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Experimental studies on the effect of injection timing in a SI engine using dual injection of n-butanol and gasoline in the intake port

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HIGHLIGHTS

- System of varying blend ratio of alcohol and gasoline was developed.
- n-Butanol improves the torque and efficiency at higher throttle position.
- Use of n-butanol blend (50% by mass) or neat gasoline is good at lower throttle than neat n-butanol.
- Completing fuel injection before the inlet valve opens reduced HC emission.
- Injection phasing or sequence influences the HC and CO emissions little.

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ABSTRACT

Alcohols can be used in spark ignition (SI) engines along with gasoline in the blended form. However, phase separation which occurs in the presence of moisture restricts the amount of alcohol that can be blended. On the other hand, for effective engine operation, the ratio of alcohol to gasoline has to be varied based on the engine operating condition. n-Butanol has properties close to gasoline and has not been widely investigated as an engine fuel. In this work, two injectors were mounted in the intake port of an automotive SI engine (bore = 62 mm, stroke = 66 mm, compression ratio = 9.4) to inject gasoline and n-butanol separately so that the fuels hit the back of the intake valve. The engine was fully instrumented for the measurement ofperformance, emissions and combustion parameters. Initially experiments were conducted with simultaneous injection of n-butanol and gasoline (1:1 mass ratio = But 50S) using the two injectors with different injection timings at 25% and 60% throttle positions at 3000 rpm. Subsequently different injection timings for the two fuels were tried to study the influence of sequencing. The results were compared with gasoline and n-butanol (But100) using a single injector. Around 26% reduction in hydrocarbon (HC) emission with simultaneous injection of gasoline and n-butanol (But50S) at 25% and 60% throttle positions was observed with an injection timing of 64° CA before in let valve opening as compared to open valve injection. B100 was superior at high throttle positions and gasoline or B50S was suitable at 25% throttle as regards performance and emissions. At 60% throttle, injecting n-butanol just before the start of injection of gasoline is beneficial for reducing HC andcarbon monoxide (CO) emissions. In the case of lean operation (equivalence ratio of 0.82) there is no significant influence of injection phasing except for a small improvement in thermal efficiency. On the whole this method of operating the engine can lead to good engine performance over wide operating conditions since the ratio of the fuels can be varied.

1. Introduction

Several alternative fuels like ethanol, butanol, methanol, biodiesel, natural gas, liquefied petroleum gas and hydrogen are being investigated for their use in internal combustion engines. Bio-fuels like bio-alcohol have the potential to control net global CO_2 emissions and also to reduce consumption of fossil fuels. Alcohols can be used as fuels for spark ignition (SI) engines due to their good antiknock quality, high flame velocity and because of the presence of oxygen in their molecule that helps combustion. Amongst alcohols, n-butanol is an emerging renewable fuel which can be produced from biological sources. A comparison between the properties of gasoline, ethanol and 1-butanol which is also known as n-butanol is shown in Table 1. Butanol's calorific value and stoichiometric air fuel ratio are close to those of gasoline. Its latent heat of evaporation is higher than gasoline. It is also less corrosive than other alcohols [1–3]. The wide flammability limits and high

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Nomenclature

BSFC	brake specific fuel consumption (g/kW h)
BTE	brake thermal efficiency (%)
But100	n-butanol
But50S	n-butanol and gasoline by 1:1 mass ratio simultaneously
CA	crank angle (°)
CO	carbon monoxide (% vol)
CO_2	carbon dioxide (% vol)
COV	co-efficient of variance (%)
FPGA	Field Programmable Gate Array
HC	hydrocarbons (ppmv)
HRR	heat release rate (J/° CA)
IMEP	indicated mean effective pressure (bar)
IVO	inlet valve opens
MBD	mass burn duration (° CA)
MBT	minimum advance for best torque (° CA before TDC)
NDIR	non-dispersive infrared
NI	National Instruments
PP	peak pressure (bar)
NO_x	oxides of nitrogen (ppmv)
SI	spark ignition
TDC	top dead centre
UEC	universal engine controller
ϕ	equivalence ratio (actual fuel air ratio by stoichiometric fuel air ratio)

flame speed of n-butanol will allow the engine to operate with lean mixtures, high thermal efficiency and low cycle by cycle variations [3–6]. Only limited studies have been conducted on n-butanol in SI engines. Hence, in this work the performance of n-butanol in different proportions along with gasoline using a dual injection system was evaluated in a SI engine.

2. Background and objective

In experiments conducted on n-butanol in SI engines, blends up to But40 (40% n-butanol and 60% gasoline by volume) performed similar to gasoline. However, Hydrocarbon (HC) and carbon monoxide (CO) emissions were higher for blends like But60 and But80. Emission levels of Nitrogen oxides (NO_x) were lower due to the high latent heat of evaporation of n-butanol [6]. Lower combustion duration was also recorded with the blends as compared to operation on neat gasoline [3,7]. No differences in HC, CO and NO_x emissions were observed between But10 and gasoline [1]. Though lower CO levels were observed with blends of n-butanol as compared to gasoline, HC emission levels were higher at low loads [7]. Tests with ethanol gasoline blends showed that at 20% throttle and low speeds (3000 rpm) E05 (5% Ethanol and 95% gasoline by volume) gave the highest torque and at high speeds E30 was the best. At 40% and 60% throttles, E20 and E30 were observed to be the best. At high throttle conditions no clear trend was observed [8].

Alcohol gasoline blends can separate in the presence of water. However, the stability of blends of n-butanol and gasoline is good even in the presence of moisture. This is because of the low solubility of n-butanol in water, unlike ethanol which is fully miscible with water. Earlier studies have reported that n-butanol can be used as a co-solvent to avoid separation of the phases when ethanol–gasoline and methanol–gasoline blends are prepared [1,9–12]. M20 (Methanol 20% by volume in gasoline), E20 and But20 reduced CO emissions even at fuel rich conditions as compared to gasoline. HC emissions were observed to be higher than with neat gasoline when alcohol gasoline blends were used instead [9]. Butanol–gasoline blends (But35) improved the torque at low and medium speeds in a carbureted engine; However, the values of torque at high speeds were similar to that with gasoline [13]. It has also been reported that operating the engine with 100% iso-butanol at part throttle, reduced the brake thermal efficiency by 12%. The reason for this drop in efficiency is poor vaporization of iso-butanol due to its high latent heat [14]. Emission characteristics have been reported to be different with different isomers of butanol; however no major change in performance has been reported with different isomers of butanol [15]. The amount of alcohol in the blend has to be varied based on operating conditions to ensure good performance and low emissions [6,8,11,12,14]. In addition, the high latent heat of evaporation of alcohols leads to problems during cold starting. Cold startability can be improved by heating the fuel, heating the air and by starting the engine using only gasoline [1,2,11,12]. These are however not possible with pre-blended fuels. In an attempt to vary the alcohol to gasoline ratio on line blending methods have been tried [12].

Simultaneous injection of alcohol and gasoline into the intake manifold through separate injectors will also avoid the problem of phase separation and will also allow the use of varying

Table 1
Properties of gasoline, ethanol and n-butanol [1,2,4].

Property	Gasoline	Ethanol	n-butanol
Chemical formula	C_4–C_{12}	C_2H_5OH	C_4H_9OH
Composition (C, H, O) (mass%)	86, 14, 0	52, 13, 35	65, 13.5, 21.5
Lower heating value (MJ/kg)	42.7	26.8	33.1
Density (kg/m^3)	715–765	790	810
Octane number ((R + M)/2)	90	100	87
Boiling temperature (°C)	25–215	78	118
Latent heat of vaporization (25 °C) (kJ/kg)	380–500	904	716
Self-ignition temperature (°C)	≈300	420	343
Stoichiometric air/fuel ratio	14.7	9.0	11.2
Laminar flame speed @1 bar, 393 K, Ø = 1.1 (cm/s)	≈52	≈63	≈57
Mixture calorific value (MJ/m^3)	3.75	3.85	3.82
Ignition limits in air (vol%)			
Lower limit	0.6	3.5	1.4
Upper limit	8	15	11.2
Solubility in water at 20 °C (ml/100 ml H_2O)	<0.1	Fully miscible	7.7