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# Effect of coolant temperature on air–fuel mixture formation and combustion in an optical direct injection spark ignition engine fueled with gasoline and butanol

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ABSTRACT

Diversification of the energy mix and the drive for increasing security of supply have extended the use of alternative fuels in internal combustion engines. Butanol is a viable energy source for spark ignition (SI) power units featuring higher energy density and compatibility with existing systems. The present work investigated the use of n-butanol in an optically accessible wall guided direct injection SI engine, operated at low load, as well as wide open throttle. Engine speed and injection pressure were kept constant, while coolant temperature was alternated between two values, so as to simulate cold-start and fully warmed-up conditions. In-cylinder pressure and exhaust gas emission measurements were coupled with optical results obtained through UV–visible flame visualization and 2D chemiluminescence. This allowed a more detailed insight into the occurrence of diffusive flames near the piston surface and an analysis of flame front propagation, as well as its morphology. The correlation of thermodynamic data and flame imaging with band-pass filters for recording the spatial distribution of the OH radical, soot precursors and carbonaceous structures gave information on the evolution of chemical species during combustion. While at low load the alcohol performed slightly better compared to gasoline, at wide open throttle the opposite was recorded. The effect of coolant temperature was more evident for butanol. These observations were correlated to the presence of liquid fuel film on the piston crown, which resulted in slower flame propagation and higher related emissions for the alcohol.



## 1. Introduction

Internal combustion engines are the most important technology for energy conversion in power generation and transport; they are set to be a dominant presence in these sectors and extensive research efforts are therefore directed towards their improvement [1]. Spark ignition (SI) power units are more widespread in passenger car applications, with respect to their compression ignition counterparts. They feature lower fuel conversion efficiency, but can be more easily rendered fuel-flexible and have relatively lower environmental impact, especially when considering particulate emissions [2,3]. Direct injection (DI) is one solution for SI engines that can offer improvements of fuel economy [4] and also enable knock-free operation at high specific power output [5]. On the other hand, this mixture preparation technique results in an increase of particulate emissions [6], thus creating situations in which diesel-like 'trade-off' choices need to be made. Another issue of ever greater importance when considering the changing energy mix, is the use of alternative fuels [7]. Among these, butanol is a viable choice that offers several advantages over the more widely used ethanol, such as higher energy density and increased compatibility with distribution systems [8]. It can be used as an additive in compression ignition engines [9–11] and in higher concentrations blended with gasoline [12–14] or even as pure butanol fueling in SI power units [15]. As gasoline replacement, butanol requires practically no engine modifications [16], but only changes in injection and ignition control strategies. One issue reported in several investigations is that this long chain alcohol has relatively poor evaporative properties [17] that can offset the advantage of high laminar flame speed, especially at

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increased load [18,19]. Apart from its higher latent heat of evaporation, butanol also features relatively low saturation pressure at temperature levels usually encountered during the intake process [20]; this latter property can result in reduced rates of evaporation and can therefore influence combustion development.

As reported in the previous paragraphs, the use of butanol has been investigated, both as blends and as complete gasoline replacement. Most studies related to DI applications were focused on part load conditions, with only port fuel injection being relatively well covered; also, the effect of coolant temperature has been only partially investigated. Therefore, an experimental campaign was organized for studying two intake pressure settings specific for low and medium to high load, at coolant temperature values chosen to simulate a high thermal regime and operation during warm-up. Measurements were performed on an optically accessible, wall guided DISI engine. The present study combined in-cylinder pressure measurements with UV–visible emission detection in order to investigate the effect of coolant temperature on air–fuel mixture preparation and combustion. Specifically, macroscopic flame parameters determined through digital imaging were correlated with thermodynamic parameters. Moreover, two types of band-pass filters were used in order to provide information on the spatial distribution of the $OH^*$ radical and soot precursors. Exhaust gas measurements were also performed to follow the variation of CO, HC, $NO_x$ and opacity values when changing fuel type, load and coolant temperature settings.

## 2. Experimental

An experimental campaign was organized for covering 0.3 and 1.0 bar intake pressure settings, at 314 and 340 K coolant temperature. The last parameter was controlled using an external cooling–heating system and the choice of the two values was based on butanol's saturation pressure. All measurements were performed at 2000 rev/min on an optically accessible SI engine; Table 1 lists the main engine characteristics and further details can be found in [15].

Fig. 1 shows a schematic representation of the experimental setup, with the combustion chamber visible through the piston crown, via a Bowditch design [21]. The cylinder head was taken from a commercial power unit with similar bore-stroke geometry and coupled to the engine block. Ignition was performed by a commercial coil with a low resistance spark plug with 0.8 mm distance between the electrodes, which was centrally located. The fuel system provided wall guided DI at 100 bar, with the nozzles oriented so that the six sprays impinged mainly on the piston, for the chosen start of injection (SOI) setting of 300 CAD BTDC. Spark timing was fixed at 15 CAD BTDC for the wide open throttle (WOT) condition, and 35 CAD BTDC for the low load level. This spark advance was preferred for the 0.3 bar intake pressure case in order to provide an engine stability level close to that obtained with butanol at WOT and 314 K coolant temperature (i.e. the highest coefficient of variation among all studied cases). This ensured a direct comparison of the effect of increasing injected fuel quantity when load was higher.

Butanol was used as an alternative to gasoline, and the latter was considered as the reference energy source; their properties are listed in Table 2. Fuel flow was set in order to obtain close-to-stoichiometric operation for both load levels; a factor of 1.21 was applied for multiplying injection duration when using butanol compared to gasoline, so as to cover the combined effect of air–fuel ratio and fuel density. It should be noted that the higher thermal regime (i.e. 340 K coolant temperature) was considered as the reference case; while for gasoline the variations are minimum due to changes in the combustion chamber walls temperature, this effect was significant for the alcohol, as it will be evident further on. For easier identification of all the conditions that were investigated, engine control parameters were listed in Table 3.

In-cylinder pressure was measured with an accuracy of $\pm 1\%$ with a flush-mounted quartz transducer; a piezo-resistive sensor was used to monitor intake pressure and the related values were employed for referencing. Sets of 200 consecutive cycles were recorded and averaged for each case after reaching quasi-steady state, in order to reduce the effect of noise and cycle-to-cycle variations, as well as to evaluate engine stability [22]. Exhaust gas emissions were monitored through measurements of CO and HC concentrations by NDIR analyzers, while for $NO_x$, the chemical method was used; these measurements featured an accuracy of $\pm 3\%$.

### *2.1. Optical setup*

UV–visible digital imaging and chemiluminescence measurements were performed to visualize the flame front propagation. Specifically, an intensified CCD (ICCD) camera (array size of 1024 × 1024 pixels with a pixel size of 13 × 13 μm, 16-bit pixel digitization, 1 MHz sustained repetition rate and 6 kHz with MCP) was used; the full-chip configuration was employed. The set-up allowed a resolution of 90 μm per pixel. In addition to the broadband acquisition that exploits the high quantum efficiency of the ICCD in the 250–700 nm spectral range, two 50 × 50 mm band-pass filters (Asahi Spectra Inc.) were used to selectively record flame emissions at 310 nm for the $OH^*$ radical and 690 nm for soot precursors. The high transmission (65%) and small width (10 nm FWHM) allowed to select OH detection and without interference of

**Table 1**
Engine specifications.

| | |
|---|---|
| Displacement | 399 cc |
| Stroke | 81.3 mm |
| Bore | 79.0 mm |
| Connecting rod | 143 mm |
| Compression ratio | 10:1 |
| Number of valves | 4 |
| IVO | 3 CAD BTDC |
| IVC | 144 CAD BTDC |
| EVO | 153 CAD ATDC |
| EVC | 0 CAD ATDC |
| Ignition | centrally located spark plug |

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