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Full Length Article

Comparison of performance and emissions for gasoline-oxygenated blends up to 20 percent oxygen and implications for combustion on a spark-ignited engine

I. Schifter *, U. González, L. Díaz, G. Sánchez-Reyna, I. Mejía-Centeno, C. González-Macías

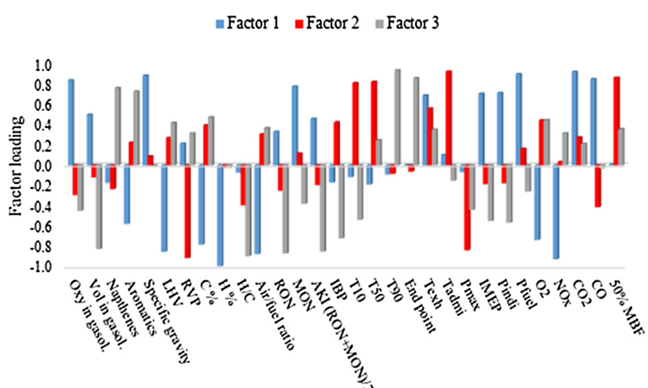
Instituto Mexicano del Petróleo, Dirección de Investigación en Transformación de Hidrocarburos, Eje Central Lázaro Cárdenas No. 152, San Bartolo Atepehuacan, Mexico D.F. 07730, Mexico

HIGHLIGHTS

- Ethers, alcohols and one carbonate blended at oxygen contents ranging from 3.5 to 20 wt% with three base gasolines.
- Prepared fuels and a commercial gasoline were tested in a single cylinder spark-ignition engine.
- Results suggest that oxygen contents and specific gravity are directly correlated with CO and CO_2 emissions and inversely correlated with NOx emissions.
- Hydrogen fuel content is directly correlated with NOx emissions and inversely with CO_2.
- Naphthenes, iso-paraffins T_{90} and final boiling point looks like have a marginal effect in engine performance and emissions.

GRAPHICAL ABSTRACT

The relationships between fuel formulation, engine performance and its exhaust emissions for different oxygenated gasolines were studied. Results are supported by both direct analysis of test matrix and statistic factor. Fuel oxygen contents varies from 3.5 wt% up to 20 wt% using three different groups (i.e. ethers, alcohols and one carbonate). Fuel properties related to initial phases of evaporation i.e. Reid Vapor Pressure, T10, T50 and heat of vaporization suggest an important effect of mixture formation and fuel metering in the combustion development.



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ABSTRACT

Although experimental studies have shown that alcohol fuels burn cleaner than unleaded gasoline, there is limited information regarding the comparison among the alcohol fuels as gasoline additive in spark-ignited engines. Therefore, in this work, twelve different fuel formulations varying base composition (three different base gasolines), oxygenated level (3.5 wt% up to 20 wt%) and oxygenating agent (i.e. ethers, alcohols and one carbonate) were burned in a spark-ignited engine (AVL 5401 SI single cylinder) engine electronically controlled to investigate the relationships between fuel formulation, engine

Abbreviations: (A/F)stoich, Air fuel ratio at stoichiometric conditions; 50% MBF, 50% mass burned fraction; ATDC, After top dead center; A/F, Air to Fuel ratio; AKI, Antiknocks index; ASTM, American Society for Testing Materials; CAD, Crank angle degrees; H/O, Hydrogen to oxygen ratio; CO, Carbon monoxide; CO2, Carbon dioxide; CFR, Cooperative Fuel Research Engine; DMC, Dimethyl Carbonate; ETBE, Ethyl tert-butyl ether; EtOH, Ethanol; FID, Flame ionization detector; FTIR, Fourier-Transform Infrared Spectroscopy; H/C, Hydrogen to carbon ratio; HC, Hydrocarbons; GC, Gas chromatograph; GDI, Gasoline direct injection engines; HoV, Latent heat of vaporization; i-BuOH, iso-butanol; IMEP, Indicated mean effective pressure; LHV, Low heating value; MeOH, Methanol; MON, Motor octane number; MTBE, Methyl-tert-butyl ether; NOx, Nitrogen oxides; O/C, Oxygen to Carbon ratio; O/H, Oxygen to hydrogen ratio; O2, Oxygen; RVP, Reid Vapor Pressure; RON, Research octane number; S, Sensitivity; SI, Spark Ignited; U. S.EPA, United States Environmental Protection Agency.

* Corresponding author.
E-mail address: ishifter@imp.mx (I. Schifter).

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performance and exhaust emissions at constant spark advance (without combustion phasing optimization). Fuel properties related to initial phases of evaporation i.e. Reid Vapor Pressure, $T_{10,}$ T_{50}, and heat of vapori7zation suggested an important effects of mixture formation and fuel metering in the combustion development. Experimental results were supported by both direct analysis of test matrix and statistical analysis. Moreover, results indicated that oxygen content and specific gravity were directly associated with CO and CO_2 emissions, and inversely associated with NOx emissions. Hydrogen fuel content was directly associated with NOx emissions and inversely with $CO_{2.}$ Naphthenes, iso-paraffins, $T_{90,}$ and final boiling point showed marginal effect on engine performance and emissions.

1. Introduction

The use of biofuels and oxygenated compounds became of increasing importance as components in the formulation of automotive gasoline are daily business for the refinery blending plants. As Aakko-Saksa et al. [1] emphasize, current conventional cars will continue to take the major share of gasoline vehicles fleets for at least the next 10–20 years, so that to establish and assess other fuel composition options is necessary. Blending gasoline with oxygenates has a proven potential to increase the thermodynamic efficiency by enhancing knock resistance.

Replacing one or other additive means that the specifications and volume of the petroleum base fuels will have to be adapted in order to meet vapor pressure, octane number specifications and other requirements for the gasoline pool sold at refilling stations, which in turn has an effect on the composition and on other specifications of the petroleum base fuels [2,3].

Reformulated gasoline introduced in ozone-nonattainment areas of Mexico mandated a maximum oxygen content 2.0 wt% oxygen, and the volatile organic compounds emissions could be reduced by setting the blending Reid vapor pressure (RVP) to a value up to 7.9 psi [4]. These amendments catalyzed the development of methyl-tert-butyl ether (MTBE) industries, to enhance the octane number, and to reduce exhaust emissions [5].

Since 2008, in México, it is required by biofuels promotion law to increase the volume of renewable that is blended into the transportation fuel pool, much of which is likely to be ethanol (EtOH). Dernotte et al. [6] noted that adding alcohol to conventional hydrocarbon fuels, tested on a spark–ignition engine causes a small increase in fuel octane rating, thereby reducing fossil-fuel consumption and carbon dioxide (CO_2) emissions [7–8].

According to Meng et al. [9], most of the gasoline contains up to 10% ethanol in the U.S., and up to 20%–25% in Brazil; furthermore the gasoline has been used in conventional cars without modification [9–10], however in 2010 and 2011, the U.S. EPA granted a partial waiver for 15% ethanol to be sold to consumers opening the door for future increases, in model year 2001 model-year and later gasoline vehicles [11].

Turbocharged GDI engines can be more fuel-efficient and offers a performance benefit due to the higher volumetric efficiency at high load [11–12], furthermore Jung et al. [12] identified the 30% EtOH blend as a potential high octane rating fuel that will enable fuel-efficient technologies without end-gas knock concerns.

As stated by Balat and Balat, and others references, higher ethanol content fuels, such as E85 in the U.S. and pure EtOH in "flex-fuel" vehicles in Brazil can reduce the reliance on petroleum fuels and enhance energy independence [9,13], however the development of a high blend and gaseous biofuels market are still not well-understood yet [14].

Anderson and Elzinga [15] noted that gasoline refiners have faced a series of increasingly stringent environmental constraints narrowing their options for maintaining high levels of fuel octane.

Among the various renewable fuels, alcohols, such as EtOH, methanol (MeOH), isobutanol, (i-BuOH) are the most popular fuels utilized in internal combustion engines [7–8]. Schifter et al. [16] used gasoline and gasoline-ethanol blends at the ratios of 0–20% ethanol in a single cylinder engine, and demonstrated that the combustion rate, efficiency and fuel consumption increased. In addition, the increment of ethanol ratio in the blend caused a decrement in the hydrocarbons (HC) and carbon monoxide (CO) emissions, but an increase in nitrogen oxides (NO*x*) emission. The compatibility of bio-ethanol with both vehicle and fuel distribution systems has also been a major concern, this is particularly in markets with a significant population of older vehicles.

Interesting gasoline components are butanol and their isomers, or ethers such as MTBE and ethyl-tert-butyl ether (ETBE). Schifter et al. [17] studied the increase of MTBE in regular gasoline (15, 25 and 51% volume) on the performance and combustion characteristics of a single cylinder engine, and results compared with five model year 2003–2010 concluding that no immediate adverse effects were observed as MTBE content increased up to 51%; the most relevant results showed only small reductions in NOx emissions as the MTBE content increased [17].

The literature about the use of high proportions of ETBE blended with gasoline is scarce. Shiblom et al. [18] conclude that the levels of ETBE ranging from 0.0 to 23.5 vol% (3.7 wt% O_2) in gasoline produced no detrimental effects of the ETBE on metal or elastomeric parts common to gasoline delivery and fueling system.

Several European countries use ETBE as a fuel additive [5] and, according to Matsumoto et al. [19], Japanese oil industries started to blend 7% bio-ETBE into automobile fuel in 2010 in view that ETBE exhibits high octane rating, a lower blending Reid Vapor Pressure and reasonably high oxygen contents. It also has lower volatility and water solubility compared with MTBE [5,20].

Dimethyl carbonate (DMC) is a flammable clear liquid boiling at 90 °C. Adding a small quantity into a base gasoline, DMC offers the possibility to introduce a large amount of oxygen into the blended fuel [21–22]. Gopinath, and Ganapathy Sundaram [22] reported that gasoline-DMC blends (D5-D20) tested in a single cylinder engine showed that the blending's with DMC increased the thermal efficiency of engine as compared to 100% gasoline. The authors also found that CO and HC emissions decreased with the increment of DMC in the blend.

In our previous work [20] we found that for a gasoline-DMC blend containing 3.52% volume (2.7 wt% oxygen), the minimum changes in fuel formulation narrow the possibility of undesirable effects of oxygenation, at the same time, the increments in combustion speed associated with DMC seem to be larger than the theoretical prediction [20].

According to Tunér [23], methanol has not reached the same level of use as ethanol. However, there is a quite substantial experience with methanol from several fleet studies [24–26]. Methanol is in commercial use today, particularly in China with some local