Available online at www.sciencedirect.com
ScienceDirect
International Journal of Hydrogen Energy 32 (2007) 3073–3083
International Journal of HYDROGEN ENERGY
www.elsevier.com/locate/ijhydene

Increase of passenger car engine efficiency with low engine-out emissions using hydrogen–natural gas mixtures: A thermodynamic analysis

P. Dimopoulos[a,*], C. Rechsteiner[a,b], P. Soltic[a], C. Laemmle[a,c], K. Boulouchos[c]

[a] *Empa, Swiss Federal Laboratories for Materials Testing and Research, Laboratory for I.C. Engines, CH-8600 Dübendorf, Switzerland*
[b] *Fiat Powertrain Technologies, Iveco Motorenforschung AG, Schlossgasse 2, CH-9320 Arbon, Switzerland*
[c] *Aerothermochemistry and Combustion Systems Laboratory ETH, Swiss Federal Institute of Technology, CH-8092 Zürich, Switzerland*

Received 2 November 2006; received in revised form 29 December 2006; accepted 29 December 2006
Available online 26 February 2007

Abstract

In this study a state of the art passenger car natural gas engine was optimised for hydrogen natural gas mixtures and high exhaust gas recirculation (EGR) rates in the part load domain. With optimal combinations of spark timing (ST) and EGR rate the achievements are significant efficiency increase with substantially lower engine-out NO_x while total unburned hydrocarbons or CO-engine-out emissions are not affected. Comprehensive investigations of the parameter space using design of experiments (DoE) algorithms provided a complete picture of the potential of such applications. Combustion analysis on the other hand allowed to identify improvements on the basis of accelerated combustion caused by the hydrogen as well as the reduced gas exchange losses due to EGR and associated less required throttling for a given engine output. The best combinations of EGR rate, hydrogen-fraction in the fuel and ST exhibited optimal in-cylinder pressure characteristics accompanied by moderate combustion peak temperatures and low expansion cylinder temperatures.

Keywords: CNG; Hydrogen; Mixtures; Passenger car engine; Exhaust gas recirculation (EGR); Design of experiments (DoE); Combustion analysis

1. Introduction

A significant reduction of CO_2 emissions in the mobility sector is a major challenge for the next decades. In combination with efficient powertrain technologies, the potential of natural gas is excellent for a comparably high and cost effective reduction in CO_2 and toxic emissions in the near future.

In the recent past our laboratories have demonstrated the potential of a natural gas optimised engine vehicle with the clean engine vehicle (CEV) project. The vehicle used was a production line small sedan (model year 2000) with a curb weight of 1020 kg. The achieved goal was 30% lower CO_2 emissions than the gasoline vehicle while staying in compliance with Euro-4 as well as SULEV emission limits [1]. Vehicle performances have been improved in respect to the level of the gasoline version. Therefore, the engine compression ratio was increased while a specially developed turbocharging strategy was implemented. As far as this point no EGR has been implemented.

The EGR in modern SI-engines is used for mainly reducing engine-out NO_x emissions. In addition there is a possible improvement in fuel consumption due to three factors: (1) reduced pumping work, since for the same brake load less throttling is required (higher amount of inert gas as well as higher temperature of the intake gas [2]); (2) reduced heat loss to the walls because of reduced burn gas temperature and (3) a reduction in the degree of dissociation in the high temperature burned gases. According to [3,4] the fuel conversion efficiency at part load can be increased up to 4.5% when using the appropriate EGR amount. However, EGR also reduces the combustion rate which counteracts the beneficial effects leading to elongated combustion and/or inefficiently large spark timing (ST) advance. In combination with the relatively slow-burning natural gas and the "slow" pancake shaped combustion chambers often in SI-low-price automotive applications this countereffect can be detrimental. In addition the unburned hydrocarbon emissions increase with

---

* Corresponding author. Tel.: +41 44 8234337; fax: +41 44 8234041.
E-mail address: panayotis.dimopoulos@empa.ch (P. Dimopoulos).

0360-3199/$ - see front matter © 2007 International Association for Hydrogen Energy. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijhydene.2006.12.026

Nomenclature

Abbreviations

bmep	brake mean effective pressure
bsfc	brake specific fuel consumption
CNG	compressed natural gas
CR	compression ratio
CR_φ	volume ratio at crank angle φ
DoE	design of experiments
ECU	engine electronic control unit
EGR	exhaust gas recirculation rate
EVO	exhaust valve opening
IVC	inlet valve closing
MY	model year
SI	spark ignition
ST	spark timing
TDC	top dead center
THC	total unburned hydrocarbons
TWC	three way catalyst

Latin characters

B	engine bore dimensions
s_p	mean piston speed
m_f	fuel mass introduced in the cylinder per engine stroke
p_{cyl}	cylinder pressure
p_{mi}	mean indicated pressure
$p_{mi,gx}$	break mean indicated pressure through gas exchange
Q_b	combustion heat introduced by the fuel
Q_{ic}	incomplete combustion heat losses
Q_{LHV}	lower heating value of the fuel
Q_{rc}	real combustion heat losses
Q_{rg-bb}	real gas and blow-by losses
Q_{wh}	cylinder wall heat losses
$r_{cv,\varphi}$	constant volume ratio
T_{cyl}	cylinder temperature
V_c	cylinder volume at TDC
V_D	cylinder displacement volume
V_φ	cylinder volume at crank angle φ
W_{gx}	gas exchange work

Greek characters

α_w	heat transfer coefficient, cylinder gas to walls
β_i	regression coefficients for the DoE modelling
γ	ratio of the specific heats of the working fluid
η_{cv}	fuel conversion efficiency of the constant volume process
η_f	effective fuel conversion efficiency
η_i	indicated fuel conversion efficiency
η_{rc}	real combustion efficiency
φ	crank angle

increasing EGR. Nevertheless variable valve timing can reduce the HCs substantially [5]. On the other hand the described EGR-benefits at part loads have the opposed effects at high loads.

In the engine under consideration (more details in Section 2) only a modest part of the EGR benefits could be reaped [6], due to the "slow" combustion chamber and the absence of any special charge motion within the cylinder.

Several studies, example [7,8], showed that addition of H_2 to gasoline allows stable operation of the engine under extreme conditions, such as ultra-lean air–fuel mixtures, or very high rates of exhaust gas recirculation (EGR). In parallel some research was performed in respect to the combustion of H_2-CNG mixtures. In [9] a comprehensive overview of the results known so far is provided. The reported results indicate decreased HC and CO, increased NO_x emissions and mainly increased fuel conversion efficiency when substituting parts of the CNG by hydrogen. The studies referred used different engines while the focus was mainly in lean combustion. In addition no systematic EGR variation has been performed, [9–11].

The present study based on a production car engine optimised for CNG combustion (as described in [1], and in Section 2) focuses on the systematic variation of the EGR and the ST for three different fuel compositions. The objective is to meet the most stringent emission standards and at the same time to optimise system costs, mainly by reducing the amount of precious metals in the catalyst [12], while improving fuel economy.

2. Engine and fuels

2.1. Engine and testing

The original engine was a Volkswagen Polo (a typical European small sedan, MY2000) naturally aspirated four cylinder gasoline engine with a displacement of 1.0 L with an output of 37 kW at 5000 RPM and 86 Nm at 3000 RPM. This engine was modified for CNG fuelling. The compression ratio was increased to 13.5 while turbocharging was implemented in order to reach the original engine performances [1]. The engine was operated strictly stochiometric and used one pre- and one main TW catalyst [13]. As reported in [1,14] pure CNG operation reduced the CO_2 emission by 30% in respect to the original gasoline configuration, while the vehicle reached the Euro-4 and SULEV emission standards [14]. One cylinder was equipped with a pressure transducer. Cylinder pressure data have been processed by a transient recorder and analysed by WEG, a heat release software package developed at ETH Zurich [15]. Engine-out exhaust gas was analysed by a Horiba MEXA-9200DF analyser. A separate line of this analyser was used for measuring CO_2 in the intake in order to quantify the amount of EGR. At first the amount of internal EGR was determined [6]. For the operating points of interest in this paper the internal EGR was estimated around 1 mass-%.

In order to run high EGR-rates in combination with the pancake type and "slow" combustion chamber one additional