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An Investigation of the Combustion and Emission Characteristics of Compression Ignition Engines in Dual-Fuel Mode

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Abstract

Nowadays automobiles have become significantly essential to our modern life style. On the other hand, future of automobiles, built on the internal combustion engines, has been badly hit by the twin problems due to diminishing fuel supplies and environmental degradation. Thus, it is very important to identify some clean-burning, renewable, alternative fuels to ensure the safe survival of internal combustion engines. However, it is not possible to have a common alternative fuel for universal application in the existing engines that have been designed to operate on petroleum-based fuels. Towards this, scientists have proposed a range of solutions for diesel engines, one of which is the use of gaseous fuels as a complement for liquid diesel fuel. These engines, which use conventional diesel fuel and gaseous fuel, are referred to as 'dual-fuel engines'. In this work an attempt is made to find the role of various operating parameters in optimizing engine operating and design parameters, and the effect of the type of gaseous fuel on the performance and emissions of the gas diesel engines. The 'dual fuel concept' is a promising technique for controlling both NOx and soot emissions even on existing diesel engine. But, HC, CO emissions and 'bsfc' are higher for part load gas diesel engine operations.

1. Introduction

National interest in generating alternative fuels for internal combustion (IC) engines continues to be strong due to environmental concerns and/or the uncertainties associated with the future availability of fossil fuel. Mostly, the interest lies in identifying alternative sources of fuel energy supply. Natural gas, bio-derived gas and liquids appear more attractive in view of their friendly environmental nature [1,2].The gaseous fuels are getting more positive response from researchers and end-users compared to past because of current unfolding developments. Gas is clearly the fossil fuel of least environmental impact. When burnt, it produces virtually insignificant SOx and relatively little NOx, the main constituents of acid rain, and substantially less CO_2, a key culprit in the greenhouse debate, than most oil products and coal [3].

Gaseous fuels have high octane numbers, and therefore, suitable for engines with relatively high compression ratio. Gaseous fuels also promise to be suitable for higher compression engines, since it is known that they resist knock more than conventional liquid fuels, as well as producing less polluting exhaust gases if appropriate conditions are satisfied for its mixing and combustion. Therefore, it is more economical and of environmental advantage to use gaseous fuel in diesel engines that use the 'dual-fuel concept' [4, 5]. Due to limited resources of fossil fuels, alternative solutions have been proposed by many scientists. In 1939, the first commercial dual-fuel engine, fuelled by town gas or other types of gaseous fuels, was produced by the National Gas and Oil Engine Company in Great Britain. This type of

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engine was relatively simple in operation and was mainly employed in some areas where cheap stationary power production was required. During the Second World War, scientists in Great Britain, Germany and Italy paid more attention to the possible application of dual-fuel engines in civil and military areas due to the shortage of liquid fuels. Some vehicles with diesel engines were successfully converted to dual-fuel running. Different kinds of gaseous fuels, such as coal gas, sewage gas or methane, were employed in conventional diesel engines [6-7]. After the Second World War, due to economical and environmental reasons, dual-fuel engines have been further developed and employed in a very wide range of applications from stationary power production to road and marine transport, such as in long and short haul trucks and buses. Some conversions from the original compression ignition diesel engines to dual-fuel operation are made by manufacturers utilizing a double plunger system or two pumps in the injection system of the engine to handle the small quantity of diesel fuel required for ignition [8].

Diesel engines, with appropriate relatively simple conversion can be made to operate on gaseous fuels efficiently. Such engines usually have the gaseous fuel mixed with the air in the engine cylinders, either through direct mixing in the intake manifold with air or through injection directly into the cylinder. The resulting mixture after compression is then ignited through the injection of a small amount of diesel fuel (the pilot) in the usual way. This pilot liquid fuel auto-ignites to provide ignition sources for subsequent flame propagation within the surrounding gaseous fuel mixture. Unlike the spark ignited gas engine, which requires an adequate and uninterrupted gas supply, most current dual-fuel engines are made to operate interchangeably, either on gaseous fuels with diesel pilot ignition or wholly on liquid fuel injection as a diesel engine. Accordingly, a dual-fuel engine tends to retain most of the positive features of diesel operation [9]. Even it surpasses occasionally those of the diesels, producing higher power outputs and efficiencies. This is achieved without significant smoke or particulates emission and with reduced NOx production [10], while having reduced peak cylinder pressures and quieter operation. When considering a gaseous fuel for use in existing diesel engines, a number of issues are important. These issues include the engine operating and design parameters, and type of gaseous fuel supply to the engine.

2. Literature Review

2.1 Dual-fuel concept

Available technologies for reciprocating IC engines are generally divided in two categories: compression-ignition (CI) and spark-ignition (SI) engines. In CI engines (diesel engines), air is compressed at pressures and temperatures at which the injected liquid fuel fires easily and burns progressively after ignition. Whereas, SI engines (Otto engines) that runs according to the Beau de Rochas cycle [11], the carbureted mixture of air and vaporized fuel (high octane index) is compressed under its ignition point and then fired at a chosen instant by an independent means. In a dual-fuel engine, both types of above combustion coexist together, i.e. a carbureted mixture of air and high octane index gaseous fuel is compressed like in a conventional diesel engine. The compressed mixture of air and gaseous fuel does not auto-ignite due to its high auto-ignition temperature. Hence, it is fired by a small liquid fuel injection which ignites spontaneously at the end of compression phase. The advantage of this type of engine is that, it uses the difference of flammability of two used fuels. Again, in case of lack of gaseous fuel, this engine runs according to the diesel cycle by switching from dual-fuel mode. The disadvantage is the necessity to have liquid diesel fuel available for the dual-fuel engine operation [12].

2.2 Modification in internal combustion gas engines

In dual-fuel gas diesel engines, the normal diesel fuel injection system still supplies a certain amount of diesel fuel. The engine however induces and compresses a mixture of air and gaseous fuel that is prepared in the external mixing device. The compressed mixture is then ignited by energy from the combustion of the diesel fuel spray, which is called pilot fuel. The amount of pilot fuel needed for this ignition is between 10% and 20% of the operation on diesel alone at normal working loads and the amount differs with the point of engine operation and its design parameters. During part load engine operation, the fuel gas supply is reduced by means of a gas control valve. However, a simultaneous reduction of the air supply decreases the air quantity induced. Hence, the compression pressure and the mean effective pressure of the engine are decreased. This would eventually lead to a drop in power and efficiency. The drastic reduction in the compression conditions might even become too weak for the mixture to effect self-ignition.

Therefore, dual-fuel engines should not to be throttled/ controlled on the air side.

Ideally, there is a need for optimum variation in the liquid pilot fuel quantity used any time in relation to the gaseous fuel supply so as to provide for any specific engine the best performance over the whole load range desired [12]. Usually, the main goal, for both emissions and economic reasons, is to minimize the use of the diesel fuel and maximize its replacement by the cheaper gaseous fuel throughout the whole engine load range. Normally, the change over from dual-fuel to diesel operation and vice versa can be made automatically, even under load conditions [3].

2.3 Combustion processes in gas diesel engine and conventional diesel engine

The combustion processes in CI engines running on pure diesel fuel can be divided into four stages as shown in Fig. 1. They are, A–B: period of ignition delay; B–C: premixed (rapid pressure rise) combustion; C–D: controlled (normal) combustion; and D–E: late combustion. Point ‘A’ is the start of fuel injection and ‘B’ for start of combustion.

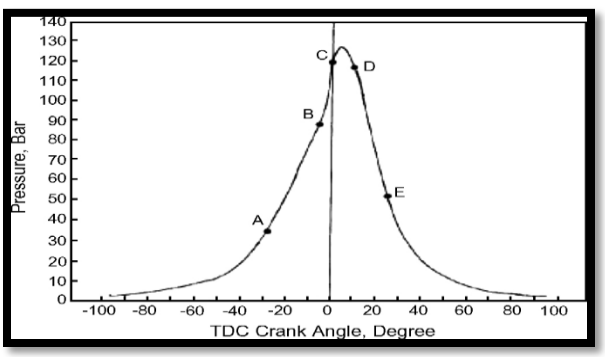

Fig: 1. Details of combustion processes in diesel engine [13]

However, the combustion processes in gas-fumigated dual-fuel engines using pilot injection have been identified to take place in five stages as shown in Fig. 2. They are the pilot ignition delay (AB), pilot premixed combustion (BC), primary fuel ignition delay (CD), rapid combustion of primary fuel (DE) and the diffusion combustion stage (EF).

Ignition delay (AB) of injected pilot fuel exists longer than the pure diesel fuel operation. This is due to the reduction in oxygen concentration resulting from gaseous fuel substitution for air. The pressure rise (BC) is moderately low as compared to pure diesel fuel operation due to the ignition of small quantity of pilot fuel.

Again, there is a finite time lag between the development of the first and second pressure rises due to a longer ignition delay of gas– air mixture, a

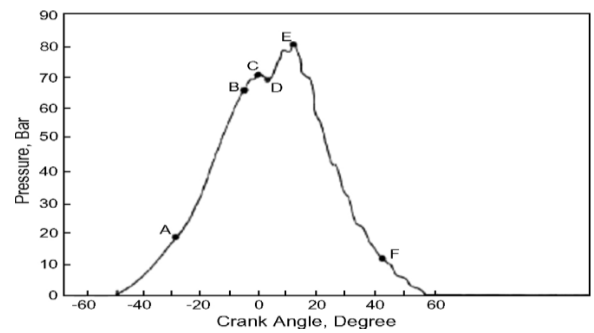

Fig: 2. Dual-fuel pilot injection pressure–crank angle diagram [13]

result of the high self-ignition temperature. However, this ignition delay is short as compared with the initial delay period due to the pilot fuel injection. The pressure decreases slowly (CD) until the actual combustion of the fumigated gas starts. The phase of combustion (DE) is very unstable because it started with flame propagation that has been initiated by the spontaneous ignition of pilot fuel. The pressure rise here does not cause any operating problem since it occurs in an increasing cylinder volume. Diffusion combustion stage (EF) starts at the end of rapid pressure rise and continues well into the expansion stroke. The success of this phase primarily depends on the length of ignition delay [13].

3. Performance of ‘‘gas diesel engines’’

Gaseous fuels are considered to be good alternative fuels for passenger cars, truck transportation and stationary engines that can provide both good environmental effect and energy security [4]. However, as some of the engine operating and design parameters namely, load, speed, compression ratio, pilot fuel injection timing, pilot fuel mass, inlet manifold condition, composition of gaseous fuel candidates vary, the performance of the dual-fuel gaseous engines are affected.

3.1 Effect of engine load

The effect of load on combustion noise for the diesel and dual fuel engine (Fig. 3), at an engine speed of 1200 rpm is examined by Selim [14]. The pressure rise rate (combustion noise) for the diesel engine increases slightly when the load increases. For the dual-fuel mode, the combustion noise also increases when the load increases and is always higher than that for the diesel fuel case. Increasing the load at constant speed results in an increase in the mass of gaseous fuel admitted to the engine, since the pilot mass injected remains constant at all loads. This increase in the mass of methane then causes an increase in the ignition delay period of pilot diesel which then auto-ignites and starts burning the gaseous fuel at a higher rate of pressure rise. This is also shown by Nielsen et al. [15] on dual-fuel engine where natural gas is admitted in the inlet air manifold.

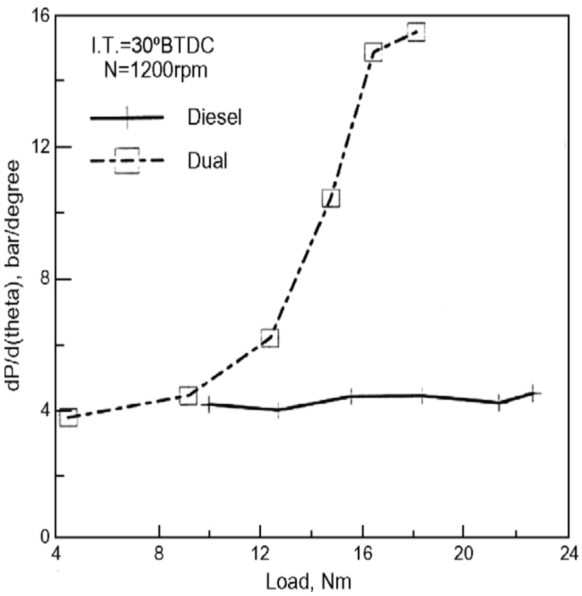

Fig: 3. Effect of engine load on pressure rise rate for the diesel and dual-fuel engines [14]

Concentration of pollutants is investigated with diesel alone and dual-fuel mode (producer gas) at different loads (10, 20, 30 and 40 kW) and is given in Table 1. NOx emissions in dual-fuel mode are lower than the emissions from diesel engine in diesel alone mode. SO2 levels are low in dual fuel mode. This is due to low sulphur content in biomass fuel. The CO emission in dual fuel mode is higher than that of diesel alone. High concentration of CO in the dual-fuel exhaust is an indication of incomplete combustion. At part load condition, concentration of CO increases.

An experimental investigation has been conducted by Papagiannakis and Hountalas [19] to examine the effect of dual fuel combustion on the performance and pollutant emissions of a DI diesel engine. The engine has been properly modified to operate under dual-fuel operation. Under dual-fuel operation, an effort has been made to keep the pilot amount of diesel fuel constant, while the power output of the engine is adjusted through the amount of gaseous fuel. Referring to Fig. 4, the term 'z' refers to the percentage of gaseous fuel. At part engine load, cylinder pressure under dual-fuel operation diverges from the respective values under normal diesel operation. The lower cylinder pressures observed under dual-fuel operation during the compression stroke are the result of the higher specific heat capacity of the NG–air mixture. The total heat release rate under dual-fuel operation is slightly higher compared to the one under normal diesel operation; revealing late combustion of the gaseous fuel. But, the effect on the cylinder pressure is small since it is in the expansion stroke. At high engine load (Fig. 5), the cylinder pressure traces under dual-fuel operation diverge again from the respective values under normal diesel operation during the compression stroke and the initial stages of combustion. This difference is again more evident at low engine speed where the combustion rate under dual-fuel operation during the premixed controlled combustion phase is significantly lower compared to the one under normal diesel operation. It is revealed that the total rate of heat release under dual-fuel operation is obviously higher compared to the one under normal diesel operation. The effect is stronger at low engine speed, revealing later combustion of the gaseous fuel and this obviously has an effect on the 'bsfc'.

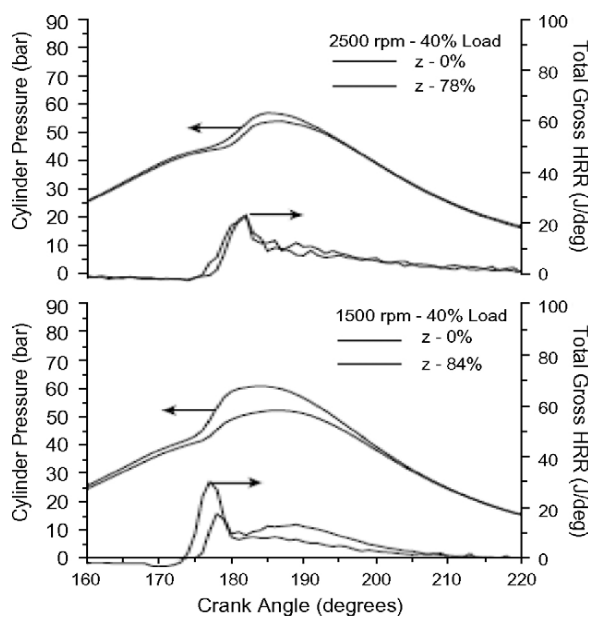

Fig: 4. Cylinder pressure and total heat release traces under normal diesel (z=0%) and dual-fuel (z > 0%) operation for 1500 and 2500 rpm engine speed at 40% load [19]

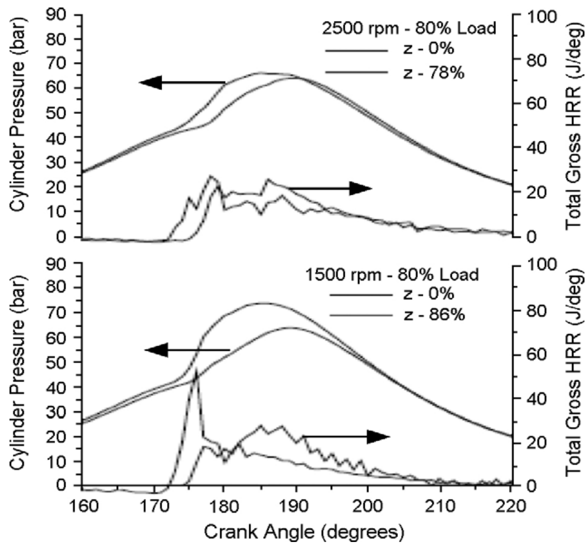

Fig: 5. Cylinder pressure and total heat release traces under normal diesel (z = 0%) and dual-fuel (z > 0%) operation for 1500 and 2500 rpm engine speed at 80% load [19].

3.2 **Dual-Fuel engine emissions**

The formation of nitric oxide (NO) is favored by high oxygen concentration and high charge temperature [11, 21, 22]. NOx concentration is affected considerably by the presence of gaseous fuel–air mixture. The concentration of NOx under dual-fuel operation is lower compared to the one under normal diesel operation at the same engine operating conditions (i.e. engine speed and load). At low engine loads, the NOx concentration under dual-fuel operation is slightly lower compared to the one under normal diesel operation (Fig. 6).This is mainly as a result of the lower rate of premixed controlled combustion of the gaseous fuel, which results in lower charge temperature inside the combustion chamber compared to normal diesel operation. At higher load, the NOx concentration under dual-fuel operation is considerably lower compared to the one under normal diesel operation.

The rate of CO formation is a function of the unburned gaseous fuel availability and mixture temperature which controls the rate of fuel decomposition and oxidation [21,23]. The CO emissions under dual-fuel operation are significantly higher as shown in Fig. 7. At low engine speed, CO concentration under dual-fuel operation clearly decreases with the increase of engine load. This is the result of the improvement of gaseous fuel utilization especially during the second phase of combustion. At high engine speed, the increase of engine load does not seem to affect the concentration of CO due to the less time available for combustion.

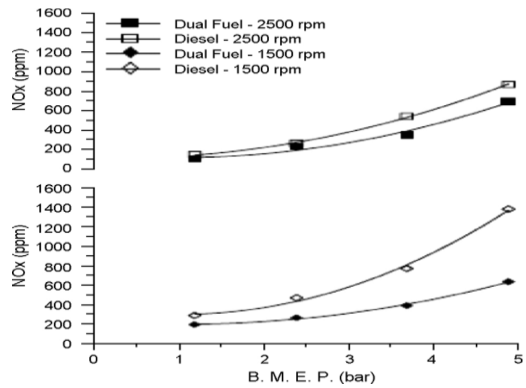

Fig: 6. Variation of nitric oxide under normal diesel and dual-fuel operation versus load at 1500 and 2500 rpm engine speed [19]

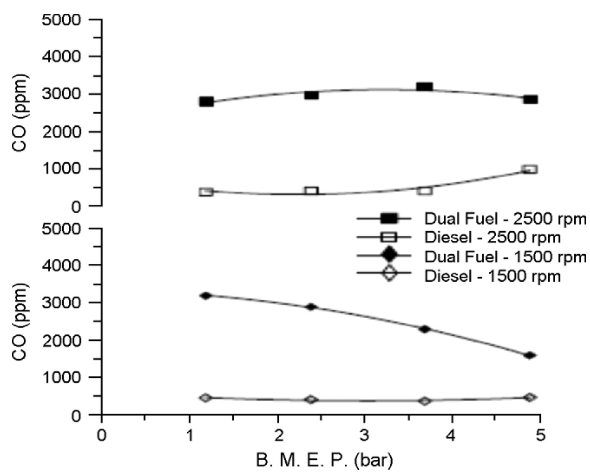

Fig: 7. CO under normal diesel and dual-fuel operation versus load at 1500 and 2500 rpm engine speed [19]

At low engine load, HC emissions under dual-fuel operation are considerably higher compared to the ones under normal diesel operation (Fig. 8). With the increase of engine load, there is a sharp decrease of HC emissions under dual-fuel operation. This is the result of the increase of burned gas temperature that helps oxidize efficiently the UBHCs. But for all cases examined, the HC emissions are considerably higher under dual-fuel operation compared to normal diesel operation.

Soot emissions under dual-fuel operation are considerably lower compared to the ones under normal diesel operation for all cases examined as it is shown in Fig. 9. It can be seen that under normal diesel operation, soot emissions increase with increasing engine load.

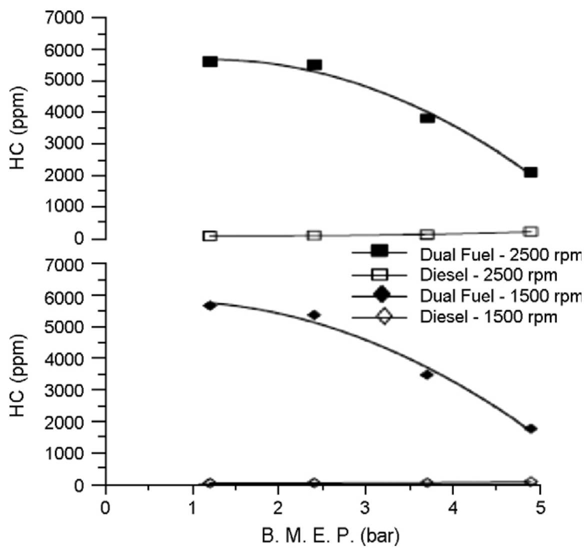

Fig: 8. UBHC under normal diesel and dual-fuel operation versus load at 1500 and 2500 rpm engine speed [19]

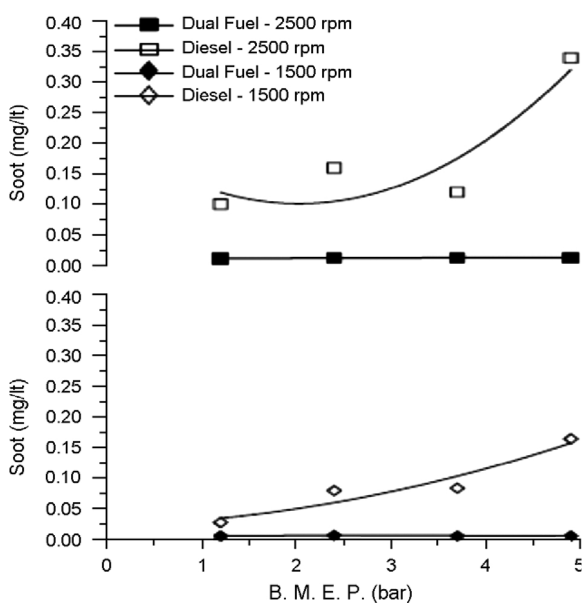

Fig: 9. Soot emissions under normal diesel and dual-fuel operation versus load at 1500 and 2500 rpm engine speed [19]

3.3 Effect of pilot fuel injection timing

The injection timing of the pilot fuel is an important factor that influences the performance of dual-fuel engines. For a fixed total equivalence ratio, advancing the injection timing increase the peak cylinder pressure because more fuel is burned before TDC and the peak pressure moves closer to TDC. Retarding the injection timing decreases the peak cylinder pressure because more of the fuel burns after TDC. This is because, the pilot fuel combustion is delayed and thus, the temperature of the mixture is not enough to propagate the flame in the whole gaseous fuel–air mixture; and consequently, incomplete combustion of the gaseous fuel mixture takes place. The charge temperature increases with advancing the injection timing of the pilot fuel and the associated higher energy release rates of the mixture. Similarly, the rates of pressure rise during the combustion of the gaseous fuel increases with advancing the injection timing of the pilot fuel.

The effect of advanced injection timing on the performance of NG used as primary fuel in dual-fuel combustion has been examined by Nwafor [2]. The injection is first advanced by 5.58 (i.e. 35.58 BTDC). The engine runs for about 5 min at this timing and then stops and with subsequent attempts, he fails to start the engine. But after changing the injection to 33.58 BTDC, the engine runs smoothly, but seems to incur penalty on fuel consumption especially at high load levels. The poor performance of gas engines at low load levels is due to the effect of gas residuals and low cylinder temperature. It is also due to the reduction in combustion efficiency caused by reduced flame propagation speed and increased compression work resulting from the large amount of air–gas inducted. The diesel fuel operation produces the highest BTE at the two speeds (Fig. 10a and b). Standard timing shows little improvement over the advanced system at 3000 rev/min. However, at 2400 rev/min the dual-fuel mode standard and advanced timing show similar trends at low and intermediate load levels. Fig. 13(a) and (b) shows that diesel fuel operation produces the shortest delay periods at both test speeds.

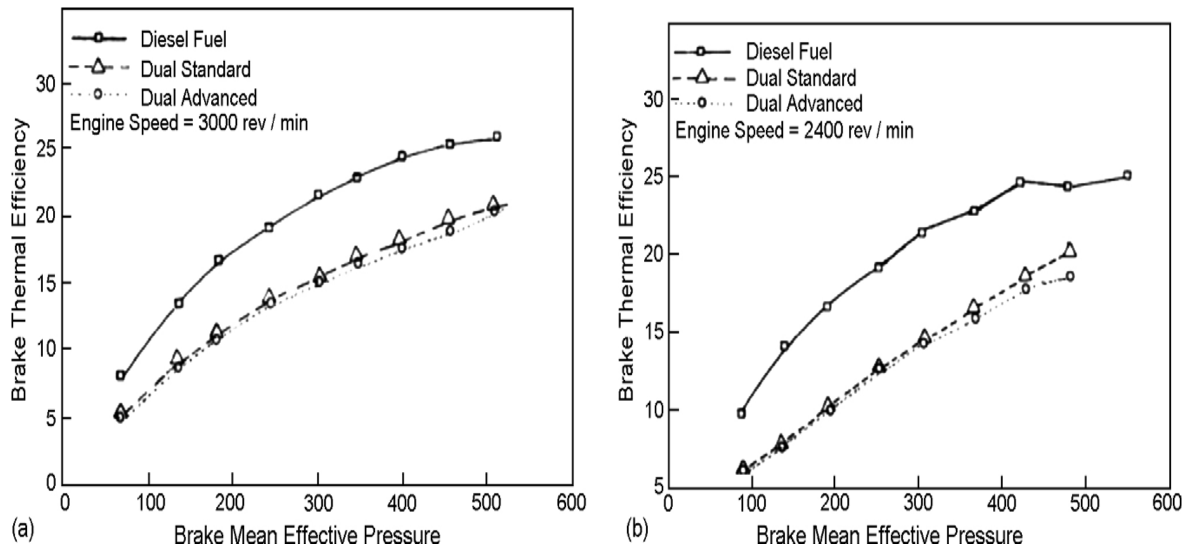

Fig: 10. Injection advanced effect on gas combustion—BMEP (kN/m2) versus BTE (%) [2]

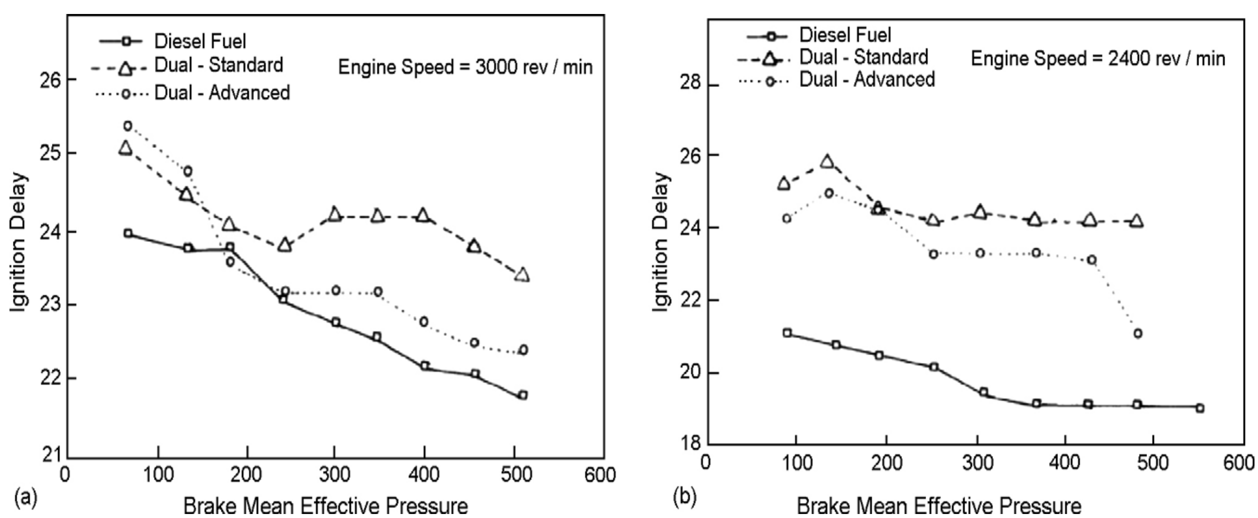

Fig: 11. Injection advanced effect on gas combustion—BMEP (kN/m2) versus ignition delay (deg.) [2]

Standard dual-fuel timing at 3000 rev/min shows longer delay periods at high loads than the advanced injection timing operation. There is a very significant difference between the ignition delays of diesel fuel and dual-fuel operations at 2400 rev/min. Standard dual-fuel timing also shows the longest delay period. At high loads and combustion temperatures, the ignition delay is reduced and combustion is dominated by the system temperature. At low loads with longer delay periods, greater proportion of pilot fuel takes part in premixed combustion, thus increases the tendency of diesel to knock. Very poor atomization results in a relatively long delay period, due to the slow development of very fine droplets. Dual fuel operation with advanced timing shows the highest exhaust temperatures at 3000 rev/min (Fig. 11a and b). The dual-fuel mode with the standard timing also shows a marginal increase over the operation on pure diesel fuel. The standard timing dual-fuel unit produced the highest cylinder wall temperatures while the advanced system showed the lowest values at this speed.

However, the diesel fuel operation produces the lowest cylinder wall temperatures, whereas the standard unit offers the highest values. The best fuel economy is realised when running on pure diesel fuel and hence, the thermal efficiency of the gas engine is less than that of pure diesel fuel case. The results from Fig. 12(a) and (b) indicate that the HC emissions of the gas-fuelled engine are higher than that in pure diesel fuel operation. Diesel fuel operation gives the lowest HC emissions at both speeds. Dual-fuel standard timing shows higher concentration of HC in the exhaust at low load levels over the advanced injection unit. HC emissions increase due to several factors, including quenching, lean combustion, wall wetting, cold starting and poor mixture preparation. For both test conditions, the HC levels are relatively high in dual-fuel operations and stay reasonably high throughout the load range.

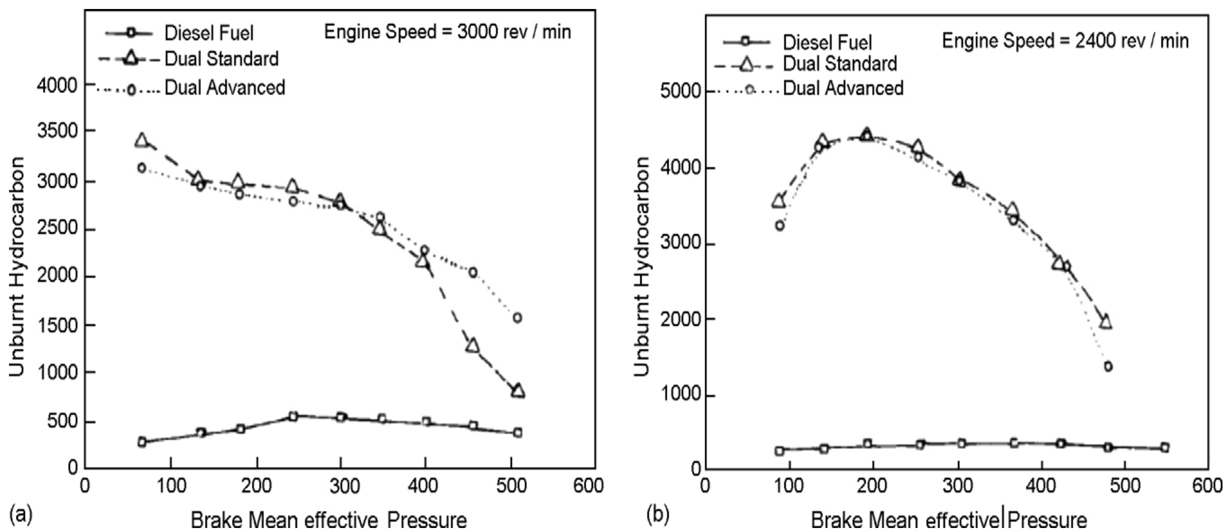

Fig: 12. Injection advanced effect on gas combustion—BMEP (kN/m2) versus UBHC (ppm) [2]

4. Conclusions

Researchers in various countries have carried out many experimental works using gaseous fuels as diesel engine fuel substitute in a dual-fuel mode of operation. An attempt has been made here to review the previous studies on dual-fuel concept. The overall observation from these experimental results is that the engine operating and design parameters, namely, load, speed, pilot fuel injection timing, pilot fuel mass, compression ratio, inlet manifold conditions and type of gaseous fuel play an important role in the performance and exhaust emissions of dual-fuel diesel engines. The ignition characteristics of the gaseous fuels need further more experimental research for a long-term use in a dual-fuel engine.

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