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Novel Investigation of Combustion and Noise Characteristics of Biomass Derived Producer Gas Fired Modified Dual Fuel Compression Ignition Engine

Mandeep Singh Kaler[1], S.K. Mohapatra[2] and Harmanpreet Singh[3]

[1,3]PG Research Scholar (MED) Thapar University, Patiala-147004
[2]Head & Sr. Professor (MED) Thapar University, Patiala-147004
E-mail: [1]mandeepkaler96@gmail.com, [2]skmohapatra@thapar.edu, [3]harmandhiman92@gmail.com

Abstract—*The heavy duty diesel engines are a good alternative for various electrical and mechanical energy requirements in the rural and off grid regions. Due the robust nature of these engines, these are also associated with a significant noise, which originates from various sources in the engine. The noise is associated with the robust engine parts, such as orifices at the intake and the exhaust of the engine, turbochargers, superchargers, combustion chamber, etc. Due to a random expansion and compression of air/exhaust gases in these parts, sound waves are generated. There is another aspect known as "the fast depletion of the conventional fuels", which has attracted the world as a whole towards the use biofuels such as biogas, bio-oil, biodiesel, producer gas, etc. in these conventional IC engines. It is observed in most of the cases that these heavy duty engines show enhanced performance in terms of fuel combustion and the emission characteristics. Meanwhile, a different trend is observed in the case of noise characteristics of these engines. A novel experimental investigation was carried to observe the relation between the combustion characteristics and the noise radiations of a producer gas and diesel fired dual fuel compression ignition engine. This engine produced 3.5 kW of mechanical power at 1500±5 RPM. The engine was tested for noise investigation on both pilot fuel mode as well as dual fuel mode. The dual fuel mode operation shows a significant increase in the cylinder pressure in comparison to the pilot fuel mode operation. Due to this increase in the cylinder pressure, a slight increase of 3.4 dB in the noise characteristics of the dual fuel engine was observed. The maximum noise of 92.1 dB was observed at ~80% load. This noise was further suppressed to 91.7 dB at 100% load.*

1. INTRODUCTION

The population in almost every country is increasing at a high pace. In order to provide adequate resources the whole population, the resource providers are now shifting on some more efficient and preferably renewable resources. For example, in the electricity generation department, emphasis is laid on the use of large resources of biomass, which is available freely or at an exceptionally low cost. Talking about the electricity generation, there is an aspect known as "rural electrification". It is a better and an efficient technique to provide electric energy to the off grid regions or the regions which are located very far from the transmission grid. [1] In order to fulfil the purpose of rural electrification, heavy duty CI engines are used, which are very robust. The issue of fast depletion of the conventional fuels is a great threat to these generation devices. In order to make these engines more fuel efficient and less polluting, charging devices such as supercharger, turbocharger, EGR (Exhaust Gas Recirculation), etc. are used. These devices contain a lot of orifices, where random compression as well as expansion of air/exhaust gas takes place. Due to this compression and expansion of the air/ exhaust gas, sound waves are formed, which are one of the various sources of noise in the CI engine. [2]

1.1 Dual fuel engines

As the name suggests, a dual fuel engine is the one, which uses two types of fuels, out of which, one of the fuel is gaseous in nature and the other is the liquid one. In many cases, both the fuels are gaseous in nature, but at least one of the fuels is gaseous in nature. [3] At the time of the world war I, infrastructure was developed enough to generate a significant amount of natural gas. Due to lack of developer resources, its use was limited to household purposes, or in some of the steel industries. But due to certain circumstances, it found its application in the dual fuel engine. Nowadays, due to its non polluting nature, it's highly recommended to run both light and heavy vehicles on natural gas, as far as possible in the highly populated cities. Although the gaseous fuels such as LPG (Liquefied Petroleum Gas), Natural gas, etc. require a high compression ratio, yet they have enough self ignition temperature, that the combustion is self sustained in most of the cases. [4] Those cases, in which the combustion doesn't take place at its own, are initially ignited by a conventional fuel and the engine run on the gas fuel afterwards. Due to the robust nature and heavy duty of diesel engines, these can be easily run on various liquid fuels and even crude oil. Due to the high compression ratio of the diesel engine, the dual fuel engine is preferred to be made out by modifying existing diesel engines. At both the dual fuel mode as well as the single fuel mode, the diesel engines respond very quickly to the variations in the load, speed as well as to the change in the supply and the nature of the fuel. [5]

1.1.1. *Working principle:* ***The dual fuel engine works on diesel cycle. The gaseous fuel (primary fuel) is added to the air inducted by the engines or supplied by the supercharger at a pressure slightly above the atmospheric pressure. A mixture of air and gaseous fuel is compressed in the cylinder just like air in fuel normal diesel operation. Some point in the compression stroke, near top dead center (TDC) a small charge of liquid fuel called pilot fuel (secondary fuel) is injected through a conventional diesel fuel system. This pilot fuel injection acts as a source of injection. The gas-air mixture in the vicinity of the injected spray ignites at a number of places establishing a number of flame fronts. Thus, combustion starts smoothly and rapidly. [6]***

In a dual fuel engine the combustion starts in a fashion similar to the compression ignition engine, but it propagates by flame fronts, in a manner similar to the spark ignition engines. The power output of the engine is normally controlled by changing the amount of primary gaseous fuel added to inlet manifold. The pilot oil quantity is usually kept constant for a given engine and is about 5 to 7 percent of the total heat of the engine at full load. Dual fuel engine is capable of running on either gas or diesel oil or a combination of these two over a wide range of temperature ratios. [7]

1.1.2. *Factors affecting combustion in a dual fuel engine:* ***A large number of factors affect the combustion in a dual fuel engine. Among them the important one's are:***

3.1.1 *Pilot fuel quantity:* ***Ignition in dual fuel engine occurs in an envelope enclosing the pilot spray and then propagates to the rest of the charge. The pilot fuel undergoes pre combustion reactions and releases thermal energy which increases the temperature of the gaseous fuel and a flame front is developed. If the amount of pilot fuel is increased more energy will be available to the gaseous fuel and the combustion would be very rapid resulting in an increase in the maximum rate of pressure rise. Therefore a large quantity of pilot fuel will result in knocking because of very rapid rates of pressure rise. This could be stopped by injecting lesser fuel quantity. [8]***

- *Injection timing:* ***The normal injection timing is within 20 to 16o BDC. Advancing the injection timing results in higher maximum cylinder pressure and knocking occurs at a leaner mixture. Retarding the injection timing reduces the ignition delay, but despite this reduced ignition delay the combustion starts only after TDC. This reduces the maximum rate of pressure rise and also the efficiency of the engine as part of the expansion stroke is lost without giving any useful power output. However the overall effect of the injection timing is not very high except that at a slightly retarded timing there is some improvement in the efficiency, but the rate of pressure rise also increases making the engine more near to knocking condition. [6]***

- *Effect of cetane number of pilot fuel:* ***With increase in the cetane number of pilot fuel the rate of pressure rise near the knock limit is slightly reduced. Thus a slight increase in the mixture strength is allowed near the knock limit. However, the power output is not improved. The use of low cetane number fuels results in poor performance of the engine and greatly affects the combustion. In general the ignition quality of the pilot fuel has little effect on the combustion in dual fuel engines as compared to the ignition quality of the primary fuel. [9]***

- *Effect of type of gaseous fuels:* ***The knock limited output of the dual fuel engine is greatly dependent on the type of gaseous fuel used. As already stated the power output of a dual fuel engine varies logarithmically with the reciprocal of the absolute inlet temperature of all hydrocarbon fuels, but varies linearly with inlet temperature when hydrogen is the fuel. Methane, which is a main constituent of natural gas does not undergo decomposition during the compressions in the engine and is more resistant to knock, pre ignition and backfiring from the cylinder into the gas/air inlet than other gases such as town gas etc. The main effect of the type of fuel is in the ignition and knocks limits. Due to wide variation in the composition of various types of gaseous fuels available all over the world, it is not possible to give their effect on performance of dual fuel engine. [10]***

- *Effect of throttling:* ***It is usual for the conventional SI engine to resort to throttling for richer mixtures and improve the part load efficiency. However, when throttling is used on a dual fuel unit maximum cylinder pressure reduces greatly. This is because in a throttled dual fuel engine ignition occurs very late in the cycle because of ignition delay. Thus, combustion occurs after TDC and a reduced maximum cylinder pressure is the result. The amount of throttling before the ignition failure limits are reached is very low. A diesel engine can run up to 50 percent throttling while decrease of 0.05 bars in the inlet pressure might cause ignition failure due to increased ignition delay in a dual fuel engine.***

- *Effect of mixture strength:* ***The mixture strength is the charge of a dual fuel engine is strongly dependent on the amount of pilot fuel injected into the combustion chamber. [11]***

1.2 Noise and its characteristics of the CI engines:

It has been investigated that the combustion parameters such as ignition quality, fuel stability, flow properties, etc. in an IC engine are greatly influenced by the chemical and the physical properties of the fuel. In case of reciprocating engines, there are many sources from which noise is produced. These are:

1.2.1. *Combustion noise:* ***The combustion noise is mainly caused due to unsteady and sometimes uneven combustion of the fuel in the combustion chamber. The fluctuation in the frequencies produced by the combustion roar is the main cause of combustion noise. The pressure forces responsible for the combustion noise in the dual fuel engine are dependent on the parameters such as fuel injection system, which is further dependent on the fuel's chemical and physical properties such as cetane number in case of CI systems and octane number in case of SI systems, bulk modulus, viscosity, etc. Apart from the fuel properties, the combustion noise is also influenced by the design of the combustion chamber and it designed geometry. There are some other reasons of excessive combustion noise. These can be classified as:***

- Improper combustion due uneven charge distribution
- Knocking in case of dual fuel CI engines due to sufficiently large ignition delay.
- Detonation in case of dual fuel SI engines due to high compression ratio, overheating of the engine, poor octane rating of the fuel, etc.

1.2.2. *Exhaust noise:* ***The exhaust gases are sent into the atmosphere from the engine manifold by a tail pipe. During the scavenging action of the engine, the exhaust gases get compressed. Due this compression, the generated pressure waves produce the sound waves, which come in the form of exhaust noise. In the passage from the engine exhaust manifold to the gas exhaust in the atmosphere, there are present a number of orifices, which compress and decompress the exhaust gases. These orifices contribute to the secondary sources of the exhaust noise. [12]***

Presently the technique of biomass gasification to use various biomass materials to run the dual fuel engines is gaining much importance. In most of the reported literature, various types of hard woods are used for the production of the producer gas. The use of cotton stalk specifically to produce the producer gas is the least reported. A significant amount of work has been done on the performance analysis of the producer gas fired dual fuel engines.

In most of the experimental investigations, it has been observed that on dual fuel mode, in spite of a smooth running of the engine, there is a significant variation in the combustion characteristics of the engine, which in case of dual fuel engines has not been yet reported. Apart from the combustion characteristics, it is actually physically observed that there is also a slight variation in the noise characteristics of the engine. This analysis is also lagging in most of the reported literature. Due to these shortcomings of the so far reported literature, the following objectives were made:

- Use of cotton stalk for the production of producer gas.
- Use of so produced producer gas in a dual fuel CI engine.
- Investigation of the combustion characteristics of the dual fuel engine.
- Investigation of the noise characteristics of the dual fuel engine.

2. MATERIALS AND METHODS

The material used for the production of producer gas was waste cotton stalk. The initially available cotton stalks had a length of a few meters, which was reduced to < 20mm using a shredder. Various properties of the fuel are listed in table 1.

Table 1: Proximate analysis, calorific value and size specifications of the raw materials

Component	Sugarcane bagasse
Volatile matter (%)	64.72
Moisture (%)	7.75
Fixed carbon (%)	23.42
Ash (%)	4.11
CV (kJ/kg)	18489.78
Size (before processing)	Stalks of length < 2m.
Size (after processing)	1mm to 25mm

The processed fuel was introduced in a downdraft biomass gasifier for the production of producer gas. The gas so produced was cooled and washed using a venturi type spray tower. It was further ultra cleaned to a purity of ~99.9% using a set of charcoal and safety filters. This ultra clean was then introduced into the dual fuel engine at flow rate of 5.15 Nm^3/hr using a self fabricated gas carburetor in order to ensure mixing of the gas with the inhaled air. The mixture of air and producer gas was then inhaled by the engine. In the investigation, it was assumed that the engine has a constant volumetric efficiency. Due to which the part of air inhaled is now replaced as an equal amount of gas. The specifications of the dual fuel CI engine are represented in table 2.

Table 2: Specifications of the DFCI engine setup

Parameter	Specification
Engine make	Kirloskar
Engine model	AV-1
Engine type	VCR (Variable Compression Ratio)
Cylinders	1
Strokes	4
Start type	Electric start
Bore	87.5mm
Stroke	110mm
Capacity of the engine	553 cc
Maximum power	3.7 kW at 1500 RPM
Connecting rod length	234mm
Compression ratio	12 -18
Dynamometer	Eddy current type
Dynamometer arm length	185mm

Orifice diameter	20mm
Fuel	Diesel alone and blends of diesel and producer gas
Cooling system	Water cooling

To prevent the heating up of the engine and the dynamometer, the water was supplied at a flow rate of 250 and 75 LPH to the water jacket and the dynamometer cooling system. The engine was run on a fixed compression ratio of 16. The loads on the engine were varied from 1 kg to 11 kg with a difference of 2 kg. The results of the investigation are presented in the next section.

3. RESULTS

3.1 Combustion characteristics of the DFCI engine:

In order to investigate the combustion characteristics of the DFCI engine, various pressure transducers were used in the combustion chamber and thermocouples gave the values of temperature at various points. The information provided by the pressure transducers and the thermocouples was sent to the ICE test rig, which amplified the signals and sent to the computer. In computer, “ICenginesoft 9.0” software provided by Apex Innovations Pvt. Ltd. was used to interpret the amplified results. The combustion characteristics provided by the software are as follows:

3.1.2 Cylinder pressure: In Fig 34 the variation of cylinder pressure is plotted with respect to the crank angle. The maximum pressure reached in case of the pilot fuel mode was less as compared to the dual fuel mode. The maximum pressure in case of diesel mode was 42.63 bar and it was seen at 10^{o} after TDC (Top Dead Center) whereas the peak pressure of 49.3 bar was recorded in case of dual fuel mode at an angle of 13^{o} after TDC. It is observed that the peak pressure is higher in the case of dual fuel mode as compared to the diesel mode. This can be explained as: In the case of dual fuel mode, air and the gaseous fuel are compressed and when the compressed charge approaches the TDC, it is on the verge of burning and the temperature of the air-gas mixture is slightly lower than its self ignition temperature. When this hot air-gas mixture gets an injection of diesel at a high pressure, there is a sudden combustion in the whole region. No flame front is formed, the whole charge burns collectively. Due to this, there is a sharp rise in the pressure in the case of dual fuel mode.

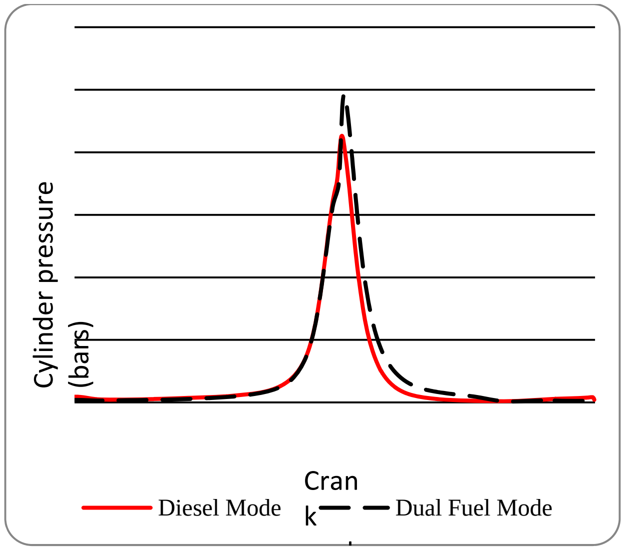

Fig. 1 Variation of cylinder pressure with crank angle.

3.1.2** Mean temperature of gas:* ***In this case the mean temperature of the gas was investigated by taking the readings for 10 cycles. All the values of the 10 cycles for each degree (^{o}) of crank were averaged to a single value and plotted on the graph. It is observed that the diesel mode shows a regular trend and a slight increase in the mean gas temperature after and near the TDC followed by a decrease in the same fashion. Whereas in dual fuel mode, it is observed that mean gas temperature is slightly higher than the dual fuel mode upto TDC. As soon as the diesel injection starts after TDC, there is a sharp rise in the mean temperature of the gas. It is observed that the maximum values of the mean temperature are 582.56^{o}C (at 10^{o}) and 885.59^{o}C (at 18^{o}) in diesel and dual fuel modes respectively. In this investigation, again a sharp increase in the mean gas temperature is noted in the case of dual fuel mode. As explained earlier, due to the sudden burning of the charge, there is a sharp increase in the average/mean temperature of the gas. Also, due to the governor system, more fuel is injected than the required amount on the dual fuel mode, which causes more fuel to burn and increases the mean temperature of the gas.

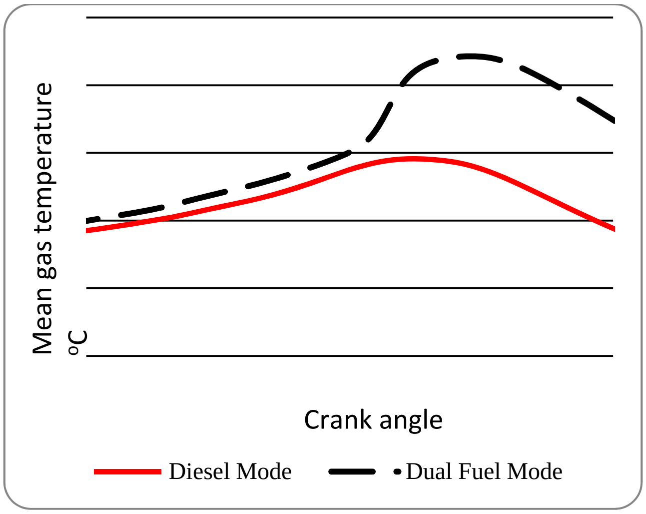

Fig. 2: Variations of mean gas temperature with crank angle.

3.1.3 *Net heat release:* ***In this investigation, the trend for the net heat release was obtained for the various angles of the crank. In both the cases, it is found that the maximum heat is released near the TDC At an angle of 5^o before TDC, an increase in the net heat release is noted in both cases but more in case of diesel mode. At TDC there is a sharp rise in the net heat release and a peak value of 21.2 J/deg was observed at 5^o after TDC in diesel mode. Whereas in case of dual fuel mode, an increase is noticed, but not as sharp as in the case of diesel mode. The peak value of 10.43 J/deg was observed in the case of dual fuel mode. In this investigation, it is observed that the dual fuel mode radiates/releases heat at a lower pace, whereas the diesel mode releases heat quite faster. The reason for this trend is the incomplete combustion in the case of dual fuel mode. Due to air deficiency, the charge is not able to burn completely so the heat release rate decreases in the dual fuel mode.***

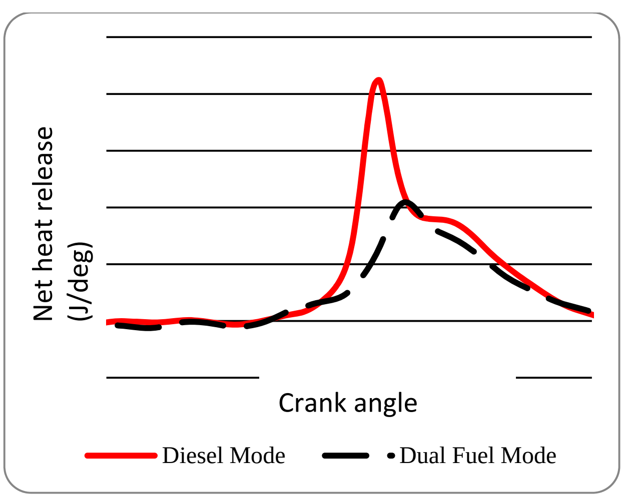

Fig. 3 Net heat release variations with respect to crank angle.

3.1.4 *Noise characteristics:* ***For this investigation, "CESVA Sound Level Meter and Spectral Analyser" model SC310 was used. The sound level observed using this device are shown below:***

As shown in Fig. 4, an increase in the noise produced by the engine is noted when operated at high load, but at load >83% the noise levels show a slight decrease in dual fuel mode and this decrease is noted at load >66% on diesel mode.

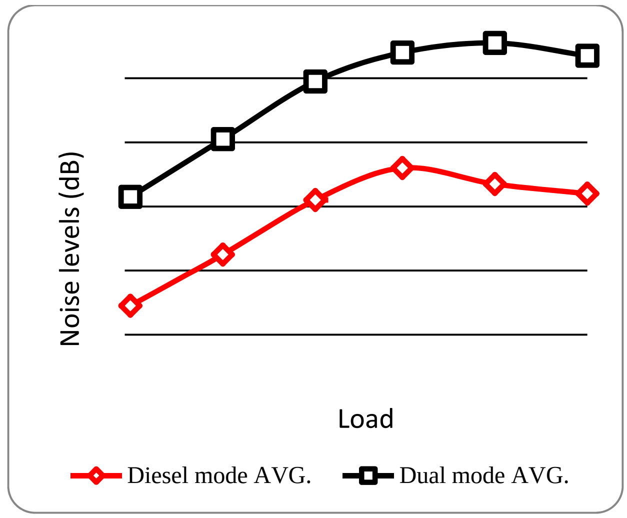

Fig. 4 Variation of noise levels with variation in load.

On an average, there is an increase of ~3.4dB of noise levels when the engine is operated on the dual fuel mode. The combustion noise in an engine is dependent on various chemical and the physical properties of the fuel. The physical properties include density, viscosity, bulk modulus, etc. In the previous research, it has been reported that with an increase in density and viscosity of the fuel, there is a significant reduction in the noise of the engine. Where as if the density and the viscosity of the fuel is decreased, it results in an increase in the noise of the engine. In the present work on dual fuelling, the density as well as the viscosity of the air, gas and diesel mixture gets decreased, which results in an increase in combustion noise and hence the exhaust noise also.

4. CONCLUSION:

In the experimental investigation, it was observed physically that the engine showed a smooth operation which was self sustained. From the present work, the following can be concluded:

- The engine showed a smooth and sustained working on dual fuel as well as pilot fuel mode.
- There was a significant increase in the cylinder pressure on the dual fuel mode operation.

- A significant increase in the mean gas temperature was observed on dual fuel mode.
- There was a slight decrease in the net heat release on the dual fuel mode.
- A slight increase of ~3.4 dB in the noise radiations was recorded.

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