PERFORMANCE AND EMISSION STUDY ON DICI AND HCCI ENGINE USING RAW PONGAMIA OIL AND DIESEL

by

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The present work investigates the performance and emission characteristics of pongamia oil and diesel fuelled direct injection compression ignition (DICI) and homogeneous charge compression ignition (HCCI) engine. The primary objective of the work is to investigate the feasibility of application of unmodified pongamia oil in Diesel engine and to estimate the maximum fraction of diesel fuel replaced by the neat pongamia oil. This investigation also deals with the HCCI operation using unmodified pongamia oil. In DICI mode the neat pongamia oil is admitted into the engine in the form of pongamia oil and diesel blends. The blend that offers highest diesel replacement is considered as the test blend and it is tested further to find its maximum possible brake thermal efficiency by changing the engine operating parameters. The selected maximum blend is then tested in the new setting of the engine to determine the maximum possible performance and emission characteristics. The conventional emissions of DICI engine such as NO and smoke are disappeared in the homogeneous charge compression ignition mode of operation. The HCCI engine tested in the present work is fuelled by 40% neat pongamia oil and 60% diesel fuel through direct injection and vapour induction, respectively. The ignition or combustion phasing of the HCCI operation is carried out by the exhaust gas recirculation method. The amount of exhaust gas re-circulation governs the timing of combustion. The results of the experiments show that the neat pongamia oil performed well in HCCI mode and offered approximately ten times lower NO and smoke emission. Finally, the results of the DICI mode and HCCI mode are compared with each other to reveal the truths of neat pongamia oil in heterogeneous and homogeneous combustion.

Key words: *performance, emission, direct injection compression ignition, homogeneous charge compression ignition, exhaust gas recirculation, vaporizer, raw pongamia oil*

Introduction

The rapid depletion of petroleum resources and continuous addition of green house gases causes an intensive search of alternative fuels for the existing petrol and diesel fuels.

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Many alternative fuels have been identified and tested successfully in the existing engines with and without modifications. The present work investigates the feasibility, performance and emission characteristics of higher vegetable oil blends (more than 20%) in DICI and HCCI mode of operation. Pongamia oil, a known non-edible vegetable oil was used in this investigation in the form of neat pongamia oil and diesel blend.

The ignition or combustion phasing of the HCCI operation was carried out by the exhaust gas re-circulation (EGR) method. The amount of EGR governs the timing of combustion. The results of the experiments show that the neat pongamia oil performed well in HCCI mode and offered approximately ten times lower NO and smoke emission. Finally, the results of the DICI and HCCI mode of operations are compared with each other to reveal the truths of neat pongamia oil in heterogeneous and homogeneous combustion.

In the present investigation 40% pongamia oil and 60% diesel blend was chosen as a test fuel. The blends such as 20% and 30% pongamia oil were not considered for the present investigation [1]. Since, the aim of the present investigation is for higher percentage of replacement of diesel with pongamia oil without compromising on performance and emission levels. The blend 50% pongamia oil was also not considered for the investigation as it emits higher percentage of smoke.

Methodology

The engine used for the investigation is a Diesel engine and its operating parameters were optimized for diesel fuel operation. Hence, the test engine operating parameters were modified again in such a way to offer best performance for the new test fuel 40% pongamia and 60% diesel fuel (40P). The test fuel 40P was then tested in the new engine setting to determine the maximum possible performance and emission characteristics.

The same proportion of raw pongamia oil and diesel fuel was tested in the HCCI engine to study the performance and emission characteristic. In HCCI engine the test fuels such as pongamia oil and diesel fuel was admitted through direct injection device and vapouriser, respectively. Since, the boiling point of neat pongamia oils is more than 400 °C; the vapourisation of neat pongamia oil consumes more heat energy. In addition to that the vapourisation of neat pongamia oil deposits wax like materials in the heater which affects the heater function. Hence, in the present work raw pongamia oil was admitted through direct injection device with early injection timing. In HCCI operation the ignition or combustion phasing was carried out by the EGR method. Finally, the results of the DICI and HCCI modes were compared to reveal the truths of 40P operation in heterogeneous and homogeneous combustion.

Experimental set-up

A single cylinder air cooled DICI engine was used for conducting experiments in both DICI and HCCI mode of operation. The engine used in the set-up was coupled with an eddy current dynamometer for loading the engine. The inlet side and outlet side of the engine has necessary measuring facility. The specifications of the engine used for the experiment are given in tab. 1, the schematic of the experimental set-up is shown in fig. 1.

Results and discussion

Investigation on DICI mode using 40P

The engine operating parameters considered for optimisation were injection timing, injection pressure, and compression ratio (CR). The parameters considered for the optimisation has been fixed based on the preliminary experiment. An experiment has been conducted for finding best combination of parameters suitable for the test fuel operation. The optimum combination of parameters has been chosen based on the maximum brake thermal efficiency (BTE). The parameters and their values for different levels used for the experiments are shown in tab. 2.

Table 1. Engine specifications

Bore × stroke	87.5 mm × 110 mm
Connecting rod length	220 mm
Compression ratio	17.5:1
Rated power output	4.4 kW at 1500 rpm
Displacement volume	662 cm^3
Injector operating pressure	220 bar

Table 2. Engine operating parameters

Parameters	Level 1	Level 2	Level 3
Injection timing (inj. Tmg)	25	27	29
Injection pressure (inj. Pr)	250	275	300

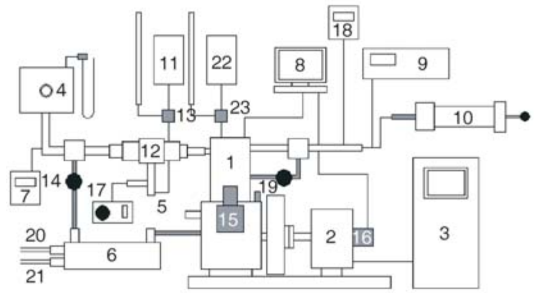

Figure 1. Experimental set-up
1 – Diesel engine, 2 – eddy current dynamometer, 3 – dynamometer control, 4 – anti pulsating drum, 5 – diesel vapouriser, 6 – EGR cooler, 7 – inlet temperature indicator, 8 – computer with DAQ, 9 – gas analyzer, 10 – smoke sampling pump, 11 – diesel tank, 12 – diesel vapouriser manifold, 13 – three way cock, 14 – EGR regulator, 15 – diesel fuel injection pump, 16 – crank angle (CA) encoder, 17 – power regulator for vapouriser, 18 – exhaust temperature indicator, 19 – inductive pickup, 20 – water inlet for EGR cooler, 21 – water outlet for EGR cooler, 22 – pongamia oil tank, 23 – three way cock

From the full factorial experiments it was found that the best combination of engine operating parameters that offered maximum BTE was 275 bar – injection pressure, 27° bTDC – injection timing, and 19 – CR. The test fuel that holds higher fraction of raw vegetable oil was tested in the modified engine that has the best combination of engine operating parameters. This study revealed the performance and emission characteristics of raw vegetable oil fuelled DICI engine.

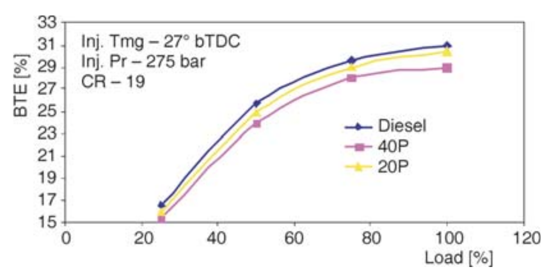

Figure 2. Variation of BTE with load

Figure 2 shows the variation of BTE of 40P at various load conditions. From the figure it is seen that the BTE of 40P is lower than that of diesel fuel operation at all load conditions. This is mainly due to the inferior combustion performance of unmodified vegetable oil present in the fuel blend. The unmodified vegetable oil requires comparatively longer time for complete combustion due to the heavier molecular structure. Hence, it offers comparatively lower combustion temperature and pressure [2]. This is the main reason for the lower BTE of 40P blend at all load conditions. However, the drop in BTE is not much lower than the reference fuel (diesel). The BTE of 40P fuel at full load is 28.8% which is 3% lower than diesel fuel operation.

Figure 3 shows the variation of NO emission of 40P at various load conditions. It is observed that the NO emission of 40P blend is lower than standard diesel operation at all load conditions. The heavier molecule structure of unmoditied vegerable oil (UVO) fires longer than diesel fuel and hence, it offers comparatively lower combustion temperature and pressure. This is the main reason for the production of lower NO emission by 40P.

Figure 4 shows the variation of CO emission of 40P at various load conditions. It shows higher CO emission for 40P blend than that of standard diesel operation at all loads. This may be due to the poor combustion behaviour of the UVO present in the fuel blend. The production of low combustion temperature due to the burning of UVO is the main reason for the higher CO emission.

The CO emission is generally an indication of incomplete oxidation of fuel [2]. The heavier molecular structure of the UVO permits the fuel to burn longer than diesel fuel and hence, the burning of UVO extended long in the expansion stroke. This fuel vapour finds relatively low combustion temperature and pressure and hence the large fractions of UVO vapour combusted partially. This is the main reason for the higher CO emission at full load.

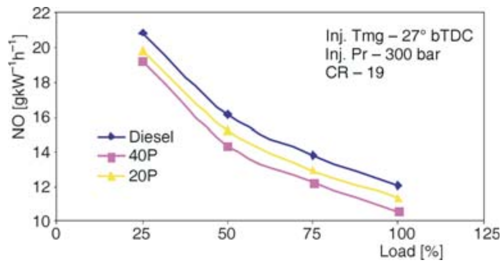

Figure 3. Variation of NO emission with load

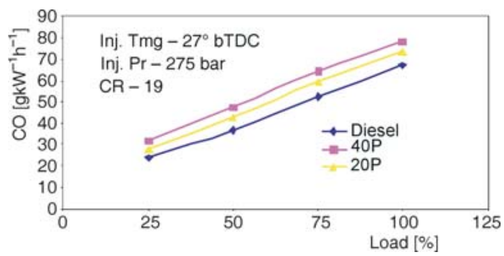

Figure 4. Variation of CO emission with load

Figure 5 shows the variation of HC emission of 40P at various load conditions. The HC emission of 40P is higher than that of standard diesel operation at all loads. This may be due to the production of lower combustion temperature. The heavier molecular structure and longer duration of combustion are considered as the probable reasons for higher HC emission [3]. In addition to that the fuel vapour left in the crevice is not combusted and hence, they are emitted as HC emission during exhausting. The HC emission of 40P at full load is 275 ppm, which is 65 ppm higher than standard diesel operation.

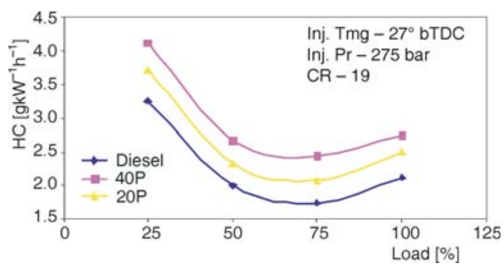

Figure 5. Variation of HC emission with load

Figure 6 compares the variation of smoke intensity of 40P at various load conditions. It is observed that the 40P blend offers comparatively higher smoke emission than that of diesel fuel operation at all loads. More specifically, at full load, it offers approximately two Bosch smoke number (BSN) higher smoke than that of standard diesel operation. This is due to the pyrolysis (charring) of the UVO vapours present in the cylinder at the time of full load. The generation of lower combustion temperature by extended duration of UVO combustion caused the higher smoke emission [1, 4] .

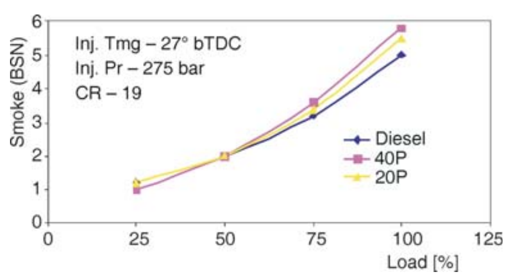

Figure 6. Variation of smoke intensity with load

Figure 7 compares the cylinder pressure diagram of 40P fuel and diesel fuel operation. From the figure it is found that the 40P ignites around three degrees earlier than diesel fuel operation. This is mainly because of the early ignition enabled by UVO fuel vapours. The UVO produced fuel vapours very rapidly as soon as it was injected into the cylinder. This forms an air fuel mixture and combusts little earlier than diesel fuel. Hence, it shows a little ignition advance than that of diesel fuel.

Though it ignites earlier the peak pressure produced by this fuel is not higher than the diesel fuel. Approximately, 5 bar pressure difference exist between the fuels. This is the main reason for the lower BTE of the 40P.

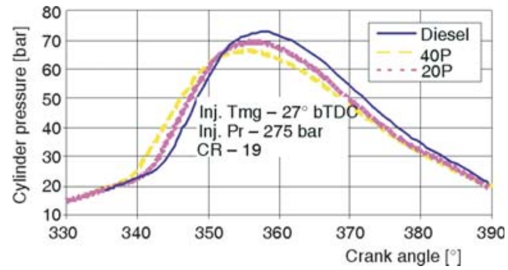

Figure 7. Variation of cylinder pressure with crank angle at full load

Figure 8 compares the heat release rate of 40P blend with standard diesel operation at full load. It is seen that the two phase of combustion is clearly visible and distinguishable in both fuel operation. The first phase of combustion of 40P is lower than standard diesel operation as it ignites earlier than diesel fuel. The rapid production of intermediate compounds in the 40P operation is the main reason for the earlier heat release. However, the first phase of combustion is not higher than diesel fuel and the second phase of combustion is higher and longer than diesel fuel operation. This is mainly due to the combustion behaviour of UVO present in the fuel blend. This behaviour is the main reason for the lower combustion pressure and temperature. In addition to that this behaviour is the main reason for the lower BTE of 40P blend.

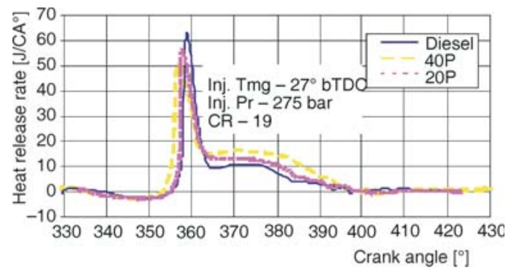

Figure 8. Variaton of net heat release rate at full load

Investigation on HCCI mode using 40P

The test engine was operated by 40P fuel in which 40% pongamia oil is blended with 60% diesel fuel. The diesel fuel was inducted in the form of vapour and the pongamia oil was injected into the engine cylinder by the regular diesel injection system with early injection timing. An EGR system was also used in this method to get precise control over the ignition phasing timing [5].

The quantity of EGR admitted into the engine along with fuel air mixture plays a vital role in controlling ignition timing and performance of the 40P fueled HCCI engine. More specifically it is used to retard combustion and to reduce the combustion temperature and pressure by absorbing considerable amount of heat from the combustion. To study the effect of EGR on the performance, emission, and combustion characteristics the engine was tested under various EGR proportions. The results of 40P fueled HCCI engine under various load conditions with various proportions of EGR are given.

Figure 9 shows the variation of BTE at various load conditions with various proportions of EGR. The admission of exhaust gas along with fuel-air mixture dilutes the mixture strength and helps to ignite the mixture closer to top dead centre (TDC). However, EGR ratio beyond 15% reduces BTE by making the mixture more sluggish. The excessive addition of EGR retards combustion more and produce peak pressure after TDC. These are the possible reasons for lose

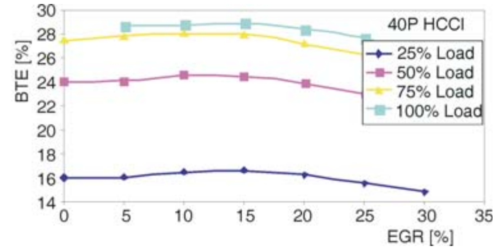

Figure 9. Variation of BTE with EGR

of BTE after 15% of EGR admission. This trend is more visible at higher loads. The application of EGR is more necessary at higher loads because the cylinder temperature is quite high and causes the mixture to ignite in uneven timings [6]. From the figure it is also seen that the full load test without EGR was not observed due to sever engine roaring and unstable operation. Hence, the full load test was conducted with sufficient EGR quantity and found that the 15% EGR offers better performance than that of other fractions. From this experiment it is proved that the use of EGR is more desirable at higher loads compared to lighter loads for establishing smooth and stable HCCI operation. The observed reading shows that the 15% EGR provides better performance at all load conditions than that of other EGR fractions. Therefore, the experiment concludes that the 15% EGR fraction is the optimum EGR ratio for this experiment.

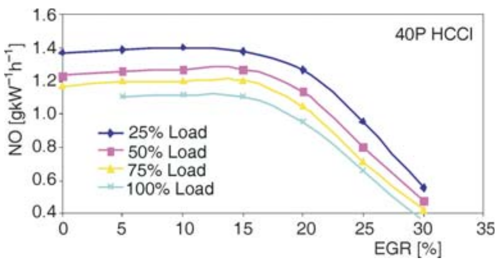

Figure 10. Variaton of NO with EGR

Figure 10 shows the variation of NO_x emission with various EGR proportions at various loads. From the figure, it is observed that the addition of EGR increases the NO_x up to certain limit and then decreases drastically. The addition of EGR helps to shift peak pressure towards TDC and help to improve the performance of the HCCI engine [7]. However, excessive addition of EGR dilutes the fuel-air mixture and causes the sluggish behaviour of the mixture. These are the main reasons for the reduction of NO_x after 15% of EGR. The same trend persists in all load conditions. The presence of more homogeneous mixture and no fuel droplet firing are also contributes considerably in the reduction of NO_x emission from the HCCI engine. It is already proved that the addition of exhaust gas changes the ignition timing and shifts the peak pressure towards TDC. This changes the engine performance and causes a mild increase in NO_x emission. This trend is predominant at higher loads compared to lighter loads.

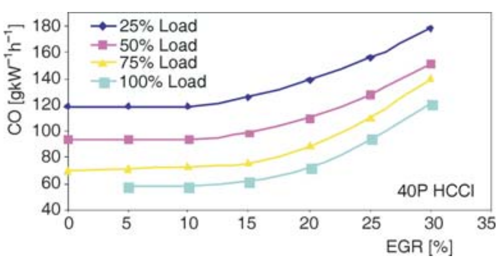

Figure 11. Variation of CO with EGR

The HC and CO emission

Higher HC and CO emissions are one of the major setbacks of HCCI engine. One major factor, which contributes to higher HC and CO emissions, is low temperature combustion due to lean mixture strength and higher EGR levels.

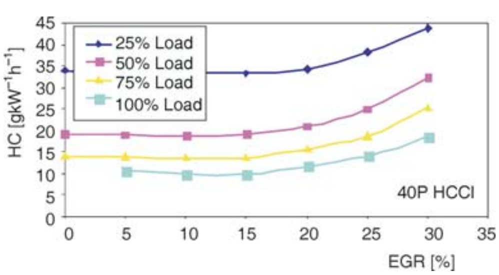

Figure 12. Variation of HC with EGR

Figures 11 and 12 show the variation of HC and CO emission with various EGR proportions at various loads. In which, the better performance is observed near optimum EGR fraction. The CO emission of HCCI engine is comparatively higher than DICI mode due to low combustion temperature and pressure [6, 7]. In the DICI engine more fuel combusts in the first stage of combustion and causes higher combustion temperature. This is the main reason for the lower CO and HC emission of DICI mode. The figure also shows that the addition of exhaust gas up to 15% improves the performance of CO and HC emission. However, this trend reverses after 15% EGR and increases CO and HC emission drastically. This is due to the reduction of combustion reaction rate and mean temperature of combustion. The same trend is visible in all load conditions and it is clearer in higher loads. However, this is a conventional behaviour of HCCI engine. In HCCI mode, the HC and CO emissions are typically around 30 times higher than the standard diesel operation.

Smoke emission

Low smoke emission is another attraction of HCCI combustion. However, in diesel fuelled HCCI engine smoke reduction is dependent on efficient control of EGR [8]. This is experienced in the present work also that is the EGR proportion plays a vital in the smoke emission. The supply of exhaust gas during suction stroke mixes well with the fuel-air mixture and dilutes the mixture. This provides a very lean chance to the smoke emission. However, the excessive supply of EGR reverses the trend and increases the smoke emission. The absence of diffusion combustion and localized fuel rich mixture are the important reasons for the reduction of smoke emission. Generally, NO_x formation occurs in hot zones and the soot emission occurs in the fuel rich zones.

From fig. 13 it can be observed that the engine operated with 40P exhibits a significant reduction in smoke at all loads. This is due to the presence of charge homogeneity and absence of liquid fraction of fuel pockets [9]. However, at higher loads due to more injection of 40P causes an increase in smoke emission. At higher loads the injected 40P finds less time to evaporate the fuel and hence fuel droplets are participating in the combustion. This is the main reason for the increased smoke emission.

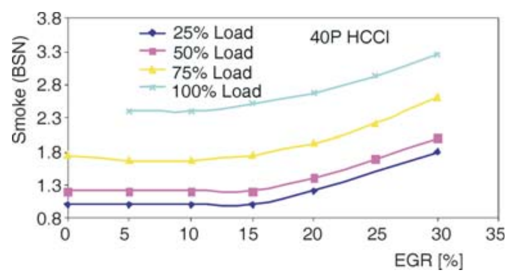

Figure 13. Variaton of smoke with EGR

Combustion characteristics

The timing of ignition plays a vital role in the performance of HCCI engine. The timing of ignition is determined by the conditions inside the cylinder during the compression stroke. The condition of the mixture inside the cylinder must be tuned in such a way to auto-ignite the mixture in appropriate ignition timing. The EGR used in this method helps to maintain this constantly at all load conditions. Also, the EGR helps to change the condition of mixture rapidly by changing the combustion temperature and pressure [5]. The gases such as CO_2, N_2, and water vapour present in the exhaust gas are considered as inert gases and are not participating in combustion but absorbs considerable amount of heat from the combustion. Hence, the mixture ignites close to TDC and decreases combustion pressure and temperature. However there is a limit in adding EGR, excessive addition EGR causes poor performance by making the mixture too sluggish.

From the figs. 14 and 15 it is seen that the increases in EGR rate shifts the cylinder pressure towards TDC and at the same time decreases peak pressure. The mixing of exhaust gas reduces the strength of fuel-air mixture and the temperature of mixture. This makes the mixture to fire close to the TDC and cause to improve the performance of the engine. This is the main reason for improved BTE close to 15% EGR fraction. However, the addition of EGR increases CO and HC emission. The same trend is visible in heat release rate also. The two phases of combustions are not clearly shown in this combustion. The timing of occurrence of maximum heat

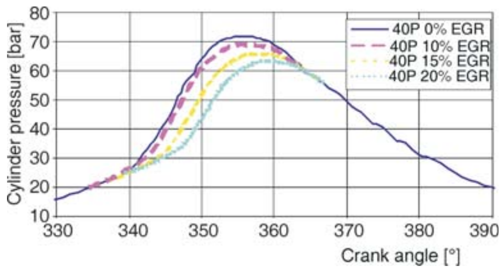

Figure 14. Variaton of cylinder gas pressure with EGR

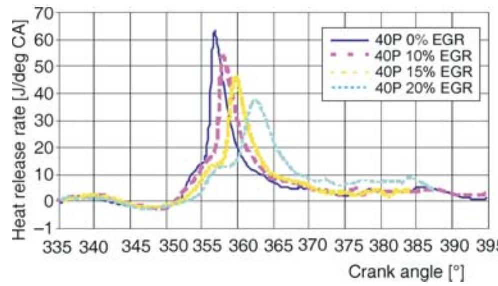

Figure 15. Variation of HRR with EGR

release and the duration of heat release changes with respect to the EGR rate [10]. The dilution effect caused by EGR and the heat absorption behaviour are the two main reasons for the previous said phenomenon.

Comparison of DICI mode with HCCI mode

The early researchers proved that the application of neat vegetable oil more than 20% produces many undesirable effect and operational problems. The present work investigates the feasibility of application of neat vegetable oil more than 20% and its performance and emission behaviour in DICI and HCCI modes of operation. The detailed experiments were conducted and its results are presented in the previous chapter. From the experimental results it is found that the 40P operation is possible without worsening engine performance and emission characteristics. This was achieved after changing engine operating parameters considerably. However, the emission behaviour of 40P is still inferior to the diesel fuel. Hence, the same fuel was tested in HCCI modes to study the change of emission performance of 40P. The results of DICI and HCCI mode of operation are compared in the following discussion to exhibit the performance and emission characteristics of 40P.

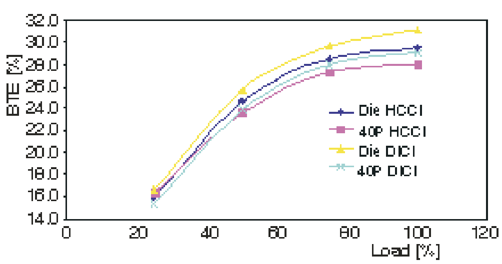

Figure 16. The BTE comparison of 40P with diesel fuel used in DICI and HCCI mode of operation

Figure 16 compares the BTE of 40P with diesel fuel (Die.) obtained in DICI and HCCI modes of operation. From the results of the experiments it is found that the BTE of 40P in DICI mode is higher than that of HCCI mode of operation. This is mainly due to the reduction of air quantity in HCCI mode by the diesel vapour and EGR. The neat oil injection also takes considerable amount of time for complete combustion [11]. These are the main reasons for the reduction of performance of 40P in HCCI operation. The lower heating value of pongamia oil and its heavier molecular structure are also caused for the reduction of BTE. The BTE of 40P is lower than that of diesel fuel used in the same methods. The BTE of 40P used in HCCI mode is 5% lower than that of diesel fuel used in the same method and it is 3.5% lower than that of 40P used in the DICI mode.

Figures 17 and 18 compares the emission performance of 40P with diesel (Die.) fuel used in DICI and HCCI mode of operation. It can be concluded that the CO and HC emission of 40P is higher than that of diesel fuel used in the same methods. In DICI mode of operation 40P offered higher CO and HC emission than that of diesel fuel. The same trend was repeated in HCCI mode of operation. This is due to the higher molecular weight of neat vegetable oil used in

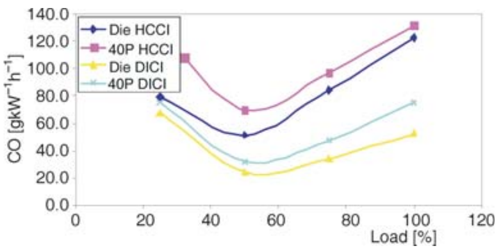

Figure 17. The CO emission comparison of 40P with diesel fuel used in DICI and HCCI mode of operation

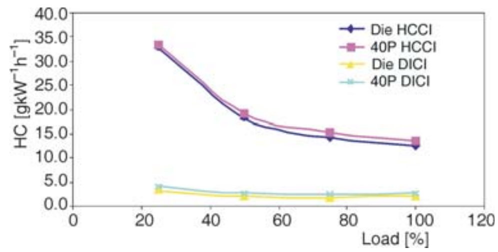

Figure 18. The HC emission comparison of 40P with diesel fuel used in DICI and HCCi mode of operation

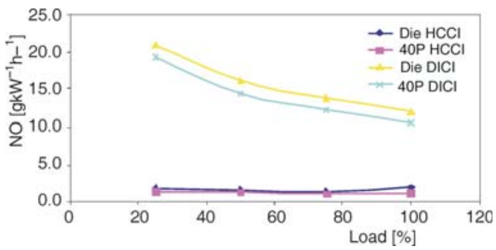

Figure 19. The NO emission comparison of 40P with diesel fuel used in DICI and HCCI mode of operation

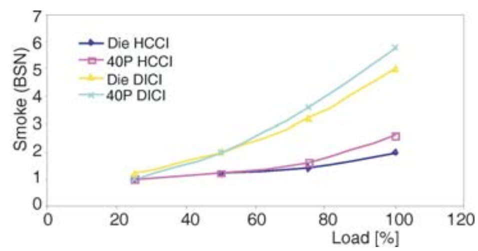

Figure 20. Smoke emission comparison of 40P with diesel fuel used in DICI and HCCI mode of operation

the blend. Usually, heavier molecular fuels take more time to combusts fully and offer longer duration of combustion [12]. Though the same trend it was repeated in HCCI mode of operation, the emission values are higher than that of DICI mode of operation.

Figure 19 the NO emission of 40P is lower than that of diesel fuel in both mode of operation and it is clearly visible in DICI mode of operation. In HCCI mode, both fuels are offering very low NO emission and the difference between both are insignificant. The heavier molecular structure and higher viscosity of neat oil causes the fuel to fire longer than the diesel fuel [12, 13]. These are the main reasons for the lower combustion temperature and lower NO emission of 40P than that of diesel fuel operation. In HCCI mode of operation, both fuels are offering very low NO emission. This is due to the supply of exhaust gas and diesel vapour along with fresh air induction. These are the main reasons for the lower combustion temperature and lower NO emission in HCCI mode.

Figure 20 compares the smoke emission of 40P with diesel fuel used in DICI and HCCI mode of operation. From the figure it is found that the smoke emission of 40P is higher than that of diesel fuel in DICI mode of operation. This is due to poor spray performance and viscous nature of neat vegetable oil. The rapid production of intermediate compounds consumes most of the oxygen present in the combustion chamber and reduces the availability of oxygen for further combustion. This process extends the combustion and causes the fuel particles to turn into soot and smoke [14]. These are the main reasons for the higher smoke emission of 40P in all mode of operation.

Figures 21 and 22 compare the peak cylinder pressure and peak rate of heat release of 40P with diesel fuel in both DICI and HCCI mode of operation. From these figures it is found that the diesel fuel offered highest peaks in all mode of operation than that of 40P.

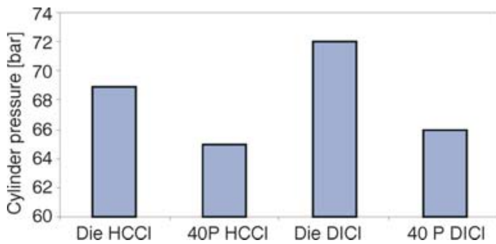

Figure 21. Cylinder pressure comparison of 40P with diesel fuel used in DICI and HCCI mode of operation

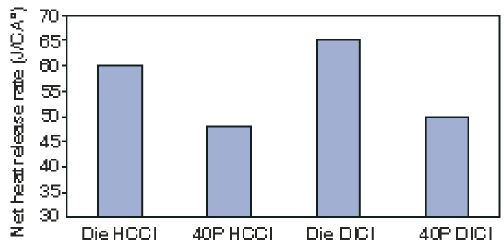

Figure 22. Net heat release rate comparison of 40P with diesel fuel used in DICI and HCCi mode of operation

The rapid production of intermediate compounds from the 40P made the fuel to fire earlier than the diesel fuel and extended the combustion longer than that of diesel fuel. This is the main reason for the lower peak of 40P in all mode of operation. This is the main reasons for the lower BTE of 40P in all mode of operation. The higher peak pressure and higher rate of heat release are the main reasons for the higher BTE of diesel fuel in all modes of operations.

Conclusions

The following major conclusions are arrived after conducting a detailed experimental investigation using 40P in both DICI and HCCI mode of operations. The results of DICI mode revealed that 40P offered 6% lower BTE, 12% lower NO, and 16% higher smoke than that of diesel baseline operation. Also, this mode offered 16% higher CO and 33% higher HC than that of diesel baseline operation.

The results of HCCI mode showed that the 40P offered 5% lower BTE, 4% lower NO, and 25% higher smoke than that of diesel fuel used in the same mode of operation. Also, this mode offered 7% higher CO and 10% higher HC than that of diesel fuel operation.

Comparatively, DICI mode offered 4% higher BTE than that of HCCI mode. The HCCI mode offered 55% reduced smoke and 80% reduced NO than that of DICI mode of operation.

Thus the results of the experiments proved that the 40P performed well in both DICI and HCCI mode of operations without compromising on its performance and emission behaviour.

Acronyms

BTE – brake thermal efficiency
bTDC – before top dead centre
CA – crank angle
CR – compression ratio
DICI – direct injection compression ignition
Die. – diesel
EGR – exhaust gas recirculation
HCCI – homogeneous charge compression ignition
TDC – top dead centre
UVO – unmodified vegetable oil
40P – 40% pongamia oil and 60% diesel fuel

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