Exploring the Potential of Microalgae Bioalcohol and Biodiesel in Arresting Particulate Smoke Emissions and Greenhouse Gases using Post-Injection Activated Regeneration Trap

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Research Article

Keywords: Active Regeneration, Diesel Particulate Filter, Diesel Oxidation Catalyst, Microalgae, Biodiesel, Bioalcohol

Posted Date: March 8th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1357066/v1>

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Abstract

The rapid deterioration of the atmospheric air quality due to the rise in vehicular emissions is a cause for concern in a global scale. Hence, it is crucial to establish efficient control measures to mitigate these crises. In this context, the objective of this study is to explore the effect of post injection parameters on a continuous active regeneration trap (CART) to mitigate harmful greenhouse gases (GHG) and particulate smoke emissions (PSE) using diesel fuel reformulated by long-chain microalgae bio-alcohol and low – density microalgae biodiesel. Furthermore, the efficiency of the CART unit is analyzed based on its ability to mitigate the harmful emissions without sacrificing the engine performance characteristics. From the study, it was observed that the maximum de-smoke efficiency of 67.85% is observed at a post injection timing (PIT) of 20°CA aTDC at a post injection mass (PIM) of 4 mg for low load condition while operating on microalgae biodiesel. While operating on microalgae bio-alcohol, the maximum de-smoke CART efficiency was observed as 67.25% and 55.78% for low and medium load conditions at a PIT and PIM of 20°CA aTDC and 2 mg while operating on the microalgae bio-alcohol. Likewise, the maximum de-HC CART efficiency was obtained at a PIT and PIM of 10°CA aTDC and 1 mg with a reduction of about 75% and 73.8% for medium and high load conditions. A slight reduction in oxides of nitrogen with the complete elimination of carbon monoxide emissions is observed after CART treatment for both the fuels.

1. Introduction

The accelerated deterioration of the global air quality due to the toxic gases and carcinogenic particulates primarily emanating from the transportation sector have detrimental effects on the human health and environment in the form of global warming and climate change. In a recent survey, it is estimated that most of the air pollution, nearly two-thirds, are due to vehicular emissions from both commercial and domestic transport sectors (Soleimani et al. 2021). Compression ignition (CI) engines emit non-volatile compounds like particulate smoke matter and aromatic hydrocarbons that are extremely dangerous to human health as they can cause respiratory and cardiovascular ailments (Hesterberg et al. 2012). Hence, it is vital that the treatment of these harmful emissions is facilitated before they are emitted into the atmosphere. The treatment of these vehicular emissions can be expedited using a suitable combination of after-treatment devices and establishing effective injection strategies while operating on a cleaner fuel as compared to diesel fuel (Jacob and Ashok 2020). In recent years, exhaustive research have been conducted using various long-chain alcohols and biodiesel in CI engines as alternative fuels. However, these fuels have higher unsaturated fatty acid methyl esters and oxygen content which tend to produce a significant number of oxides of nitrogen (NOX) and smoke emissions if the operation parameters are not calibrated in accordance with the after-treatment device (Rajasekar et al. 2020). Moreover, the feedstock used for fuel extraction plays a major role in deciding the fuel composition and the performance output on operation. Typically, alcohols with long carbon chains are free of fatty acid compositions that are derived from a sustainable feedstock tend to produce lesser emissions due to their efficient combustion characteristics.

From the literature available, the physicochemical properties of long chain alcohols and less dense and viscous biodiesel fuels complement positively on the engine output characteristics. More importantly, the R-OH in higher alcohols are efficient in restricting NOX and soot formation as compared to the oxygenated biodiesel types (Atmanli and Yilmaz 2018). However, despite the favorable fuel properties, the complete control of the emissions from the tail-pipe is still a challenge. To effectively treat emissions from CI engines, after-treatment devices are employed in several combinations to meet the stringent emission norms without sacrificing the engine performance outputs. Conventionally, the most common forms of after-treatment units are diesel particulate filter (DPF), lean NOX trap and diesel oxidation catalyst (DOC). These units are either used individually or in combinations depending upon the vehicle type (Ayodhya and Narayanappa 2018). Multiple studies have been conducted to analyze the efficiency of the after-treatment units while operating individually and in combination. For instance, Chung et al. (2012) conducted a study to identify the most optimal arrangement of after-treatment systems between SCR, DOC and DPF units using numerical models. Upon experimental validation, the study concluded that the arrangement of DOC-DPF-SCR was more robust in controlling significant amount of emissions which is in par with the legislative emissions norms (Lao et al. 2020). In a similar study, Apicella et al. (2020) explored the efficiency of DOC-DPF unit and SCR unit individually. The study concluded that the maximum control of polycyclic aromatic hydrocarbon emission and soot emissions is achieved with the DOC-DPF combination which has an emission reducing efficiency of more than 40% at high load condition. For these units to work effectively, certain amount of exhaust gas temperature (EGT) is required to provide the heat required by the catalyst for the oxidation or regeneration process. The management of EGT across the after-treatment can be facilitated using various techniques. A study conducted by Wu et al. (2021) claimed that the most effective way of managing EGT across the after-treatment device is by calibrating the main and post injection parameters for both active and passive regeneration. The study also concluded that the variation of the throttle pedal position influences the EGT significantly. To understand the role of EGT in after-treatment units, Chen et al. (2020) conducted a study to understand the effects of passive and active regeneration at optimal EGT in a DOC-DPF combination using methanol-diesel dual fuel engine. The study stated that employing delayed post injection effectively facilitated the required regeneration temperature in the unit and controlled particulate matter, carbon dioxide (CO₂) and nitrogen dioxide (NO₂) with a slight penalty on fuel consumption. The presence of oxygen content in the fuel plays a major role in improving the post injection characteristics and after-treatment unit efficiency. To understand the role of oxygenated fuels in after-treatment regeneration, Rodríguez et al. (2016) explored the effect of five oxygenated and paraffinic diesel fuel surrogates such as alcohol-diesel fuel and biodiesel-diesel based on DPF regeneration efficiency in a Euro 5 diesel engine. The study confirmed that the oxygenated nature of alcohol-diesel fuel required lesser EGT and resulted in the maximum reduction of soot emissions attributing to its rapid oxidation pattern during active regeneration using delayed post injection. In few studies, attempts were made to control vehicle emissions by using post injection to facilitate complete combustion of the soot produced without the use of after-treatment devices. Wu et al. (2019) conducted a study to observe the effect of post injection parameters on the unregulated and regulated emissions by calibrating the post injection timing and mass from 20°CA aTDC to 120°CA aTDC and 5 to 15 mg. The study concluded that soot particulate matter,

CO₂, carbon monoxide (CO), light hydrocarbon (HC) emissions increased significantly when the post injection mass increased above 10 mg. Furthermore, the study also recommends the employment an after-treatment device while using post injection strategies to significantly curb regulated and unregulated emissions. From the literature reviewed, it is evident that oxygenated bioenergy - diesel fuel surrogate can be opted as a suitable fuel source for post injection strategies to activate the after-treatment unit to mitigate particulate smoke emissions and other greenhouse gases in CI engines. Furthermore, the ideal configuration of after-treatment unit using active regeneration method is DOC-DPF arrangement. Using these elements, the objectives and methodology for this study were formulated for systematic experimentation to observe the influence of post injection parameters on CI engine operating at maximum throttle pedal position (MTPP) condition.

2. Motivation And Objective Of The Proposed Study

The alarming rise in air pollution primarily emanating from the transportation sector are having detrimental effects on the environment and living beings. Hence, it is crucial that the untreated emissions emanating from vehicles be effectively controlled using high quality fuels and efficient after treatment devices and injection strategies. The tail pipe emissions can be significantly controlled using targeted injection strategies and a combination of after-treatment devices. In this context, the objective of this study intends to study the effect of post injection parameters on a continuous active regeneration trap (CART) to mitigate harmful greenhouse gases (GHG), particulate smoke emissions (PSE) and other toxic emissions gases using diesel enriched by long-chain microalgae bio-alcohol and low-density microalgae biodiesel at MTPP condition. Furthermore, the efficiency of the CART unit is analyzed based on its ability to mitigate the harmful emissions without sacrificing the engine performance characteristics. The novelty of this study is to establish a third generation bio-energy as a suitable diesel fuel surrogate to mitigate GHGs and PSEs with the help of post-injection activated CART unit for a light commercial CI engine.

3. Materials And Methodology Of The Study

This section highlights the test equipment and methodology followed in this study to observe the combined effect of post injection parameters and after-treatment unit while operating on diesel fuel enriched by long-chain microalgae bio-alcohol and microalgae low density biodiesel.

3.1. Physicochemical properties of the test fuels

In order to reformulate and enrich the test diesel fuel, the long chain microalgae bio-alcohol and the microalgae low density biodiesel was synthesized in a previous study which was dedicated for the fuel synthesis (Jacob and Ashok 2021a). From the precursor study, the long chain alcohol that was synthesized from *S. quadricauda* microalgae was 2-methyl-1-butanol which is otherwise known as *n*-amyl alcohol (AA100). Similarly, the biodiesel acquired from *C. pyrenoidosa* microalgae is represented as CP100 as synthesized from a previous study (Jacob and Ashok 2022). To analyze the potential of the bioenergy mixtures with conventional diesel fuel, the bioenergy derivatives are blended with diesel. The

mixtures are prepared for 20% which is represented by AA20D80 and CP20D80 where D80 represents 80% diesel vol. and are tested as per ASTM 7544 standard and the same is highlighted in Table 1.

3.2. Equipment and procedure for experimental analysis

This section highlights the methodology and the experimental test engine, emission analyzers and the DOC-DPF used for experimental analysis.

3.2.1. Methodology and set-up for the optimization of post injection parameters

The experimental analysis was carried out in a single-cylinder, water-cooled four-stroke light commercial CI engine as shown in Fig. 1. The schematic representation shows the path of the signals between the measuring devices and data acquisition system which is integrated with a digital workstation. The set-up is equipped with a NIRA i7r electronic management system to tune the post injection parameters to facilitate optimal exhaust gas temperature for effective CART operation. The air flow and the fuel flow are measured using an air flow sensor and a standard burette set-up. The cylinder pressure sensor is mounted directly on the cylinder head to acquire the sensor data. An on-board combustion analysis software, ECAS, is used to visualize and store the recorded data from the sensors. To apply load, a water-cooled bi-directional dynamometer with a load cell is integrated with the test rig.

The current study is an extension of an ongoing study where the optimal pilot injection timing, pilot injection mass, main injection angle and injection pressure for each load condition were established using prediction models (Jacob and Ashok 2021b). The obtained finest combination of these engine input parameters is shown in Table 2 for diesel fuel, long-chain microalgae bio-alcohol and microalgae low density biodiesel with respect to different loads. Hence, the results of that study were frozen and used as inputs to optimize the post injection parameters for AA20D80, CP20D80 and diesel fuel. The experiment was carried out for post injection timing (PIT) at a crank angle (CA) after top dead center (aTDC) of 10° and 20° respectively. For each PIT angle, the post injection mass (PIM) was varied from 1 to 4 mg at MTPP condition while operating on AA20D80 and CP20D80 for low, medium, and high load. This 100-cycle experimental plan is carried for 3 times at MTPP condition and the respective mean of the outputs were used to interpret the cyclic variations within the combustion data. To analyze the emissions generated during steady-state operation, an AVL manufactured DiTEST unit is used to quantify HC, CO, NO_x and CO₂ emissions. The gas analyzer is coupled with the digital workstation using a USB and an in-built AVL-Dix AU software. The specifications of the test set-up is discussed in Table 3.

3.2.2. Components in CART unit for treating tail-pipe pollutants

To facilitate the oxidation of greenhouse gases and particulate smoke emissions, an after-treatment device consisting of a diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) is employed in this study as shown in Fig. 2. The DOC unit is layered with platinum catalyst that is shielded by an outer

layer of silicon carbide that is doped by a mixture of aluminum oxide and cerioxide. Similarly, the DPF unit is fitted with a ceramic honeycomb matrix that effectively traps smoke particulates and breaks the carbon deposition. The combined effect of post injection parameters and DOC-DPF unit act as a continuous active regeneration trap (CART) while operating on diesel fuel enriched by AA20D80 and CP20D80. As the untreated raw emissions transverse through the exhaust tailpipe, the fuel that is introduced into the cylinder as post injection gets pushed out in the exhaust stroke to increase the exhaust gas temperature (EGT). Initially, as the exhaust gases and smoke enters the DOC unit, at an EGT of about 280°C – 300°C, the HC, CO and organic fractions of diesel particulates get oxidized into CO₂ and water. These reactions are considered as desired reactions, whereas, the conversion of nitrous oxide to nitrogen dioxide is considered as an undesired reaction due to the toxic nature of NO₂ as compared to NO. Equ. 1, 2 and, 3 shows the reactions within the DOC.

The smoke particulates get trapped in the DPF and is continuously regenerated by post-injection by oxidizing the carbon particulates in the smoke emissions to CO₂ and at a temperature of 300°C – 350°C as shown in Equ. 4. The NO₂ generated from the DOC gets reconverted to NO as shown in Equ. 5. The behavior of the EGT is constantly monitored across the CART unit to ensure that the required temperature is achieved to reduce the harmful greenhouse gases and smoke emissions.

4. Results And Discussion

During the experimentation, certain observations were made while using the finest combination obtained from the earlier study and varying the post injection parameters in this study with respect to different loads for AA20D80, CP20D80 and diesel fuel at MTPP condition. The unique variations observed in the engine output characteristics and the efficiency of CART unit in mitigating greenhouse gases and smoke emissions are discussed in this section.

4.1. Combustion outputs on post injection optimization

The combustion parameters are highly influenced while optimizing the post injection parameters at MTPP condition while operating on CP20D80, diesel fuel and AA20D80 for various loads. This section discusses the variations in peak in-cylinder pressure (PCP) and peak heat release rate (PHRR) to contrast and compare the outputs of the test fuels.

4.1.1. Influence of post injection parameter calibration on the cylinder pressure

The PCP varies uniquely for different PIT and PIM while operating on AA20D80, CP20D80 and diesel fuel as shown in Fig. 3. At low load condition, a higher PCP is observed at early PIT for AA20D80, CP20D80 and diesel fuel operation as compared to late PIT. Similarly, a dip is observed in PCP at a PIM of 4 mg for all PIT while running on AA20D80. The maximum PCP is achieved at 1 mg and 2 mg PIM for AA20D80 and diesel fuel at 10°C aTDC PIM with a value of 46.43 bar and 46.69 bar respectively. Similarly, at the stated PIT, the maximum PCP is observed at a PIM of 4 mg and 2 mg for CP20D80 with a value of 46.11 bar. The reason for the higher PCP of diesel fuel at 10°C aTDC as compared to AA20D80 and CP20D80 can be attributed to the higher cetane number and lower latent heat of vaporization that reduces the ignition delay and enhance the combustion behavior. Moreover, early PIT of 10°C aTDC preserves the cylinder temperature and pressure produced as compared to late PIT at 20°C aTDC due to the expansion of resident heat.

At medium load condition, the maximum PCP of AA20D80 is attained at a PIM and PIT of 1 mg and 20°C aTDC with a value of 53.24 bar. Similarly, the maximum PCP for CP20D80 and diesel was observed at a PIT and PIM of 10°C aTDC and 4 mg. The reason for the deteriorating trend in PCP across the PIT of diesel fuel operation is due to the excessive consumption of the oxygen during the main injection that reduces cylinder temperature due to heat transfer and expansion (Santhosh and Kumar. 2020). Additionally, the inherent oxygen content of CP20D80 and AA20D80 might be responsible for the increase in PCP even at late PIT and low PIM. Also, the longer ignition delay of CP20D80 and AA20D80 facilitates a fuel accumulation which combusts altogether at the uncontrolled combustion phase and carries forth to the expansion stroke. Hence, due to the heat expansion, the PCP is still high at delayed PIT for CP20D80 and AA20D80 fuel operation.

At high load condition, the PCP of CP20D80 and AA20D80 increases at all PIT and PIM except at 3 mg. The suspected reason for the increase in PCP even at early and late PIT is due to the longer ignition delay which causes premixed combustion due to the inferior cetane number of CP20D80 and AA20D80. This combustion phenomenon is further boosted by the oxygenated nature of the fuel which facilitates combustion even after the depletion of oxygen by the main injection fuel combustion. On the contrary, the absence of inherent oxygen content in diesel fuel will have to depend on the heat generated during the main injection as the oxygen in the air-fuel mixture gets used up before the post injection.

4.1.2. Variation of peak heat release rate on post injection optimization

Figure 4 illustrates the change in peak heat release rate (PHRR) for CP20D80, diesel and AA20D80 fuels for different PIT and PIM while operating on different load conditions. As observed, at low load condition, maximum PHRR for AA20D80 and CP20D80 was obtained at a PIM and PIT of 1 mg and 10°C aTDC with a value of 51.68 j/deg. The decrease in PHRR for CP20D80 and AA20D80 at 10°C aTDC might be

due to the cooling effect produced due to the higher latent heat of vaporization of alcohols thereby quenching the heat released. At medium load condition, the maximum PHRR for AA20D80 was attained at a PIM and PIT of 1 mg and 20°CA aTDC with a value of 66.84 j/deg. Similarly, the maximum PHRR was attained at a PIM of 3 mg for CP20D80 and diesel at a PIT of 20°CA aTDC with a value of 65.67 j/deg respectively. The maximum PHRR obtained by AA20D80 and CP20D80 is a result of the combined pre-mixed combustion of the fuel accumulated due to the prolonged ignition delay of CP20D80 and AA20D80 which combusts as the piston moves down for the expansion stroke. Hence, a small amount of PIM is enough to replenish the PHRR at a delayed PIT. For diesel fuel operation, the maximum PHRR is attained due to its high cetane number which creates shorter ignition delay and primarily produce the heat during the main injection (Nutakki et al. 2022). During expansion stroke, a larger PIM that is sufficiently atomized boosts the heat output even at a delayed PIT. At an early PIT of 10°CA aTDC, the PHRR for both the fuels are at their lowest while operating on medium load.

At high load condition, the PHRR obtained by AA20D80 are higher than diesel fuel operation and CP20D80 fuel at all PIT and PIM. The maximum PHRR for AA20D80 was attained at a PIT of 20°CA aTDC and PIM of 1 mg with a value of 70 j/deg respectively. The decrease of PHRR of diesel fuel operation across the PIT is due to the lack of oxygen that is required for the combustion of PIM during the after-burn phase. Due to the consumption of oxygen during the controlled combustion, the PIM does not combust completely and losses heat. On the other hand, despite its quenching effect, the pre-mixed combustion of the lower cetane AA20D80 and CP20D80 fuel releases more heat due to the combined combustion of the accumulated fuel at higher load condition. The heat is further fed by the vaporization of the atomized PIM.

4.2. Behavior of EGT across the CART unit while operating on microalgae bioenergy

In order to effectively utilize the CART unit, the EGT entering the DOC and DPF has to be maintained above 300°C to ensure complete oxidation of greenhouse gases and particulate smoke particles (Mera et al. 2021). Hence, the required EGT is obtained by optimizing the PIT and PIM at various loads while operating on CP20D80, AA20D80 and diesel fuel. Figure 5 depicts the behavior of EGT across the CART unit at a PIT of 10°CA aTDC across PIM for AA20D80, CP20D80 and diesel fuel while operating at low, medium and high load conditions. As observed, at low load condition, the EGT at the exhaust for AA20D80 is more than diesel fuel and CP20D80, whereas, at medium load, the EGT at exhaust is more for diesel operation at all PIM concentrations. At all load conditions, the EGT at the exhaust was maximum at a PIM of 4 mg for CP20D80, AA20D80 and diesel fuel operation. Correspondingly, the EGT at DOC and DPF were at their maximum at a PIM of 4 mg for both fuels. The maximum value of EGT was achieved at medium load condition for AA20D80 and diesel fuel operation with a value of 686.5°C and 730.2°C at a PIT and PIM of 10°CA aTDC and 4 mg. Moreover, the corresponding temperature from AA20D80 and diesel fuel operation at DOC and DPF are 585°C and 399.5°C for AA20D80 and 646.6°C and 477.2°C for diesel fuel across the CART unit. The loss of EGT from DOC to DPF unit is due to the heat absorbed by the platinum catalyst for oxidizing carbon and hydrocarbon emissions. The reason for the higher EGT

profile of diesel fuel across the CART unit is due to the lower latent heat of vaporization that does not produce a quenching effect like AA20D80 and effectively channel the heat generated from the high cetane fuel across the CART unit.

As the PIT gets further delayed to 20°CA aTDC, the EGT profile decreases as compared to 10°CA aTDC across the CART unit for all three fuels as shown in Fig. 6. Generally, the delayed PIT is primarily focused on eliminating PSE by feeding heat and increasing the EGT to reach the regeneration temperature at the DPF unit. The maximum value of EGT at exhaust was recorded as 630.8°C and 636.2°C for CP20D80 and diesel at a PIM of 4 mg under medium load condition. Correspondingly, the EGT temperature of DOC and DPF at the above stated condition were 547.3°C and 409°C for CP20D80 and 558.5°C and 419.4°C for diesel fuel respectively. The higher EGT profile of diesel can be attributed to the longer residence of the high temperature residual gases which is trapped due to the delayed combustion due to the influence of post injection parameters. Hence, the heat generated gets carried from the controlled combustion phase to the after-bun phase and boosts the EGT profile and channels it across the CART unit.

4.3. Performance characteristics on post injection optimization

The incorporation of post injection parameters have significant effects on the engine output performance characteristics while operating on CP20D80, AA20D80 and diesel fuel at MTPP condition. In order to understand these variations, this section discusses the influence of post injection parameters on performance parameters to analyze the differences between both the test fuels.

4.3.1. Effect of fuel consumption on post injection optimization

Figure 7 describes the variation in BSFC for diesel and CP20D80, AA20D80 fuels for different PIT and PIM while operating on different load conditions. The general trend shows an increase in fuel consumption as PIM increases for all three fuels. The increase fuel consumption is predominantly more at low load condition than medium and high load condition. Furthermore, maximum BSFC is observed at a PIM of 4 mg for both the fuels at all PIT and load conditions. At low load condition, diesel fuel shows minimal consumption at all PIT as compared to CP20D80 and AA20D80. The suspected reason for the increased consumption of CP20D80 and AA20D80 can be explained by the lower cetane number of the fuel which prolongs the ignition delay and increases the duration of uncontrolled combustion phase as compared to diesel fuel (Duraismy et al. 2021). Hence, the time left for stabilizing the controlled combustion phase reduces for efficient combustion of the accumulated fuel. Additionally, the oxygen rich nature of the fuel that causes a reduction in the lower heating value and high latent heat of vaporization.

At medium load condition, the BSFC was at its highest at a PIT of 10°CA aTDC and a PIM of 4 mg with a value of 0.6 kg/kWh for AA20D80 and 0.52 kg/kWh for diesel fuel. Due to the higher cetane number and calorific value of diesel fuel, the heat to work conversion is achieved with less fuel consumption for

obtaining the power equivalent to AA20D80 operation at early PIT. The lowest BSFC was observed at a PIT and PIM of 20°C aTDC and 1 mg for AA20D80. This can be explained by the ignition delay of AA20D80 for the delayed PIT that facilitates premixed combustion and combusts the accumulated fuel during the expansion stroke. Hence, the fuel required for producing heat to work output is minimal at a PIT 20°C aTDC. At high load condition, the lowest consumption is observed for CP20D80 which is 2.7% more than diesel fuel at a PIT and PIM of 20°C aTDC and 1 mg. At higher speeds, the in-cylinder temperature and pressure is high and the fuel necessary to produce the same amount of power is lower for both the fuels. Since the cetane number and calorific value of diesel is higher than CP20D80, the combustion behavior is better than CP20D80 which consequently improves the fuel economy.

4.3.2. Variation of brake thermal efficiency on post injection optimization

Figure 8 describes the variation in brake thermal efficiency (BTE) for CP20D80, AA20D80 and diesel fuels for different PIT and PIM while operating on different load conditions. The lowest BTE was achieved at a PIT and PIM of 20°C aTDC and 4 mg for CP20D80, AA20D80 and diesel fuel. The suspected reason for this decrease is the delayed introduction of PIT which gets initiated at the expansion stroke thus resulting is the volumetric expansion and loss the heat. At low load condition, the maximum BTE was achieved by diesel and AA20D80 at a PIT of 10°C aTDC and a PIM of 1 mg with a value of 27.54% and 26.42% respectively. The slightly higher BTE value for diesel can be attributed to the higher cetane number of diesel and no oxygen content which facilitates low heat losses due to evaporation and exhibit better combustion (Elkelawy et al. 2021).

At medium load condition, the maximum BTE was achieved at a PIT of 10°C aTDC and a PIM of 1 mg with a value of 32.44%, 31.33% and 31.78% for diesel, CP20D80 and AA20D80 respectively. The reason for the decrease in BTE for AA20D80 can be attributed to the reduced lower heating value and higher latent heat of vaporization that tend to absorb the heat from the combustion chamber and produce a cooling effect that result in lower heat release rate. Additionally, the longer ignition delay caused by the lower cetane number of AA20D80 and CP20D80 prolongs the combustion duration till the piston reaches the end of compression stroke. Consequently, the heat produced is lost to the engine parts by transfer and collectively reduce the BTE. At high load condition, the maximum BTE was achieved by diesel fuel with a value of 37.82% which is 3.7% and 1.4% more than CP20D80 and AA20D80 at a PIT of 10°C aTDC and a PIM of 1 mg. The detrimental effects of delayed PIT and higher PIM is evident as the lowest BTE is observed at 20°C aTDC and 4 mg for higher loads with a value of 29.93% for AA20D80 and 29.78% for CP20D80 as compared to diesel fuel. The slight variation between the BTE outputs for both the fuels maybe due to the lower requirement of fuel at higher loads which reduces the influence of fuel properties on the heat to work output. In addition to this reason, the initiation period of the PIT and PIM play an important role in retaining the heat generated from the controlled combustion phase.

4.4. Effect of post injection activated CART unit on tail pipe emissions

The influence of post injection parameters on emission characteristics while employing the CART unit while operating on CP20D80, AA20D80 and diesel fuels are discussed in this section. Regulated emissions that fall under the umbrella of greenhouse gases (GHG) such as HC and CO are primarily focused along with particulate smoke emissions and NO_x . The emissions are analyzed at the tail pipe and represented as treated and untreated forms after passing through the CART unit emissions for each pollutant.

4.4.1. Mitigation of particulate smoke emissions using CART unit

Figure 9 illustrates the variation in particulate smoke emissions (PSE) between its treated and untreated form for CP20D80, AA20D80 and diesel fuel for different PIT and PIM under various load conditions. The general trend shows a significant control of PSE by the CART unit for all PIT and PIM while contrasting CP20D80, AA20D80 and diesel fuel results under all the load conditions. At low load condition, the lowest smoke emissions are observed for AA20D80 at its untreated state at a PIT and PIM of 20°CA aTDC and 4 mg with a value of 1.517 FSN which is 25.67% less than diesel. Similarly, at a PIT and PIM of 20°CA aTDC and 1 mg, the lowest PSE are observed for CP20D80 with a value of 2.064 FSN at its untreated state which is 4.46% less than diesel. Correspondingly, at the same condition, the treated form of the smoke emission for AA20D80 and CP20D80 after the CART unit treatment shows a significant reduction of up to 64.9% and 35.34% as compared to diesel fuel. The significant reduction of PSE can be attributed to the delayed PIT of 20°CA aTDC and higher PIM of 4 mg that get vaporized during the expansion stroke. Consequently, the heat generated gets directly channeled into the DPF in the CART unit during the exhaust stroke and gets continuously regenerated via the oxidation process as discussed in section 3.2.2.

At medium load condition, AA20D80 has the highest PSE mitigation ability with the CART unit as nearly 52.7% as compared to CP20D80 and diesel which mitigated up to 50.12% and 32% at a PIT and PIM of 20°CA aTDC and 4 mg. The lower efficiency of diesel fuel can be attributed to the delayed PIT and higher PIM which pushes the high cetane vaporized diesel fuel from the expansion stroke and channels the heat generated into the DPF for oxidation of PSE into CO_2 at a temperature of 419.4°C . At high load condition, CP20D80 and AA20D80 recorded the lowest PSE at its untreated form at a PIT and PIM of 10°CA aTDC and 2 mg which is 9.19% and 3.25% less than diesel fuel. Correspondingly, at the same operating condition, the CART unit treated the PSE up to 45.09% and 44.35% at a temperature of 333.1°C and 363.5°C for CP20D80 and AA20D80 respectively. The reason can be attributed to the longer ignition delay of CP20D80 and AA20D80 that prolongs the combustion duration in addition to the delayed PIT which channels the heat during the expansion stroke to be utilized by the DPF (Wei et al. 2021). Furthermore, the oxygenated nature of these fuels facilitated superior combustion nature and negated the need for more PIM.

4.4.2. Effect of post injection optimization on oxides of nitrogen emissions

Figure 10 describes the variation between treated and untreated NO_x emissions for AA20D80, CP20D80 and diesel fuel at different PIT and PIM under various load conditions. The general trend shows a slight reduction of NO_x emissions as the exhaust gas passes through the CART unit for all the test fuels at all PIT and PIM. At low load condition, AA20D80 recorded the lowest untreated NO_x emissions at a PIT and PIM of 10°CA aTDC and 4 mg with a value of 134 ppm followed by diesel and CP20D80 with a value of 141 ppm and 152 ppm. Correspondingly, the treated form after the CART unit showed a 12.53%, 2.23% and 9.92% reduction for CP20D80, AA20D80 and diesel fuel. In this study, nitrous oxide is measured to represent the NO_x emissions. The reason for the slight reduction of NO_x emissions while operating on AA20D80 can be attributed to its high latent heat of vaporization. Hence, a cooling effect is produced which absorbs the heat within the combustion chamber and lowers the cylinder temperature thereby reducing NO_x emission formation. Additionally, as the gases enter the DOC, the nitrous oxide gets converted into nitrogen dioxide due to oxidation by the platinum catalyst. Furthermore, nitrous oxide is re-liberated as the nitrogen dioxide passes on to the DPF unit (Vignesh and Ashok 2020). Hence, the difference between the treated and untreated NO_x for AA20D80 is lower.

At medium load condition, the maximum untreated NO_x emission are observed at a PIT and PIM of 20°CA aTDC and 4 mg for AA20D80 and CP20D80. Correspondingly, an average reduction of about 18% and 19.14% in NO_x emission is facilitated by the CART unit for both the fuels under the same condition. The reason for the higher NO_x emission may be due to the higher residence time of the gaseous mixture within the cylinder due to the prolonged combustion duration caused by the delayed PIT. Moreover, the higher PIM rejuvenates the heat that is produced during controlled combustion and consequently increase NO_x emissions. At high load condition, the untreated NO_x emission of AA20D80 is higher for the PIM of 2, 3 and 4 mg for all PIT and at 20°CA aTDC for CP20D80 as compared to diesel fuel. Correspondingly, the treated NO_x emission by the CART unit is lower for diesel than CP20D80 and AA20D80 for most of the operating conditions. The reason for the higher NO_x emission can be attributed to the longer ignition delay of CP20D80 and AA20D80 that result in fuel accumulation and cause cumulative premixed combustion. Furthermore, the oxygenated nature of the fuel enhances the combustion nature and produces high in-cylinder temperature that supports NO_x emission formation.

4.4.3. Mitigation of hydrocarbon emissions using CART unit

The variation between the treated and untreated HC emissions are described in Fig. 11 for AA20D80, CP20D80 and diesel fuel at different PIT and PIM under various load conditions. As observed, a significant reduction of HC emissions by the CART unit is achieved at all PIT and PIM for CP20D80, AA20D80 and diesel fuel under all load conditions. The concentration of HC increases on increments of PIM and on delaying the PIT for the fuels. The maximum untreated HC emissions were observed for AA20D80 which is 18.96% higher as compared to CP20D80 and diesel fuel at a PIT of 20°CA aTDC. Correspondingly, for the same operating condition, the treated form after CART unit shows a reduction efficiency of 63.8%, 42.55% and 53.62% for CP20D80, diesel and AA20D80 fuels. The primary reason for the increase in HC emissions in AA20D80 is due to the delayed PIT and higher PIM which facilitates

incomplete combustion since the combustion is prolonged to the expansion stroke (Rajak et al. 2018). This phenomenon is also boosted by the longer ignition delay and higher latent heat of vaporization of AA20D80 which further inhibits complete combustion of the accumulated fuel due to the cooling effect. However, the late combustion of PIM facilitates sufficient heating for the platinum catalyst in the DOC which consequently oxidizes the HC. Moreover, the inherent oxygen content of CP20D80 and AA20D80 plays a major role in facilitating effective oxidation within the DOC unit to significantly control HC emission formation.

In medium load condition, the highest HC emissions was recorded at a PIT and PIM of 20°C aTDC and 4 mg for AA20D80 at its untreated form and at 10°C aTDC for CP20D80 for both its treated and untreated form. Similar to low load condition, AA20D80 shows an increase of 18.09% as compared to diesel. At this condition, the CART unit arrests nearly 63.34% of the HC emissions while operating on CP20D80 and 67.85% while operating on diesel fuel. The larger fuel requirement at medium load condition boosted by the longer ignition delay by CP20D80 results in the evaporation of the fuel that is accumulated before spontaneous combustion. Due to this reason, incomplete combustion might be the factor in increasing HC emissions. However, the heat output from the incomplete combustion is effectively utilized in the DPF unit for regeneration. At higher loads, the least HC emissions are observed at a PIT and PIM of 10°C aTDC and 1 mg for all the fuels. The reason for the reduced HC emissions at early PIT and lower PIM might be due to the high in-cylinder temperature that is produced at higher speeds which results in a complete combustion. In addition to this phenomenon, the PIM at early PIT feeds more heat for effective CART unit operation to mitigate HC emissions in the DOC unit.

4.4.4. Elimination of carbon monoxide emissions using CART unit

The treated form of CO emissions are not represented since the CART unit completely eliminated the CO emissions from the exhaust gases at all the test operating conditions and fuels based on the reaction shown in Equ. 1. Figure 12 represents the variations of untreated carbon monoxide (CO) emissions for AA20D80, CP20D80 and diesel fuel at various PIT and PIM under different load conditions. At low load condition, the untreated CO emissions originating from the exhaust gases are lower for CP20D80 than AA20D80 and diesel fuel by an average of about 16.67% at all PIT and PIM. The primary reason for the low CO emissions for CP20D80 can be attributed to the oxygenated nature of the fuel which still facilitates efficient combustion even after the depletion of intake oxygen in the air fuel mixture during main injection period (Solomon et al. 2020). Similarly, the reason for the increase for AA20D80 can be due to the reduction of in-cylinder temperature in the expansion stroke which is further exacerbated by the higher latent heat of vaporization that results in a quenching effect and cause the incomplete combustion.

At medium load condition, the lowest CO for AA20D80 and diesel was observed at a PIT and PIM of 20°C aTDC and 3 mg with a value of 0.07 and 0.09% vol. respectively. Similarly, a 2.2% reduction of CO emissions is observed for CP20D80 as compared to diesel fuel at a PIT and PIM of 10°C aTDC and 4

mg. The reason for the reduction may be attributed to the delayed PIT and the oxygenated nature of AA20D80 and CP20D80 that facilitates complete combustion even though the main injection combustion uses up the oxygen from the intake air. Similarly, at high load condition, the lowest CO emissions are observed at a PIT of 20°CA aTDC across all the PIM for both the fuels. The suspected reason for the reduced CO at delayed PIT maybe attributed to the efficient combustion of the lower fuel quantity at high load. Hence, the PIM was purely utilized by the CART unit catalyst for oxidizing the CO emission into CO₂.

4.4.5. Variation of carbon dioxide emissions on post injection optimization

In the operation of the CART unit, carbon dioxide (CO₂) emissions are formed as a product of oxidation between the oxygen and the GHGs and PSEs at an EGT above 300°C within the CART unit. Hence, higher CO₂ emission output signifies that the combustion behavior and the CART unit is highly efficient is sufficiently controlling the harmful GHGs, PSE and other emission gases. Figure 13 describes the variations between untreated and treated CO₂ emissions for CP20D80, AA20D80 and diesel across different load conditions at various PIT and PIM. The general trend shows an increase in CO₂ emissions after the CART unit for both AA20D80 and CP20D80 fuel operation. This signifies that the combustion nature and the mitigating ability of the CART unit is highly efficient for both the fuels.

At lower load condition, the highest CO₂ emissions was recorded for CP20D80 which is 3.09% more than diesel fuel. Also, the CO₂ emission output achieved for diesel fuel is 19.58% more than AA20D80 at a PIT and PIM of 10°CA aTDC and 3 mg. The suspected reason for the increase of CO₂ emissions might be due to the complete combustion of the CP20D80 fuel attributing to its oxygenated nature that reduces the duration of uncontrolled combustion phase and normalizes with the controlled combustion phase faster. Correspondingly, the CO₂ emissions acquired after the CART unit showed a 2.26% increase and a 1.6% decrease for diesel fuel as compared to AA20D80 and CP20D80. The suspected reason for the increase of CO₂ emissions might be due to the complete combustion of the diesel fuel attributing to its higher cetane number and lower latent heat of vaporization that reduces the duration of uncontrolled combustion phase and normalizes with the controlled combustion phase faster (Rajamohan and Kasimani 2018). The increased CO₂ emissions after the CART unit for diesel fuel indicate that the post injection parameters were introduced at the optimal time for maximizing the oxidation of GHGs and PSEs within the unit.

At medium load condition, the maximum CO₂ emissions were acquired at a PIT of 10°CA aTDC and at a PIM of 1 mg and 4 mg while operating on AA20D80 and CP20D80 fuels for both its untreated and treated forms. As compared to diesel, the CO₂ emissions generated by AA20D80 were lower which might be due to the cooling effect caused by the lower cetane fuel that reduces the in-cylinder temperature and produces pockets of low temperature zones where incomplete combustion happens. At higher loads, the maximum untreated and treated CO₂ emissions is observed at a PIT of 10°CA aTDC and 20°CA aTDC and at a PIM of 3 mg for CP20D80, diesel and AA20D80 fuels. The major reason for the higher treated

CO₂ emissions is due to the delayed PIT and higher PIM that channels the heat from the after-burn phase and boosts the EGT for the CART unit. Consequently, at the optimal EGT, maximum reduction of GHGs and PSEs are facilitated which in turn increases the CO₂ emissions.

4.5. Efficiency of the CART unit in mitigating GHGs and PSEs using post injection

The efficiency of the CART unit is represented based on its ability to control the GHGs, PSEs and NO_x emissions individually after the CART unit treatment. The general expression used to determine the CART efficiency for each emission is shown in Equ. 6 –

$$de - (X)(\%) = \frac{(X) \text{ Upstream} - (X) \text{ Downstream}}{(X) \text{ Upstream}} \times 100 - \text{Equ. (6)}$$

Where, (X) represents HC or NO_x or smoke emissions. Similarly, upstream represents the emissions captured before the CART unit and downstream signifies the emission observed after the CART unit.

Figure 14a describes the CART efficiencies of HC, NO_x and smoke emissions at a PIT of 10°CA aTDC across PIM for various load conditions while operating on AA20D80, CP20D80 and diesel fuels. As observed, a gradual reduction in the CART efficiency is evident for de-HC for AA20D80 and CP20D80 as PIM increases. The maximum de-HC efficiency is observed at 1 mg for all loads owing to the higher probability of incomplete combustion at higher PIM. Similarly, the highest de-smoke efficiency is observed at 2 mg, 4 mg and 1 mg for low, medium and high load conditions operating on AA20D80 and at 1 mg for CP20D80. The reason might be due to the oxygenated nature of the fuels which provides the demanded power and EGT for effective regeneration of the trapped carbon deposits even at low PIT. The maximum de-NO_x efficiency of 23.34%, 27.24%, and 30.96% is observed at low, medium and high load at a PIM of 1 mg for CP20D80 owing to decrease in cylinder temperature at lower PIM and delayed PIT.

At 20°CA aTDC PIT, a maximum de-smoke and de-HC of 67.85% and 62.71% is observed at 3 mg and 1 mg at low load condition while operating on AA20D80 which is more than diesel fuel as shown in Fig. 14b. Similarly, a maximum de-smoke and de-HC of 66.1% and 67.85% is observed at 4 mg and 1 mg at low load and high load condition while operating on CP20D80. This is due to the higher fuel consumption at lower loads that increases the probability of incomplete combustion for HC emission formation. However, this favors the mitigation of PSE positively as the delayed PIT and higher PIM is utilized effectively for regenerating in the CART unit. In all cases, the de-NO_x efficiency is lower as compared to other emissions which can be attributed the trade-off nature between PSE and NO_x emission formation at higher in-cylinder temperature (Pan et al. 2019). To some extent, simultaneous reduction of PSE and NO_x emission is observed despite the lower reduction efficiency of the CART unit for NO_x emission. It is noteworthy to point out that the CART unit is 100% efficient in controlling CO emissions for both the fuels at all PIT and PIM which result in a higher CO₂ emission efficiency.

5. Conclusion

The present study explores the influence of post injection activated CART unit to mitigate GHGs, PSEs, and NO_x emission without sacrificing the engine performance outputs using microalgae bioenergy derivatives and diesel fuel in a light commercial CI engine. Some of the key observations from these study are as follows -

- The lowest BSFC and maximum BTE was observed for diesel fuel which is 1.36% lesser and 1.48% more than AA20D80 and 2.7% lesser and 3.7% more than CP20D80 at a PIM of 1 mg and PIT of 20°CA aTDC and 10°CA aTDC under high load condition.
- Maximum PCP and PHRR was recorded for AA20D80 which is 1.15% and 6.52% more than diesel fuel operation at a PIM of 1 mg and a PIT of 20°CA aTDC under high load condition.
- The optimal EGT for the effective operation of the CART unit was acquired at a PIM of 4 mg and a PIT of 10°CA aTDC under low load and medium load condition for AA20D80 and CP20D80 fuel with the value of 711.9°C, 637.8°C, and 468°C at the exhaust, DOC and DPF.
- The maximum de-smoke CART efficiency was obtained at a PIT of 20°CA aTDC and at a PIM of 2 mg and 4 mg for AA20D80 and CP20D80 with an average reduction of about 67.25% and 67.85% at low load condition.
- Simultaneous reduction of PSE and NO_x emission is observed despite the lower de-NO_x efficiency of the CART unit at all PIT and PIM.
- Complete elimination of CO emissions is observed at all post injection conditions for AA20D80, CP20D80 and diesel fuel after CART unit treatment.
- The maximum de-HC CART efficiency was obtained at a PIT of 10°CA aTDC and 20°CA aTDC and at a PIM of 1 mg for AA20D80 and CP20D80 with an average reduction of about 75% and 67.85% at medium and high load conditions.

This study concludes that the incorporation of post injection parameters effectively mitigates GHGs and PSEs significantly while operating on AA20D80 and CP20D80 assisted by the CART unit. Furthermore, as a future scope, this study can be extended by incorporating a selective catalytic reduction after-treatment unit with the CART unit and to effectively control NO_x emissions.

Declarations

Acknowledgement

Authors wish to thank Department of Science Technology (DST), India for funding of this work under the scheme of ASEAN-India Science & Technology Development Fund (AISTDF) for the project (CRD/2018/000061).

Authors Contributions:

Bragadeshwaran Ashok and Ashwin Jacob contributed to the Conceptualization, Investigation, Data Curation and Project administration. Material preparation, data collection and analysis were performed by Ashwin Jacob and Bragadeshwaran Ashok. The first draft of the manuscript was written by Ashwin Jacob, Jino Lawrence, Arockia Suthan Soosairaj, Jayaganthan Anandan and Manoj Elango. All authors read and approved the final manuscript.

Ethics declarations

Ethical approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Competing interests: The authors declare no competing interests.

Data Set : Not Applicable

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Tables

Table 1. Physicochemical properties of the synthesized long-chained microalgae bio-alcohol and diesel fuel

Properties	Diesel	AA100	AA20D80	CP100	CP20D80
Kinematic Viscosity (mm ²)	3.511	2.89	3.381	3.14	2.602
Latent Heat of Vaporization (kJ/kg)	273	308.02	340.7	-	-
Oxygen Content (% wt.)	0	17.2	3.62	22	5.2
Calorific Value (MJ/kg)	42.53	35.06	39.7	32.5	38.2
Density at 15 °C (kg/m ³)	851	815	843	832.8	823.1
Cetane number	49	22	46.6	48.2	48.7
Flash Point (°C)	74	49	123	170	83
Lower heating value (MJ/kg)	43.352	42.5	41.772	-	-

Table 2. Finest combination of input parameters as default for post injection optimization

Fuel	Load (%)	Finest combination			
		Injection Pressure (bar)	Pilot Timing (° bTDC)	Pilot Mass (%)	Main Timing (° bTDC)
CP20D80	0	600	28	24	14
	20	500	27	20	15
	40	600	26	24	12
	60	700	27	20	15
	80	600	28	24	14
Diesel	0	600	28	24	14
	20	500	27	20	15
	40	600	26	24	12
	60	700	27	20	11
	80	600	28	24	14
AA20D80	0	600	28	24	14
	20	500	27	20	15
	40	600	26	24	12
	60	500	27	20	15
	80	600	28	24	14

Table 3. Technical specifications of limitations of the test engine and the emission analyzer

Engine Setup	
No. of Cylinders	1
Volume	625 cc
Compression Ratio	18:1
No. of Valves	2
No. of Strokes	4
Cooling System	Water Cooled
Speed	Variable Speed
Max Torque	38Nm @ 1100–2000 rpm
Max Power	11BHP @ 3000 rpm
Emission Analyzer Setup	
Type	AVL DiTEST Gas 1000BL
Operating temperature	5 - 45 °C
Storage temperature	0 - 50 °C
Ambient pressure	750 - 1100 hPa
Minimal gas flow	120 l/h
Normal gas flow	180 l/h
Max. Overpressure GAS IN	450 hPa

Figures

Figure 2

3-D model of the post injection activated CART unit with a DOC-DPF arrangement

Figure 3

Variation of PCP across various loads for different PIT and PIM while operating on CP20D80, AA20D80 and diesel fuel

Figure 4

Variation of PHRR across various loads for different PIT and PIM while operating on AA20D80, CP20D80 and diesel fuel

Figure 5

Variation of EGT across the CART unit at a PIT of 10°C aTDC for different loads and PIM while operating on AA20D80, CP20D80 and diesel fuel

Figure 6

Variation of EGT across the CART unit at a PIT of 20°C aTDC for different loads and PIM while operating on AA20D80, CP20D80 and diesel fuel

Figure 7

Variation of BSFC across various loads for different PIT and PIM while operating on AA20D80, CP20D80 and diesel fuel

Figure 8

Variation of BTE across various loads for different PIT and PIM while operating on AA20D80, CP20D80 and diesel fuel

Figure 9

Influence of post injection on PSE for CP20D80, AA20D80 and diesel fuels before and after CART unit treatment

Figure 10

Influence of post injection on NO_x emissions for AA20D80, CP20D80 and diesel fuel before and after CART unit treatment

Figure 11

Influence of post injection on HC emissions for AA20D80, CP20D80 and diesel fuel before and after CART unit treatment

Figure 12

Influence of post injection on CO emissions for AA20D80, CP20D80 and diesel fuel before the CART unit

Figure 13

Influence of post injection on CO₂ emissions for AA20D80, CP20D80 and diesel fuel before and after CART unit treatment

Figure 14

a. Efficiency of the CART unit at a PIT of 10°CA aTDC for AA20D80, CP20D80 and diesel fuel across various loads

b. Efficiency of the CART unit at a PIT of 20°CA aTDC for AA20D80, CP20D80 and diesel fuel across various loads