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Application of response surface methodology in optimization of performance and exhaust emissions of secondary butyl alcohol-gasoline blends in SI engine

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ABSTRACT

Producing an optimal balance between engine performance and exhaust emissions has always been one of the main challenges in automotive technology. This paper examines the use of RSM (response surface methodology) to optimize the engine performance, and exhaust emissions of a spark-ignition (SI) engine which operates with 2-butanol–gasoline blends of 5%, 10%, and 15% called GBu5, GBu10, and GBu15. In the experiments, the engine ran at various speeds for each test fuel and 13 different conditions were constructed. The optimization of the independent variables was performed by means of a statistical tool known as DoE (design of experiments). The desirability approach by RSM was employed with the aim of minimizing emissions and maximizing of performance parameters. Based on the RSM model, performance characteristics revealed that increments of 2-butanol in the blended fuels lead to increasing trends of brake power, brake mean effective pressure and brake thermal efficiency. Nonetheless, marginal higher brake specific fuel consumption was observed. Furthermore, the RSM model suggests that the presence of 2-butanol exhibits a decreasing trend of nitrogen oxides, carbon monoxides, and unburnt hydrocarbon, however, a higher trend was observed for carbon dioxides exhaust emissions. It was established from the study that the GBu15 blend with an engine speed of 3205 rpm was found to be optimal to provide the best performance and emissions characteristics as compared to the other tested blends.

1. Introduction

Energy shortage of fossilized fuel, as well as its adverse environmental impact are given due attention globally. Owing to the unsustainable nature of fossilized fuel, its rapid depletion and overdependence must be addressed immediately [1–3]. Moreover, the utilization of these conventional energy resources, mainly in transportation areas, has led to major environmental side effects [4,5]. This trend of energy consumption is envisaged to continue in the near future [6]. The emission of greenhouse gasses (GHG) namely carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxides (CO), and unburned hydrocarbon (HC) are of interest as it affects the earth's climate change [7]. As the utilization of fossilized fuel is deemed to be the primary contributor of the aforementioned GHG, the research community as a whole are continuously investigating on the search for cleaner alternative fuels such as alcohol, bio-diesel, and vegetable-oil [8–10]. These alternative energies are fundamentally environmental-friendly; however, they are still required to be evaluated in terms of engine performance and emission characteristics [11].

Transportation is one of the leading causes of environmental problems in almost every part of the world [12,13]. Furthermore, it is expected that the number of vehicles, especially cars, and light trucks, are to increase to up to 1.3 billion by 2030 and to over 2 billion vehicles by 2050 [14]. In order to facilitate the effort for a better environmental condition throughout the world, the European Union (EU) have pledged that by the year 2020, 20% and 10%, of its transportation fuels and energy supply, respectively must be replaced by renewable resources [15]. For spark-ignition (SI) engines, alcohol is considered one of the feasible solutions for fuel substitution [16]. This is because the presence of excess oxygen in alcohol allows gasoline fuels to produce better engine combustion

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Nomenclature

Abbreviations

ANOVA	analysis of variance
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
DoE	design of experiment
ECI-multi	electronically controlled multi-point fuel injection
EU	European union
G100	gasoline
GBu5	5% 2-butanol + 95 gasoline
GBu10	10% 2-butanol + 90% gasoline
GBu15	15% 2-butanol + 85% gasoline
GHG	greenhouse gasses
HC	unburned hydrocarbon
LHV	low heating value
NO_x	nitrogen oxides
ppm	parts per million
RSM	response surface method
RSE	relative standard error
rpm	revolutions per minute
SI	spark ignition
SOHC	single overhead camshaft
WTO	wide throttle open
n-butanol	primary butyl alcohol
2-butanol	secondary butyl alcohol

Symbols

A	engine speed
Adj R^2	adjusted R^2
AP	adequate precision
B	fuel blend
F – value	value of F-statistic
R^2	coefficient of determination
p-value	probability value
S_{Error}	standard error
$\bar{X}$	mean of data collections
σ	standard deviation
n	number of data collections

[17]. There are three types of alcohol that have recently attracted the attention of automotive researchers for their potential future use, viz. methanol, ethanol, and butanol [18–20]. A considerable amount of literature investigated on the use of methanol and ethanol as sustainable alternative fuels, however, limited attention is paid to the use of butanol. Although ethanol is presently the dominant biofuel [21,22], butanol is seen as a viable fuel supplement to gasoline fuels, and it has been proposed as one of the next-generation of biofuels [23].

Butanol, as compared to ethanol and methanol, has a higher heating value and lower volatility, stoichiometric air–fuel ratio, octane number, and auto ignition temperature, thus making it more readily extendable to be blended with gasoline fuels [24,25]. Moreover, according to Fortman et al. [26], butanol has been proposed as a viable alternative not only for gasoline and diesel fuel but also for ethanol as well. This is primarily due to butanol's higher energy content and lower solubility in water that allows it to be easily transported through existing fuel pipelines. The mixture of butanol-gasoline blends also accommodates high compression ratios without inducing knocking [27]. Nonetheless, the major drawback that prevents butanol's use in internal combustion engines is its much higher production cost compared to gasoline, which has been the subject of other research studies [28]. However, the recent enhancement of genetically modified bacteria will increase butanol yield at a lower cost margin and make it suitable on a life-cycle basis as an imminent fuel supplement [29].

The successful use of butanol utilization under SI engine performance and emissions characteristics has been demonstrated previously by studies that used them as one of the blending components. One of the recent experimental studies by Elfasakhany [30] investigated the effects of adding dual butanol isomers in an unleaded gasoline fuel towards its performance and emissions characteristics of a single-cylinder, four-stroke, port fuel injection SI engine. The fuels had been prepared according to these percentages of volume: 3% (1.5% volume of iso-butanol and 1.5% volume of *n*-butanol), 7% (3.5% volume of iso-butanol and 3.5% volume of *n*-butanol), and 10% (5% volume of iso-butanol and 5% volume of *n*-butanol) of butanol in gasoline blends. Following the mixture of dual butanol isomers and gasoline blends, a slight decrease in the torque and brake power of about 3.6%, 4%, and 2.1%, and of 5.9%, 7.2% and 4.6%, respectively were noted, for mixtures of 3%, 7%, and 10% blended fuels respectively, compared to the unleaded gasoline. As for exhaust emissions, Elfasakhany discovered that all emissions decreased by 2.9%, 4.3%, and 5.7% (CO), 8.2%, 12%, and 15% (HC), and 42%, 41%, and 39% (CO_2) for 3%, 7%, and 10% blended fuels in comparison to unleaded gasoline. The author opined that the better engine performance offered by the mixture of *n*-butanol and iso-butanol is presumably due to the different laminar burning velocities of *n*-butanol and iso-butanol, that in effect shortens the combustion duration in the engine.

In another major study done by Feng et al. [31] 30% and 35% *n*-butanol–gasoline blends were used in a single-cylinder, four-stroke, high-speed motorcycle spark ignition engine at different speeds and full load condition. A slight decrease in brake power and brake torque was observed upon the utilization of the aforementioned blend. Nonetheless, it is worth to note that as the ignition timing is changed to a more advanced degree of crank angle, higher brake power and torque were achieved by both blended fuels as compared to neat gasoline. Conversely, the drawback reported by altering the crank angle is the higher production of NO_x and CO_2. According to Chen et al. [32], researchers have not treated butanol–gasoline blend in a gasoline direct injection engine in much detail. In their study, 15%, 30%, and 50% *n*-butanol–gasoline blend fuels were tested in a gasoline direct injection engine at a single engine speed kept constant at 2000 rpm and three different engine brake mean effective pressures (BMEP), i.e. 0.2 MPa, 1.0 MPa, and 1.8 MPa. It was reported that the brake specific fuel consumption increases with the increase in butanol fraction. However, the brake thermal efficiency (BTE) improves especially for the 50% fuel blends. Further results revealed that increasing the *n*-butanol fraction reduces the exhaust temperature and NO_x emissions but increases the HC and CO emissions. Wallner et al.'s [33] study of using an *n*-butanol–gasoline blend in a gasoline direct injection engine found that there were few