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Butanol or DEE blends with either straight vegetable oil or biodiesel excluding fossil fuel: Comparative effects on diesel engine combustion attributes, cyclic variability and regulated emissions trade-off

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A B S T R A C T

This work investigates comparatively the effects of using as base fuels straight vegetable oil (SVO) and its biodiesel in blends with 10% or 20% of either *n*-butanol or DEE as supplements, excluding fossil fuel. The combustion attributes, cyclic variability, and all regulated emission trade-offs are examined in an experimental, 'Hydra' diesel engine at three loads. Cylinder pressure diagrams and related heat release rate analysis disclose and aid the interpretation of the differences observed in combustion attributes among all bio-fuels blends. Since low ignition quality fuels, such as the present bio-fuel supplements, may give rise to unstable engine operation and so detrimental performance, this work focuses also on the comparative examination of the strength of cyclic combustion variations as reflected in the cylinder pressure diagrams, by analyzing for maximum pressure and rate, indicated mean effective pressure, and ignition delay, using statistical analysis tools for averages and coefficients of variation (COV). The above results and the different physical and chemical properties of bio-fuels are used to aid the interpretation of engine stability differences observed among all bio-fuels examined, as well as the balance of all four exhaust emissions. The latter reveal defeat of smoke-NOx trade-off and interesting CO-HC adverse trade-off.

1. Introduction

During the last decades, the increasingly stringent exhaust emission regulations have dominated the automotive or the energy industry in general, and forced manufacturers to new developments [1]. Thus, scientists and engineers working in the research community strive to develop engines that meet these strict environmental constraints [2], while maintaining high engine specific power output and reliable operation [3]. Effective solutions to this task form the devising of both internal [4] and external engine measures [5], while fuel related techniques follow close [6].

Diesel engines of today are established as the dominating power-train solution in the world market, owing to their substantial improvements regarding specific fuel consumption, reduction of pollutant emissions, and emitted noise mitigation [7]. This has been achieved over the last years, apart from engine-related techniques, by using alternative fuels [8], which contribute to significant pollutant emissions reduction, either gaseous [9] or mainly liquid bio-fuels [10]. This presupposes that they are properly selected for an overall satisfactory operation of the engine.

On the other hand, energy security is a key ingredient for the economic stability of every country, especially for those that do not have (or have inadequate) fossil or nuclear resources. In this context, depleting reserves and uncertainty in the prices of crude oil, coupled with continuously growing concern over global warming and environmental degradation in general (e.g. acid rain, smog, climatic changes), have raised public and scientific awareness and led to substantial efforts for the development of alternative fuel sources [11]. Among those, bio-fuels (oxygenated by

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nature) have assumed a substantial role, since they possess the vital benefit of being renewable and hence showing an ad hoc advantage in reducing the emitted carbon dioxide [12].

One of the prominent areas where the high demand for petroleum-based fuels manifests itself is the transportation and agricultural sector, thus constituting an important field where the use of bio-fuels emerges as a very promising, long-term, alternative solution. Bio-fuels made from agricultural products, may not only offer benefits in terms of exhaust emissions, but also reduce the world's dependence on oil imports, with local agricultural industries supported and farming incomes enhanced, with the added advantage that they can be used near the place of their production [13]. Among those, liquid bio-fuels such as vegetable oils and their derived biodiesels [14] are considered as very promising for use in diesel engines, as well as lighter alcohols like ethanol or heavier ones like *n*-butanol [15], or the isomer ether of butanol, diethyl ether [16].

A recently appeared publication [17] reviewed the state of liquid bio-fuels in Greece and presented the current situation in production and research, inside the framework of EU Renewable Energy policies and mandatory targets, as Greece is EU Member State. It presented the production potential in terms of cultivated crops along with the industrial activity on bio-fuels and their distribution in the country, and discussed the research activities. Among those, straight vegetable oil (SVO) has been considered as possible alternative to biodiesel fuel for diesel engines owing to its lower cost (no transesterification process), and in Europe SVOs achieved a measurable share in bio-fuels market around 5%, with interest e.g. for diesel passenger cars [18] or bus engines powering the mini-bus fleet in the major Athens area [19].

The advantages of vegetable oils (as diesel fuels) are the minimal sulfur and aromatic content, and the higher flash point and lubricity [20], whereas their disadvantages include primarily the very high viscosity, the higher pour point, and the lower cetane number, calorific value and volatility [21]. The advantages of biodiesels are the minimal sulfur and aromatic content, and the higher flash point, lubricity and cetane number [22], whereas their disadvantages include the higher viscosity (though much lower than the vegetable oils one), the higher pour point, the lower calorific value and volatility, the hygroscopic tendency, and the lower oxidation stability [23].

Butanol is a biomass based renewable fuel that can be produced by alcoholic fermentation of the biomass feedstock used for ethanol production. It possesses less hydrophilic tendency, higher heating value and cetane number, lower vapor pressure, higher viscosity (and lubricity) and (almost perfect) miscibility than ethanol [24]. Thus, butanol has properties much closer to diesel fuel than ethanol, rendering it preferable for blending with conventional diesel fuel. Unlike vegetable oils, biodiesels or ethanol, it has been experimented much less on diesel engines, but the relevant literature on the subject is increasing at amazing rates in the last years as e.g. evidenced in Scopus search. The isomer that has most been experimented with and used in the present study is 1-butanol, better known as *n*-butanol (normal butanol), having a straight chain structure with the hydroxyl group at the terminal carbon [25].

Diethyl ether (DEE), otherwise called simply 'ethyl ether' or more simply 'ether', an isomer ether of butanol, can be produced from ethanol, which is produced itself from biomass, via a dehydrating process with strong dehydrating agents, thus also being a bio-fuel. DEE has several favorable properties for blending with diesel fuel, including very high cetane number, reasonable energy density for on-board storage, high oxygen content, low auto-ignition temperature, broad flammability limits, and high miscibility in diesel fuel. Its disadvantages include high volatility, propensity for peroxidation in storage and low lubricity [26]. Few works exist on the use of DEE/diesel fuel blends in diesel engines, which were formerly reviewed in Ref. [26] and recently by this group in Ref. [16].

Interrelated to the operation of internal combustion engines is the phenomenon of variations in the cylinder pressure from one cycle to another, even under nominally steady-state operating conditions [27]. Any deviation in pressure time development reduces the efficiency and reliability of the engine, increases its noise, and induces power fluctuations [28]. Measurements and analysis of cyclic variability in spark-ignition engines have been reported in many researches, such as the study of cyclic variations and average burning rates in Ref. [29] and the influence of cyclic variations on nitric oxide formation in Ref. [30].

In contrast, the corresponding analyses for diesel engines have not kept pace, though randomness in the cylinder pressure was known to exist even in those, probably owing to their lower strength of cycle-to-cycle variations. Wing [31] dealt with this aspect in a multi-cylinder, DI diesel engine having a rotary fuel injection pump being suspect of cyclic pressure variations. Sczomak and Henein [32] experimenting on a CFR pre-chamber diesel engine, running with various low-ignition quality fuels, pointed out that these may cause cyclic irregularity. In Ref. [33] for a single-cylinder, DI diesel engine fueled with neat diesel fuel, stochastic analysis techniques were used.

Equally, few works (two handfuls) exist examining the combustion cycle-to-cycle variations when using liquid bio-fuels in compression-ignition (diesel) engines working in the conventional diesel mode (as concerns the present study), which are briefly outlined as follows. The fluctuations of i.m.e.p. were studied in diesel engine using among others mixture of biodiesel and anhydrous ethanol in small proportions, blended with diesel fuel [34]. The i.m.e.p. and max pressure variations were studied of diesel fuel blend with 10% dimethyl carbonate in diesel engine operated with multiple split-injection and heavy exhaust gas recirculation [35]. Cyclic variations of i.m.e.p., max cylinder pressure, and heat release peak were tested in non-road diesel engine fueled with different biodiesel/diesel fuel ratios [36]. Cyclic variations of max cylinder pressure were tested in diesel engine fueled with neat biodiesel or neat diesel fuel [37]. The stochastic nature (randomness) of combustion cyclic variations was revealed for the present diesel engine using neat cottonseed oil or its neat biodiesel [38]. The same randomness result was reported for this engine operated with either ethanol/diesel fuel blends [39], or *n*-butanol/diesel fuel blends [40], or diethyl ether/diesel fuel blends [41]. The research group in Ref. [42] used alcohol additives to biodiesel/diesel blended fuel B30 (diesel fuel blend with 30% biodiesel) in diesel engine, with alcohol in proportion of 6% of either ethanol or butanol, examining cylinder pressure variations. The same research group in Ref. [43] used small proportions of DEE additive (2%, 4%, 6% and 8% by vol) to biodiesel/diesel blended fuel B30 in diesel engine, examining i.m.e.p. variations.

A Literature search also shows that very few works exist in compression-ignition (diesel) engines operating in the conventional diesel mode, fueled with binary blends of SVO or biodiesel with *n*-butanol or DEE (excluding diesel fuel in the blends) as concerns the present study, which are briefly outlined as follows concerning reports on experimental exhaust emission results. Neat Rapeseed oil and its blends with up to 29% by vol *n*-butanol were used in single-cylinder, DI diesel engine, at various loads [44]. Neat biodiesel Karanja oil methyl ester and its blends with up to 20% by vol DEE were used in single-cylinder, air-cooled, agricultural DI diesel engine, at various loads [45]. Thevetia Peruviana oil methyl ester and its blends with up to 20% by vol DEE were used in single-cylinder, water-cooled, DI diesel engine, at various loads [46].