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# Performance and economic analysis of a direct injection spark ignition engine fueled with wet ethanol

Thompson Diórdinis Metzka Lanzanova *, Macklini Dalla Nora, Hua Zhao

*Brunel University London, Centre for Advanced Powertrain and Fuels Research (CAPF), Kingston Lane, Uxbridge, Middlesex UB8 3PH, United Kingdom*

## HIGHLIGHTS

- Stable SI engine operation with 20% water-in-ethanol and $\lambda = 1.3$.
- Greater water-in-ethanol content reduced NOx emissions.
- Operational cost reduction of up to 31% was achieved.

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## ABSTRACT

The use of wet ethanol with higher water content than the conventionally used in internal combustion engines can reduce fuel production costs due to lower energy expense during the distillation phase. However, during its combustion the extra water content may result in the deterioration of fuel conversion efficiency and therefore a global energy evaluation should be considered. This research investigated the operation of a single cylinder direct injected spark ignition engine running with gasoline, anhydrous ethanol and several wet ethanol compositions (5–20% of water-in-ethanol volumetric content) under stoichiometric and lean air/fuel ratios. Two part load conditions of 3.1 bar and 6.1 bar indicated mean effective pressure were evaluated at 1500 RPM. The impacts of increased water-in-ethanol content and lean operation on combustion and emissions were discussed. Higher water content affected the heat release rate, which increased the combustion duration and initial flame development phase. Lower nitrogen oxides emissions could be achieved with higher water-content ethanol at the expense of higher unburned hydrocarbon emission. An analysis of wet ethanol energy production costs and engine operation conditions was carried out. The lean engine operation with 10% (v/v) water-in-ethanol fuel showed global energy savings around 31% compared to anhydrous ethanol at stoichiometric conditions.



## 1. Introduction

In the last decades the growing concern on carbon dioxide emissions has increased the demand on renewable biofuels in order to complement, or even substitute, fossil fuels for automotive applications. More recently with the adoption of the Paris Protocol [1] several nations have agreed to reduce global greenhouse gas emissions in order to hold the global average temperature below 2 °C above pre-industrial levels. In this scenario, bioethanol produced from fermented sugars from various agricultural crops has been explored worldwide as an alternative to gasoline in spark ignition (SI) internal combustion engines (ICE).

Ethanol production can be adapted according to the local crop availability, which does not only reduce oil dependency and increases energy security but also stimulates the local agricultural, industrial and commercial activities in emerging countries [2,3]. In a well-to-wheel analysis, when land usage for ethanol crop production is in accordance with some policies, the greenhouse gas (GHG) emission of ethanol is much lower than that of fossil fuels, as most of the GHG generated during its combustion and industrialization is absorbed during the crop cultivation [4–6]. Nevertheless, ethanol usage is still linked to its production price, which is directly related to the energy consumption during the whole biofuel production cycle.

The use of ethanol in SI engines has been explored both as an anti-knock additive to gasoline and as dedicated fuel. The conventional water volumetric content is around 5% when used as dedicated fuel. When mixed with gasoline, the water content is usually below 1% to avoid phase separation. Compared to gasoline,

* Corresponding author. Tel.: +44 7477640793; fax: +44 1895266698.
*E-mail addresses:* mepgtdl@brunel.ac.uk, lanzanova@gmail.com (T.D.M. Lanzanova).

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**Nomenclature**

| | |
|---|---|
| ICE | internal combustion engine |
| BDC | bottom dead centre |
| CAD | crank angle degree |
| CAI | controlled auto ignition |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $COV_{imep}$ | coefficient of variation of IMEP |
| DI | direct injection |
| $e$ | ethanol volumetric content |
| E100 | anhydrous ethanol |
| $E_{ind}$ | expended energy in fuel production |
| EVC | exhaust valve closure |
| EVO | exhaust valve opening |
| ExxWyy | mixture of xx% ethanol and yy% Water (v/v) |
| FDA | flame development angle |
| FID | flame ionization detector |
| $FID_{ppm}$ | raw FID measurement |
| FVVT | fully variable valve train |
| GHG | green house gases |
| GRON95 | 95 RON United Kingdom standard unleaded gasoline |
| HCCI | Homogeneous Charge Compression Ignition |
| HRR | Heat Release Rate |
| IMEP | indicated mean effective pressure |
| in-Cyl T | in-cylinder temperature |
| ISCO | indicated specific CO emission |
| $ISgas_i$ | indicated specific gas emission |
| ISNOx | indicated specific NOx emission |
| ISTHC | indicated specific THC emission |
| IVC | inlet valve closure |
| IVO | inlet valve opening |
| $k_{FID}$ | FID correction factor |
| $k_w$ | dry-to-wet correction factor |
| LHV | lower heating value |
| MBT | minimum spark advance for best torque |
| MFB | mass fraction burned |
| NOpC | normalized energy engine operational cost |
| NEEPWE | normalized energy expense in the production of wet ethanol |
| NOx | nitrogen oxides |
| NVO | negative valve overlap |
| NWREE | normalized water removal energy expense |
| OH | hydroxyl |
| $P_I$ | indicated power |
| PLIF | Planar Laser Fluorescence |
| PRRm | maximum pressure rise rate |
| PVO | positive valve overlap |
| $\dot{q}_{exh}$ | exhaust mass flow rate |
| RCCI | reactivity-controlled compression ignition |
| RON | Research Octane Number |
| rpm | revolution per minute |
| SI | spark ignition |
| TDC | top dead centre |
| TDCf | firing top dead centre |
| THC | total hydrocarbon (used in this work as a total unburned organic emission estimative) |
| $THC_{ppm}$ | corrected FID measurement |
| UEGO | universal exhaust gas oxygen |
| $u_i$ | raw gas exhaust factor |
| v/v | volume/volume |
| $\lambda$ | excess of air factor – lambda |
| $[x_i]$ | gas concentration in ppm |

ethanol presents higher knock resistance and higher latent heat of vaporization (904 kJ/kg for ethanol against 350 kJ/kg for gasoline). The increased ethanol charge cooling effect can lead to higher volumetric efficiency [7] and lower in-cylinder heat transfer [8]. Ethanol direct injection (DI) with concomitant gasoline port fuel injection has been also investigated [9]. In order to take advantage of the greater cooling effect, ethanol DI fraction must be controlled to provide enough cooling effect without fuel impingement and cold start issues. Moreover, ethanol's lower heating value (LHV) is 37% lower than that of gasoline, which increases the volumetric fuel consumption for the same energy substitution. It also presents corrosive effects in some alloys [7].

The energy usage for ethanol production may vary from place to place due to the chosen crop [10–12] and distinct industrial technologies. In most situations the net energy balance from ethanol production cycle is positive. The main ethanol production steps from cereals are milling, saccharification, fermentation, distillation and dehydration. If ethanol is produced from sugar syrups (molasses), which is a by-product from sugar refining processes, only fermentation, distillation and dehydration processes are needed. As ethanol and water are fully miscible and form an azeotrope mixture, distillation cannot be used to achieve ethanol-in-water volumetric concentrations beyond 95.6%. As shown in some studies [13–15], the energy expense trend to achieve ethanol-in-water volume fractions up to 80% increases in a linear trend. From 80% toward the azeotropic point, the energy requirement trend for distillation becomes exponential. This fact highly reduces the net energy balance of the bioethanol life cycle and consequently increases its final market price. To achieve anhydrous ethanol, distinct dehydration processes are used. Although great energy reduction has been achieved through the use of more sustainable dehydration techniques, such as molecular sieves, the energy expense is still considerably high [16]. In most cases, the ratio of gained energy of fuel LHV in MJ/L to the expended energy to dehydrate the same volume of ethanol (99% of ethanol or more) is very low, which further reduces the bioethanol net energy balance.

Using distillation and dehydration energy requirement data presented elsewhere [13–15] and the total energy expense to produce one litre of ethanol from distinct crops worldwide [11,12,17–19], it is possible to estimate the ratio of gained energy per unit of volume of fuel LHV to the expended energy $E_{ind}$ to produce the same volume for distinct water-in-ethanol volume fractions. This calculation shows that LHV/$E_{ind}$ reaches its maximum value for mixtures containing between 80% and 90% of ethanol-in-water. These ethanol–water mixtures would provide the best net energy balance compromise and the best monetary profit once the fuel conversion efficiency could be kept similar. Nevertheless, a deeper analysis of using such fuels in current spark ignition engines has not been proposed.

Previous studies using wet ethanol were carried out in different engines. The use of a catalytic igniter has been explored to efficiently burn wet ethanol with up to 30% of water content [20,21]. Lower NOx emission and higher brake conversion efficiency were obtained compared to gasoline operation. Homogeneous Charge Compression Ignition (HCCI) through intake air heating in high compression ratio engines has also been extensively explored in an effort to reduce gaseous emissions and achieve higher engine efficiencies while using wet ethanol (up to 40% of water content) [22–24]. Negative valve overlap (NVO) has also been explored to reach HCCI operation through hot residuals