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Research article

Influence of injection timing and exhaust gas recirculation of a *Calophyllum inophyllum* methyl ester fuelled CI engine

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ABSTRACT

The present work examines the prospect of using 100% *Calophyllum inophyllum* methyl ester as a promising alternative fuel for future generation. In this research work, a strategy is developed to reduce NO_X emissions of *Calophyllum inophyllum* biodiesel fuelled diesel engine by varying the injection timing between 21°, 23° and 25° bTDC and by admitting exhaust gas recirculation at the rate of 10%, 20% and 30%. The experiments are conducted in a four stroke diesel engine using 100% *Calophyllum inophyllum* biodiesel and the engine characteristics are compared with neat diesel engine. Certain important parameters like brake specific energy consumption, brake thermal efficiency, heat release rate, in-cylinder pressure, exhaust emissions including NO_X and smoke density are evaluated for various injection timing and EGR rates. Retardation of injection timing to 21° bTDC reduces the NO_X emissions very marginally with significant loss in engine performance. It is found that 10% exhaust gas recirculation rate could reduce the NO_X emissions more effectively which would meet the proposed Euro V standards. Thus it is observed that exhaust gas recirculation is an effective method to control emissions of 100% *Calophyllum inophyllum* biodiesel without much compromise in engine efficiency when compared to the influence of injection timing.

1. Introduction

The increased dependency on petroleum products has aggravated quicker exhaustion of fossil fuels which has driven us to look for alternative sources of fuels. The properties of biodiesel extracted from vegetable oils are found out to be similar to that of diesel fuel and hence it is considered as a suitable alternative source of energy for use in the internal combustion engines [1]. Biodiesel is a renewable and biodegradable fatty acid methyl ester extracted from any kind of vegetable oil and animal fats [2]. Nowadays, the usage of edible oil from food crops for the production of biodiesel is limited in countries like India, because of their abundant need for domestic purposes which made researchers to narrow down and sharpen their focus of extracting biodiesel from non-edible feedstock [3,4]. Some of the non-edible oil that are widely used for the process of biodiesel production are *Jatropha curcas*, *Calophyllum inophyllum*, Pongamia pinnata, *Ricinus communis* and *Ceiba pentandra* [5]. *Calophyllum inophyllum* is one of the non-edible feedstock which is accessible in the coastal areas of India, Sri Lanka, East Africa, Australia and Southern Asia [6] and reported to be more prominent in countries like India, Indonesia and USA. *Calophyllum inophyllum is* a potential non-edible feedstock for future biodiesel production which is more economical, more eco-friendly, easily cultivatable in any wastelands and has an upper hand over non-edible oils as reported by Atabani and Aldara [6].

Low volumetric energy capacity, high kinematic viscosity, poor cold-flow properties, inferior oxidation stability and higher NOx emissions are some of the disadvantages of using *Calophyllum inophyllum* biodiesel which prevents its widespread usage [7]. One yet major limitation of *Calophyllum inophyllum* feedstock is that its rich content of free fatty acids, which should be properly removed during trans-esterification process. The normal trans-esterification process would result in higher viscous nature of the oil which would diminish the quality of the biodiesel that would be yielded. Previous researchers like Ong et al. [5,7] produced biodiesel which met the standards set by American Society of Testing and Materials (ASTM) by using a two-stage acid-alkali trans-esterification process for *Calophyllum inophyllum* oil with an optimum methyl ester yield of 98.53% which comply with ASTM D6751 and EN14214 standards. Monirul et al. [8] had recently conducted experimental studies on performance and emission characteristics of *Calophyllum inophyllum* methyl ester diesel blends at full load under various engine speeds ranging from 1000 to 2400 rpm. The average brake specific fuel consumption got increased by nearly 10% for 20% *Calophyllum inophyllum* methyl ester diesel blend compared to neat diesel. The NO_X emissions for 20% *Calophyllum inophyllum* methyl ester diesel blend was higher and amounts to 337.3 ppm at 2400 rpm compared to 20% palm and 20% Jatropha biodiesel blends. They also observed that peak in-cylinder pressure of 20% *Calophyllum inophyllum*

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methyl ester diesel blend was higher than that of corresponding palm and Jatropha biodiesel blends in the premixed combustion phase. Mosarof et al. [9] had conducted similar studies on Palm and *Calophyllum inophyllum* methyl ester diesel blends on an automobile diesel engine. They reported the smoke opacity of 30% *Calophyllum inophyllum* biodiesel blend was lower compared to corresponding Palm biodiesel blend and neat diesel.

The influence of variation of injection pressures 200 bar, 220 bar and 240 bar neat *Calophyllum inophyllum* methyl ester was investigated by Nanthagopal et al. [4]. They reported that *Calophyllum inophyllum* methyl ester injected at 220 bar had shown better performance and emission characteristics except NO_X and the results are comparable with that of conventional diesel. It was examined and reported that the NO_X emissions of *Calophyllum inophyllum biodiesel* was relatively higher than neat diesel at all injection pressures. Moreover, the NO_X emissions of *Calophyllum inophyllum* biodiesel increased with increase in injection pressure. The impact of anti-oxidants on *Calophyllum inophyllum* biodiesel blends was investigated by Fattah et al. [10]. They found that NO_X emissions increased with increase in *Calophyllum inophyllum* biodiesel blends compared to neat diesel. They reported that with the addition of anti-oxidants, a slight increase in brake power and reduction in brake specific fuel consumption was observed. The NO_X emissions were reduced by 3.6% with marginal increase in HC and CO emissions.

From the literatures cited, it is observed that NOx emissions increased, with reduction in HC and CO emissions for all biodiesels when compared to neat diesel fuelled operated engine. This is because the biodiesels possess higher oxygen content compared to the diesel fuel. The above problem of NO_X emissions is quite worthy for *Calophyllum inophyllum* biodiesel also. Thus to implement any biodiesel fuel for commercial long term application, the reduction of NOx should be addressed sensibly, especially when diesel engine is fuelled with 100% biodiesel. Fuel injection timing is one of the major operating parameter that affects the combustion and emission characteristics of a diesel engine. Retarding the fuel injection timing decreases the effective duration of combustion, which ends up in incomplete combustion. The incomplete combustion results in reduced brake thermal efficiency with increase in brake specific fuel consumption. The positive side of retarding the fuel injection timing helps in reducing the NOx emission to much satisfactory level as reported by many researchers [11,12,13].

Rahman et al. [14] had compiled the research studies carried out by many researchers across the globe in analyzing the effect of injection timing variation for biodiesel fuelled engines. They reported that an increase in HC and CO emissions were observed with decrease in NO_X emission when the injection timing is retarted for biodiesel blends. However, advancement of injection timing results in marginal increase of brake power and exhausts gas temperature with reduced volumetric efficiency and brake specific fuel consumption. Mohan et al. [15] had carried out performance and emission characteristics of Mahua methyl ester biodiesel blend by varying the injection pressures and fuel injection timing on a stationary power developing diesel engine for both household and commercial applications. They varied the injection pressure between 225, 250 and 275 bar and injection timing between 19°, 21°, 23°, 25° and 27° bTDC. They reported from their studies that either by increasing the injection pressure to 275 bar or by retarding the fuel injection timing to 21° bTDC the strict emission norms of central pollution control board could be met by 20% Mahua methyl ester biodiesel blend.

Palash et al. [16] critically reviewed the various NO_X reduction techniques like addition of exhaust gas with fresh air, retardation of injection timing, fuel emulsification, water injection, low temperature combustion and simultaneous technology for biodiesel operated diesel engine.

They reported that EGR and injection timing retardation are the most effective viable methods for reducing NO_X emissions. They also concluded that retardation of injection timing is the most adaptable technique for NO_X reduction up to 38%, whereas EGR could reduce NO_X to a maximum extend of 84%. The exhaust gas recirculation is more widely and acceptable methodology for NO_X reduction due to its easy adaptability and highly economical nature for diesel engines. Bhaskar et al. [17] had conducted experiments with 20%, 40%, 60%, 80% and 100% fish oil methyl ester in a direct injection diesel engine and has chosen 20% FOME as the optimum blend for NO_X reductions using exhaust gas recirculation. They reported that NO_X emissions increased with increase in FOME concentration in the biodiesel blends. EGR of 10%, 20% and 30% were employed to reduce NO_X for the 20% fish oil methyl ester. It was suggested that 20% EGR was the optimum rate for the reduction of NO_X without appreciable hike in soot values. The performance and emission characteristics of 20% soybean biodiesel with 5%, 10% and 15% EGR addition were investigated in a direct injection diesel engine by Can et al. [18]. They found that 5% and 10% of EGR rates had not much affected the brake thermal efficiency and performance characteristics. It was found that BSFC increased by 6% and BTE decreased by 3% when 15% EGR was introduced at full load of 15 Nm and rated speed of 2200 rpm. NO_X emissions decreased by 55% and soot emissions increased by 15% when 15% EGR was admitted inside the engine cylinder.

Qi et al. [19] had investigated the influence of exhaust gas recirculation (EGR) and injection timing retardation on the performance, combustion and emission characteristics of direct injection diesel engine when fuelled with neat soybean biodiesel. They reported that with increase in EGR rate or with injection time retardation the BSFC and soot emissions slightly increased whereas remarkable reduction in NO_X emission was observed. Thus they concluded that EGR and retardation of injection timing were the effective methods to reduce NO_X for biodiesel operated engine without much compromise in the engine performance.

Soloiu et al. [20] investigated the charcoal slurry as renewable fuel in direct injection compression ignition engine and its influence on injection system characteristics. It was found that the combustion peak pressure for charcoal slurry comparable to conventional diesel with longer ignition delay period. In addition, the net heat release rate was higher for charcoal slurry fuel than that of diesel at maximum engine load. In an another investigation, Soloiu et al. [21] used n-butanol as supplementary to biodiesel through port fuel injection in diesel engine in order to reduce the NOx and soot emissions simultaneously. The experimental results suggested that n-butanol injection in biodiesel fuelled engine reduced 90% soots emissions and 50% NOx emissions at higher injection rate. However, the non-regulated emission of aldehyde increased significantly during n-butanol addition in diesel engine. It has been conclude that the injection of n-butanol at higher injection pressure could be a viable technique for simultaneous reduction of NOx and soot in diesel engine. A low temperature combustion strategy is achieved using port fuel injection of n-butanol in biodiesel fuelled diesel engine through PCCI technique by Soloiu et al. [22]. It has been revealed that the soot emission is reduced up to 90% along with 74% reduction of NOx at 3 bar indicated mean effective pressure during idling condition. The multifuel capability of indirect injection diesel engine is experimentally investigated suing cotton seed biodiesel as fuel by Soloiu et al. [23]. The study concluded that 50% cotton seed biodiesel with diesel could be a feasible blend for obtaining better performance in diesel engine.

In-depth exhaustive review of available scientific literatures has shown a vacuum in implementing 100% *Calophyllum inophyllum* biodiesel as an alternate renewable energy source for practical applications due to engine exhaust NOx emissions and greenhouse gases. The literatures have not arrived at systematic investigation for deploying 100% CIME in diesel engine to reduce NOx emissions by varying the injection timing and EGR rate. Based on this critical scenario, a strategic methodology has been developed in order to implement neat *Calophyllum inophyllum* biodiesel by conserving energy through recirculating the exhaust gases and at the same time reducing the NOx emissions. In addition, the heat energy released due to combustion is controlled by varying the injection timing to reduce engine out emissions for adapting