Fuel 117 (2014) 286–293

Contents lists available at ScienceDirect

Fuel

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

Performance and emissions of iso-stoichiometric ternary GEM blends on a production SI engine

L. Sileghem *, A. Coppens, B. Casier, J. Vancoillie, S. Verhelst

Department of Flow, Heat and Combustion Mechanics, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

HIGHLIGHTS

- Gasoline–ethanol–methanol mixtures can be used as 'drop-in' fuels for E85.
- These fuels can help to remove the biomass limit of ethanol.
- Iso-stoichiometric GEM fuels are compared on an engine test bench.
- Similar BTE, volumetric efficiency and knock behavior are reported.

ARTICLE INFO

Article history:
Received 31 July 2013
Received in revised form 12 September 2013
Accepted 15 September 2013
Available online 25 September 2013

Keywords:
Ternary blends
Methanol
Ethanol
Flex fuel vehicles
SI engine

ABSTRACT

Removing the biomass limit is one of the great challenges to further enlarge the share of renewable ethanol as alternative for fossil fuels. One of the possible solutions for this constraint are the ternary GEM (Gasoline–Ethanol–Methanol) blends. The air-to-fuel ratio of these blends is hereby chosen at the value of an E85-blend (9.75 kg air/kg fuel) while the ethanol is replaced by methanol/gasoline and therefore these blends are called 'iso-stoichiometric'. If the methanol is produced out of renewable sources, these blends can help extend the part of clean fuels on the market. The ternary blends show few differences in physical properties for the total range of possible blends and are considered as drop-in alternatives to the original E85-blend for a flex fuel engine. In this paper the performance and engine-out emissions of four of these GEM-blends were examined on a 4 cylinder 1.8 l PFI production engine. A single cylinder engine with high compression ratio was used for a preliminary study of the knock behavior of these blends. The measurement results are compared with those on neat gasoline, methanol and ethanol to demonstrate the potential of these ternary blends as a fossil fuel alternative. All the GEM fuels which were tested gave very similar results to E85 and can therefore indeed be used as 'drop-in' fuels for flex-fuel vehicles.

1. Introduction

It is well-known that fossil fuels are being consumed worldwide in enormous amounts and that the demand for energy keeps increasing every year at high rates. The transportation sector is one of the big consumers and during the last decades people have become aware that we cannot depend on these fossil fuels forever because of the shrinking reserves, negative climate change and bad air quality [1]. Hydrogen [2] and electrification are widely cited as possible solutions these days. Electrification and hydrogen are widely investigated and electric city cars are already in use. Nevertheless, the low volumetric energy density of batteries and hydrogen provide these vehicles with a limited range, compared to conventional ICE vehicles. A transition to either hydrogen vehicles or battery electric vehicles will result in increases in both vehicle and infrastructure costs making it questionable if they will become competitive with vehicles running on liquid fuels in the near future.

Driven by the Renewable Energy Directive in the EU [3] and The Energy Independence and Security Act in the US [4], biofuels are likely to be used at increasingly high concentrations over the next years due to the compatibility with modern vehicles and the distribution and fueling infrastructure. For now, bio-ethanol has the lion's share when it comes to non-petroleum-derived transportation energy. Currently, the largest part of the bio-ethanol is used in low level blends but it can also be used in high level blends like E85 (nominally 85 v/v% ethanol in gasoline) in flex-fuel vehicles. Flex-fuel vehicles are able to run on ethanol concentrations from

Abbreviations: AFR, Air to Fuel Ratio; BMEP, Brake Mean Effective Pressure; BSFC, Brake Specific Fuel Consumption; BTDC, Before Top Dead Centre; BTE, Brake Thermal Efficiency; CoV, Coefficient of variation; CR, Compression Ratio; (D)OHC, (Double) OverHead Camshaft; ECU, Engine Control Unit; EGR, Exhaust Gas Recirculation; GEM, Gasoline, ethanol, methanol; ICE, Internal Combustion Engine; IMEP, Indicated Mean effective Pressure; LHV, Lower Heating Value; MBT, Minimum Spark advance for Best Torque; PFI, Port Fuel Injection; SI, Spark Ignition; TP, Throttle Position; TWC, Three Way Catalyst.

* Corresponding author. Tel.: +32 496631601.
E-mail address: Louis.Sileghem@UGent.be (L. Sileghem).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.09.043

0% up to 85% by volume in gasoline. There are already millions of flex-fuel vehicles on the market but few of these vehicles regularly use E85 [5]. Nevertheless, they represent a potentially large market for alcohol fuels.

Despite of the projected growth, bio-ethanol is not considered to be viable in the long term as a substitute for fossil fuels, due to the biomass limit [6]. This biomass limit is different for each country, and depends on the amount of biomass that can be grown there, the amount of energy required by the country, any impact of land-use change that may arise, and limits set by any impact on the food chain [7,8]. It has been estimated that this limits the potential of biofuels to about 20% of the energy demand in 2050 [9].

Compared to ethanol, methanol is actually more versatile from a production point of view. Methanol can be produced from a wide variety of renewable sources (e.g. gasification of wood, agricultural by-products and municipal waste) and alternative fossil fuel based feed stocks (e.g. coal and natural gas). A number of workers have even proposed a sustainable closed-carbon cycle where methanol is synthesized from hydrogen, produced from renewable electricity, and atmospheric CO_2, thus forming a liquid hydrogen carrier and making it an 'electrofuel' [10].

Methanol has been successfully used in large-scale fleet trials [11] and studied on engine test benches [12,13]. Because of the high octane index, high heat of vaporization and low combustion temperatures, the power and efficiency is significantly higher for methanol (and ethanol) compared to gasoline. This is certainly true for highly pressure-charged engines, where aggressive downsizing is possible on these alcohols [14].

2. Iso-stoichiometric ternary blends

Turner et al. [7,15] presented the concept of ternary blends of gasoline, ethanol and methanol in which the stoichiometric air-to fuel ratio is controlled to be the same as that of conventional E85 alcohol-based fuel. In fact, starting from any binary gasoline–ethanol mixture, a ternary blend of gasoline, ethanol and methanol can be devised in which the fraction of each component is chosen to yield the same stoichiometric air to fuel ratio (for E85, this is ~9.75:1 depending on the AFR of the gasoline which can vary somewhat). In this study the Euro 95 gasoline that was used in the experiments has an AFR of 14.4. The gasoline has been analyzed with mass spectrometry and no alcohols were found in the gasoline. In Fig. 1, the concept of these ternary blends is shown for equivalent 'E85' blends. On the right side of Fig. 1, the composition of normal E85 can be seen (85 v/v% ethanol and 15 v/v% gasoline). On the left side of Fig. 1, the binary mixture of gasoline and methanol is shown in which all the ethanol is replaced with gasoline and methanol. This results in a M57 blend (57 v/v% methanol and 43 v/v% gasoline). In between these two blends, any iso-stoichiometric ternary blend can be determined by drawing a vertical line in Fig. 1 and reading the blend ratios on the left axis of the figure (for example the yellow dotted line in Fig. 1). Turner et al. [15] found that all the possible iso-stoichiometric ternary blends starting from a binary blend of gasoline and ethanol have, beside the same AFR, essentially identical volumetric energy content (based on the masses and densities of the individual components), constant octane numbers and constant latent heat. This opens the possibility to use these ternary blends as drop-in fuels for flex-fuel vehicles without the danger of upsetting the on-board diagnostics of the engine management system. If the methanol used is of a renewable and energy-secure nature then, for a fixed volume of ethanol in the fuel pool dependent on the biomass limit, an increased level of renewability and energy security is achieved. This overall situation is made possible by the fact that there are more E85/flex-fuel vehicles in existence than can currently be serviced by the E85 fuel supply chain.

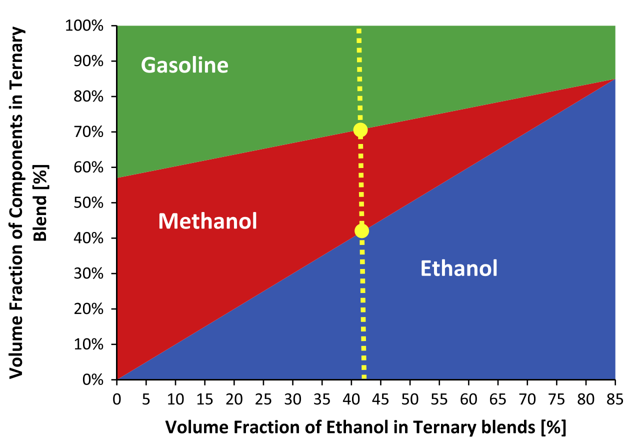

Fig. 1. Iso-stoichiometric GEM blends equivalent to conventional E85 [15].

Turner et al. [15] tested the drop-in ability of the iso-stoichiometric GEM blends in two flex-fuel vehicles. One vehicle was provided with a physical sensor for alcohol content and the other vehicle had a 'virtual' sensor. A physical sensor measures directly the alcohol concentration of the fuel relying on the electric permittivity or the resistance of the fuel, while a virtual sensor utilizes an algorithm based on the information of the other sensors of the engine to calculate the alcohol concentration. A 'virtual' sensor has the advantage that there is no additional cost in hardware.

During vehicle testing, the hypothesis that iso-stoichoimetric GEM blends can function as drop-in alternatives to binary ethanol–gasoline blends has been confirmed. There were only two malfunction lights when running on the binary gasoline–methanol blend with the vehicle with the 'virtual' sensor. Turner et al. [15] stated that this could be due to phase separation as the vehicle was not subjected to road shocks or accelerations on the test bench and that some form of cosolvent might be necessary when methanol and gasoline are blended together. Compared to the gasoline tests on the same vehicles, there was an overall efficiency improvement of approximately 5% when using the alcohol blends. Turner et al. [15] performed also cold start tests. The only fuel blend which failed the cold start test was the normal E85 blend. This is to be expected as ethanol is harder to start than gasoline or methanol, and so reducing the proportion of this component and replacing it with larger amounts of the other two would only be expected to improve the situation. This means that there is the possibility with GEM blends to effectively extend gasoline displacement during winter months when currently, with existing commercial E85 fuels, the ethanol content is decreased to levels close to 70% in order to maintain cold startability. A year-round fixed blend ratio is therefore a possibility.

It is important to notice that the tests were conducted on a vehicle and the emissions were measured at the end of the tailpipe without knowing what the ECU was actually doing. As a result, measurements on an engine test bench and engine-out emissions are indispensable to learn the full effect of replacing ethanol by methanol/gasoline in the GEM-blends. This is addressed in this study where different iso-stoichiometric blend are tested on engine test benches.

Next to the hypothesis, other benefits of the GEM-blends were discussed like the potential economic advantage. Turner et al. [15] showed that with wholesale prices of \$3.11, \$2.30 and \$1.11 per US gallon for gasoline, ethanol and methanol respectively, the price of the blends can be made significantly lower than gasoline on an energy basis. With these prices, with ternary blends containing more than 25% by volume of methanol, a reduction in motoring costs could be realized just through a reduction in the relative price of the fuel versus gasoline. Since the vehicles would