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The potential of methanol as a fuel for flex-fuel and dedicated spark-ignition engines

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HIGHLIGHTS

- ▶ Methanol and gasoline operation are compared on two atmospheric flex-fuel engines.
- ▶ Methanol enables a relative efficiency increase of 10% while reducing NO_x and CO_2.
- ▶ Throttleless load control strategies using lean-burn and EGR are evaluated for methanol.
- ▶ EGR strategy allows to increase part load efficiency while maintaining low emissions.
- ▶ A high CR, turbo engine with this strategy reaches diesel-like efficiencies on methanol.

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ABSTRACT

Using light alcohols in spark-ignition engines can improve energy security and offers the prospect of carbon neutral transport. The properties of these fuels enable considerable improvements in engine performance and pollutant emissions. Whereas most experimental studies have focused on ethanol, this paper provides experimental results gathered on various methanol-fuelled engines. A comparison against gasoline on two flex-fuel engines yielded relative efficiency benefits of about 10% for methanol thanks to more isochoric combustion, less pumping, cooling and dissociation losses. Lower combustion temperatures allowed to reduce engine-out NO_x by 5–10 g/kWh. The CO_2 values dropped by more than 10%. Alternative load control strategies, employing mixture richness or exhaust gas recirculation (EGR) to control load while keeping the throttle wide open, were compared on a single cylinder engine. The EGR strategy seems preferable as it allows to increase part load efficiency up to 5% without sacrificing in terms of tailpipe emissions. Finally, this load control strategy of choice was applied to a turbocharged, high compression ratio engine to demonstrate that methanol can be used in dedicated engines with diesel-like efficiencies (up to 42%) and emission levels comparable to or lower than gasoline engines.

1. Introduction

1.1. Renewable transportation fuels

Hydrogen and electrification are two approaches to de-carbonizing transport that receive a lot of attention these days. However, their inherently low energy densities and high associated infrastructure costs make it unlikely that these solutions will become competitive with liquid fuels in the near future. Conversely, sustainable liquid alcohols, such as ethanol and methanol, are largely compatible with the existing fuelling and distribution infrastructure and are easily stored in a vehicle.

Biofuels, such as ethanol, can only constitute part of our energy supply because of the limited area of arable land [1]. Methanol, on the other hand, can be produced from a wide variety of renewable sources (e.g. gasification of wood, agricultural by-products and waste products [2]) and alternative fossil fuel based feed stocks (e.g. coal and natural gas [3]). A number of workers have even proposed a sustainable closed-carbon cycle where methanol is synthesized from renewable hydrogen and CO_2 from power plants [4] or the atmosphere [5]. Methanol can be used in low-cost internal combustion engines with only minor adjustments to ensure material compatibility [6] and enables increased engine performance compared to gasoline, as will be explained below.

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1.2. Methanol as a fuel for internal combustion engines

Methanol has the potential to increase engine performance and efficiency, thanks to a variety of interesting properties. Properties of gasoline, methanol and ethanol relevant to their use in internal combustion engines are summarized in Table 1. The main favourable properties of light alcohols include:

- High heat of vaporization, which in combination with the low stoichiometric air to fuel ratio leads to high degrees of intake charge cooling as the injected fuel evaporates.
- Elevated knock resistance, which is partly due to the considerable cooling effect. This opens opportunities for increased power and efficiency by applying higher compression ratios, optimal spark timing and aggressive downsizing.
- High flame speeds, which enable qualitative load control using mixture richness or varying amounts of EGR.

These properties and their favourable effects are most pronounced for methanol. A more extensive discussion on their implications for engine performance and emissions can be found in earlier publications [7,8].

Despite its interesting properties, the use of methanol as a fuel has met resistance due to toxicological and fire safety concerns. As discussed in several recent reviews [3,9], this issue is often overstated as methanol's toxicity (to human health and the environment) is on the same order as other fuels being considered as gasoline and diesel substitutes. In terms of fire safety methanol is substantially less hazardous than gasoline and for this reason it has been the preferred racing fuel in the US for many years.

1.3. Published work on alcohol engines

Published experimental work on alcohol engines indicates that the increase in power and efficiency depends on whether an engine is designed for alcohol operation only or for flexible fuel operation on both gasoline and alcohol.

In dedicated alcohol engines, the elevated knock resistance can be used to raise the compression ratio (CR) (to levels of 12:1 and above) without the need for spark retarding to avoid knock. Thanks to this design change Ford was able to obtain 20% more power and 15% higher efficiency from their M85 (a mixture of 85 vol.% methanol and gasoline) Escort model compared to its gasoline equivalent, and this was in 1981 [10]. Clemente et al. reported similar figures for a more recent dedicated ethanol engine designed for the Brazilian market [11].

The elevated flame speed and wide flammability limits of alcohols open some alternative options for load control, especially for methanol. Pannone and Johnson [12] have published results from an experimental turbocharged lean-burn methanol engine. The reported brake thermal efficiencies are up to 14% better than for stoichiometrically fuelled engines with throttled load control [15]. Engine-out CO emissions were reduced by over 50%, while unburned fuel emissions mildly increased. The tailpipe NO_x penalty of the lean burn strategy reached up to 150%, making the practical use of such a strategy questionable.

More interesting is to exploit the wide dilution limits of alcohols in a strategy using stoichiometric fuelling and exhaust gas recirculation (EGR) to control the load, thus reducing throttling losses and enabling three-way catalyst aftertreatment. Brusstar et al. demonstrated this using a 1.9 l turbocharged diesel engine with a CR of 19:1 that was converted for SI operation on methanol [13]. The high compression ratio enabled peak brake thermal efficiencies higher than the baseline diesel engine (40%) for operation on methanol (42%). Elevated levels of EGR (up to 50%) were used to spread the high efficiency regions to part-load operating points. Throttleless operation was possible down to a BMEP (brake mean effective pressure) of 6 bar.

Flexible fuel vehicles (FFVs) were developed during the 1980s to avoid the chicken and egg problem associated with the lack of alcohol refuelling stations. The lower knock resistance of gasoline meant the CR could no longer be increased a lot. Still FFVs attained about 5% more power and efficiency due to increased volumetric efficiency, lower flow losses and more isochoric combustion [10]. Today, active knock control and aggressive spark retarding make it possible to combine high CR and flexible fuel operation.

Bergström et al. took full advantage of the evaporative cooling effect by using E85 in a production turbocharged flex-fuel engine with direct injection [14]. Operation on E85 enabled the application of optimal ignition timing, increasing the engine's power by 20%. The mean brake thermal efficiency over a NEDC (New European Driving Cycle) was improved by over 5% compared to operation on gasoline.

As might be clear from the cited references, most of the recent work has focused on ethanol, whereas quantitative data for methanol-fuelled engines remains scarce. The present paper aims to demonstrate the potential of neat methanol-fuelled engines by analysing existing [15,16] and new, unpublished experimental results gathered on various engine test benches in terms of power, efficiency, greenhouse gas and pollutant emissions. In the first part of this paper the efficiency and noxious emissions are compared between gasoline and neat methanol operation on two normally aspirated flex-fuel engines. Next, the potential of two alternative load strategies are tested on a normally aspirated single cylinder flex-fuel engine. The strategies under consideration are wide open throttle lean burn operation and wide open throttle, stoichiometric operation with varying amounts of EGR to control load. Finally the wide open throttle EGR strategy is applied to a high compression ratio engine, representing the potential of dedicated methanol engines.

Table 1
Properties of typical gasoline, methanol, ethanol and hydrogen relevant to internal combustion engines [28,29,8].

Property	Gasoline	Methanol	Ethanol
Chemical formula	Various	CH_3OH	C_2H_5OH
Oxygen content by mass (%)	0	50	34.8
Density at NTP (kg/l)	0.74	0.79	0.79
Lower heating value (MJ/kg)	42.9	20.09	26.95
Volumetric energy content (MJ/l)	31.7	15.9	21.3
Stoichiometric air to fuel ratio (kg/kg)	14.7	6.5	9
Energy per unit mass of air (MJ/kg)	2.95	3.12	3.01
Research octane number (RON)	95	109	109
Motor octane number (MON)	85	88.6	89.7
Sensitivity (RON–MON)	10	20.4	19.3
Boiling point at 1 bar (°C)	25–215	65	79
Heat of vaporization (kJ/kg)	180–350	1100	838
Reid vapour pressure (psi)	7	4.6	2.3
Mole ratio of products to reactants[a]	0.937	1.061	1.065
Flammability limits in air (λ)	0.26–1.60	0.23–1.81	0.28–1.91
Laminar flame speed at NTP, λ = 1(cm/s)	28	42	40
Adiabatic flame temperature (°C)	2002	1870	1920
Specific CO_2 emissions (g/MJ)	73.95	68.44	70.99

[a] Includes atmospheric nitrogen. NA: not available. NTP: normal temperature (293 K) and pressure (101325 Pa).

2. Experimental set-up and procedures

The main specifications of the three engines and the corresponding measurement equipment used in the current study are summarized in Tables 2 and 3.