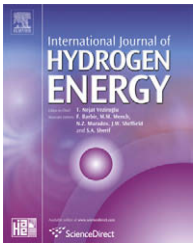
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 34 (2009) 2504–2510

Available at www.sciencedirect.com

ScienceDirect

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



Efficiency comparison between hydrogen and gasoline, on a bi-fuel hydrogen/gasoline engine

S. Verhelst[*], P. Maesschalck, N. Rombaut, R. Sierens

Department of Flow, Heat and Combustion Mechanics, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium

ARTICLE INFO

Article history:
Received 2 December 2008
Received in revised form
6 January 2009
Accepted 6 January 2009
Available online 3 February 2009

Keywords:
Internal combustion engine
Hydrogen
Gasoline
Bi-fuel
Efficiency
Emissions

ABSTRACT

The combustion characteristics of hydrogen compared to gasoline offer the potential of an increased engine efficiency, especially at part load. Here, results are presented of the brake thermal efficiency of a bi-fuel hydrogen/gasoline engine, at several engine speeds and loads. Results on hydrogen are compared to results on gasoline. Hydrogen offers the possibility of a more flexible load control strategy. Where possible, results are compared between the wide open throttle, lean burn strategy and the throttled stoichiometric strategy.

1. Introduction

Greenhouse gas emission by the transport sector is a hot topic these days. There is a strong drive towards legislation limiting the fleet average CO_2 emissions [1]. The use of hydrogen as an energy carrier is one option with the potential of lowering CO_2 emissions investigated by the vehicle manufacturers. However, affordable fuel cell vehicles seem to be a long way off [2]. An interesting alternative is using hydrogen in internal combustion engines (ICEs). Next to being less expensive, hydrogen-fueled ICEs offer a number of other benefits of which the most practical one is the ability to run in bi-fuel or flex-fuel operation. These benefits, and experimental research on hydrogen-fueled ICEs are reviewed by the authors elsewhere [3].

Hydrogen is a very versatile engine fuel when it comes to load control. The high flame speeds of hydrogen mixtures and its wide flammability limits permit very lean operation and substantial dilution. The engine efficiency and the emission of oxides of nitrogen (NO_x) are the two main parameters used to decide the load control strategy. Constant equivalence ratio throttled operation has been used but mainly for demonstration purposes [4–6], as it is fairly easy to run a lean burn throttled hydrogen engine (when accepting the severe power output penalty). Where possible, wide open throttle (WOT) operation is used to take advantage of the associated increase in engine efficiency [7–9], regulating load with mixture richness (qualitative control) instead of volumetric efficiency (quantitative control) and thus avoiding pumping losses. Limitations to WOT operation are due to misfires, unburned hydrogen and decreased stability at very low load (e.g. idling) and NO_x emissions at medium to full load. Thus, throttling is used at very low loads to increase combustion stability and decrease unburned hydrogen emissions [6,10–13]. Moreover, this increases the efficiency at these (ultra-lean) conditions:

---

[*] *Corresponding author*. Tel.: +32 9 264 3306; fax: +32 9 264 3590.
E-mail address: sebastian.verhelst@UGent.be (S. Verhelst).

0360-3199/$ – see front matter © 2009 International Association for Hydrogen Energy. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijhydene.2009.01.009

Nomenclature

Greek symbols

λ	air to fuel equivalence ratio,

Abbreviations

bmep	brake mean effective pressure,
BTDC	before top dead center,
BTE	brake thermal efficiency,
CVVT	continuously variable valve timing,
DI	direct injection,
EGR	exhaust gas recirculation,
ICE	internal combustion engine,
IT	ignition timing,
IVO	intake valve opening time,
MAF	mass air flow,
MBT	minimum spark advance for best torque,
PFI	port fuel injection,
TDC	top dead center,
TP	throttle position,
TWC	three way catalyst,
WOT	wide open throttle.

the efficiency gain through decrease of unburned hydrogen emissions (and possibly also by a shorter, more efficient combustion) offsets the efficiency loss by throttling. The engine efficiency using throttled or WOT operation is compared in Refs. [6,14], the lean limit at which throttling is introduced is engine dependent and ranges from $\lambda = 3$ [11] to $\lambda = 4$ [6,10].

For higher loads, flame temperatures quickly exceed the NO_x generation limit. This results in a NO_x limit to WOT operation. One could restrict the mixture richness and use sufficiently lean mixtures to stay below a 10 or 100 ppm NO_x limit, but this implies a large decrease in maximum power output. Alternatively, the engine can be throttled above this limit, using stoichiometric mixtures and thus enabling the use of a conventional three way catalyst for NO_x reduction [10]. The mixture richness is then set slightly rich of stoichiometric so that some unburned H_2 is present in the exhaust which is a very effective reducing agent for NO_x [15]. However, this strategy implies a decrease in engine efficiency. Yet another strategy is the use of EGR to control load: using stoichiometric mixtures but instead of throttling, recycling exhaust gas in a proportion dependent on the power demand [14,16,17]. This gives a better efficiency compared to throttling. EGR is also a means to allow backfire-free operation at stoichiometric mixtures, enabling a higher power output if NO_x emissions are a boundary condition [16,18]. Water injection can also be used to decrease NO_x emissions from the richer mixtures [11,19], and is more effective than EGR [4] but is mostly considered impractical. Work has been reported using a 'dual fluid injector' for DI [18], which injects hydrogen and liquid water directly in the combustion chamber, for decreased NO_x.

Finding means to maximize engine efficiency is very important for H_2 ICEs considering the H_2 on-board storage challenge. Quantifying the efficiency of H_2 ICEs is useful for assessing the possible vehicle range. Several papers have reported efficiencies of engines operated on hydrogen. Ford [6,14,20] published figures obtained on a dedicated hydrogen engine, where (among others) the compression ratio was optimized to take advantage of the high auto-ignition temperature of hydrogen. Tang et al. [6] mapped the brake specific fuel consumption, both for a constant equivalence ratio, throttled strategy as a wide open throttle strategy (regulating load with mixture richness). Brake and indicated thermal efficiencies were shown, as a function of equivalence ratio, for different compression ratios and engine speeds. The maximum indicated thermal efficiency was 52%, which was for a $\lambda = 3.3$ and 5000 rpm condition. The maximum brake thermal efficiency peaked at 38%, around $\lambda = 2$ and 2000 rpm. Natkin et al. [14] reported brake thermal efficiencies of a comparable engine, with the addition of a supercharger to increase the power output. The supercharged engine reached a maximum indicated thermal efficiency of 50% and a maximum brake thermal efficiency of 37%. The authors also report a relative increase of 15–20% in brake thermal efficiency at the lower loads when using the equivalence ratio to control load (WOT, qualitative control strategy) rather than throttling (quantitative control strategy). Finally, in a joint publication with Westport Innovations and Pacific Northwest National Laboratory, Ford report an estimated peak brake thermal efficiency of 45% obtained on a single cylinder DI engine [20].

BMW [10,15,21,22] reported efficiency figures for the different load control strategies. Eichlseder et al. [22] provide a limited comparison of the efficiency of hydrogen versus gasoline operation. Next to the properties of hydrogen that are beneficial for the efficiency, see above, it is also noted that higher wall heat losses are to be expected for hydrogen, which has a negative effect on the efficiency. Berckmüller et al. [10] showed an indicated thermal efficiency map for a port fuel injected engine, including the wide open throttle strategy, throttled stoichiometric and supercharged stoichiometric strategies. Indicated thermal efficiencies reached 40% at low load and 32% at high load. They also mapped the stoichiometric + EGR strategy as an alternative to the throttled stoichiometric approach, which resulted in increased efficiency (roughly 2 percentage points). Rottengruber et al. [15] plotted a similar map, but using direct injection at the higher loads, which enabled higher efficiencies compared to the PFI supercharged approach.

Several other papers also report efficiencies, as a function of equivalence ratio and ignition timing [19], as a function of the injection timing and intake manifold geometry for a PFI engine [23], as a function of the injection timing and injector location for a DI engine [24], etc.

All of these papers show efficiency figures above those typically reached with gasoline, but no direct comparisons are included. The BMW Hydrogen 7 semi-production vehicle [21] is a bi-fuel vehicle but unfortunately no efficiency figures were stated in the paper. For the mono-fuel derivative, fuel consumption figures are reported by Wallner et al. [25], but those are for the vehicle so include transmission losses etc.

The authors found only one report of efficiency measurements on the same engine, on gasoline as well as on hydrogen