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Engine performance evaluation and pollutant emissions analysis using ternary bio-ethanol–iso-butanol–gasoline blends in gasoline engines

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Exhaust gas emissions and performance analysis of current gasoline engines using ternary bio-ethanol–iso-butanol–gasoline blends have been experimentally investigated. A research engine of 4-stroke, spark-ignition, single-cylinder and small size (engine capacity 147 cm^3) is operated over a wide range of engine speeds (2600–3400 r/min) using different rates of the ternary (or three-component) blends (3,7 and 10 vol% bio-ethanol–iso-butanol in gasoline). In addition, ternary blends are compared with dual iso-butanol–gasoline blends as well as neat gasoline fuel at same engine conditions without tuning. Results show that when ternary fuel blends are used, the exhaust gas emissions of UHC (unburned hydrocarbons) and CO indicate 15% and 20% lower than those of neat gasoline fuel and 9% and 14% lower than those of the dual fuel blends. The performance analysis of ternary blends utilize a higher brake power, torque, volumetric efficiency and exhaust gas temperature than those of the iso-butanol–gasoline blends by 0.8%, 1.2%, 0.4% and 0.6%. On the other hand, the ternary blends provide little drop in engine performance compared to neat gasoline; however, by increasing the blend rate value (>10 vol%), the engine performance would exceed those of the neat gasoline fuel.

1. Introduction

The limited fossil fuel reserves and severe its environmental pollution together with its non-renewable nature have led to a world-wide search for renewable and alternative fuels in internal combustion engines. Different countries have shown recently a vivid interest for the use of bio-fuels such as bio-ethanol and most recently bio-butanol in their fleet. Bio-ethanol is a biomass-based renewable fuel, which can be produced by alcoholic fermentation of agricultural residues (Hansen et al., 2009; Eseji et al., 2007; Bhutto et al., 2015; Tehrani et al., 2015; Karlsson et al., 2014; Neupane et al., 2013; Pereira and Ortega, 2010). Because of its high octane number bio-ethanol is a good spark-ignition engine fuel.

Bio-ethanol was first suggested as an automotive fuel in USA in the 1930s, but was widely used only after 1970 (Agarwal, 2007). Bio-ethanol is currently the most familiar alcohol fuel used in the transport sector in a world-wide (Nichols, 2003; Black, 1991; Yu and Tao, 2009; Khatiwada and Silveira, 2011; Ometto and Roma, 2010; Beer and Grant, 2007; Nguyen and Gheewala, 2008). Bio-ethanol is being used either as pure or as a gasoline additive as a spark ignition engine fuel. In the USA, for example, 10% bio-ethanol–gasoline blend is offered at thousands of service stations as automobile fuel (Alasfour, 1998a). This is because up to 10 vol% bio-ethanol blend in gasoline can be used in vehicles designed to operate on gasoline fuel without any modifications. The use of bio-ethanol blends showed a significant improvement in brake torque, power, volumetric efficiency, and emissions when compared to the gasoline fuel (Elfasakhany, 2014a; Park et al., 2010; Najafi et al., 2009; Koç et al., 2009; Yucesu et al., 2006). In addition, the CO and HC (hydrocarbons) decrease with increasing amount of bio-ethanol in fuel blends (Wua et al., 2004; Al-Hasan, 2003). However, bio-ethanol's high latent heat causes problem for cold engine starting condition due to its poor evaporation (Kabasin et al., 2009; Jin et al., 2011). In hot climates, on the other hand, bio-ethanol suffers from adverse effects, which is a vapor lock. It suffers also from incompatibility with some engine material and system, in case of high its content in gasoline. Its fully miscible in water is another disadvantage. Compared with drawbacks of bio-ethanol, iso-butanol has many advantages. Iso-butanol's low vapor pressure enhance cold engine starting condition; it has the ability to be blended with gasoline in any concentrations without (or with a little) needs for system modifications (Irimescu, 2011); it causes

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less corrosive and better fuel economy due to its higher energy density (Gu et al., 2010; He et al., 2003; Chen et al., 2010; Liaquat et al., 2010; Srinivasan and Saravanan, 2010; Balat et al., 2008); it has lower solubility in water; also its higher boiling point (117.7 °C) and flash point (29 °C) make iso-butanol safer to use than bio-ethanol (Abdehagh et al., 2014). A comparison between bio-ethanol and iso-butanol on the basis of the properties and behaviors with material was reported by Szukzyk, (2010).

The use of iso-butanol as fuel blends has been investigated in SI (spark-ignition) engines revealing reductions in power, exhaust temperature and thermal efficiency and little boost in emissions compared to pure gasoline, which is adverse effect of bio-ethanol–gasoline blends. Alasfour, (1997, 1998a, 1998b, 1999) and others, e.g., (Bata et al., 1989; Kelkar et al., 1988; Irimescu, 2012), showed that fuel conversion efficiency decreased when the engine was fueled with iso-butanol–gasoline blends. He et al., (2003) in another study investigated the comparative of using iso-butanol as fuel blends with gasoline for SI engines instead of bio-ethanol. The study applied mixtures containing 10, 30 and 50% iso-butanol blended with gasoline. Engine performance was dropped within variation of 5% up to 50% and a drop in fuel conversion efficiency by up to12% for the three types of fuel blends compared to gasoline. Elfasakhany, (2015a) investigated pollutant emissions (CO, CO_2 and HC) and engine performance, including output torque, brake power, volumetric efficiency, in-cylinder pressure and exhaust gas temperature of gasoline engine using neat gasoline and iso-butanol–gasoline blends by up to 10 vol% iso-butanol. The engine, which was operated without modification for all test fuels, was operated at speed range of 2600–3400 r/min. Results affirm that neat gasoline provides lower CO and HC emissions than those of the blended fuels for speeds higher than or equal to 2900 r/min; however, for speeds lower than 2900 r/min, it was shown an contradictory results. The performance results of blended fuels showed also lower values compared to pure gasoline. Rice et al., (1991) studied iso-butanol–gasoline blends of 20% iso-butanol in a spark-ignition engine. They come up with lower HC emission for fuel blends but as the concentration of iso-butanol increases, HC increases speedily.

The present work was motivated by the advantages and disadvantages of bio-ethanol and iso-butanol. As discussed above, it is found many advantages for bio-ethanol but due to some drawbacks, researchers moved forward to another generation, which is iso-butanol. But the new generation has also some drawbacks. Accordingly, this research is trying to invest the advantages of iso-butanol to recover the drawbacks of bio-ethanol since most of bio-ethanol drawbacks are advantages for iso-butanol and vice versa, as discussed above. In particular, problems arise when using bio-ethanol–gasoline blends fuel is reduced by adding iso-butanol to such blends and also the same strategy for iso-butanol–gasoline blends, e.g., by adding bio-ethanol to it. This strategy is trusted since iso-butanol has been used as a co-solvent to improve the phase stability of bio-ethanol–gasoline blends (Alasfour, 1998a). However, satisfactory engine performance and pollutants of the ternary (or three-component) blended fuels need to be proved, which is the aim of the present work.

Ternary blended fuels are scanned in literature and found seldom. Turner et al., (2013) studied the opportunity to use ternary blends of gasoline, bio-ethanol and methanol as a fuel in SI engines. But the study did not provide how the engine performance, such as power, torque, volumetric efficiency etc., will be with this new fuel blends. Rodríguez-Antón et al., (2015) studied ethanol–ETBE (ethyl tert-butyl ether)–gasoline blends and showed that such blends can change engine performance and environmental directives but could also prevent compliance with some fuel regulations. Nazzal, (2011) investigated performance of spark ignition engine using ternary fuel blends (6% bio-ethanol–6% methanol–88% gasoline) and dual fuel blends (12% bio-ethanol–88% gasoline and 12% methanol–88% gasoline). The performance was evaluated at a variety of engine operating conditions and results showed that when ternary or both dual fuel blends are used, the brake power and brake thermal efficiency increase slightly compared with gasoline fuel. It is found also that BSFC (brake specific fuel consumption) enhanced for all fuel blends compared with gasoline. Sileghem et al., (2014) investigated ternary bio-ethanol–methanol–gasoline blends and showed an improvement in engine performance and emissions compared with gasoline. Siwale et al., (2014) studied and compared the effects of ternary blends (53% methanol, 17% n-butanol and 30% gasoline) with dual blends (20% methanol–80% gasoline and 70% methanol–30% gasoline) against performance, combustion and emission characteristics of a naturally-aspirated spark ignition engine. The study came up with a recommendation of using ternary blends than the dual blends or neat gasoline. Elfasakhany, (2015b) investigated performance and exhaust emissions of spark-ignition engine fueled with bio-ethanol–methanol–gasoline blends using low rates of blends (3–10 vol % bio-ethanol and methanol). The study compared ternary fuel blends with dual ones, e.g., bio-ethanol–gasoline blends and methanol–gasoline blends, at similar rates and also with the pure gasoline. Results concluded that all fuel blends (ternary and dual) provide better performance and emissions than those of pure gasoline. Methanol–gasoline blends presented the lowest emissions of CO and HC among all test fuels. The emissions of ternary blends are lower than those of neat gasoline and bio-ethanol–gasoline blends. Ternary blends showed higher volumetric effeciency and torque than those of bio-ethanol–gasoline blends and higher brake power than that of methanol–gasoline blends. Elfasakhany, (2016a) in another study examined the n-butanol–iso-butanol–gasoline blends, which is the first of its kind in internal combustion engines, on gasoline engine performance and emissions; the ternary fuel blends were compared with results of dual fuel blends, e.g., iso-butanol–gasoline and n-butanol–gasoline blends, and pure gasoline. The results moved toward using ternary fuel blends than the dual ones or neat gasoline. Elfasakhany and Mahrous, (2016) in one more study examined performance and emissions of n-butanol–methanol–gasoline blends and compared results with single alcohol-gasoline blends and neat gasoline. They concluded that in case of using lower rate of alcohol in gasoline, single alcohol should be used. However, in case of high rate of alcohol in gasoline, dual alcohol is recommended. Balaji et al., (2010) studied engine performance (fuel consumption, volumetric efficiency, brake thermal efficiency, brake power and torque) and exhaust emissions (CO, HC and NOx) using bio-ethanol–iso-butanol–gasoline blends in single cylinder SI engine with varying engine torque and constant engine speed conditions. They applied ternary blends of 10% bio-ethanol–2.5% iso-butanol, 10% bio-ethanol–5% iso-butanol and 10% bio-ethanol–7.5% iso-butanol in gasoline. In addition, they used dual blends of 10, 20 and 30 vol% bio-ethanol in gasoline. The result showed that ternary and dual blends increase the brake power, volumetric and brake thermal efficiencies and fuel consumption compared to pure gasoline. The CO and HC emissions decrease, while the NOx emission increases for blends (ternary and dual) compared to pure gasoline.

In the current study ternary bio-ethanol–iso-butanol–gasoline blends are investigated and compared with neat gasoline and iso-butanol–gasoline blends to demonstrate the potential of the ternary blends as a fossil fuel alternative. The current study is different from the early one, e.g., (Balaji et al., 2010), which is thought the unique study used bio-ethanol–iso-butanol–gasoline blends, according to the best of author knowledge, in that the early study was performed at constant engine speed where there is a