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Combustion and emission characteristics of a light duty diesel engine fueled with hydro-processed renewable diesel

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ABSTRACT

Bio-fuels are being used in an internal combustion engine for curbing regulated emissions, green house gas (GHG) and as a key to address energy security issues. Hydro-processed renewable diesel (HRD) is perceived as one of the potential drop-in alternative fuels for compression ignition (CI) engine as its cetane number is higher than petro-diesel. Combustion analysis of a single cylinder CI engine fueled with HRD and petro-diesel were compared and correlated with emissions characteristics. Soot morphology of PM emissions of the engine fueled with diesel and HRD were also analysed using a high resolution transmission electron microscope (HR-TEM). The HRD fueled engine showed longer combustion duration; smaller in-cylinder pressure and heat release rate (HRR) peak than diesel. Particle sizes of soot particles collected from the exhaust of HRD fueled engine were significantly smaller than diesel particles. Nitrogen oxides (NOx), particulate matter (PM) and carbon dioxide (CO_2) emissions of the engine fueled with HRD showed substantial reductions as compared to diesel. Hence, HRD fuel is considered as a promising alternative drop-in fuel for CI engine as it is offering a solution to the problem of NOx-PM trade-off associated with diesel engine.

1. Introduction

Energy is considered as the backbone of any growing economy. A recent world energy outlook report states that India will be the largest source of future demand growth in energy, whose share of global energy use rises to 11% by 2040. It is also estimated that the global car fleet doubles from today to reach 2 billion by the year 2040. But fuel demand for passenger vehicles would decline after mid 2020s due to greater efficiency, fuel switching including penetration of electric vehicles. It was highlighted that the renewables and efficiency are the key mechanisms to drive forward the low-carbon transition and reduce pollutant emissions [1]. The global crude oil scenario has been registering a paradigm shift from fossil to shale oil (tight oil) in the recent past. But shale oil is not renewable and it's relatively low cost makes other, more environmentally acceptable, alternatives (carbon neutral transport fuels) less attractive than they otherwise would be [2]. India imports most of its crude oil for its energy requirement from Middle East countries. The recent slowdown in oil production in this region may threaten supply from this source in the short term. Therefore, energy security is still a major challenge for Indian economy. India is a diesel driven economy and petro-diesel currently accounts for 40.42% of total production of all types of petroleum products [3]. Complying with stringent emission norms for the latest automotive engines poses additional challenges for the automotive and fuel-producing industries. In the wake of these challenges, biofuels, being renewable in nature and offering the hope of some measure of self-reliance, has been emphasised during the last decade as one of the viable alternatives for compression ignition (CI) engines. Hydroprocessed Renewable Diesel (HRD) has been identified as a prospective drop-in alternative fuel for CI engine application in the recent past. HRD is also known by terms such as hydrotreated vegetable oil (HVO), hydrogenated vegetable oil, renewable diesel, green diesel, bio-hydrogenated diesel (BHD), hydrogenation derived renewable diesel (HDRD) [4]. It possesses similar physico-chemical properties as petro-diesel and can be produced from any triglyceride oil by utilising the existing infrastructure of conventional petroleum processing facilities [5].

Thermodynamic combustion diagnosis is a vital analytical tool for studying the pollutant formation inside an engine. Armas

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et al. [6] found that the mean values of the indicated mean effective pressure (IMEP) of an engine fueled with HRD, calculated from in-cylinder pressures, were similar to petro-diesel fuel over the New European Driving Cycle (NEDC). Ogunkoya et al. [7] and Petersen et al. [8] showed smaller in-cylinder pressures peak and reduced rates of increase in-cylinder pressure for engines fueled with HRD compared to petro-diesel. The main reason behind this trend is thought to be the shorter ignition delay, the smaller premixed fraction and slower initial combustion rates for HRD fuel as compared to diesel. Mangus et al. [9] also observed lower in-cylinder pressures peak and advanced combustion timing for HRD fuel compared to petroleum ultra-low sulphur diesel (ULSD) in an engine with an adjusted injection timing. These differences are due to the lower volumetric energy content of HRD, which reduces the premixed burn phase. Caton et al. [10] reported that, over most of the engine operating maps for HRD fuel, peak pressures are 2–6% lesser than diesel. The higher cetane value of HRD leads to shorter ignition delay and premixed combustion phase, resulting in lower combustion peak pressures. Another view proposed by Mattson et al. [11] indicated that hydroprocessed fuel, having a lower viscosity (promotes better mixing) and volumetric energy content but significantly higher CN, results in a reduced amount of early combustion, which ultimately leads to a decrease in peak pressure as compared to ULSD. In contrast to the above findings Kousoulidou et al. [12] showed the opposite trend for in-cylinder pressure of a light-duty, common rail, Euro 5 diesel engine fueled with neat hydrotreated waste cooking oil (HWCO). The increase in the in-cylinder pressure for HWCO during the pilot injection was more prominently observed at low loads, but at higher loads this difference got narrowed down and resulted in a value similar to that for diesel. This trend is attributed to the very high cetane number of the HWCO fuel, resulting in shorter ignition delay and thus earlier ignition, favouring the development of higher pressures. Overall, it may be inferred that HRD fueling results in smaller in-cylinder pressure peaks than diesel owing to its higher CN which ultimately leads to shorter ignition delay.

Aatola et al. [13] reported that less heat is released in the premixed combustion phase because of the shorter ignition delay period (very high cetane number). McDaniel et al. [14] investigated the combustion properties of catalytic hydrothermal conversion diesel fuel (CHCD-76) compared to petro-diesel as a base fuel. Test results elucidated the shorter ignition delay than for the base fuel. Combustion phasing shifts were quite small, with the maximum rate of heat release showing a modest decrease with the catalytic hydrothermal conversion fuels due to their moderately higher cetane values. Similar trends of lower heat release rates for an engine fueled with HRD were also reported by others [7,9]. Drenth et al. [15] showed the heat release rate peak of renewable diesel (HRD) was similar to that for petroleum diesel. Millo et al. [16] reported the injector command signals, in-cylinder pressure traces and heat release rates for three different engine loads at constant engine speed (2, 5 and 8 bars BMEP at 1500 rpm) for a blended F30 fuel (30% vol. blend of Farnesane with 70% vol. ULSD) and ULSD. No significant differences were observed between ULSD and F30 in terms of combustion development and injection patterns. Hence, it was concluded that no injection timing adjustments were required with the use of blended fuel in an ECU controlled engine with closed loop combustion. Sugiyama et al. [17], reported that for a single injection heat release rate for HRD advances due to shorter ignition delay which enhances combustion efficiency. While at medium and high loads, the difference between HRD and diesel with respect to ignition delay and rate of heat release were observed to be smaller, owing to the increased internal gas temperature at the start of combustion.

Kousoulidou et al. [12] used hydrotreated waste cooking oil (HWCO) in a common rail diesel engine and showed similar peak values for heat release rate (HRR) for HWCO and diesel. It was suggested that this similarity might be a result of the higher CN and shorter ignition delay for HWCO compensating for the higher heating value for this fuel. Mattson et al. [11] reported that hydroprocessed fuel showed lower peaks of heat release rate than ULSD during the premixed combustion phase for low to medium loads, but this trend was reversed at full load conditions where diffusion combustion phase dominates and fuel ignites as soon as it is prepared and mixed with sufficient oxygen. Overall it emerged that HRD fuel results in lower heat release rates than diesel in an engine owing to its higher CN which leads to shorter ignition delays and lower volumetric heat contents.

NOx emitted from a diesel engine or vehicles fueled with HRD fuel, in neat as well as blended form, have been studied extensively by various researchers. The reported results on NOx emissions are a bit ambiguous. A majority of researchers [7,9,13,18–25] showed that HRD fuel reduces NOx due to lower in-cylinder pressure peaks, whereas some were uncertain about the effect of HRD on NOx emission [6,17,26,27]. A few have reported that HRD fuel increases NOx emissions [12,28,29] due to its higher CN and heating value. Happonen et al. [30] studied the emission characteristics of an engine optimized for HVO fuel. It was reported that by adjusting engine parameters for HVO, particulate mass and NOx can both be reduced by over 25%. Bugarski et al. [31] showed that HRD fuel results in 20% and 30% average reductions in nitrogen oxides (NO_X) and nitric oxide (NO) concentrations respectively in both a mechanically controlled, naturally aspirated (NA), direct injected, light-duty engine and an electronically controlled, turbocharged (TC) medium-duty engine.

Soot is considered as the main precursor for PM formation. Its formation during combustion is a complex phenomenon and depends on many parameters such as fuel/air ratio, ignition delay, and fuel properties (density, viscosity, CN, aromatic and sulphur content). Most of the reported results on mass-based PM show decreasing trends for engines fueled with HRD as compared to diesel [6,17,19–21,23,28–30,32,33], owing to the higher CN and negligible sulphur and aromatic contents of HRD. In contrast to this trend, Karavalakis et al. [34] found that HVO50 and HVO100 fuels result in higher PM mass emissions than ULSD over the UDDS cycle, while for the HHDDT cycle a reduction in PM was observed. The higher PM mass trends were explained on the basis of higher the cetane number of HVO fuels, which may promote a growth of the diffusive combustion thus eliminating the benefits of the aromatic-free characteristics.

Carbon dioxide (CO_2) emissions from a HRD fueled engines were observed to be lower than for diesel-fueled engines [7,10,12,21,29,31,32,34,35]. The reduction in CO_2 is mainly attributed to lower mass fuel consumption, and the higher calorific value and higher H/C ratios of HRD as compared to diesel.

Based on a literature review it emerged that HRD fuel properties such as CN, calorific value, H/C ratio etc. influence its combustion characteristics such as in-cylinder peak pressures, heat release rates, combustion temperatures etc., which in turn can result in lower CO, HC, PM and CO_2 emissions as compared to diesel [36]. But NOx emissions of an engine fueled with HRD are influenced not only by the fuel properties but also by type of engine (heavy-duty or light-duty), injection timing, combustion chamber design, type of fuel injection system, test cycle including engine speed and torque, etc. Our previous work on estimation of the emission characteristics of a heavy duty CI engine fueled with HRD showed marginally higher values of NOx as compared to diesel, which may be attributed to the design parameters of the engine used in that work, such as turbo-charging and a relatively lower compression