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Research Paper

Numerical analysis of a downsized spark-ignition engine fueled by butanol/gasoline blends at part-load operation

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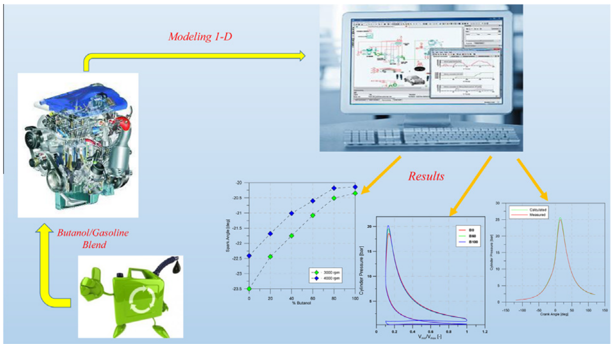
HIGHLIGHTS

- Bio-fuels will reduce the overall CO_2 emission.
- The properties of butanol/gasoline–air mixtures have been determined.
- A 1-D model of a SI engine has been calibrated and validated.
- The butanol content reduces the combustion duration.
- The optimal ignition timing slightly changes.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, the performance of a turbocharged SI engine, firing with butanol/gasoline blends, has been investigated by means of numerical simulations of the engine behavior. When engine fueling is switched from gasoline to alcohol/gasoline mixture, engine control parameters must be adapted. The main necessary modifications in the Electronic Control Unit have been highlighted in the paper.

Numerical analyses have been carried out at partial load operation and at two different engine speeds (3000 and 4000 rpm). Several n-butanol/gasoline mixtures, differing for the alcohol contents, have been analyzed.

Such engine performances as torque and indicated efficiency have been evaluated. Both these characteristics decrease with the alcohol contents within the mixtures. On the contrary, when the engine is fueled by neat n-butanol, torque and efficiency reach values about 2% higher than those obtained with neat gasoline.

Furthermore, the optimal spark timing, for alcohol/gasoline mixture operation, must be retarded (up to 13%) in comparison with the correspondent values of the gasoline operation.

In general, engine performance and operation undergo little variations when fuel supplying is switched from gasoline to alcohol/gasoline blends.

1. Introduction

Nowadays, the interest in the use of bio-alcohol, as an alternative fuel for spark-ignition engines, has grown according to energy crises and climatic problems.

Bio-alcohols, including ethanol, butanol, methanol etc., can be derived from several kinds of crops by means of a fermentation process (first generation biofuels); alternatively, they can be made from cellulose which is available from non-food crops (second generation biofuels).

In the last years, several technologies able to convert cellulose to butanol are in the R&D phase [1]. As a consequence, the interest

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about the behavior of SI engines firing with butanol or gasoline/butanol blends is grown.

Butanol refers to a primary alcohol with a four carbon structure (C_4H_9OH). It exists in four isometric forms: n-butanol, iso-butanol, sec-butanol and terz-butanol. The laminar combustion characteristics of butanol-isomers/air mixtures have been widely studied in [2–5]. In Ref. [5] experimental data relative to laminar burning velocity of n-butanol and iso-octane blends are also reported.

In comparison with ethanol, a few studies have been conducted on the behavior of SI engines fueled by butanol. Most of them focus on the pollutant emissions of SI engines firing with gasoline/butanol blends [6–8]. Generally, small differences have been found in comparison with engines burning pure gasoline.

The performance of a single cylinder engine fueled by 30% n-butanol/gasoline blend has been experimentally investigated in Refs. [9,10]. Results show that, when butanol is added to gasoline, the brake specific fuel consumption increases, while both the engine torque and the engine thermal efficiency decrease. When the engine runs stoichiometric, the efficiency reduction is about 4.5%.

Blends of n-butanol and gasoline with ratios ranging from 0% up to 100% have been studied in Ref. [11] by using a single cylinder Cooperative Fuels Research (CFR) SI engine. Tests were performed under stoichiometric air-to-fuel ratios at a given engine torque. Results show that the combustion durations for pure n-butanol and butanol/gasoline blends are comparable to those obtained with gasoline fueling. The 50% mass fraction burned slightly shifts toward top dead center when n-butanol is added to gasoline. Therefore, to achieve the maximum thermal efficiency, the spark advance should be delayed compared to the optimal one used for pure gasoline. Thermal efficiency trends are reported just to compare pure gasoline to pure n-butanol. Results show that the efficiency of an engine firing with pure butanol is higher than that obtained with pure gasoline firing.

In Ref. [12], tests on 0%, 5%, 10%, 20%, 50% and 75% butanol/gasoline blends have been carried out for evaluating the performance of a medium-duty transportation spark ignition (SI) engine. Tests have been done varying the engine load at several engine speeds. About the thermal efficiency, the results do not always delineate univocal trends. In general, the overall efficiency of butanol/gasoline blends is lower in comparison to gasoline for all speeds, particularly for lower engine speeds. However, they pointed out that at medium engine speed (3500 and 4500 rpm) some blends (20% and 50% of butanol in gasoline) allowed thermal efficiencies slightly higher than or close to those of gasoline fueling.

Summarizing the literature review, when a SI engine operates at part load, it seems that the use of gasoline/butanol blends involves thermal efficiencies lower than those obtained with pure gasoline. Conversely, pure butanol allows achieving efficiency higher that that obtained with pure gasoline. Furthermore, the spark timing must be adjusted in order to achieve the highest engine efficiency.

At the end, in the authors' opinion, adding butanol to gasoline do not significantly modify the engine performance. Since butanol can be produced from biomasses, the last one is an interesting result. Thus, it is well known that producing fuels from biomasses can balance the net amount of CO_2 emissions in the atmosphere.

The aim of this paper is to investigate about both the efficiency and the optimal spark advance of a SI engine fueled by several kinds of butanol/gasoline blends. Investigations have been carried out by means of a numerical model able to reproduce the turbulent flame development of a premixed charge.

Table 1 shows the properties of the analyzed blends.

It is worth noting that increasing the butanol percentage the energy content per mass unit decreases. Therefore, to release the same heat, it is necessary to increase the burning mass. The heat released for volume unit of stoichiometric air/fuel mixtures decreases with increasing butanol concentration.

2. Numerical approach

A 1-D model has been used in order to estimate the performance of an engine fueled by gasoline/butanol blends. This 1-D model reproduces the whole lay-out of a downsized spark-ignition engine and it has been widely described in Refs. [13,14]. The engine main features are summarized in Table 2.

The physical properties of the mixture have been calculated in the hypothesis of ideal gas, according to the data reported on the Burcat database [15].

The combustion process has been modeled by means of a quasi-dimensional predictive approach based on the work of Keck and Tabaczynski [16,17]. A spherical flame propagates from the spark-plug, while the combustion rate is controlled by means of a turbulent entrainment process.

The mass entrainment rate into the flame front is calculated as:

$$\frac{dM_e}{dt} = \rho_u A_f (u' + S_L) \tag{1}$$

where M_e is the mass of the unburned mixture, ρ_u is the unburned density, A_f is the surface area at the edge of the flame front, u' is the turbulent intensity and S_L is the laminar flame speed.

The burned mass rate is calculated as:

$$\frac{dM_b}{dt} = \frac{(M_e - M_b)}{\tau} \tag{2}$$

where M_b is the burned mass and τ is the time constant.

These equations state that the unburned mixture of fuel and air is entrained into the flame front through the flame area at a rate proportional to the sum of the turbulent and laminar flame speed. The burning rate is proportional to the amount of the unburned mixture behind the flame front, ($M_e - M_b$), divided by a time constant, (τ).

The time constant is calculated by dividing the Taylor microscale λ, by the laminar flame speed:

$$\tau = \frac{\lambda}{S_L} \tag{3}$$

where

Table 1
Comparison of fuel properties.

		B0	B20	B40	B60	B80	B100
Butanol mass percentage	(%)	0	20	40	60	80	100
Lower heating value	(MJ/kg)	43.4	41.34	39.28	37.22	35.16	33.1
Air to fuel ratio	(kg/kg)	14.6	13.9	13.2	12.5	11.8	11.1
Energy per volume unit of air/fuel mixture (p = 1.01 bar; T = 25 °C)	(MJ/m^3)	3.5	3.45	3.41	3.36	3.31	3.27
Stoichiometric laminar flame speed at p = 1.01 bar; T = 25 °C	(cm/s)	28.05	28.88	29.73	30.60	31.50	32.7
CO_2 mass over heat released	(kg/kJ)	7.28E−05	7.14E−5	7.01E−5	6.87E−5	6.74E−5	6.60E−05
Density (T = 20 °C)	(kg/dm^3)	0.750	0.762	0.774	0.786	0.789	0.810
Latent heat of vaporization	(kJ/kg)	350	393,880	437,760	481,640	525,520	569,400