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Experimental investigation of combustion, emissions and thermal balance of secondary butyl alcohol-gasoline blends in a spark ignition engine

I.M. Yusri [a,*], Rizalman Mamat [a,b], W.H. Azmi [a,b], G. Najafi [c], N.A.C. Sidik [d], Omar I. Awad [a]

[a] Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Malaysia
[b] Automotive Engineering Centre, Universiti Malaysia Pahang, 26600 Pekan, Malaysia
[c] Tarbiat Modares University, Tehran, Iran
[d] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81300 Johor, Malaysia

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ABSTRACT

An experimental investigation of butanol as an alternative fuel was conducted. A four-cylinder, four-stroke gasoline engine was used to investigate the engine combustion emissions and thermal balance characteristics using 2-butanol–gasoline blended fuels at 50% throttle wide open. In this experimental study, the gasoline engine was tested at 2-butanol–gasoline percentage volume ratios of 5:95 (GBu5), 10:90 (GBu10) and 15:85 (GBu15) of gasoline to butanol, respectively. Combustion analysis results showed that 2-butanol–gasoline blends have a lower in-cylinder pressure, rate of pressure rise and rate of heat release. However, as the 2-butanol addition increases in the blended fuels, increasing trends of in-cylinder pressure, rate of pressure rise and rate of heat release are observed, but it is still lower than G100 fuels. Moreover, even 5%, 10% and 15% additions of 2-butanol in the gasoline fuels improve the COV of IMEP by 3.7, 3.46 and 3.26, respectively, which indicates that the presence of 2-butanol stabilises the combustion process. Comparative analysis of the experimental results by exhaust emissions produced an average of 7.1%, 13.7%, and 19.8% lower NO_x for GBu5, GBu10 and GBu15, respectively, over the speed range of 1000–4000 RPM. Other emission contents indicate lower CO and HC but higher CO_2 from 2500 to 4000 RPM for the blended fuels with regard to G100. The thermal balance analysis mainly exhibits an improvement in effective power, cooling energy and exhaust energy by average differences of 3.3%, 0.8% and 2.3% for GBu15 compared with G100.

1. Introduction

Presently, every corner of this world is facing issues regarding the availability and environmental impact of fossil fuel. Given that fossil fuel is a non-renewable energy source, rapid depletion and overdependence on non-renewable energy must be addressed immediately [1–3]. In addition, the utilisation of these conventional fuels, especially from the transportation sectors, has led to adverse effects on environmental systems [4]. The primary concern is the emitted greenhouse gasses (GHG) of carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxides (CO) and unburned hydrocarbon (HC) [5,6]. In the viewpoint of this energy crisis, the combustion of fossil fuels is a significant contributor to the increase in the level of emissions, so automotive researchers are directed to search for clean alternative fuels such as alcohol, biodiesel and vegetable oil [7–9].

Utilisation of alternative energy is an inevitable choice for harmonious stability between humans and the environment and sustainable economic growth in human society. European Union (EU) members have targeted that by 2020, 20% and 10% of its energy supply and transportation fuels must be substituted by renewable energy resources, respectively [10]. Among all types of alternative fuels, alcohol is considered as the most suitable fuel substitution for spark ignition engines because it allows gasoline fuels to combust more completely owing to the presence of oxygen, which improves the engine combustion [11]. Three types of alcohol have recently attracted the attention of automotive researchers: methanol, ethanol and butanol [12–14]. For the past few years, the investigation of methanol and ethanol has received considerable critical attention with less attention paid to butanol as a sustainable alternative fuel.

* Corresponding author.
E-mail addresses: yusri890@yahoo.com, m.yusri890@gmail.com (I.M. Yusri), rizalman@ump.edu.my (R. Mamat).

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In the alcohol family, butanol comprises four chains of carbon with formula $C_4H_{10}O$. There are four types of butanol isomers: 1-butanol (i.e., *n*-butanol), 2-butanol, *tert*-butanol and isobutanol [15–17]. Each butanol has different physical and chemical properties based on different isomer structures. Butanol can be produced by the fermentation process from various renewable resources such as corn, wheat, sugarcane and potato [18,19]. Compared with methanol and ethanol, butanol has the most similar fuel properties to gasoline fuel such as heating value, stoichiometric air–fuel ratio, octane number and auto ignition temperature, thus making it more suitable to be blended with gasoline fuels [9,13,20]. In addition, butanol can be transported through existing fuel pipelines because it is insoluble in water [21]. Given all the advantages offered by butanol, it has been proposed as a next-generation biofuels as an alternative to conventional fuels [8,22].

The past decade has seen the rapid development in the field of alternative fuels, in which butanol is one of the interesting topic to be discussed. Feng et al. is one of many research groups who have conducted investigations using *n*-butanol in spark ignition engines [23]. They conducted research on *n*-butanol–gasoline blends of 30% (Bu30) and 35% (Bu35) *n*-butanol on a single-cylinder four-stroke spark ignition engine. Following the mixture of *n*-butanol–gasoline blends, it was noted that the rate of heat release (ROHR) for pure gasoline fluctuated more than that of Bu30 and Bu35. Szwaja and Naber [24] investigated *n*-butanol–gasoline blends in a single-cylinder four-stroke spark ignition engine. In their study, they considered several parameters such as the effect of spark timing with 4, 8, 10, 14 and 18 °CA (degree of crank angle) bTDC (before top dead centre), butanol blend ratio by volume ratios 0, 20, 40, 60, 80 and 100% of *n*-butanol and compression ratio impact. It was reported that the advanced combustion duration of the *n*-butanol–gasoline mixture was shortened with advanced °CA. The findings of this experimental study also suggest that an increase in *n*-butanol volume ratio produced higher in-cylinder combustion pressure compared with the pure gasoline fuels. Meanwhile, increasing the compression ratio from 8:1 to 10:1 will result in shortening the ignition delay. Butanol–gasoline blends were also reported to have better combustion stability, which is evaluated based on the coefficient of variation (COV) of indicated mean effective pressure (IMEP). These results are consistent with Dernotte et al. [25], who claimed that the addition of 20%, 40%, 60% and 80% butanol will improve the combustion stability by reducing the COV of IMEP. Irimescu et al. [26] compared the combustion characteristics of Bu100 (100% butanol) and neat gasoline (G100) on a single-cylinder four-stroke direct injection SI engine. The most important clinically relevant finding in his investigation is that Bu100 produced higher peak pressure by 10%, which also resulted in the improvement of IMEP compared with G100 fuels. They suggested that this phenomenon occurred owing to the fast combustion development during the premixed conditions. However, there are certain drawbacks associated with the use of *n*-butanol–gasoline mixture in a direct injection SI engine owing to the cold start, lack of fuel atomization and dilution of the oil [27]. Chen et al. [28] evaluated the impact of *n*-butanol addition by percentage of (15%, 30% and 50%) in gasoline fuels on a turbocharged gasoline direct injection (GDI) type. The engine was operated at 2000 RPM with three different engine brake mean effective pressures (BMEP) equal to 0.2, 1.0 and 1.8 MPa. According to them, increased butanol proportions in gasoline fuels were found to raise the peak in-cylinder pressure and rate of heat release. Furthermore, the butanol addition influenced the ignition delay and the combustion duration, whereas in this study, it was observed that in each different engine, BMEP reduces the ignition delay and combustion duration with increasing *n*-butanol fraction in butanol–gasoline blends.

In terms of emission characteristics, numerous studies have been attempted in which *n*-butanol–gasoline mixture was identified as a major contributing factor to the reduction of engine emissions. Dernotte et al. [25] studied the emission characteristics of several *n*-butanol–gasoline blends (0%, 20%, 40%, 60% and 80% *n*-butanol volume percentages) using a spark ignition engine and discover that Bu60 and Bu80 produce higher HC by 47%; meanwhile, lower CO emissions were reported for Bu20 and Bu40 compared with gasoline fuels. However, NO_x emission levels are the same for all blends except Bu80. Elfasakhany [29] evaluated the effect of low-ratio *n*-butanol–gasoline blends (3%, 7% and 10% *n*-butanol volume) in a single-cylinder four-stroke naturally aspirated spark ignition engine. Based on his results, even low fractions of *n*-butanol percentages can significantly reduce the CO, CO_2 and HC compared with gasoline. However, he added that an increase in engine speed will simultaneously produce higher engine emissions. Singh et al. [30] measured emissions for HC, CO and NO_x for *n*-butanol–gasoline blends with 5, 10, 20, 50 and 75% *n*-butanol in a four-cylinder four-stroke spark ignition engine. Brake-specific emissions for HC, CO and NO_x, especially for Bu50 and Bu70, were lower compared with gasoline, particularly at higher engine speeds and loads. Costagliola et al. [31] compared the emission behaviour of different alcohols between ethanol–gasoline blends (10, 20, 30 and 85% volume ethanol in gasoline) and *n*-butanol–gasoline blends with 10% *n*-butanol. Based on the reported study, the highest reduction of emissions was produced by E85% with 20% and 15% reduction for HC and (CO and NO_x), respectively. Sayin and Balki [32] analysed the effect of different compression ratios (9:1, 10:1 and 11:1) for different isobutanol–gasoline blends (10%, 30% and 50%) in a single-cylinder four-stroke air-cooled gasoline engine. Throughout the experiment, it was reported that a higher compression ratio (11:1) capable of maintaining the emissions of HC and CO at a lower level, however, yielded higher CO_2 emissions. The maximum decrease was attained for ISB50 (isobutanol 50%) at a compression ratio of 11:1 with decreased CO and HC by 27.6% and 28.1%, respectively, and increased CO_2 by 30.6% compared with gasoline. Gu et al. [33] investigated the influence of exhaust gas recirculation of the *n*-butanol–gasoline blends with 10, 30, 40 and 100% *n*-butanol in a three-cylinder, port fuel injection, spark ignition engine. The findings suggest that EGR can generally reduce NO_x emissions yet increase HC and CO emissions fuelled with all blended *n*-butanol.

The existing literature on *n*-butanol mixtures is not limited to spark ignition engines. The investigations in the field of combustion and emission characteristics was also adapted to different types of engines, including diesel and homogenous charge compression ignition (HCCI) engines. One of the major reasons is that the *n*-butanol chemical structure contains oxygen and has good dissolubility with diesel without any cosolvents [34]. Chen et al. [35] tested a multi-cylinder diesel engine fuelled with dimethylfuran–diesel, *n*-butanol–diesel, and gasoline–diesel fuel blends in proportions of 30% in a mixture of different diesel fuel blend types. Based on their studies *n*-butanol–diesel fuel blends shorten the combustion duration ranging between 10% and 90% of mass fraction burn point. Zhang [36] studied the effects on emission characteristics in a low-temperature compression ignition engine combustion system with 20% and 40% *n*-butanol addition by volume in diesel fuels. Their results showed that soot emissions were significantly reduced with 40% *n*-butanol blends in the diesel fuels, with nearly all the soot bump removed. In another study, Yao et al. [37] examined the effects of diesel blends with different contents of *n*-butanol (0%, 5% 10% and 15% by volume) on a heavy-duty diesel engine. The results revealed that *n*-butanol is capable of reducing CO and soot without major consequences on the brake-specific fuel consumption. Similar studies concerning the application of *n*-butanol–diesel fuel blends in diesel engines can be found in