Fuel xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

A study of mechanical variable valve operation with gasoline–alcohol fuels in a spark ignition engine

Alasdair Cairns [a,*], Hua Zhao [a], Alan Todd [b], Pavlos Aleiferis [c]

[a] School of Engineering & Design, Brunel University, Uxbridge UB83PH, UK
[b] MAHLE Powertrain Ltd, St. James Mill Rd., Northampton, NN55TZ, UK
[c] Department of Mechanical Engineering, University College London, Torrington Place, London, WC1E7JE, UK

HIGHLIGHTS

- ▶ High ethanol content fuels enabled further small fuel and NO*x* emissions savings.
- ▶ The primary mechanism was faster burning and improved residual gas tolerance.
- ▶ Butanol had a negligible effect on residual gas tolerance, regardless of volume.
- ▶ For all fuels, variable valve timing offered the greatest NO*x* reduction potential.

ARTICLE INFO

Article history:
Received 19 July 2012
Received in revised form 7 October 2012
Accepted 18 October 2012
Available online 7 November 2012

Keywords:
Spark ignition
Variable valve actuation
Ethanol
Butanol

ABSTRACT

This work involved study of the effects of gasoline–ethanol and gasoline–butanol blends on the combustion, fuel economy and engine-out emissions of a single cylinder research engine equipped with a mechanical variable valvetrain on the inlet and variable valve timing on the exhaust. Gasoline or iso-octane were splash blended with varying amounts of ethanol or 1-butanol and studied under a range of part-load engine conditions. During warm idle operation, high ethanol content fuels allowed significant improvement in tolerance to internally recycled burned gases, primarily associated with increased burning velocities of such blends when near to stoichiometric fuelling levels. In turn this allowed higher valve lifts to be used, with reduced throttling locally at the inlet valves, further small fuel savings and reductions in engine-out emissions of NO*x*. Conversely, the use of 1-butanol had a negligible effect on residual gas tolerance, regardless of blend volume. At moderate speeds and loads, where throttling losses were less, it was apparent that the valvetrain could still be used to attain additional thermal efficiency improvements including reduced compression losses and further expansion work for all fuels. However, a trade-off with increased pumping losses during the exhaust stroke was apparent, with the throttling moved from the inlet to the exhaust valves at the most retarded valve timings studied. For all fuel blends, it was extremely interesting to note that variable valve timing alone offered the greatest NO*x* reduction potential at moderate loads, insinuating the ability to operate variable valve timing with and without early intake valve closing may offer one viable path to meeting future engine emissions targets.

1. Introduction

The ability to vary the inlet and exhaust valve events of the Spark Ignition (SI) engine is well-known to facilitate improved compromise between performance, fuel economy and emissions. Variable Valve Timing (VVT) is one such established technique for improving the fuel economy of the gasoline engine. There are several mechanisms by which VVT influences fuel consumption including:

- Increasing or delaying valve overlap, which increases trapped residuals and reduces engine pumping losses (where the trapped residual gases occupy part of the cylinder volume and hence allow less vacuum to be used in the inlet system at part-load).
- Late Inlet Valve Closure (IVC), which further decreases pumping losses by allowing further increased intake pressures (given the piston pushes some of the air back into the inlet system).
- Late Exhaust Valve Opening (EVO), which can increase expansion work.

As a result, fuel economy can be improved by up to ~5% over the European drive cycle, for example [1–3]. The choice of

---

* Corresponding author. Tel.: +44 (0)1895265175.
E-mail address: alasdair.cairns@brunel.ac.uk (A. Cairns).

0016-2361/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2012.10.041

Please cite this article in press as: Cairns A et al. A study of mechanical variable valve operation with gasoline–alcohol fuels in a spark ignition engine. Fuel (2012), http://dx.doi.org/10.1016/j.fuel.2012.10.041

optimum VVT strategy is highly dependent on exhaust manifold design, engine compression ratio, cam phasing limits due to valve-to-piston clash, part-load residual dilution tolerance and the importance of Wide Open Throttle (WOT) performance relative to part-load fuel consumption and emissions. A so-called dual-independent VVT strategy (where the timing of the inlet and exhaust valves may be varied independently) offers high overlap potential and reasonable compromise between maximising WOT torque and minimising part-load fuel consumption and emissions [4,5].

In relatively recent years, there has also been growing interest in fully variable valvetrain systems for additional improvements, such as:

- Further reduction in throttling losses via load control directly at the inlet valve(s), hence the traditional intake throttle can effectively be disregarded.
- Increased thermal efficiency through greater effective expansion ratio.

Numerous fully variable valvetrain strategies exist depending on application, but the currently reported work is most concerned with those SI engine strategies claiming to enable improved part-load fuel efficiency. During his notable study in this vein, Tuttle compared the effects of Late Inlet Valve Closing (LIVC) and Early Inlet Valve Closing (EIVC) in a gasoline single cylinder research engine. In early experiments [6], IVC was delayed by between 60° and 96° crank. Fuel consumption was observed to reduce by up to 6.5% and was accompanied by lower engine-out emissions of NO*x* ($\sim$24%) but similar hydrocarbon levels. Tuttle concluded that 96° was the maximum delay that could be tolerated due to loss of effective compression ratio, which would significantly limit the attainable speed-load map (assuming no external compression was available). In later work [7] it was concluded that the EIVC strategy was favourable at part-load, allowing de-throttled operation over a wider speed-load window, albeit reliant on 200° crank range of inlet valve closing for greatest CO_2 reduction.

For such EIVC operation it is necessary to employ a much shorter inlet cam duration, allowing the exact required mass of air to enter the cylinder before closing the valves at the appropriate phase during the intake stroke. Thereafter the engine effectively acts in a manner akin to an “air spring”, expanding the fresh charge below atmospheric pressure prior to the compression stroke. One major limitation of such operation is reduction of the in-cylinder turbulence intensity, associated with increased time under closed valve conditions. This was previously well demonstrated by Cleary and Silvas [8] under part-load cruising conditions (1300 rpm/3.3 bar net IMEP), where EIVC resulted in prolonged combustion duration, reduced in-cylinder gas temperatures, reduced engine-out emissions of NO*x* (up to 25%) and increased values of unburned hydrocarbons (also $\sim$25%). The deterioration in burn rate was reduced by switching to a LIVC strategy but, under the reduced valve duration conditions tested, the pumping losses were worse than the conventionally throttled case.

Recent benefits claimed from part-load EIVC operation are highly dependent on the valvetrain system employed. At one end of the spectrum, various electro-magnetic and electro-hydraulic systems have been proposed. Such “camless” systems have been reported to allow the greatest potential for reduction in breathing losses [9,10] and/or can be used to realize advanced modes of operation such as controlled auto-ignition [11,12]. However, in general these systems often still have significant issues to overcome including packaging, noise, limited engine speed and cost. Therefore, the majority of “fully” variable valvetrain systems entering production have been mechanically based, often producing sinusoidal valve lift profiles of reducing valve lift in proportion to valve duration and providing fuel economy benefits of around 10% over the European drive cycle [13,14]. Elsewhere, Sellnau and co-workers [15] have also demonstrated how simpler two-stage mechanical valve actuation can allow viable compromise on a cost-benefit basis, achieving 5.5% improvement in fuel economy and $\sim$46% reduction in NO*x* over the US warmed-up Phase 3 Environmental Protection Agency drive tests (cycles 19–23).

The combination of EIVC with homogeneous direct fuel injection has also begun to warrant interest, with potential for further part-load fuel savings via increased compression ratio. For example, workers on the “Hotfire” collaborative project previously examined such effects in both optical and thermodynamic single cylinder SI engine assemblies [16,17]. During this study, greatest fuel consumption benefits were achieved when just one of the two inlet valves was actuated. However, the swirl dissipated quickly once the valve closed and the fuel economy benefits recorded varied substantially depending on which of the two inlet valves was activated. This was associated with the asymmetric layout of the injector and spark plug within the combustion chamber. Following such fundamental studies, the Fiat “Multiair” system has emerged and is now being transferred to advanced SI applications [18]. This system decouples the closing of the intake valves from the conventional mechanical cam via a variable hydraulically collapsed connecting piston and arguably provides a good compromise in terms of cost between prior proposed fully variable electro-hydraulic and conventional mechanical systems.

On another note, in recent years there has also been significant global interest in alcohol fuels for SI engines, especially “lower” alcohol fuels of reduced carbon count. The idea of using alcohol as automotive fuel is not new [19–21]. However, attention has now intensified as such fuels may present one viable renewable solution, with potential to be used in a near CO_2-neutral manner through efficient conversion of biomass. First generation biofuels have largely been based on ethanol, where national fuel quality standards typically allow between 5% and 10% volume inclusion within the existing gasoline pool. The main exception is Brazil, where fuels produced from sugar cane are widely available in “gasohol” to neat ethanol forms [22]. Elsewhere where less favourable biomass production limits exist, another exception is availability of gasoline containing up to 85% ethanol (“E85”) available as a niche product for flex-fuel vehicles [23–25]. In summary, production of biofuel from feedstock is clearly limited on a global basis. Next generation processes are therefore currently being investigated that may allow such fuels to be efficiently mass-produced from alternative sources such as cellulose, algae or even recovered waste [26]. In the meantime efforts are also underway to maximise the impact of existing biofuel stock [27,28].

Compared to gasoline, the lower alcohols exhibit high latent heat of vaporisation and anti-knock rating, which makes them attractive for use in future “downsized” highly boosted SI engines that endure significantly higher peak in-cylinder pressures and temperatures [29]. Such downsizing may help offset the low energy density of ethanol [30], while problems with cold start due to reduced volatility can also be reduced via, for example, advanced DI operating strategies [31,32]. However, gasoline–ethanol blends are known to exhibit azeotropic behaviour, with profound effects on the vaporisation and thermodynamic properties of the blend. Kar and co-workers [33] previously performed cycle resolved in-cylinder temperature measurements and reported that blends with less ethanol content (0–30%) tended to evaporate more readily while higher concentrations (>50%) with reduced vapour pressure did not and hence exhibited reduced “evaporative power”.

Elsewhere, “higher” alcohols such as propanol, butanol and pentanol have also been considered for automotive use [34–36]. From a thermodynamic stance the higher alcohols generally exhi-

Please cite this article in press as: Cairns A et al. A study of mechanical variable valve operation with gasoline–alcohol fuels in a spark ignition engine. Fuel (2012), http://dx.doi.org/10.1016/j.fuel.2012.10.041