas

There are various properties of syngas which can affect the combustion process in IC engines. Among them the most important is flammability limit which is very important characteristic in the safety and fuel for IC engine. The other one is laminar flame velocity or burning velocity an essential parameter for the investigation of combustion chamber operation and emission performance.

2.1.1 Syngas flammability limits

The flammability limit is the generally used as, index for representing the flammability characteristics of gases. It defines the range of concentration of the fuel in a fuel-air mixture at specified temperature and pressure that allows ignition initiated flame to propagate and sustain. In accordance with generally accepted usage, the flammability limits are known as those regions of fuel–air ratio within which flame propagation can be possible and beyond which flame cannot propagate. It is mainly affected by the nature of fuel, direction of propagation, size and shape of combustion chamber, temperature and pressure [11]. And there are two distinct separate flammability limits for the fuel–air mixture, namely, the leanest fuel-limit up to which the flame can propagate is termed as lower flammability limit (LFL), and the richest limit is called as upper flammability limit (UFL) [12]. The flammability limits for combustible gases of syngas are given in Table 2.

Table 2: The properties of hydrogen, carbon monoxide and methane.

Fuel Properties	**H_2**	**CO**	**CH_4**
Fuel LHV (MJ/kg) [MJ/Nm^3]	(121) [10.8]	(10.2) [12.7]	(50.2) [35.8]
Air-Fuel Ratio (mass) [mole]	(34.4) [2.38]	(2.46) [2.38]	(17.2) [9.52]
Peak flame Temp (K) @ 1 atm	2378	2384	2223
Flammability Limit φ (Lean/Rich)	0.01/74.2	0.34/6.80	0.54/1.69
Flame Speed at Stoich. (cm/sec)	270	45	35

The fact that the H_2 and CO are the main flammable constituents of syngas, syngas inherits the characteristic features of these gases. However the presence of inert gases like nitrogen and carbon dioxide in the gas mixtures narrows the flammability limit. This is shown in Figure 1.

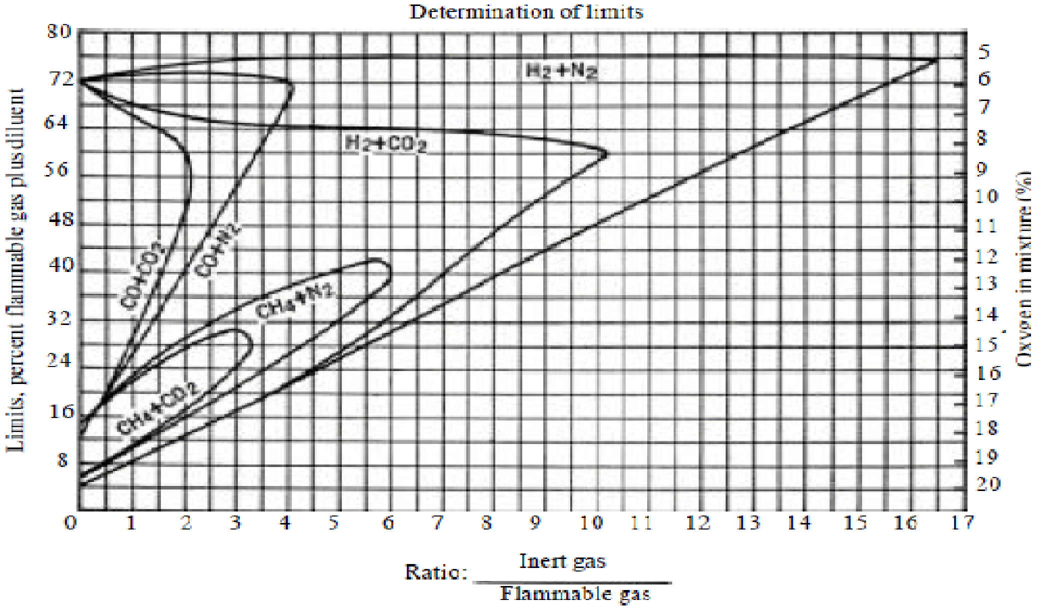

Fig.1: Flammability limits of H_2 , CO, CH_4 with varying mixtures of CO_2, N_2.

Flammability limit, the lower flammability limit in particular, is indicator of combustibility of fuels and therefore more emphasis should be given to the engine atmosphere, oxidizer (air-fuel ratio) and ignition energy for the sustainability of combustion [13,14].

Flammability limit is a very important characteristic in the safety and fuel for IC engine research.

2.1.2. Laminar flame velocity

The laminar flame velocity is the rate at which the flame propagates through quiescent unburned fuel-oxidant mixtures in the direction perpendicular to the expansion wave surfaces under laminar flow condition [11,12]. As it is very sensitive to fuel-oxidant mixtures, LFV is a very essential parameter for the investigation of combustion chamber operation and emission performance. It is influenced by the fuel composition, mixture equivalence ratio, temperature and pressure.

A detailed study of LFV and its influencing factors is required in the internal combustion engines. It is observed that LFV increases with an increase in H_2/CO ratio of mixture [15]. Various properties of H_2, CO and CH_4 are shown in Table 2 [15,16].

2.2. Process Parameters in the Gasification Process to affect the Quality of Syngas Fuel

The process parameters affect various performance aspects like efficiency, product gas quality, energy and exergy inputs. The specifics of reactor design and flow patterns of air and biomass particles within a gasifier strongly influence the quality of syngas fuel generated in the gasification process. The gasification processes is affected by different factors including temperature, pressure, residence time, properties of feed materials, equivalence ratio and the superficial velocity. Theses parameters are quite interrelated and each of them affects the gasification rate, process efficiency, product gas heating value and product gases distribution.

2.2.1. Effect of the temperature and pressure

Temperature appears to have the greatest influence on the performance of the gasifiers. The compositions of the volatiles produced from a gasifier depend on the degree of the equilibrium attained by various gasification reactions. All the gasification reactions are normally reversible and the equilibrium point of any of the reaction can be shifted by changing the temperature. The temperature of the gasifier affects on the reaction rate and the composition of the product; reduction in CO, CO_2, and CH_4 occurs, yet more H_2 produced with increasing the temperature. On the other side, the char conversion decreases with the temperature increase and also lowers the heating value of producer gas. But at higher temperatures above 750 degree CO the H_2 yield starts reducing, this is attributed to the water gas shift reaction. Thus the gasification temperature is needed to be selected carefully as a trade off between the char conversion and the H_2 output.

With the increase of pressure, H_2 and CO yield reduces. The percentage of CO and H_2 decreases as the pressure increases, while the CH_4, CO_2, N_2 and unconverted char increases with increasing the pressure. The calorific value of the gas decreases as the pressure increases, since the percentage of H_2 and CO decrease significantly, as compared to the improvement in pressure is not so significant on the calorific value of the gas and the gasification efficiency [17].

2.2.2. Equivalence ratio (ER)

Equivalence ratio (ER) is a measure of the amount of external oxygen (or air) supplied to the gasifier. ER is obtained by dividing the actual oxygen (or air) to biomass molar ratio to the stoichiometric oxygen (or air) to biomass molar ratio. Oxygen is generally supplied as a gasifying and fluidizing medium. Use of air in place of oxygen though economical but has the negative effect of diluting the product gas due to the presence of nitrogen. The ER is one of the most important operating variables in biomass gasification with air. In biomass gasification, the ER varies from 0.10 to 0.30. The equivalence ratio shows two opposing effects on the gasification process. Increasing the amount of air favours gasification by increasing the temperature but, at the same time, produces more CO_2 [18].

2.2.3. Superficial velocity (SV)

Superficial velocity, SV, is defined as a ratio of the syngas production rate at normal conditions and the narrowest cross sectional area of the gasifier. Many authors have indicated that SV influences the gas production rate, the gas energy content, the fuel consumption rate, the power output and char and tar production rates. It is independent of reactor dimensions, allowing a direct comparison of gasifiers with different power outputs [19]. Low values of SV result in a relatively slow pyrolysis process with high yields of char and significant quantities of unburned tars. On the contrary, high values of SV cause a very fast pyrolysis process, formation of a reduced amount of char and very hot gases in the flaming zone. However, higher SV values may results to the decrease in gas residence time, resulting in lower efficiencies in the tar cracking processes.

2.3. Output Factors of Biomass Gasifiers

The main output parameters in the gasification process are the producer gas composition and its calorific value, thermal power of the gasifier, gas yield and the gasification efficiency.

2.3.1. Syngas composition and its calorific value

The producer gas composition depends on the feedstock, particle size, gas and feedstock flow rate, chemical reactor configurations, operating conditions or the gasification process, gasifying agent and catalyst and gas residence time. But it is mainly influenced by the temperature in the reactor, which in its turn is influenced by the ER value. In addition, concentrations of CO, H_2 and CH_4 in the producer gas are also controlled by the chemical reactions occurring in the gasification process. Therefore the type of the oxidizing agent used for gasification has a considerable influence on the calorific value of the producer gas. The concentration of CO and H_2 will reach a maximum value as ER increases and then the concentration of these useful components decreases due to the combustion intensification at higher ER values. With the rise of ER the CO_2 and N_2 concentrations also increase in the producer gas [20]. Air as an oxidizing agent produces syngas with relatively high concentrations of nitrogen and this results in a lower calorific value which usually does not exceed 6 MJ/Nm^3. In this case the producer gas is classified as poor quality fuel gas. A typical gas composition from biomass gasification in a downdraft reactor with air used as an oxidizing agent is as follows: 15-20% of H_2, 15-20% of CO, 0.5-2% of CH_4, 10-15% of CO_2 and the remaining part is made of N_2, O_2 and C_XH_Y. When, oxygen or water steam or a mixture of both is used, then the concentration of combustible components is significantly increased and the gas will be called medium calorific value gas and its value reaches upto 16 MJ/Nm^3 [21].

2.3.2. Gasification efficiency

This is an important factor for determining the actual technical operation, as well as the economic feasibility of using a gasifier system. The gasification efficiency depends on the type of biomass used, its particle size, the ER value and the design of the reactor. The gasification efficiency is usually determined on the lower heating value basis. The efficiency is calculated as the ratio of the total energy in the producer gas (sensible and chemical) and the chemical energy in the feedstock (the heating value). Depending on type and design of the gasifier as well as on the characteristics of the fuel, mechanical gasifier efficiency may vary between 60 and 75 percent. A useful definition of the gasification efficiency (%) used for engine applications is:

$$\eta_m = \frac{H_g \times Q_g}{H_s \times M_s} \times 100$$

In which:

η_m =gasification efficiency (%) (Mechanical)
H_g = heating value of the gas (kJ/m^3)
Q_g = volume flow of gas (m^3/s)
H_s = lower heating value of gasifier fuel (kJ/kg)
M_s = gasifier solid fuel consumption (kg/s)

2.3.3. Yield

It is used to measure the syngas production in cubic meters per mass of feedstock supplied to the system. The yield is directly proportional to the ER variation and to the residence time of the gases in the reduction zone. The ash content in the biomass also has a significant influence and limits the producer gas yield.

2.4. Cleaning and Cooling of Producer Gas

The combustible gases from the gasifier can be used in internal combustion engines, for direct heat applications and as feedstock for production of chemicals like methanol. Though, in order to use this gas for any of the above applications, firstly it should be cleaned of tar and dust and be cooled. Cooling and cleaning of the gas is one of the most important processes in the whole gasification system. The failure or the success of producer gas units depends completely on their ability to provide a clean and cool gas to the engines or for burners.

The temperature of gas coming out of generator is normally between 300-500^{0}C. In order to raise its energy density the gas is to be cooled first. Various types of cooling equipment have been used to achieve this end [22]. Mostly gas to air heat exchangers are used as coolers, where the cooling is done by free convection of air on the outside surface of heat exchanger. Since the gas also contains moisture and tar, some heat exchangers provide partial scrubbing of gas [23]. Thus ideally the gas going to an internal combustion engine should be cooled to nearly ambient temperature.

Cleaning of the gas is very critical. Normally three types of filters are used in this process. They are classified as dry, moist and wet.

In the dry category cyclone filters are used. They are designed according to the rate of gas production and its dust content [24]. The cyclone filters are useful for particle size of 5 µm and greater. Since 60-65% of the producer gas contains particles above 60 µm in size, the cyclone filter is an excellent cleaning device [22].

After passing through cyclone filter, the gas still contains fine dust, particles and tar. It is further cleaned by passing through either a wet scrubber or dry cloth filter. In the wet scrubber the gas is washed by water in counter current mode. The scrubber also acts like a cooler, from where the gas goes to cloth or cork filter for final cleaning.

Since cloth filter is a fine filter, any condensation of water on it stops the gas flow because of increase in pressure drop across it [25]. Thus in quite a number of gasification systems the hot gases are passed through the cloth filter and then only they go to the cooler. Figure 2 shows schematically a downdraft gasification system with cleaning and cooling train.

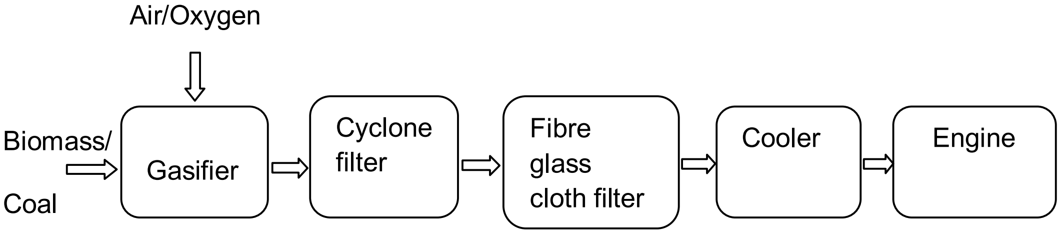

Fig. 2: Block diagram of producer gas plant.

3. SYNGAS AS A FUEL IN INTERNEL COMBUTION (IC) ENGINE

Significant research has been performed on studying and improving the operation of ICEs fuelled by producer gas. The quality of producer gas as a fuel is significantly poorer than gasoline and natural gas. Therefore the engines require certain design modifications in order to be able to run on producer gas. Many studies and experimental investigation has been done on both spark ignition and diesel engines, that were fuelled with producer gas [26-33]. They had also presented data obtained in experimental investigations on the engine’s brake power, torque, efficiency, power de-rating, emissions, exhaust temperature and knock tendency, taking into account the influence of the air/fuel equivalence and the compression ratios.

The authors came to an end with suggestions on engine design modifications, including an increase in the compression ratio. The main parameter for defining the performance of the engine is the calorific value (per unit volume) of the stoichiometric air/producer gas mixture [34]. Using a parameter named as the Engine Fuel Quality (EFQ) the authors estimated the magnitude of the power de-rating in the engine fuelled by the producer gas.

The quality of gas should be sufficiently high in terms of tar and particulates content to maintain the consistent engine's operation and to provide an adequate durability of major engine components, such as the valves, the combustion chamber, the piston, etc. The allowed particle and tar concentration in producer gas for satisfactorily operation of the internal combustion engine must be less than 50 mg/Nm^3 and 100 mg/Nm^3, respectively [35].

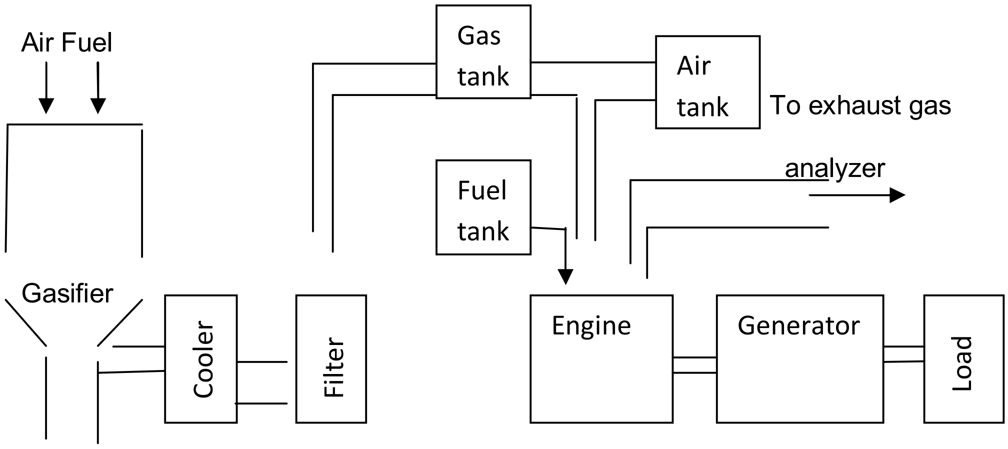

Fig. 3: Schematic diagram of fully renewable engine.

3.1. Spark ignition Engine (SI)

Syngas is a low-energy-density fuel and SI engine is having low compression ratio in the range of 8 to 12, the power degradation in SI is extensive compared to high energy-density fuels such as gasoline and natural gas [36]. The reduction in power of an engine run on producer gas is mainly due to the lower net calorific value of the air/fuel mixture [28]. The power derated to about 40-50%. About 30% power loss is due to low energy density of producer gas and the rest is accounted by the pressure drop in the intake valves and piping. A spark ignition engine on the whole requires very little modification to run on producer gas. Generally depending upon the compression ratio and rpm of engine, the ignition timing has to be advanced by about 30-40 degrees. This is done because of low flame speed of producer gas as compared to gasoline. The low flame speed of producer gas is more efficiently used in low speed engine. Thus an engine with 1500-2500 rpm is ideal for producer gas application [37].

The stoichiometric mass ratio in the air/producer gas mixture is between 1.0 and 1.2, compared to 17 for methane and thus an adequate mixing and dosage device is necessary for an engine to operate with high performance. However, addition of H_2 to CO tends to increase combustion temperatures and hence increases nitric oxide (NO) emission under stoichiometric SI combustion [38].

3.2. Compression Ignition (CI) Engine

Compression ignition (CI) engine would operate more efficiently with syngas. However, syngas cannot be used in CI engines without a means of initiating combustion, since the temperature at the end of the compression stroke is lower than the auto ignition temperature of syngas. Therefore, it is necessary to operate the engine in a dual-fuel mode, in which syngas is used as the primary fuel, and ignited by pilot diesel fuel.

It was accounted that producer gas was used in standard diesel engines in the dual-fuel mode operation and that diesel fuel savings up to 85% had been obtained [28-31]. Diesel engines have higher efficiency due to a greater compression ratio which usually varies between 12 and 24 [39]. Diesel engines also have better durability and, in some cases, require low maintenance than spark-ignition engines. Because of high compression ratio and low speeds, the derating of diesel engines running on producer gas is only between 15-30%. This is far superior to the SI engine’s derating. Even if SI engines are used in dual fuel mode their derating is still between 40-50% [37]. Few additional components such as gas mixer, non-return valve, pressure regulator and gas carburettor etc. is to be incorporated into the diesel engine setup for dual fuel operation. In spark ignition and diesel engines producer gas and air are usually mixed in an intake collector and then the air-fuel mixture now ready for combustion enters the cylinders of the engine.

Effect of H_2:CO ratio in syngas on the performance of a dual fuel diesel engine at varying load condition has also been estimated. The syngas with 100% H_2 compositions showed an improved engine performance, but, at the expense of higher NO_X emissions for an increase in load. The NO_X emissions reduced when 25% and 50% CO were added in the 100% H_2 composition syngas. At the best efficiency loading point of 80%, the maximum diesel replacement was found as 72.3% for 100% H_2 syngas mode. At same engine load, the thermal efficiency was found to be 16.1% for 50% H_2 syngas. It increased to 18.3% and19.8% when H_2 content was increased to 75% and 100%, respectively [40].

3.3. Exhaust Emission

The H_2 and CO_2 content of syngas affected the engine performance and emissions. Increased H_2 content led to higher combustion temperatures and efficiency, lower CO and Hydro Carbon (HC) emissions, but higher NO_X emissions. Increased CO_2 content influenced performance and emissions only when it reached a certain level 34% [41].

The traditional spark ignition (SI) engines always experience incomplete combustion process and large amounts of toxic emissions. Hydrogen has many notable positive combustion properties such as low ignition energy, high flame propagation speed and etc. [42,43]. As a major alternate energy source, hydrogen not only helps release the dependence on fossil fuel but also improves the combustion and emissions performance of engines [44-46].

Changwei Ji *et al.* [47-51] investigated the effect of varying syngas volume fraction on combustion and emission performance of a syngas–gasoline engine. It was observed that HC emissions are sharply decreased from 3165 to 2436 ppm when the syngas volume fraction increases from 0% to 1.84%. The reason is that the quenching distances of hydrogen and carbon monoxide are much shorter than that of the gasoline, which benefits decreasing HC emissions. Therefore, the flame of syngas-gasoline mixture could propagate much closer to the cylinder wall and crevices than that of the pure gasoline. And, NO_X emissions are generally decreased with the increase of syngas blending ratio. When the syngas volume fraction rises from 0% to 1.84%, NO_X emissions are reduced from 2047 to 1499 ppm. The oxygen concentration and combustion temperature are main factors which influence NO_X emissions remarkably. When the syngas flow rate is slightly increased, the decreased oxygen concentration in the total intake causes the decreased NO_X emissions.

The presence of CO in syngas, dual fuel engine operations resulted significant increases of the CO emissions as compared to 100% H_2 mode due to incomplete combustion of CO in the fuel-gas. For syngas that contains CO in its composition, the CO emission levels seem to be sensitive to the engine load. At low engine loads, the CO emissions were increased significantly. At 20% engine load, the CO emissions were measured as 12, 82, 106 ppm for 100, 75 and 50% H_2 syngas mode respectively. In general, for a homogeneous combustion of rich mixture when the load increased, the level of CO emissions starts to increase due to insufficient oxygen in combustion [39]. However, in these dual fuel operations, as the load increased the level of CO emissions starts to increase due to the presence of CO gas in its fuel composition including late combustion of dual fuel modes [52-54]. The NO_X reduction is a result of the lower maximum cylinder pressure and combustion temperature [39]. On the other hand, NO_X emission in the lean combustion is very low. The higher flame speed and also higher energy content of 100% H_2 syngas have resulted maximum in-cylinder pressure and combustion temperature. Hence, the NO_X emissions and exhaust gas temperature for 100% syngas fuel were higher as compared to that of 75% and 50% H_2 syngas modes.

4. CONCLUSION

This paper reviewed the gasification process, and mainly syngas production through gasification using air as an oxidising agent. The effect process parameters like equivalence ratio, superficial velocity, temperature, pressure, biomass particle size and gasifier design on the quality of producer gas have considered for study. The details of the use of producer gas in ICEs (diesel and spark ignition ones) has been discussed. Based on the above review some conclusions have been made.

- The most important factors that cause power de-rating in SI engine, is the low energy density of producer gas /air mixture and the engine's volumetric efficiency.
- The hydrogen concentration in the syngas is increased with the increase of syngas volume fraction due to the increased exhaust temperature. And, when the syngas volume fraction increases, indicated thermal efficiency is increased for syngas blended gasoline engine.
- In syngas-blended gasoline engine HC and NO_X emissions are reduced after the syngas enrichment at lean condition.

- With the high H_2-content producer gas, combustion and engine performance is better than with the low H_2-content producer gas, especially under leaner conditions.
- Increased H_2 content lower CO and HC emissions, but higher NO_X emissions. Moreover, a broader window of fuel–air equivalence ratio was found with highest thermal efficiencies for the high H_2-content producer gas.

REFRENCES

[1] A. Henham and M.K. Makkar; “Combustion of simulated biogas in a dual-fuel diesel engine”, Energy Conversion and Management, Vol. 39(16-18), pp. 2001-2009, 1998.

[2] P.L. Spath and D.C. Dayton; “Preliminary Screening-Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas”, NREL Report No. TP-510-34929, 2003.

[3] N.Z. Shilling and D.T. Lee; “IGCC-Clean power generation alternative for solid fuels”, Power Gen Asia, 2003.

[4] S.O. Bade Shrestha and G.A. Karim; “Hydrogen as an additive to methane for spark ignition engine applications”, Int. J. Hydrogen Energy, Vol. 24(6), pp. 577-586, 1999.

[5] R.W. Francisco Jr., F. Rua, M. Costa, R.C. Catapan and A.A.M. Oliveira; “On the Combustion of Hydrogen-Rich Gaseous Fuels with Low Calorific Value in a Porous Burner”, Energy Fuels, Vol. 24(2), pp. 880-887, 2010.

[6] C. Garnier, A. Bilcan, O. Le Corre and C. Rahmouni; “Characterisation of a Syngas-Diesel Fuelled CI engine”, Society of Automotive Engineers, Paper No. 2005-01-1731, 2005.

[7] B.B. Sahoo, N. Sahoo and U.K. Saha; “Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines- A critical review”, Renewable and Sustainable Energy Reviews, Vol. 13, pp. 1151-1184, 2009.

[8] A.V. Bridgwater, D. Meier and D. Radlein; “An overview of fast pyrolysis of biomass”, Organic Geochemistry, Vol. 30(12), pp. 1479-1493, 1999.

[9] R. Warnecke; “Gasification of biomass: comparison of fixed bed and fluidized bed gasifier”, Biomass and Bioenergy, Vol. 18(6), pp. 489-497, 2000.

[10] M. Lapuerta, J.J. Hernández, A. Pazo and J. López; “Gasification and co-gasification of biomass wastes: Effect of the biomass origin and the gasifier operating conditions”, Fuel Processing Technology, Vol. 89(9), pp. 828-837, 2008.

[11] J.M. Kuchta; “Investigation of fire and explosion accidents in the chemical, mining and fuel related industries: A manual”, United states Department of the Interior, Bureau of Mines., Bulletin 680, Washington DC, USA, 1986.

[12] M. Fossum and R.V. Beyer; “Co-combustion: Biomass fuel gas and natural gas”, SINTEF Energy Research, Trondheim, 1998.

[13] J. Chomaik, J.P. Longwell and A.F. Sarofim; “Combustion of low calorific value gases: Problems and prospects”, Prog. Energy Combustion. Sci.. Vol. 15(2), pp. 109-129, 1989.

[14] H.F. Coward and G.W. Jones; “Limits of flammability of gases and vapors”, United States Government Printing Office, US Department of the Interior, Bureau of Mines, Washington, DC, 1952.

[15] J. Natarajan and J.M. Seitzman; “Laminar flame properties of H_2/CO mixtures”, Synthesis Gas Combustion: Fundamentals and applications, T. Lieuwen, V. Yang and R. Yetter (eds.). Taylor and Francis group, Boca Raton, USA, 2010.

[16] G. Sridhar, H.V. Sridhar, S. Dasappa, P.J. Paul, N.K.S. Rajan and H.S. Mukunda; “Development of producer gas engines”, Proceedings of the Institution of Mechanical Engineers Part D: Journal of Automobile Engineering, Vol. 219(3), pp. 423-438, 2005.

[17] S.P. Nandi and M. Onischak; “Gasification of Chars Obtained from Maple and Jack Pine Woods”, Fundamentals of Thermochemical Biomass Conversion, R.P. Overend, T.A. Milne and K.L. Mudge (eds.), Elsevier Applied Science Publishers, London, UK, pp. 567- 578, 1985.

[18] P. Vriesman, E. Heginuz and K. Sjöström; “Biomass gasification in a laboratory-scale AFBG: influence of the location of the feeding point on the fuel-N conversion”, Fuel, Vol. 79(11), pp. 1371-1378, 2000.

[19] T. Yamazaki, H. Kozu, S. Yamagata, N. Murao, S. Ohta, S. Shiya and T. Ohba; “Effect of superficial velocity on tar from downdraft gasification of biomass”, Energy Fuels, Vol. 19(3), pp. 1186-1191, 2005.

[20] P.N. Sheth and B.V. Babu; “Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier”, Bioresource Technology, Vol. 100(12), pp. 3127-3133, 2009.

[21] P. McKendry; “Energy production from biomass (Part 3): gasification technologies”, Bioresource Technology, Vol. 83(1), pp. 55-63, 2002.

[22] “Generator Gas: The Swedish Experience from 1939-1945”, Chap. 5SERI, Solar Energy Research Institute (SERI), 1979.

[23] N.A. Skov; “The Pegasus Unit: Petroleum gasoline substitute systems”, Chap. 7, Pegasus Publishers, Olympia, Washington, 1974.

[24] “Chemical Engineer’s Handbook”, R.H. Perry and C.H. Chilton (eds.), Fifth Edition, McGraw Hill Book Company, New York, pp. 20-75, 1973.

[25] Biomass Energy Consultants and Engineers (BECE), unpublished data, 1982.

[26] S.C. Bhattachary, S.S. Hla and H.L. Pham; “A study on a multi-stage hybrid gasifier-engine system”, Biomass and Bioenergy, Vol. 21(6), pp. 445-460, 2001.

[27] U. Henriksen, J. Ahrenfeldt, T.K. Jensen, B. Gøbel, J.D. Bentzen, C. Hindsgaul and L.H. Sorensen; “The design, construction and operation of a 75 kW two-stage gasifier”, Energy, Vol. 31(10-11), pp. 1542-1553, 2006.

[28] G. Sridhar, P.J. Paul and H.S. Mukunda; “Biomass derived producer gas as a reciprocating engine fuel- An experimental analysis”, Biomass and Bioenergy, Vol. 21(1), pp. 61-72, 2001.

[29] Shashikantha, P.K. Banerjee, G.S. Khairnar, P.P. Kamat and P.P. Parikh; “Development and performance analysis of a 15 kW producer gas operated SI engine”, Proceedings of fourth national meet on biomass gasification and combustion, Mysore, India, Vol. 4, pp. 219-231, 1993.

[30] A.S. Ramadhas, S. Jayaraj and C. Muraleedharan; “Dual fuel mode operation in diesel engines using renewable fuels: Rubber seed oil and coir-pith producer gas”, Renewable Energy, Vol. 33(9), pp. 277-2083, 2008.

[31] A. Ramachandra; “Performace studies on a wood gas run IC engine”, Recent advances in biomass gasification and combustion, P.J. Paul and H. S. Mukunda (eds.), Interline Publishing, Bangalore, 1993.

[32] R. Uma, T.C. Kandpal and V.V.N. Kishore; “Emission characteristics of an electricity generation system in diesel alone and dual fuel modes”, Biomass and Bioenergy, Vol. 27(2), pp. 195-203, 2004.

[33] N.R. Banapurmath and P.G. Tewari; “Comparative performance studies of a 4-stroke CI engine operated on dual fuel mode with producer gas and Honge oil and its methyl ester (HOME) with and without carburetor”, Renewable Energy, Vol. 34(4), pp. 1009-1015, 2009.

[34] F.V. Tinaut, A. Melgar, A. Horrillo, A.D. de la Rosa; “Method for predicting the performance of an internal combustion engine fuelled by producer gas and other low heating value gases”, Fuel Processing Technology, Vol. 87(2), pp. 135-142, 2006.

[35] P. Hasler and T. Nussbaumer; “Gas cleaning for IC engine applications from fixed bed biomass gasification”, Biomass and Bioenergy, Vol. 16(6), pp. 385-395, 1999.

[36] M. Munoz, F. Moreno, J. Morea-Roy, J. Ruiz and J. Arauzo; “Low heating value gas on spark ignition engines”, Biomass and Bioenergy, Vol. 18(5), pp. 431-439, 2000.

[37] A. Kaupp and J.R. Goss; “State of the Art Report for Small Scale (to 50 kW) Gas Producer-Engine Systems”, Chap. 7, U.S.D.A., Forest Service, March 1981.

[38] H. Li and G.A. Karim; “Exhaust emissions from an SI engine operating on gaseous fuel mixtures containing hydrogen”, International Journal of Hydrogen Energy, Vol. 30(13-14), pp. 1491-1499, 2005.

[39] J.B. Heywood; “Internal combustion engine fundamentals”, Tata Mc Graw Hill, 1998.

[40] B.B. Sahoo, N. Sahoo and U.K. Saha; “Effect of H_2:CO ratio in syngas on the performance of a dual fuel diesel engine operation”, Applied Thermal Engineering, Vol. 49, pp. 139-146, 2012.

[41] U. Azimov, E. Tomita, N. Kawahara and Y. Harada; “Effect of syngas composition on combustion and exhaust emission characteristics in a pilot-ignited dual-fuel engine operated in PREMIER combustion mode”, Int. J. hydrogen energy, Vol. 36(18), pp. 11985-11996, 2011

[42] C. Ji and S. Wang; “Strategies for improving the idle performance of a spark-ignited gasoline engine”, Int. J. Hydrogen Energy, Vol. 37(4), pp. 3938-3944, 2012.

[43] J. Wang, Z. Huang, C. Tang and J. Zheng; “Effect of hydrogen addition on early flame growth of lean burn natural gas-air mixtures”, Int. J. Hydrogen Energy, Vol. 35(13), pp. 7246-7252, 2010.

[44] Y. Zhang, Z. Huang, L. Wei, J. Zhang and C.K. Law; “Experimental and modeling study on ignition delays of lean mixtures of methane, hydrogen, oxygen, and argon at elevated pressures”, Combustion and Flame, Vol. 159(3), pp. 918-931, 2012.

[45] S. Bari and M.M. Esmaeil; “Effect of H_2/O_2 addition in increasing the thermal efficiency of a diesel engine”, Fuel, Vol. 89(2), pp. 378-383, 2010.

[46] G.K. Lilik, H. Zhang, J.M. Herreros, D.C. Haworth and A.L. Boehman; “Hydrogen assisted diesel combustion”, Int. J. Hydrogen Energy, Vol. 35(9), pp. 4382-4398, 2010.

[47] C. Ji and S. Wang; “Combustion and emissions performance of a hybrid hydrogen-gasoline engine at idle and lean conditions”, Int. J. Hydrogen Energy, Vol. 35(1), pp. 346-355, 2010.

[48] C. Ji, X. Dai, B. Ju, S. Wang, B. Zhang, C. Liang and X. Liu; “Improving the performance of a spark-ignited gasoline engine with the addition of syngas produced by onboard ethanol steaming reforming”, Int. J. Hydrogen Energy, Vol. 37(9), pp. 7860-7868, 2012.

[49] C. Ji, S. Wang and B. Zhang; “Combustion and emissions characteristics of a hybrid hydrogen-gasoline engine under various loads and lean conditions”, Int. J. Hydrogen Energy, Vol. 35(11), pp. 5714-5722, 2010.

[50] X. Dai, C. Ji, S. Wang, C. Liang, X. Liu and B. Ju; “Effect of syngas addition on performance of a spark-ignited gasoline engine at lean conditions”, Int. J. Hydrogen Energy, Vol. 37(19), pp. 14624-14631, 2012.

[51] C. Ji, X. Dai, S. Wang, C. Liang, B. Ju and X. Liu; “Experimental study on combustion and emissions performance of a hybrid syngas-gasoline engine”, Int. J. Hydrogen Energy, Vol. 38(25), pp. 11169-11173, 2013.

[52] A. Tsolakis, A. Megaritis, D. Yap and A. Abu-Jrai; “Combustion Characteristics and Exhaust Gas Emissions of a Diesel Engine supplied with reformed EGR”, Paper 2005-01-2087, Society of Automotive Engineers, 2005.

[53] A. Abu-Jrai, J. Rodriguez-Fernandez, A. Tsolakis, A. Megaritis, K. Theinnoi, R.F. Cracknell and R.H. Clark; “Performance, combustion and emissions of a diesel engine operated with reformed EGR. Comparison of diesel and GTL fuelling”, Fuel, Vol. 88(6) pp. 1031-1041, 2009.

[54] M.M. Roy, E. Tomita, N. Kawahara, Y. Harada and A. Sakane; “Performance and emission comparison of a supercharged dual-fuel engine fueled by producer gases with varying hydrogen content”, International Journal of Hydrogen Energy, Vol. 34(18), pp. 7811-7822, 2009.

Anushka Pradhan is working on “Design and analysis of STHE for waste heat recovery from 5 kW gasifier system” in Maulana Azad National Institute of Technology, Bhopal, M.P. India. Email: a.pradhan2780@gmail.com

Dr. Prashant baredar is Associate Professor working in Maulana Azad National Institute of Technology, Bhopal, M.P. India. Email: prashant.baredar@gmail.com

Dr. Anil Kumar is awarded Post Doctoral Fellowship from Prince of Songkla University, Hat Yai, THAILAND. He was Assistant Professor in Energy Centre, MANIT, Bhopal, India. Before joining MANIT, Bhopal, he was working as Lecturer in Department of Mechanical Engineering in University Institute of Technology, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal (MP State Technological University). He has more than 10 years of research and teaching experience in higher technical education. He holds Ph.D. degree in solar thermal technologies from Indian Institute of Technology Delhi. Dr Kumar’s main area of interest is solar thermal technology, distribution of energy generation, clean energy technologies and application in buildings. He has published several books. Dr. Kumar has published more than 80 research articles in journals and at International conferences and also one patent in his credit. In his tenure at MANIT, he has supervised 04 Ph.D. and 20 M.Tech. students Dr. Kumar has carried various experimental projects in the area of solar water heating, solar drying for different crops, active and passive greenhouse dryer, solar collector assisted greenhouse dryers, and ground heat exchangers. Dr. Kumar has visited UK and Thailand.

*Corresponding Author: anilkumar76@gmail.com