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Research of the performance and emission characteristics of Jatropha Oil Methyl Esters (JOME) and diesel blends in a partially premixed charge compression ignition engine

Abstract: In this article for reducing NO_x and particulate matter (PM) were used partially premixed charge compression ignition (PPCCI) combustion of diesel fuel with external mixture formation technique and Jatropha oil methyl ester (JOME) blend in the main injection. Diesel fuel was injected into the intake manifold for formation of homogeneous pre-mixture beforehand and the pre-mixture is burnt in the cylinder with the balance quantity of fuel directly injected into the cylinder by a conventional injection system. For obtaining homogeneous mixture, diesel fuel was injected in the intake manifold using a solenoid-operated injector controlled by electronic control unit (ECU). Exhaust gas recirculation (EGR) technique was adopted for controlling of the start of combustion (SOC). Experiments were carried out with 10%, 20%, and 30% EGR for premixed ratio (Rp) 25% and results are compared with conventional diesel fuel operation. It was found that diesel manifold injection and JOME blend in main injection results in better mixture preparation and lower emissions. It was shown that due to homogenous lean operation, significant reduction in NO_x and PM was achieved with the PPCCI combustion mode at Rp 25% and EGR 20% in the JOME-Diesel mode of operation.

Key words: exhaust gas recirculation, jatropha methyl ester, diesel premix, charge compression ignition

Introduction

Energy is the major factor for economic growth of any country. The need for the energy is increasing day by day with the growth of population and requirement of modern energy consuming equipment for comfort living. The invention of internal combustion engine and developments in engine technology resulted in exploitation of the petroleum-based reserves which is depleting at a rapid rate [1]. Combustion of these fuels in engines release substantial amount of pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (UBHC), nitrogen oxides (NO_x) and particulate matter (PM) [2]. Reducing the such emissions and increasing the fuel economy of IC engines are the primary concern for all developing nations. There has been a world-wide interest in the search of alternatives to petroleum derived fuels due to their depletion and concern for the environment. Bio-diesel derived from edible, non-edible oils and animal fats can be used in diesel engines with little or no modifications [3-5].

It is known that Jatropha oil methyl esters are well proven alternative fuels to petroleum diesel. Unfortunately cultivation of jatropha requires huge land area and good quality jatropha plant seed for generating sufficient oil. Even though biodiesel offers reduction in Smoke, UBHC and CO emission due to the molecular oxygen present in it, NO_x emissions are higher which can be reduced by using exhaust gas recirculation.

Homogeneous charge compression ignition (HCCI) is a promising alternative combustion technology for diesel engines with high efficiency and lower NO_x and particulate matter emissions. Relative to compression ignition direct ignition engines, HCCI engines have substantially lower theses emissions [6-8]. The low emissions of PM and NO_x in HCCI engines are a result of the dilute homogeneous air and fuel mixture in addition to low combustion temperatures. The change in HCCI engine may be made dilute by being very lean, by stratification, by using exhaust gas recirculation (EGR), or combination of these methods [9, 10].

In case of using HCCI engines can be some challenges:

– high CO and UBHC emissions because of incomplete oxidation.

– the operating range of automotive engine using HCCI mode is found to be too narrow [11, 12].

– improper combustion or misfire under fuel-lean conditions limits the minimum power output at which the engine can operate.

– high heat release rates and high in-cylinder pressure may cause more wear and damage to the components.

– it is difficult to control an auto-ignition [13].

In HCCI combustion, control over the start of combustion (SOC) is the main problem [14, 15]. Conventional control techniques are not applicable, indirect methods like variable EGR technique, variable compression ratio (VCR), variable valve timing (VVT), increased intake charge temperature, equivalence ratio variation, injection timing, modulating two or more fuels, fuel additives [16-18] which alter the compression process are necessary. Since HCCI engine operates on lean mixtures, the peak temperatures always lower in comparison to spark ignition and diesel engines. Low peak temperatures prevent the formation of NO_x. However, they also lead to incomplete burning of fuel especially near the walls of the combustion chamber.

It was proposed to study the effect of partially premixed charge compression ignition (PPCCI) combustion mode a variant of HCCI combustion mode in diesel engines. In this method generally two fuels are used [19-21]. One fuel is injected in to the intake air, upstream of the intake valve to obtain a premixed charge. Remaining fuel is injected into the combustion chamber through conventional injection system. The PPCCI technique reduces NO_x and PM using partially premixed charge compression ignition (PPCCI) combustion. In this method of combustion, diesel, petrol, methanol, liquefied petroleum gas (LPG), compressed natural gas (CNG), methyl tert-butyl ether (MTBE) and acetylene are commonly used as premixed fuel or main fuel (in-cylinder injection).

In this work investigation to study the effect of Jatropha methyl ester biodiesel as main fuel and diesel as premixed fuel was carried.

In PPCCI, combustion takes place predominantly in premixed manner than in diffusive manner due to homogeneous mixture formation by fuel-air premixing [22-24]. In addition, premixed mixture combustion is faster than conventional diesel combustion as it occurs at multiple points in the cylinder. This sudden combustion causes a sharp increase in pressure and temperature leading to high maximum values. By this reason, in PPCCI combustion takes place with a highly diluted mixture to maintain the temperature and pressure low in the cylinder and is normally restricted to low loads. That's why it is possible to avoid engine damage while NOx emissions are lowered by low temperatures.

In this work, the performance, emission and combustion characteristics have been studied using jatropha oil methyl esters in CIDI and HCCI modes for determination of the optimum blend ratio of JOME with diesel in CIDI mode, the optimum EGR percentages for better tradeoff of soot and NOx emissions for JOME. It was studied the effect of PPCCI combustion mode with diesel and biodiesel blends.

Various experiments were carried out using PPCCI mode of combustion with diesel as premixed fuel with premixed ratio of 0.25 and 20% JOME as main fuel with 10%, 20% and 30% EGR. The performance characteristics (brake thermal efficiency, exhaust gas temperature), emission characteristics (UBHC, CO, NO_x and soot emissions) and combustion parameters (in-cylinder pressure, ignition delay and heat release rate) are presented.

Materials and Methods

The tests were performed on a single cylinder, four stroke, naturally aspirated, air-cooled diesel engine coupled with an electrical swinging field dynamometer. The detailed technical specifications of the engine are given in tab.1. Fig. 1 shows the schematic diagram of the experimental set-up. The intake manifold of the engine is modified to fit the primary fuel injector. AVL 415 Variable Sampling Smoke meter is used to measure the particulate matter in the exhaust. MRU delta 1600 L Exhaust Gas Analyzer is used to measure HC, CO and NO_x emissions.

AVL 615 indimeter system is used to get pressure crank angle diagram at various loads using piezoelectric pressure transducer and angle encoder and to process the same for getting various parameters such as heat release rate curve, peak pressure, angle of occurrence of peak pressure, imep, etc.

The engine was started with diesel and allowed to warm up till steady state conditions were achieved. Engine Speed, fuel consumption rate, exhaust emissions (HC, CO, and NO_x), smoke intensity, pressure-crank angle diagram and exhaust gas temperature were measured at various loads. The experiment was repeated at various loads with 20% JOME blends with diesel. The experiments were conducted on a CIDI engine maintained at 25%, 50%, 75% and 100% of brake power output at the speed of 1500 rpm with modified inlet manifold to operate the engine in PPCCI combustion mode. The experiment was repeated with premixed ratios of 0.25 at various power outputs.

In PPCCI mode the notations are used:

D-20J mode – Diesel (manifold injection)-20% JOME and 80%.

Diesel blends (main injection).

Rp – the ratio of energy of premixed fuel Q_p to the total energy Q_t.

$$Rp = Qp/Q_t = (m_p \cdot CV_p)/m_p \cdot CV_p + m_d \cdot CV_d,$$

where m is the mass of fuel and CV is the lower colorific value and subscripts p and d refer to premixed and directly injected fuel, respectively.

Table 1 – Test Engine Specifications

Engine Type	Four stroke, Air cooled, stationary, constant speed, direct injection, CI engine
No. of cylinders	1
Maximum power	4.4 kW at 1500 rpm
Maximum torque	28 N-m at 1500 rpm
Bore	87.5 mm
Stroke	110 mm
Displacement	661.5cc
Compression Ratio	17.5: 1
Injection Timing	23.40 bTDC
Loading type	Swinging field dynamometer

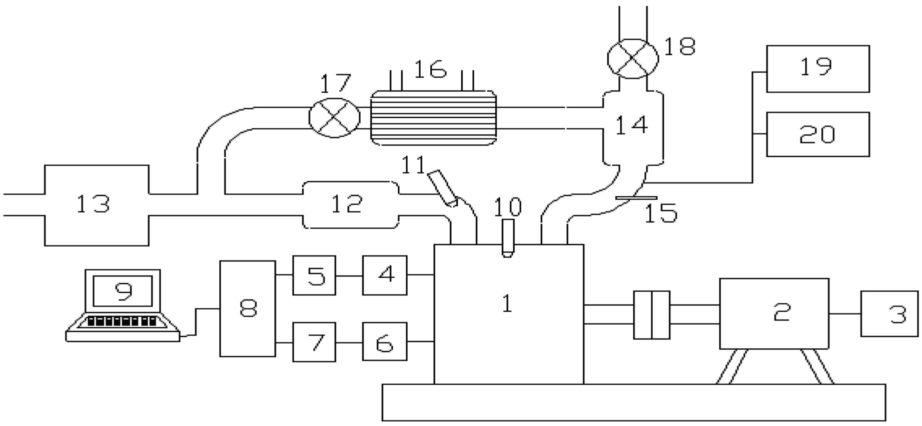

Figure 1 – Experimental setup: 1 – diesel engine, 2 – electrical, 3 – dynamometer, 4 – pressure pickup, 5 – charge amplifier, 6 – TDC position, 7 – TDC amplifier, 8 – A/D Card, 9 – personal, 10 – main injector, 11 – premixed fuel, 12 – mixing chamber, 13 – air flow, 14 – settling chamber, 15 – thermocouple, 16 – EGR cooler, 17 – EGR valve, 18 – back pressure, 19 – exhaust gas, 20 – AVL smoke

Results and Discussion

In the present work, reduction of NO_x and PM with partially premixed charge compression ignition (PPCCI) combustion was investigated. Diesel was used as a premixed fuel with premixed ratio of 0.25 along with 20% jatropha oil methyl ester (JOME) blend as main fuel with 10%, 20% and 30% EGR. Diesel fuel was injection into the intake manifold using a solenoid operated injector controlled by electronic control unit (ECU) to form premixed charge. The pre-mixed charge was burnt in the cylinder along with the fuel directly injected into the cylinder by a conventional injection system [25]. To control the start of combustion and NO_x emissions, EGR was adopted and the exhaust gas was varied from 10% to 30% in steps of 10%.

Investigation of specific energy consumption and brake thermal efficiency

The variation of SEC and brake thermal efficiency with brake power for CIDI mode and D-20J mode with premixed ratio of 0.25 without EGR and with 10%, 20% and 30% EGR are demonstrated in fig.2, 3. As the percentage of EGR increases, the SEC increases and brake thermal efficiency decreases compared to CIDI mode. When EGR is introduced the fuel air mixture is diluted and the decrease in the availability of oxygen retards the combustion. The heat release in combustion reactions is decreased and the quantity of unburned fuel is relatively large. As EGR increases, the brake thermal efficiency decreases [26, 27].

The SEC varies from 13,420 to 14,417 kJ/kWh in D-20J for premixed ratio of 0.25 without EGR and with 10%, 20% and 30% EGR compared to 12,661 kJ/kWh in CIDI mode at rated power output. The brake thermal efficiency varies from 26.8 % to 25.0% in D-20J mode for above mode compared to 28.4% in CIDI mode.

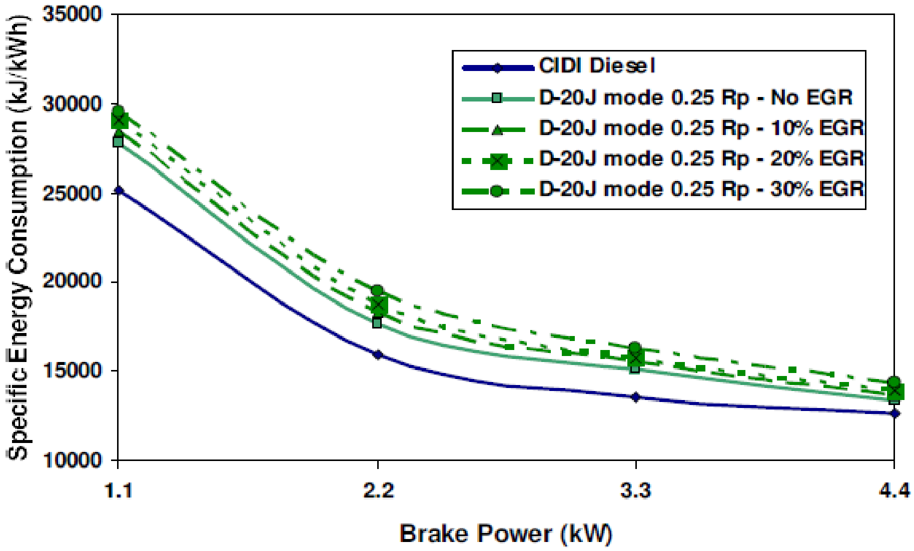

Figure 2 – Variation of specific energy consumption with brake power

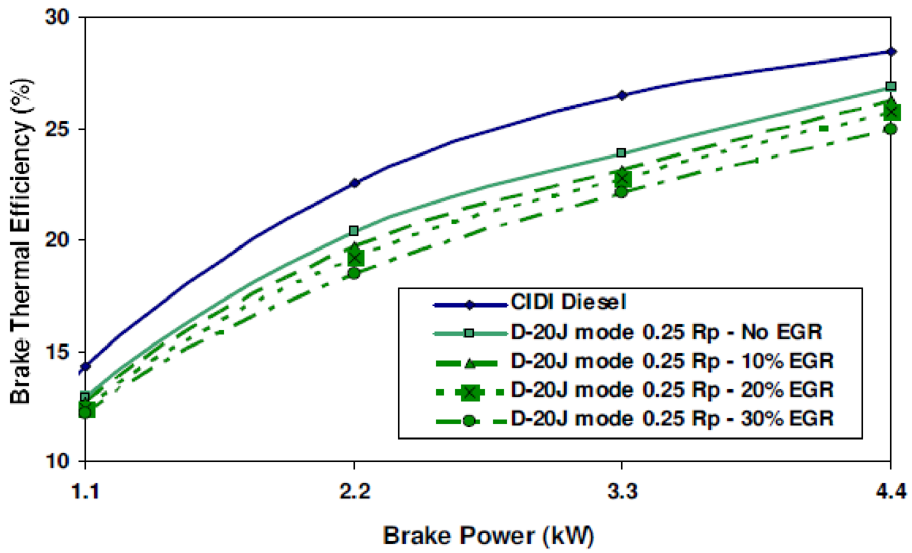

Figure 3 – Variation of Brake Thermal Efficiency with Brake Power

Impact of temperature of exhaust gas

Research the variation of exhaust gas temperature with brake power for D-20J with premixed ration of 0.25 with 10%, 20% and 30% EGR and without EGR compared with CIDI mode is shown in fig. 4. The combustion starts earlier resulting in higher in-cylinder temperature and pressure. These results in higher exhaust gas temperature at rated power output with premixed ratio of 0.25 without EGR compared to base line diesel mode. With EGR, the specific heat capacities of re-circulated H_2O and CO_2 constituents increase resulting in lower peak combustion temperature. The effect is more pronounced at higher EGR percentages. At rated power output, the exhaust gas temperature varies from 444ºC to 431ºC with 10%, 20% and 30% EGR for premixed ratio of 0.25 compared to 485ºC without EGR in D-20J mode.

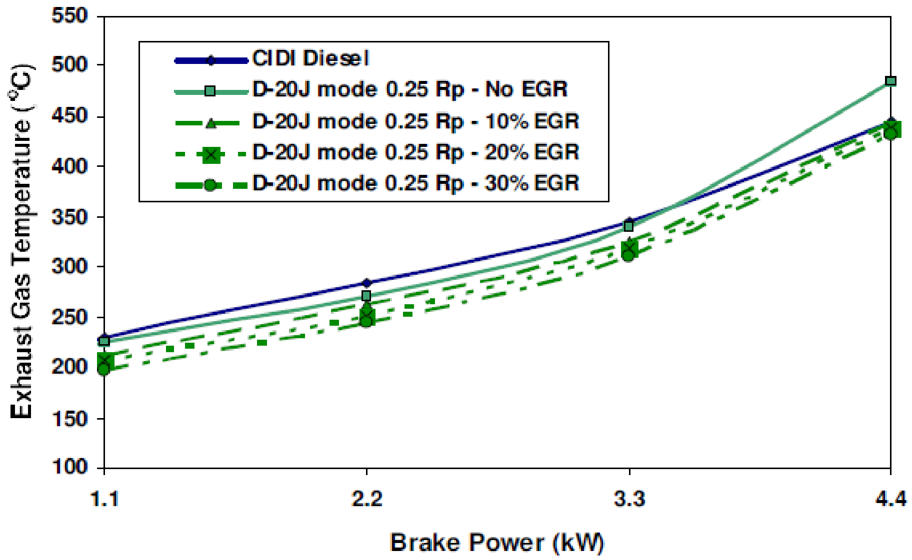

Figure 4 – Research the variation of temperature of exhaust gas with brake power

Studying unburnt hydrocarbon and emissions of CO

Fig.5 shows the variation of UBHC with brake power for CIDI mode, for PPCCI mode with D-20J 10, 20 and 30% EGR and without EGR. The variation of CO emissions is shown in figure 6 for the same operating conditions. Reduction of oxygen with EGR reduces the combustion reaction rate and temperature inside the cylinder. The burned gas temperature is low which results in increased emissions of UBHC and CO compared to CIDI mode. The peak temperatures are also relatively low to complete the oxidation of CO to CO_2 [28].

Because of lower inlet temperatures, premixed diesel fuel and in-cylinder injection of methyl ester blends are not completely evaporated which also leads to higher UBHC and CO [29, 30]. The effects of crevice volume and flame quenching may also be responsible for high UBHC and CO emissions. The UBHC emissions vary from 0.9 to 1.2 g/kWh in D-20J for premixed ratio of 0.25 without EGR and with 10%, 20% and 30% EGR compared to 0.7 g/kWh in CIDI mode at rated power output and the CO emissions vary from 17.6 to 30.9 g/kWh in D-20J mode compared to 16.7 g/kWh in CIDI mode.

Research of NO_x emissions

Fig. 7 shows the variation of NO_x emissions with brake power for CIDI mode and PPCCI mode with D-20J with 10, 20 and 30% EGR and without EGR.

The combustion starts earlier resulting in higher heat release rate, in-cylinder temperature and pressure at rated power output. These results in higher NOx formation at rated power output for D-20J mode with premixed ratio of 0.25 without EGR compared to base line diesel mode. Recirculation of exhaust gas reduces the NOx emission at all the power outputs compared to CIDI mode as oxygen available for the formation of NOx is reduced when using EGR [31, 32]. Peak combustion pressure and temperatures are reduced as EGR percentage increases. At rated power output in D-20J mode with 10%, 20% and 30% EGR the NOx emissions range from 6.2 to 3.33 g/kWh compared to 9.1 g/kWh without EGR.

Investigation of soot emissions

The variation of soot emission with brake power for PPCCI mode of operation with D-20J with 10, 20 and 30% EGR and without EGR is shown in fig.8. Soot emission in PPCCI mode with EGR is higher compared to that of without EGR. The increase in soot emission is due to reduction in oxygen content and decrease in heat release rate with EGR at all power outputs [33].

It was found that with 10% EGR and 20% EGR, soot emissions are lower than that of CIDI mode but higher than PPCCI mode without EGR. Soot emissions are higher than that of CIDI mode when EGR is creased beyond 20%. Hence, the quantity of EGR that can be re-circulated in PPCCI mode with premixed ratio of 0.25 is limited to 20% in the present work. In PPCCI mode, the soot emissions in D-20J mode at rated power output vary from 82 to 208 mg/m^3 with 10%, 20% and 30% EGR while it is 75 mg/mg^3 without EGR compared to 166 mg/m3 in CIDI mode.

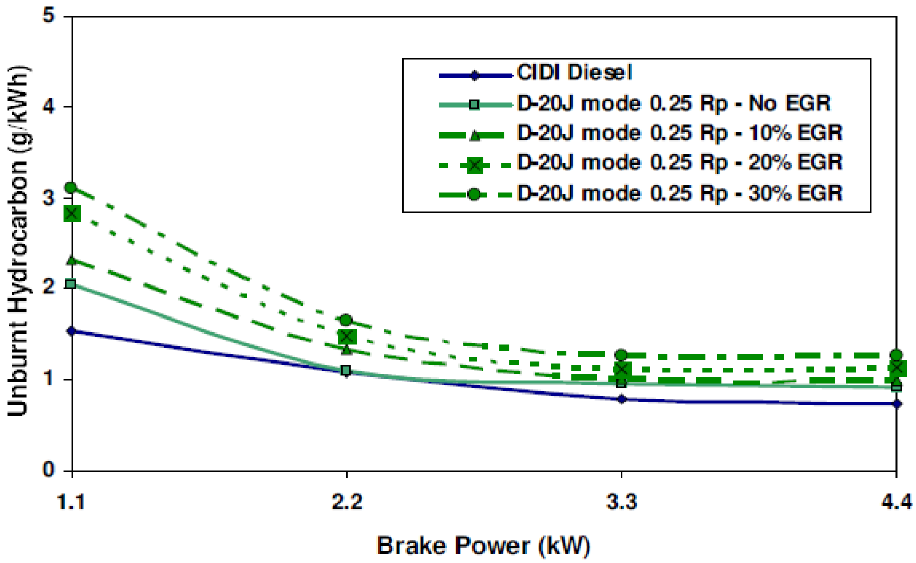

Figure 5 – Influence of variation of unburnt hydrocarbon with brake power

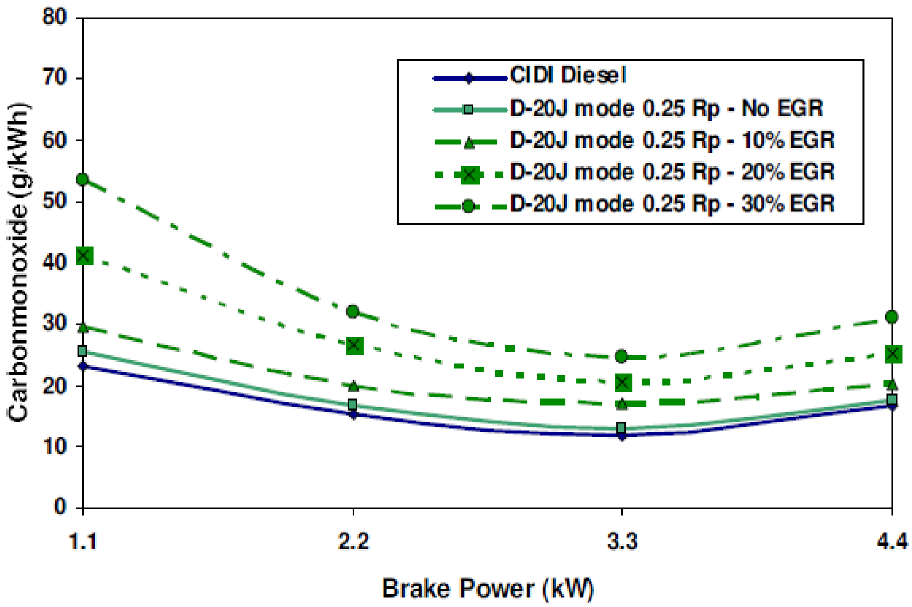

Figure 6 – Influence of variation of carbonmonoxide with brake power

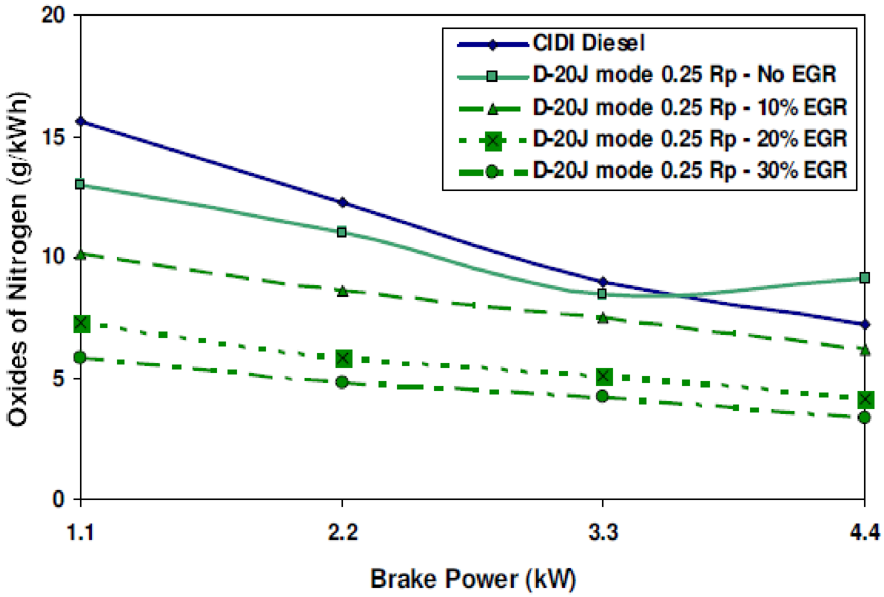

Figure 7 – Variation of NO_x with brake power

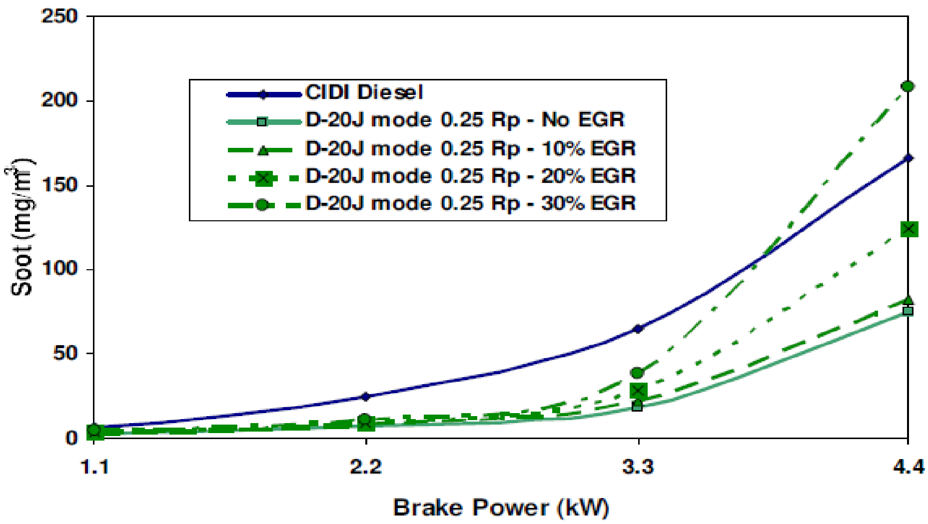

Figure 8 – Variation of soot with brake power

Research of heat release rate

Fig. 9 shows the heat release rate at rated power output for various premixed ratios in PPCCI mode compared to CIDI mode. It can be observed that the heat release curves show two peaks-one smaller magnitude and another peak of greater magnitude near TDC. The first stage of heat release is associated with low-temperature kinetic reactions (cool flames) named low temperature reactions (LTR). The second stage of heat release rate is the main heat release and named as high temperature reactions (HTR). The time delay between the LTR and HTR is named as negative temperature coefficient (NTC) region [34-38].

The negative temperature coefficient regime is characterized by a decrease in the overall reaction rate even though in-cylinder temperature increases. This leads to a lower reactivity of the system. For diesel (lower octane number fuel) the heat release in the low temperature combustion (LTC) is predominant compared to gasoline (higher octane number fuel) [39].

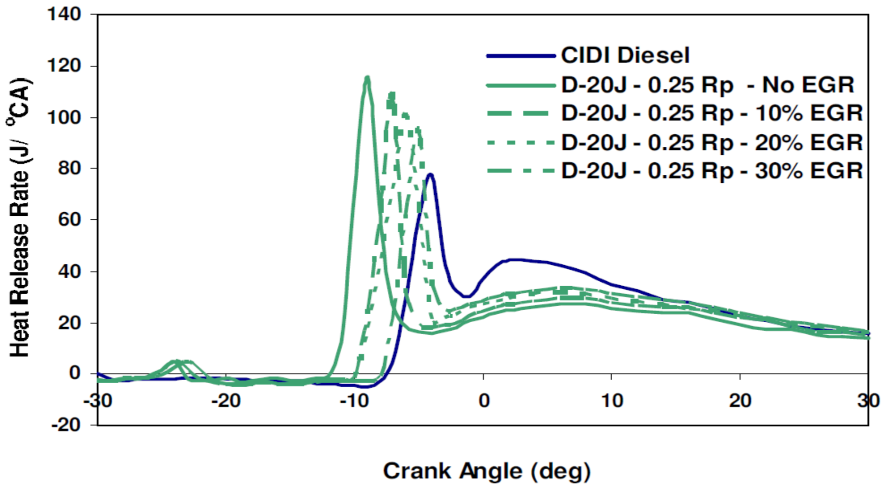

Figure 9 – Variation of Heat Release Rate with Brake Power

Fig. 10 shows the LTR, HTR and interval between LTR and HTR in D-20J mode at rated power output for premixed ratio of 0.25 without EGR and with 10, 20 and 30% EGR. It is observed that the peak LTR is not affected with increase in EGR percentage. But peak of HTR is significantly decreased as the percentage of EGR is increased. Increasing EGR percentage can delay both, the start of LTR and HTR. The EGR act as a thermal sink absorbing the heat present and lowers the heat release rate.

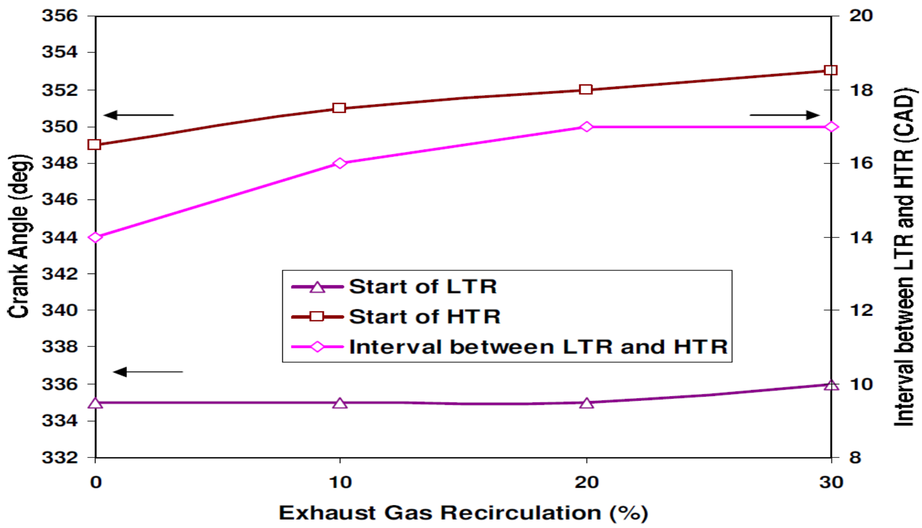

Figure 10 – LTR, HTR and Interval between LTR and HTR with Various Percentages of EGR at Rated Power Output for D-20J mode

The peak heat release rates during HTR at rated power in D-20J are 115.8, 109, 101.2 and 95.2 J/ºCA occurring at 11 to 7 ºCA bTDC for premixed ratios of 0.25 without EGR and with 10, 20 and 30% EGR while the peak heat release rates during LTR vary from 4.8 to 5.1 J/ºCA occurring at nearly 25ºCA bTDC for all premixed ratios. The time interval between LTR and HTR varies from 14 to 17ºCA.

Conclusions

Thus as a result of the performed experimental work it was found that brake thermal efficiency decreases with increase in EGR percentages. UBHC and CO emissions are higher in PPCCI mode. NO_x emissions are lower and the percentage decreases are 14.8%, 42.8% and 54.3% compared to baseline diesel mode. Soot emission decrease up to 20% EGR and increases when EGR is increased above 20% compared to CIDI mode. In D-20J the peak pressure increases up to 20% EGR and decrease when EGR is increased to 30% compared to CIDI mode. The percentage increases in peak heat release rate in D-20J are 40.6%, 30.6% and 22.8 % compared to CIDI mode. Premixed ratio of 0.25 with 20% EGR is observed to be optimum in D-20J comparing the performance, combustion and emission characteristics.

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