Fuel 225 (2018) 174–183

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Performance and combustion characteristics of a compression ignition engine running on diesel-biodiesel-ethanol (DBE) blends – Part 2: Optimization of injection timing

Andrew David Mendes Guedes, Sergio Leal Braga, Florian Pradelle*

Departamento de Engenharia Mecânica (DEM), Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Keywords:
Diesel-biodiesel-ethanol blends
Compression ignition engines
Performance
Combustion
Injection timing

ABSTRACT

Lately, renewable biofuels could be considered leading candidates for softening society's liability to fossil derivate fuels and pollutants emission issues. In this paper, taking advantage of compression ignition engine's better performance, biodiesel and ethanol dawn as renewable commercial fuels in substitution to diesel fuel without the need of geometrical engine modifications. Experimental tests were run in an Euro III multi-cylinder compression ignition engine (MWM 4.10 TCA), fueled with diesel, biodiesel (7 or 15 vol% in diesel fuel) and anhydrous ethanol (up to 20 vol%, by 5 vol% steps) blends. Each diesel-biodiesel-ethanol (DBE) blend, always containing a 1 vol% of original additive in order to ensure blend's stability, is evaluated for three engine speeds (1500, 1800 and 2100 rpm), so as for two torque conditions (25% and 50%, considering 100% baseline torque conditions established by commercial B7E0 diesel fuel for each engine speed). An investigation is carried for engine's performance parameters and combustion characteristics, regarding different injection timings for the fuel. The specific fuel consumption could be reduced 4%, while ethanol specific energetic conversion was up to 30% improved at optimized injection timings. On the other hand, the maximum pressure was increased up to 9% and the ignition delay varied 5° just by shifting the start of injection. The fuel injection timing optimization study has also shown a trend of 1° CA injection timing anticipation for each additional 5%vol of ethanol, when the engine was fueled with B15E5, B15E10 and B15E15.

1. Introduction

The awareness about emissions and liability to petroleum resources are issues of extremely relevance in the energetic context that rose during the last decades. Then, regulatory agencies and society's concern have encouraged technological developments of solutions able to optimally yield high efficiency and low emissions engines [1,2]. Environmental issues began to be internationally discussed, indeed, with the Club of Rome (1968) and endorsed later with the United Nations Conference on Human Environment in Stockholm (1972), United Nations Conference on Environment and Development in Rio de Janeiro (1992), Kyoto Protocol (1997) and Paris Agreement (2015) [3–6]. Some pessimistic projections about oil reserves' depletion threat supply's stability of fossil fuels in vogue, after almost a century of severe exploitation all over the world and also worldwide geopolitical scenarios of tension [4,7,8].

In a recent past, many countries, fearing that an excessive dependency on fossil fuels could endanger their growing path, decided to promote alternatives to petroleum fuel and its derivatives [9,10]. Biofuels dawn as alternative energy sources to traditional fossil fuels, are produced from biomass and classified as renewable energy sources, when growing cycles are respected [4,11]. Also, the development of robust biofuels productive chains can lead to higher energy independence in many countries [12,13]. In this context, biodiesel, which is a biofuel with properties similar to the traditional fossil diesel, can easily establish blends with the mentioned fossil fuel or even capable of fully replace it with little or no engine modifications. Moreover, its addition allows substantial particulate matter and CO emissions reduction [8,14,15]. Nevertheless, biodiesel is not able to entirely supply the substitution of fossil diesel demand yet and, then, ethanol can complementarily be set as an alternative biofuel in compression ignition engines as well [16].

Brazil is a country gifted with not only an extensive natural resources availability, but also in terms of favorable climatic and geographical conditions for biomass based fuels plantation [17]. Then, in 1975, began the “National Alcohol Plan”, a nationwide program financed by Brazilian government which aimed to phase out fossil fuels in automobile in favor of the sugar cane ethanol [11,18,19]. This

* Corresponding author.
E-mail address: pradelle@puc-rio.br (F. Pradelle).

https://doi.org/10.1016/j.fuel.2018.02.120
Received 11 September 2017; Received in revised form 17 February 2018; Accepted 19 February 2018

program conducted the use of ethanol in spark ignition engines and could be considered the greatest successful program for the replacement of petroleum derivatives fuels in the world [20,21].

However, when operating in compression ignition mode, ethanol brings some obstacles, such as low cetane number, poor miscibility in diesel at lower temperatures and some other proprieties (lubricity, viscosity and lower heating value) [1,22,23]. Despite being challenger, the use of ethanol in compression ignition applications is growing thanks to three main techniques that have emerged during recent years: alcohol fumigation in which alcohol is added to the intake air charge; dual fuel direct injection in which each fuel is injected separately; and ethanol-diesel blends in which fuels are mixed prior to injection [24–26]. This last strategy is noteworthy due to its simplicity: ethanol can be used in the form of solutions to replace amounts of fossil diesel fuel in compression ignition engines, without further technical modifications. Moreover, previous investigations have shown increased brake thermal efficiency and specific fuel consumption, so as a slight decrease in engine power and significant decrease in exhaust emissions when ethanol-diesel blends are compared to diesel fuel [24,27,28].

In addition, another relevant issue is alcohols' poor ignitability under compression ignition engine conditions [29], justified by its higher enthalpy of vaporization and higher thermodynamic conditions requirements for auto-ignition, comparatively to diesel [30]. Fuel ignition postponement is another peculiarity noticed when ethanol and diesel are blended, caused by ethanol's higher heat of vaporization (903 kJ/kg for anhydrous ethanol [31]) compared to diesel fuels (nearly 250 kJ/kg [31]). Then, ethanol's presence induces a great air-fuel charge heat withdraw for the blend evaporation, reducing the in-cylinder temperature, hindering auto-ignition favorable conditions and, lastly, delaying the very start of the combustion [24,32–34].

Ethanol miscibility in diesel is an issue that depends on hydrocarbon composition and wax content of the base diesel, ethanol content and temperature [35–40]. Anhydrous ethanol is highly soluble in diesel when the alcohol is below 30 vol% and temperatures are over 20 °C. On the other hand, at climatic conditions below 10 °C, ethanol is almost immiscible in diesel and this also affects fluidity and filterability of the ethanol-diesel blends. Miscibility is also associated with ethanol's water content: 1 vol% of water in ethanol is enough to induce phase separation and ethanol is a hygroscopic substance that easily picks water up from ambient air and distribution system [35,41–43].

Ergo, when fueled by ethanol-diesel blends without the help of stability additives, there are risks of eventual abnormal operation in compression ignition engines. Two additive-based approaches for blends stability can be mentioned: surfactants (emulsifiers) additions which produce stable (micro) emulsions or through co-solvents additions that produce stable and homogeneous solutions [35]. Among many co-solvents, biodiesel stands out for its similarity to diesel, enabling diesel-biodiesel blends in any proportion and presenting significant affinity with ethanol [44,45], avoiding (ethanol-diesel) phase separation under typical conditions of operation in Brazil, as observed by Pradelle [46]. A great amount of studies have investigated since 1980 diesel-ethanol-biodiesel blends with up to 30 vol% of anhydrous ethanol or up to 10 vol% of aqueous ethanol. The use of biodiesel as co-solvent for diesel-ethanol blends can also improve viscosity, density, lubricity, lower heating value and even cetane number, hence fomenting blends' stable operation in compression ignition engines [47,48]. An overview considering diesel-ethanol-biodiesel blends evaluations shows emission levels strongly depend on fuels proportions in blends. For example, ethanol leads to higher hydrocarbons emissions, while biodiesel reduce them [32,49,50].

Although biodiesel helps to reach diesel-ethanol blends stability, there are some combinations of diesel, ethanol and biodiesel contents in which blends' total homogenization may not be possible for some operational conditions [48]. For these cases, the application of further additives in the blend should be taken into account. Recently, Pradelle et al. [39,51] has also shown that a very low volumetric content (approximately 1%) of an additional co-solvent, composed by a combination of bio components, could successfully ensure diesel-biodiesel-ethanol (DBE) blends' stability through a wide range of temperatures (higher than 10 °C) and up to 20 vol% of ethanol, in which biodiesel's concentration would eventually not be enough as a co-solvent. Moreover, the results obtained by Pradelle [46] have shown that the diesel fuel replacement changed some combustion characteristics. The increased ethanol content implied in an increase of the ignition delay, due to lower cetane number, higher latent heat of vaporization and specific heat at constant pressure of ethanol, but the heat was released faster. As combustion began later, the maximum pressure was lower and observed delayed in the expansion stroke. Thus, he also suggests adjustments in fuel injection timing to maximize the engine's performance. Guedes [52] certificated that growing ethanol contents in diesel-biodiesel mixtures leads to increased ignition delays, which was verified as a harmful characteristic for engine's performance when fuel injection timing is fixed.

Fuel injection timing anticipation is a solid strategy to work around typical postponements that may occur in DBE blends combustion caused by ethanol's presence. When the injection occurs earlier, there is more time available for fuel vaporization. Then, the injection timing could be adjusted so that the charge (air-fuel) auto-ignition happens as close as necessary to the top dead center, when the pressure gradient should be the most favorable.

This paper holds evaluations in an Euro III multi-cylinder compression ignition engine fueled with DBE blends, enhanced by Pradelle's et al. [51] additional bio co-solvent in a 1 vol% overall blend's content. The study assessed engine's performance parameters and combustion characteristics regarding different injection timings for each DBE blend (containing from 0 to 20 vol%, by steps of 5 vol%) three engine speeds (1500, 1800 and 2100 rpm) and two torque levels (25% and 50% of 100% maximum torque conditions for each engine speed when fueled with the commercial diesel B7E0). Heat released, ignition delay, maximum in-cylinder pressure, specific fuel consumption and ethanol energetic conversion were investigated for a better perception about fuel injection timing optimization influence.

2. Materials and methods

2.1. Fuels

During the tests, the engine was fueled with six different blends. Two of the fuels were just diesel-biodiesel blends, while the other four were diesel-biodiesel-ethanol blends with additive.

The commercial diesel (B7E0), a blend composed by 93 vol% of diesel and 7 vol% of biodiesel, was bought in a gas station from Rio de Janeiro and its physicochemical characterization is presented in Table A1 of the Supplementary Material. This fuel was applied to set baseline torque conditions for all the tests. It was also the only fuel in which Pradelle's et al. [51] blend stabilizer additive was not used.

Meanwhile, B15E0 is a diesel-biodiesel blend formed by commercial diesel B7E0 (93 vol% of diesel + 7 vol% of biodiesel) and pure biodiesel, so that the blend can present itself as a fuel composed by 85 vol % diesel + 15 vol% of biodiesel. The B15E0 was set as a base fuel, when considering ethanol energetic conversion evaluations in DBE blends. Furthermore, pure biodiesel blended to commercial diesel B7E0 in all blends was composed 44 vol% by beef tallow biodiesel and 56 vol% by soybean biodiesel. Table A2 of the Supplementary Material shows some physicochemical properties provided by the fuel characterization.

Then, the preparation of DBE blends consists on the addition of anhydrous ethanol in a B15E0 blend previously established. Some anhydrous ethanol physicochemical properties are shown in Table A3 of the Supplementary Material.

Lastly, 1 vol% additive was added supplementary to the diesel-biodiesel blends. The final nomenclature (B15Ex) unfolds the amount of ethanol added (x vol%) to diesel B15 fuel, before the use of the additive.