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Experimental Investigation of Effect of Exhaust Gas Recirculation and Cottonseed B20 Biodiesel Fuel on Diesel Engine

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Abstract

The effect of EGR and cottonseed B20 biodiesel on engine performance, emission and combustion characteristics of a single cylinder diesel engine with power rating of 3kW and at constant speed of 1500 rpm are studied. It is observed that ignition delay is shorter with cottonseed B20 biodiesel as compared to base diesel due to biodiesel having higher cetane number and oxygenated fuel. It is decreased from 9.5 °CA with base diesel to 8.5 °CA with cottonseed B20 biodiesel. Premixed combustion phase is increased with cottonseed B20 biodiesel as compared to base diesel whereas diffusion combustion phase is decreased. The higher premixed combustion phase is responsible for higher NOx emission. Utilization of exhaust gas recirculation (EGR) 4 % and 6 % by volume shows deterioration in performance of the diesel engine. This was the main reason to use small quantity (4 % and 6 % by volume) of EGR only to reduce NOx. NOx emission increased with cottonseed B20 biodiesel whereas the emission decreased with exhaust gas recirculation. CO and HC emission decreased with cottonseed B20 biodiesel due to zero aromatic, oxygenated fuel results in clean burning of fuel. However, CO and HC emissions slightly increased with exhaust gas recirculation.

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Keywords: Biodiesel diesel blend (B20), EGR, diesel engine, combustion phases, ignition delay period, heat release rate

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1. Introduction

Due to more utilization of fossil fuel resources, there is need of alternating sources of energy to meet the requirement of the world. As per the emission point of view and the world's demand, there is need to look forward for alternating fuels because of depleting problems of fossil fuel [1]. Biodiesel production from edible and non-edible substance and its use is advantageous as per environmental and energy concern. Bio-fuels are produced primarily from food crops. Bio-diesel is clean energy source which can replace the base diesel fuel. Similarly, the emissions from fossil fuel effect on human health, global warming and air quality. The benefits of this fuel are advantageous and may get utilized by the industries and many transport system [2].

Many researchers have studied on effect of biodiesel on engine performance emission and combustion characteristics where most of the study has found on performance and emission characteristics. Some authors [2-4] observed that with use of biodiesel there is decrease in performance of the engine. The reason behind loss of power is due to higher viscosity, lower heating value. Higher viscosity results in power losses because higher viscosity decreases combustion efficiency due to bad fuel injection atomization. This loss of power can be recovered by use of additive in the fuel [2]. Similarly, ignition and combustion performance of the engine increases. With use of more biodiesel consumption also there is impact on engine economy; this is due to higher viscosity, density and its low heating value. The engine operating conditions such as loads, speed, and injection timing and injection pressure also have influence on engine economy. It has observed that with use of biodiesels it leads to formation of more NOx. It is because of more oxygen content, higher cetane number of biodiesel [3]. Some of researchers have worked on EGR and found that exhaust gas recirculation is one of the ways of reducing NOx emission which (EGR) reduces the combustion temperature. The content of unsaturated compound could effect on NOx formation.

The optimized EGR rates which match the operating conditions of diesel may not fit well with the same conditions of biodiesel engines. The problems of substituting vegetable oil to diesel are its high viscosity and low volatility [4-5]. The effect of exhaust gas recirculation shows reduction in NOx emission. This is due to lower oxygen content and reduction in the combustion temperature. With increased in % EGR NOx emission decreased from 11% to 85% at different compression ratio. It is found that with increase in compression ratio (CR) the brake thermal efficiency of the engine increases and specific fuel consumption decreases [6]. Effect of % EGR shows increase in thermal efficiency but with increased in % EGR, it effect on thermal efficiency i.e. it decreases. The engine speed effect on combustion noise i.e. it reduces. With increased in % EGR, rate of pressure rise decreases per crank angle. It has observed that 5% EGR is favourable for reducing the combustion noise and NOx emission. More over increased in pressure rise rate reduces chance of combustion noise [7].

The effect of EGR on ignition delay represents increase in trend; this is because of lower oxygen concentration. This scanty availability of oxygen slow down pre oxidation process hence ignition delay increased. With utilization of EGR oxygen concentration gets replaced by carbon dioxide (CO2), water vapour, N2 and other gases components of exhaust gas. Similarly, rate of heat released curve shift as per ignition delay and with increased in %EGR which provides lower oxygen concentration [8]. Some researchers observed that B20 fuel gives better performance and emission characteristics with varying rate of EGR 10%, 20% and 30% respectively. With this variation reduction in NOx is by 20% and 20% EGR is considering as an optimum % EGR. Similarly, there is decreased in CO and HC emission by 17.3% with electronic fuel injection system compared with utilization of EGR, where it increased at 20% EGR utilization [9]. Hussain [10] studied effect of EGR on engine performance characteristics and observed that this method is one way to reduce NOx. With this there is decreased in performance of the engine. It is found the 15% EGR rate is effective to reduce NOx without affecting on engine performance. 25% EGR valve opening is optimum for reduction of NOx and CO emission, observed by Jothithirumal [11].

Performance of engine in terms of BTE increases [12]. Saravanan [13] studied on effect of EGR at advance injection timing on combustion characteristics and observed that at advance injection timing there is longer delay period, higher cylinder peak pressure, higher maximum heat release rate and shorter combustion duration than those at standard injection timing. It is also concluded that NOx and smoke emission can be control. It is also studied that heavy use of EGR may effect on energy efficiency and engine life because of presence of sulfuric salt and other abrasive and corrosive substances [14]. Minimum NOx and CO2 emission is observed with utilization of EGR. Similarly, HC and CO emission increases. Presence of 80% diesel in fuel gives better performance results [15]. Small percentage of EGR is one of optimum and suitable method of reducing NOx amongst other. EGR of 4 to 9%
can reduce NOx by 31 to 71 % and reduced power by 1.6 to 5.6 %, but there is increased specific fuel consumption by 2.5 to 3 % [16].

**Nomenclature**

| Abbreviation | Description |
|--------------|-------------|
| CO           | carbon monoxide |
| NOx          | oxides of nitrogen |
| CO2          | carbon dioxide |
| HC           | hydro carbon |
| EGR          | exhaust gas recirculation |
| CA           | crank angle |
| BTE          | bake thermal efficiency |
| VCR          | variable compression ratio |

2. Experimental details

The experimental setup consists of single cylinder, four stroke, and VCR (Variable Compression Ratio) engine. The engine specifications are given in Table 1 and the engine setup is shown in Fig. 1. The setup is equipped with instrument for fuel flow, temperature, load, combustion pressure and crank angle measurement.

| Title          | Details                                                                 |
|----------------|-------------------------------------------------------------------------|
| Product        | 1 cylinder, 4 stroke, Diesel (Computerized) VCR engine                  |
| Product Code   | 240                                                                     |
| Engine         | Kirloskar Make                                                          |
| Power          | 3.5 KW at 1500 rpm, stroke 110mm bore 87.5 mm. 661 cc, CR 17.5, Modified to VCR, CR range 12 to 18 |
| Dynamometer    | Type Hydraulic, water cooled                                            |
| Propeller shaft| With universal joints                                                  |
| Air box        | MS fabricated with orifice meter and manometer                         |
| Fuel tank      | Capacity 15 lit with glass fuel metering column                         |
| Calorimeter    | Type Pipe in pipe                                                      |
| Piezo sensor   | Range 5000 PSI with low noise cable                                    |

One way of reducing NOx is by utilization of Exhaust Gas Recirculation (EGR) where exhaust gas coming from engine exhaust manifold is given to inlet manifold in order to reduce NOx [17-19]. When part of this exhaust is recirculation then it works as diluents to combustion mixture. Because of high specific heat of exhaust gas than fresh air, it increases the temperature of intake fresh charge as a result it decreases the temperature rise for the similar [20]. The EGR is defined in percentage as shown in Eq. 1.

\[
\%EGR = \frac{Volume \ of \ EGR}{Total \ intake \ charge \ in \ cylinder} \times 100
\]  

(1)
3. Results and discussion

Brake specific fuel consumption is a measure of fuel efficiency of any system where combustion of fuel occurs in the presence of oxygen and releases the heat. The released heat is converted in mechanical power. It has been observed that the brake specific fuel consumption is decreased with respect to load as shown in Fig. 2 (a). It is also observed that the brake specific fuel consumption increased with cotton seed B20 biodiesel as compared to base diesel. It may be due to lower calorific value (CV) of biodiesel, longer injection duration results in longer combustion duration [21]. Brake specific fuel consumption increased by 23.07 % with B20 biodiesel at the rated load. The Fig. 2 (a) data shows the percentage change with respect to base diesel. The brake specific fuel consumption also increased in the case of exhaust gas recirculation. It increased from base diesel by 7.69 % (4 % EGR), 11.53 % (6 % EGR) with diesel + EGR and 30.76 % (4 % EGR), 42.60 % (6 % EGR) with B20 biodiesel + EGR at the rated load.

Thermal efficiency indicates the extent to which the energy added by heat is converted to net-work output. The engine performance is mainly checked by this parameter. It is observed from Fig. 2 (b) that the thermal efficiency is decreased with B20 biodiesel as compared to base diesel. Thermal efficiency decreased from base diesel by 4.12 % with B20 biodiesel. It may mainly due to lower calorific value of biodiesel results in lower power. Another reason could be due to longer injection duration results in longer combustion duration tends to poor performance. Thermal efficiency also decreased with exhaust gas utilization may be due to lower oxygen content results in lower combustion temperature. It decreased from base diesel by 1.33 % at 4 % EGR and 3.9 % at 6 % EGR with diesel + EGR at the rated load. Similarly, it decreased from base diesel by 4.95 % and 5.1 % at 4 % and 6 % EGR + B20 respectively at the rated load.
The comparison of CO and HC emissions for diesel and B20 biodiesel with respect to load is shown in Figs. 3 (a) and (b). It is clearly seen from the figures that CO and HC emissions are decreased with B20 biodiesel as compared to base diesel. It may be due to oxygen content in the biodiesel results in cleaner and complete combustion. Another reason could be due to biodiesel having higher bulk modulus results in automatic advance in dynamic injection timing and higher cetane number of biodiesel tends to shorter ignition delay. The combined effect of shorter ignition delay and advance in dynamic injection timing results in higher in-cylinder temperature produces lower CO and HC emissions. The CO emission is decreased from base diesel by almost 50 % with B20 biodiesel. Similarly, HC emission decreased from base diesel by 58.33 % with B20 biodiesel.

At 4 % EGR and 6 % EGR, CO and HC emissions are increased with diesel as well as B20 biodiesel. CO emission increased from base diesel by 100 % with diesel at 4 % EGR and 150 % at 6 % EGR at the rated load. Similarly, it increased from base diesel by 50 with B20 biodiesel at 4 % EGR and 150 % with 6 % EGR. The HC emission is increased from base diesel by 33.33 % with diesel at 4 % EGR and 50 % with 6 % EGR at the rated load. Similarly, it decreased from base diesel by 33.33 % with B20 biodiesel at 4 % EGR and 0 % with 6 % EGR. In case of EGR, air gets replaced by EGR, the deficiency of oxygen with the increase of EGR percentage can be attributed to the increase in CO and HC emissions. Another reason of increase in CO and HC emissions could be due to increase in the CO₂ content of the inducted mixture instead of fresh-air. Finally, it lowers the in-cylinder (combustion) temperature results in increase in CO and HC emissions.

NOx emission is higher for biodiesel as compared to base diesel. It increased from base diesel by 3.47 % with B20 biodiesel as shown in Fig. 4 (a). It may be due to higher bulk modulus of biodiesel results in automatic advance
in dynamic injection timing, shorter ignition delay, higher spray penetration, higher in-cylinder temperature and oxygen content [21]. Exhaust gases consists of CO₂, N₂ and water vapor mainly. The part of this exhaust gas is recirculated to the engine cylinder; it acts as diluents to the combustion mixture. As it replaces the amount of fresh air, it also reduces the O₂ concentration in the combustion chamber [22]. The specific heat of EGR is much higher than fresh air; hence EGR increases the heat capacity (specific heat) of the intake charge, thus it decreases the temperature rise for the same heat release in the combustion chamber results in lower NOx emission with EGR. The NOx emission is decreased from base diesel by 3.86 % and 6.94 % at 4 % EGR and 6 % EGR with diesel respectively at the rated load. Similarly, it decreased from base diesel by 0.77 % and 3.08 % at 4 % EGR and 6 % EGR with B20 respectively at the rated load.

Amongst all the engine characteristics of compression ignition engine, one of the most important is combustion phase which is very complex phenomenon and includes start of combustion, ignition delay period, rate of pressure rise, premixed combustion phase, diffusion combustion phase and after burning phase [21]. Ignition delay is defined as difference between start of injection and start of combustion. The ignition delay for cottonseed B20 biodiesel is shorter than base diesel fuel from 9.5 ºCA to 8.5 ºCA with no utilization of exhaust gas recirculation. It is also found that at 4% EGR, ignition delay decreased to 9 ºCA with diesel and 8 ºCA with B20. Similarly, at 6% EGR ignition delay decreased to 8 ºCA with diesel and 7 ºCA with B20 as shown in Fig 4 (b). This decreased in ignition delay may be due to higher cetane number of biodiesel than diesel. Ignition delay decreased with EGR may be due to higher temperature of EGR.

The start of combustion is advanced with cottonseed B20 biodiesel as compared to base diesel as shown in Fig. 5 (a). It is mainly due to advance in dynamic injection timing because of higher bulk modulus of biodiesel [23-24]. Another reason of advance in start of combustion may be shorter ignition delay due to higher cetane number of
biodiesel. Start of combustion is advanced from 348.5 ºCA with base diesel to 347 ºCA with cottonseed B20 biodiesel. The start of combustion is retarded with both percentages of EGR. It may be due to the specific heat of EGR is much higher than fresh air; hence EGR increases the heat capacity (specific heat) of the intake charge, thus it decreases the temperature rise for the same heat release in the combustion chamber, the flame propagation rate is slower in case of EGR. It slows down the combustion process. With diesel and at 4% and 6% EGR, start of combustion retarded to 349 ºCA and 350 ºCA. With B20 at 4% and 6% EGR, start of combustion is retarded to 348 ºCA and 349 ºCA as shown in Fig. 5 (a). The pressure crank angle (P-0) parameter is used to calculate rate of pressure rise, peak in-cylinder pressure, heat release rate and combustion duration. The peak in-cylinder pressure increased from 54.72 bar with diesel to 55.61 bar with B20. This is because of higher oxygen content in biodiesel. This is also responsible for higher NOx emission. After the start of combustion, fuel gets burn with released of some amount of heat. The heat released rate in case of biodiesel decreased due to lower calorific value of biodiesel fuel. Hence, the brake thermal efficiency of the diesel engine is decreased with cottonseed B20 biodiesel. The heat released rate is used to find premixed combustion phase, diffusion combustion phase and after burning combustion phase. It is observed that premixed phase decreased with use of exhaust gas recirculation. As premixed combustion phase is responsible for higher NOx emission, it may be one of the reasons to reduce NOx emission. It decreased from 23.5 ºCA with base diesel to 20 ºCA with 6% EGR as shown in Fig. 5 (b). Similarly, premixed combustion phase decreased from 24 ºCA with cottonseed B20 biodiesel to 18 ºCA (6% EGR) as shown in Fig. 6 (a). The diffusion combustion phase is increased with diesel, cottonseed B20 biodiesel and both the percentages of EGR. However, the after burning combustion phase is decreased with diesel, cottonseed B20 biodiesel and both the percentages of EGR as shown in Figs. 5 (b) and 6 (a). The end of combustion for diesel and biodiesel blend B20 is shown in Fig. 6 (b). The end of combustion with biodiesel blend is retarded as compared to base diesel fuel with no utilization of EGR. With utilization of EGR there is slight advance in end of combustion. It has great effect on combustion duration. Combustion duration found to be longer in case of cottonseed B20 biodiesel. This may be one of the reasons for lower thermal efficiency of biodiesel fuelled diesel engine.

4. Conclusions

- BSFC increased with B20 as compared to diesel due to lower CV. BSFC also increases with increase of EGR rate because of formation of rich mixture due to insufficient oxygen supply.
- The CO and HC emissions decreased with B20 biodiesel as compared to diesel due to oxygenated fuel. However, NOx emission increased with B20.
- The temperature of exhaust gas continuously decreases with increase of EGR rate. The higher specific heat of intake air and exhaust gas mixture and lower oxygen availability are main reasons for lower in-cylinder temperature results in lower NOx emission and higher the CO and HC emissions with EGR.
- Ignition delay decreased with cottonseed biodiesel as compared to base diesel. It is mainly due to higher cetane number of biodiesel.
- Premixed combustion phase is decreased with EGR whereas diffusion phase is increased with EGR.
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