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EFFECT OF VARYING ENGINE PARAMETERS AND SYNGAS COMPOSITION ON THE COMBUSTION CHARACTERISTICS, PERFORMANCE AND EMISSION OF SYNGAS-DIESEL DUAL FUEL ENGINE – A REVIEW

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ABSTRACT
In this study, a literature survey of research papers on the effect of engine load, injection timing and syngas composition on the combustion characteristics performance and emission of dual fuel compression ignition (CI) engine using syngas was carried out. In general, operation of CI diesel engine with syngas leads to reduced engine power because syngas has lower heating value compared to diesel. However, dual fuel operation is considered as a hopeful way to control the emissions of nitrogen oxides on CI diesel engines and it affects positively on emissions of carbon dioxide, whereas it leads to a substantial increase in emissions of carbon monoxide and total hydrocarbons compared to the observed in the process of normal diesel. Advanced injection timing of diesel fuel and supercharging of the intake air-syngas mixture are techniques suggested to improve the engine performance. In addition varying of the syngas composition; especially combustible constituents (H_2, CO, and CH_4) combined with exclusion of CO_2 from syngas composition are proposed as a way to improve engine performance and reduce emissions.

Keywords: compression ignition (CI), syngas, performance, emission, combustion.

INTRODUCTION
A great interest has been emerged on the use of alternative fuels in engines operating on petroleum fuel, which is going to decline in the future. That interest was because of the serious threat posed by greenhouse gas emissions from these engines, which increases the environmental protection concerns. Biomass has the capability of absorbing carbon dioxide from the air while it was growing and releasing it back into the air when combusted in internal combustion engine. Therefore, the produced syngas from a process of biomass gasification could be a very good solution to help on the climate protection [1-6]. Syngas is a gaseous fuel consisted of combustible constituents comprised of primarily hydrogen (H_2), carbon monoxide (CO), and methane (CH_4), and non-combustible constituents comprised of carbon dioxide (CO_2), nitrogen (N_2) and water vapor (H_2O). It is also possible to find varying percentage of CO, H_2, CH_4, CO_2, N_2 and H_2O in syngas composition as stated by [7]. Syngas can not be used alone to run a compression ignition (CI) diesel engine due to its high self-ignition temperature, therefore it is used through dual fuel operation mode [8-12]. Syngas was used in a variety of syngas-powered engines, a water-cooled CI diesel engine was operated by Sobyanin *et al.* [13] [13] on a syngas generated from the common gas, a steady speed of 1300 rpm was used while testing the engine. The engine was tested at standard conditions of an unadulterated diesel and at the partial substitution of diesel by syngas on dual fuel mode [1-, 14]. Measurements of engine exhaust emission were collected, a reduction of NO_X emission was observed with the addition of syngas to the pilot fuel in each of the ultra-lean and moderately rich mixtures; while an increment of NO_X emission was acquired in the moderate mixture. Hence, the decrease of NO_X substance with the expansion of syngas could be allocated to the weakening impact of nitrogen and carbon oxides together with the left over water held in syngas. While hydrocarbon was built just marginally with syngas expansion staying at a level lower than 40 ppm. CO emission was formed extensively due to an extensive CO content in syngas. Besides, because of the weakening impact of idle segments of syngas, the diminishing of the combustion temperature and related weakening of combustion efficiency, CO presence in exhaust emission could be increase as well. The emissions from responding CI dual fuel engine working on producer gas as fuel was studied by Seridhar, *et al.* [15]. The engine was firstly operated at high engine speed utilizing diesel with producer gas. The emitted NO_X was discovered to be lower in dual fuel mode compared to pure diesel fuel, while the levels of CO were higher because of ignition inefficiencies. On the other hand, lower NO_X and CO levels were discovered when a producer gas was utilized as a flash ignition engine. Generally, the gaseous dual-fuel CI engines performance and emission are affected by some engine operating parameters, specifically load, liquid fuel injection timing, and air inlet condition. Numerous researchers have carried out a number of studies in order to study the effect of the above stated engine parameters on the performance, emission and ignition aspects of CI engines at dual fuel mode. Different engines operated with different gaseous fuels and liquid fuels were investigated by the researchers.

EFFECT OF ENGINE LOAD
Previous studies proved that such a limit of dual fuel engine may substantially vary with the changes in dual fuel engines load. Studies on a dual fuel engine

performance and emission operated by rubber seed oil with coir-pith producer gas were performed by Ramadhas, *et al.* [16]. Different producer gas to air flow ratios were inducted into an engine at distinctive load conditions. The engine was enhanced in order to achieve the maximum diesel fuel replacement in the process of dual fuel operation. An evaluation was conducted between the engine performance and emission at dual fuel engine and pure diesel mode at different load cases. Running the engine with oil-coir-pith at dual-fuel mode has demonstrated higher specific energy consumption for all loads. When compared to well-ordered diesel oil mode, the measured exhaust emission was higher at dual fuel mode operation. The replacement of liquid fuel has reduced amazingly at higher loads due to the lower calorific value of syngas and incomplete combustion. A rise in carbon monoxide emission was detected due to the increase in the flow of syngas. It was noted that the emission has reduced slightly with an upsurge in load at dual fuel mode of operation. Greater intensity of CO emission at dual fuel mode operation was due to incomplete combustion.

The effect of load variation on the combustion characteristics, performance and emission of a syngas-diesel dual fuel engine was studied by Sahoo *et al.* [17]. However, dual fuel mode with syngas generation revealed substandard engine performance at low engine load values which ranged from 20 to 40%. At part loads, there was a slight improvement on thermal efficiency. However, the thermal efficiency at dual fuel operation was enhanced over half load. At the minimal load situations, the temperature of cylinder and it's force have declined because of delayed combustion and ineffective oxidation of the syngas fuel. A reduction in the amount of diesel replacement was established in the situations of high and low engine loads. An incomplete burning of syngas was seen due to inadequate availability of oxygen at minimal and full load operations which also reduced the diesel substitution level. The volumetric efficiency has decreased for dual fuel mode at all loads as shown in Figure-1 because of the dislocation of sucked air by syngas. An increase in the NO_X concentration was noticed when the engine loaded to a high level due to the increase in cylinder temperature and pressure. The increase in NO_X concentration at higher loads was due to the faster flame travel of H_2 molecules in syngas fuel which led to increase the combustion temperature which could be interpreted from the exhaust gas temperature as shown in Figure-2. At low loads, poor combustion was noticed when using of syngas with air which resulted in the emissions of HC at a higher level. Moreover, improvement in load consequently increased the temperature inside the combustion chamber, which led to a good combustion of syngas and lower HC emissions. The HC emissions started to increase significantly again when over 80% load applied because the mixture of air and syngas became rich which led to a poor combustion, thereby diminishing the availability of air.

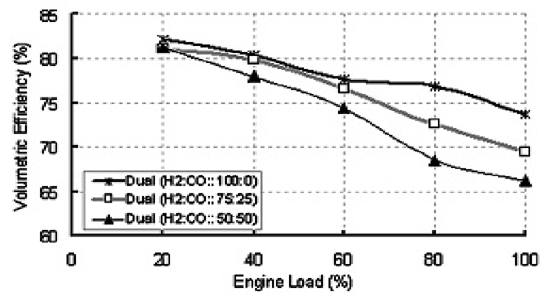

Figure-1. Volumetric efficiency VS load [17].

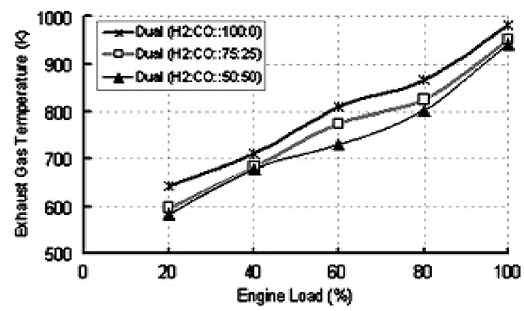

Figure-2. Exhaust gas temperature VS load [17].

Generally, the emissions of CO begins to increase when the load increases due to the deficient oxygen in combustion as stated by Heywood [21]. However, in such operations of dual fuel, the emissions of CO started to increase correspondingly with the increase in load because of the existence of CO in syngas composition including late combustion.

EFFECT OF INJECTION TIMING

Good combustion of diesel engines need auto-ignition of the fuel as it is injected near the top dead centre (TDC) into the hot swirling compressed cylinder gas. Longer delays on the diesel injection leads to unacceptable rates of pressure rise because more fuel is ready to burn when combustion occurs, advanced injection timing is expected to be a good idea for controlling these issue [18]. An investigation made by Roy *et al.* [19] regarding the effect of pilot fuel injection timing on the dual-fuel operation of an engine fuelled by simulated producer gases and diesel agreed with the above statment by Nwafor [18]. An increase on IMEP was obtained when the diesel injection timings advanced as shown in Figure-3. Similar trend was noted for indicated thermal efficiency with advanced injection timings. Figure-4 showed that the maximum cylinder pressure gradually increased with advancing the injection timing at an equivalence ratio of 0.4. Very low maximum cylinder pressure was obtained at an equivalence ratio of 0.95, this is because the main combustion occurred in the expansion stroke.

The performance and emission of a dual fuel diesel engine with advanced injection timing was investigated by Hassan *et al.* [20], a producer gas was used as primary fuel with diesel. The basic engine injection

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timing was 14° BTDC, experiments were performed using diesel fuel only, premixed dual fuel producer gas-diesel (PDF), and supercharged dual fuel producer gas-diesel (SC). Fuel injection timings were advanced to three injection timings (17°, 20°, and 23° BTDC) of both PDF and SC. It was noted that brake thermal efficiency and diesel fuel replacement increased with advanced injection timing in a supercharged engine as shown in Figures-5 and 6. In addition, emission of CO and specific energy consumption decreased significantly when compared to basic injection timing at operation with premixed producer gas and diesel at dual fuel operation as shown in Figures-7 and 8.

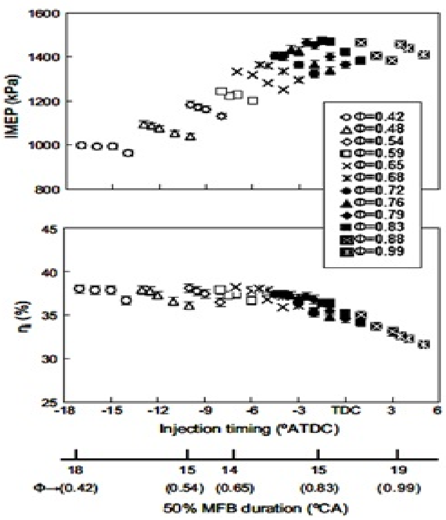

Figure-3. IMEP and η_i at various equivalence ratio [19].

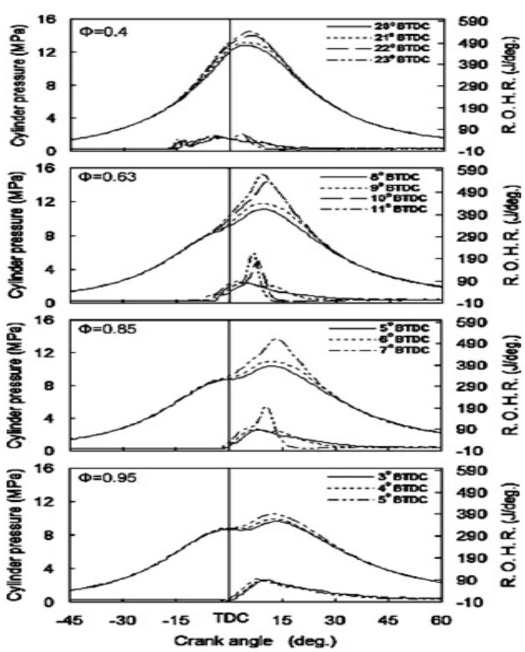

Figure-4. In-cylinder pressure and rate of heat release of low H_2 content producer gas [19].

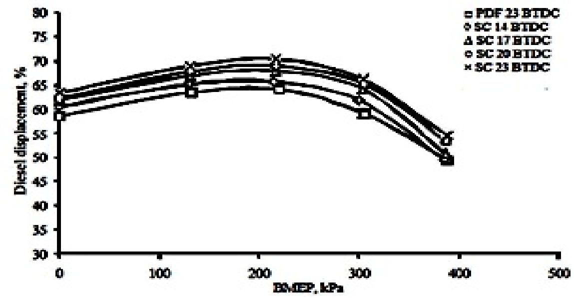

Figure-5. Diesel replacement at various injections timings [20].

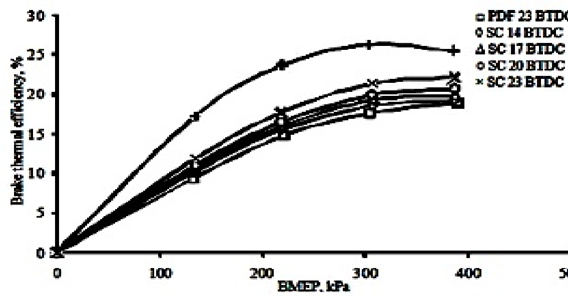

Figure-6. BTE at various injection timings [20].

The performance and emission of a dual fuel diesel engine with advanced injection timing was investigated by Hassan *et al.* [20], a producer gas was used as primary fuel with diesel. The basic engine injection timing was 14° BTDC, experiments were performed using diesel fuel only, premixed dual fuel producer gas-diesel (PDF), and supercharged dual fuel producer gas-diesel (SC). Fuel injection timings were advanced to three injection timings (17°, 20°, and 23° BTDC) of both PDF and SC. It was noted that brake thermal efficiency and diesel fuel replacement increased with advanced injection timing in a supercharged engine as shown in Figures-5 and 6. In addition, emission of CO and specific energy consumption decreased significantly when compared to basic injection timing at operation with premixed producer gas and diesel at dual fuel operation as shown in Figures-7 and 8.

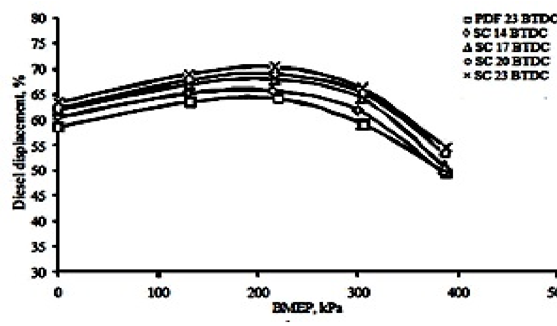

Figure-7. Diesel replacement at various injection timings [20].

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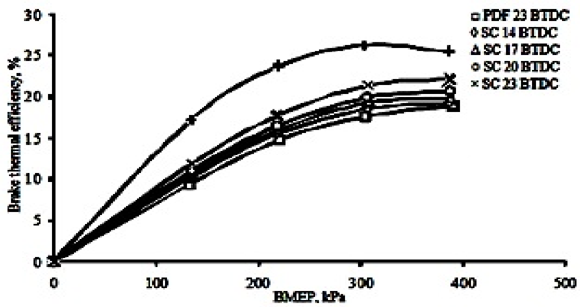

Figure-8. BTE at various injection timings [20].

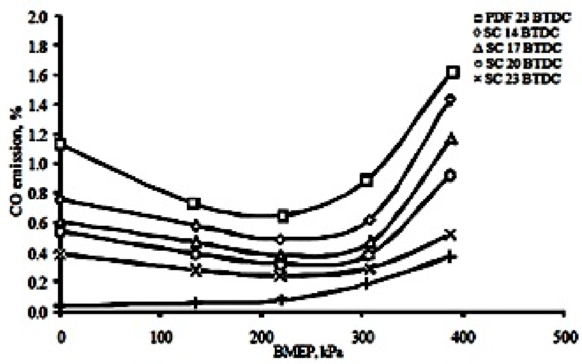

Figure-9. CO emission at various injection timings [20].

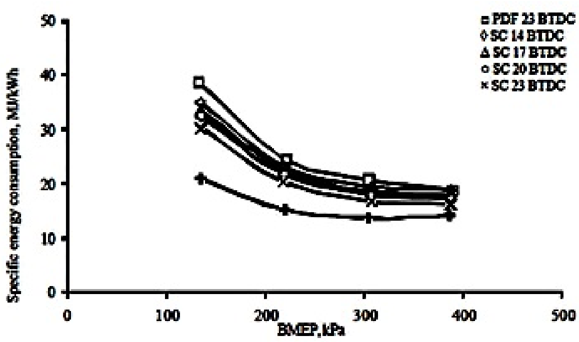

Figure-10. SEC at various injection timings [20].

EFFECT OF SYNGAS COMPOSITION

Numerous researchers carried out investigations to determine the outcome of CI engines operating with various syngas compositions as fuel. The purpose of these studies was to provide information on the effect of syngas composition on the performance and emission of a CI engines when operating with syngas in dual fuel mode. Hydrogen is a very important constituent of syngas, because it has extremely clean combustion feature, excessive speed of flame propagation, and broad flammability limits. This component if increased in syngas considerably decreases the duration of combustion and consequently upsurges the engines efficiency. Interestingly, high thermal efficiency and low emissions could be attained with the addition of H_2 amount in syngas because H_2 has immense capability to increase the lean combustion limit without any misfire [21. Methane is also one of the combustible constituents in syngas which is characterized as an outstanding anti-knock component, but the low rate of flame spread and high auto-ignition temperature are considered as two of its bad characteristics. It should be noted that the presence of carbon monoxide in a mixture of syngas fuel is very important in order to facilitate the mixture reactivity. This is because the oxidation process of CO in the presence of H_2 is a significant issue relating to oxidation process of syngas. Sung and Law [22] stated that it is obvious that in case the trace quantity of H_2 and moisture are present the overall reactivity is greatly accelerated. The oxidation between CO and OH plays important role in contributing substantial portion of the heat release.

An investigation was made by Roy, *et al.* [19] on the performance of a diesel engine dually fuelled by producer gas while changing the H_2 content and keeping the CO content constant. It was noted that when the producer gas contained 20% H_2, a greater thermal efficiency reached up to 38% was achieved with a wider range of fuel-air equivalence ratio in the range from 0.42 to 0.79. However, for engine operation with lower H_2 of 13.7% content in syngas a similar grade of thermal efficiency was achieved with narrower range of equivalence ratio from 0.52 to 0.68 as shown in Figure-9.

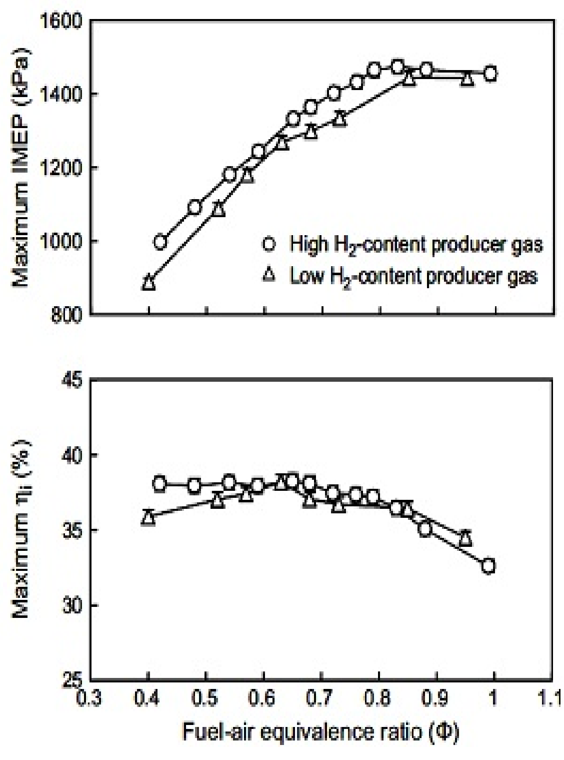

Figure-11. Maximum IMEP and η_i of two producer gases at various equivalence ratios [19].

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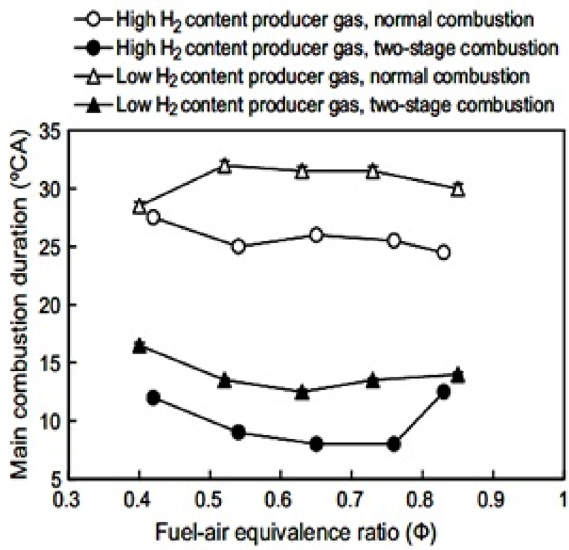

Figure-12. Main combustion of two producer gases for normal and two-stage combustion [19].

It was indicated that the producer gas composition with higher H_2 content was superior than the one with lower H_2 content, which reduced the combustion duration in the range from 4 to 5 °CA as shown in Figure-10. The producer gas composition with high H_2 content also enhanced the reduction in emission levels of CO and HC up to 25% less. While it was noted that the mixture which contained the higher amount of H_2 led to very high levels of nitrogen oxides emission. An exploration was made by Tomita *et al.* [23] in the performance and combustion characteristics of an engine dually fuelled by supercharged syngas with micro-pilot ignition. It was determined that the engine was able to work steadily by increasing the content of hydrogen in syngas even at ϕ = 0.45 achieving high level of efficiency and constant combustion, as the lean limit got enhanced by the presence of amplified hydrogen. A pilot ignited engine was oprated by Azimov *et al.* [24] with different compositions of syngas in dual fuel and supercharging mode to study the effect of syngas composition on engine performance and emissions. It was revealed that the influence of H_2 and CO_2 content in syngas was an obvious on the engine performance and emissions. However, enhanced H_2 content produced an advanced combustion temperatures and high efficiency as well as higher NO_X emissions, but the emissions of CO and HC has reduced. Nevertheless, making the equivalence ratio low has reduced the emissions of NO_x consistently for different syngas compositions. In addition, the presence of high amount of hydrogen in syngas also increased the ignitability, and reduced the ignition delay for the first stage consequently. It was indicated that the mean combustion temperature, thermal efficiency, and emissions of NO_X were diminished when CO_2 content expanded to a ratio of 34% in the syngas. An increment of CO_2 amount in syngas brought about the mixture dilution, relating decline in the fuel oxidation reactions rate and consequent combustion. Subsequently, keeping in mind the end goal to accomplish high efficiency of an engine dually fuelled with syngas (low-energy-density fuel), the concentration of CO_2 in its composition should be regulated.

Sahoo *et al.*[17] used three distinctive volumetric syngas compositions as fuels in diesel engine in dual fuel operation modes. A syngas, containing 100% $H_{2,}$ depicted better engine thermal efficiency comparatively. The main reason was the faster combustion rate and higher degree of premixing of H_2 and CO. Syngas with the volumetric composition of H_2:CO equal to 75:25, lead to the significant thermal efficiency as compared to the one with the volumetric composition of H_2:CO equal to 100:0. The former performed well due to the improved CO oxidation in the combustion chamber as oppose to the mode exclusively containing H_2 gas. The latter was less efficient due to the fact that hydrogen gas is lighter than the air, which ultimately displaced some of the air flowing into the engine air inlet; resulting of a reduced volumetric efficiency in dual fuel mode as shown in Figure-1 above. While, the precense of lower H_2 amount in syngas fuels, led to impaired maximum diesel substitution rate because of the lower rates of energy liberation and decrement in thermal efficiency. Higher levels of HC and CO emission were noticed for syngas having 25% and 50% of CO content. Figure-11 show that, syngas composition with 100% H_2 presented the highest amount of peak pressure (70.5 bar) when compared to other two compositions because of the hydrogen higher energy content, shorter combustion duration and ignition delay.

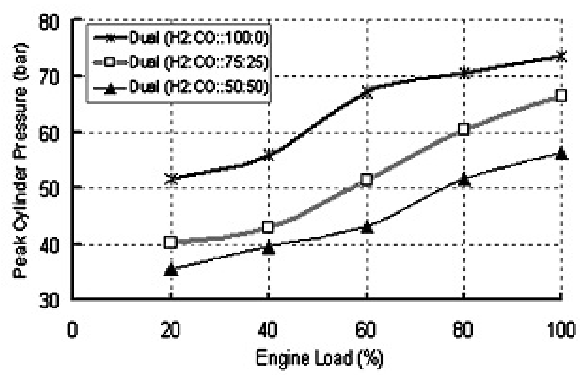

Figure-13. Peak pressure VS load [17].

It could be seen from previous research studies that the presence of hydrogen, carbon monoxide and methane are the most influential factors; affecting the performance and emission by the use of different syngas compositions in dual fuel CI engines. Furthermore, the addition of H_2 to CO-based syngas gave a rise to the combustion temperatures that eventually boosted up the nitric oxide (NO_X) emissions under stoichiometric combustion as reported by Li and Karim [25]. Alternatively, the NO_X reduction taken place when combustion temperature and maximum cylinder pressure were lowered as stated by Heywood [26]. While, NO_X discharge was getting lower when combustion entered the lean region. Another reason of elevated NO_X discharge, in dual fuel modes, could be the H_2 higher flame temperature as compared to that of CO.

CONCLUSIONS

The future scenario of syngas admixing in the syngas-diesel dual fuel engine could be linked with utilization of different compositions of imitated syngas under diverse supercharging condition. The engine performance, emission and combustion characteristics ought to be examined for different injection timing and load conditions in order to achieve maximum diesel savings at dual fuel operation. Furthermore, the flame propagation should be studied at the same conditions to know what is going inside the engine combustion chamber and support the results for engine combustion characteristic. Besides using powerful multipurpose thermo-fluid dynamics software to simulate the combustion process of syngas/diesel dual fuel engines could be a better option for accurate results. Keeping in view the comparison with previous published data/reports, it could be concluded that, positive and negative effects would be brought with the usage of syngas instead of other gaseous fuels like hydrogen. The positive effects include the low emission of CO_2 and NO_X while the negative effect is the low power output and considerable increase on THC and CO emission compared to the observed on normal diesel engine. However, performance of syngas generators should be optimized in order to overcome the negative effects, operational parameters of engines should be tuned and increasing the amount of combustible mixture inside the combustion chamber is the key method to boost the engine power output and reduce the NO_X emissions by improving the combustion.

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