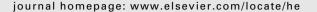
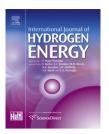


Available online at www.sciencedirect.com

# SciVerse ScienceDirect





# CFD modeling and experimental study of combustion and nitric oxide emissions in hydrogen-fueled spark-ignition engine operating in a very wide range of EGR rates

G.M. Kosmadakis a, C.D. Rakopoulos a,\*, J. Demuynck b, M. De Paepe b, S. Verhelst b

### ARTICLE INFO

# Article history: Received 10 February 2012 Received in revised form 11 April 2012 Accepted 11 April 2012 Available online 11 May 2012

Keywords:
Hydrogen
Spark-ignition engine
EGR
Combustion
NO emissions

### ABSTRACT

In the current work, the variation of EGR rates is investigated in a hydrogen-fueled, sparkignition engine. This technique is followed in order to control the engine load and decrease the exhaust nitrogen oxides emissions. The external EGR is varied in the very wide range of 12% up to 47% (by mass), where in each test case the in-cylinder mixture is stoichiometric, diluted with the appropriate EGR rate. The operation of this engine is explored using measured data with the aid of a validated CFD code. Moreover, a new residual gas term existing in the expression of the hydrogen laminar flame speed, which has been derived from a one-dimensional chemical kinetics code, is tested in a real application for appraising its capabilities. The investigation conducted provides insight on the performance and indicated efficiency of the engine, the combustion processes, and the emissions of nitrogen oxides. More precisely, an experimental study has been deployed with the aim to identify the characteristics of such a technique, using very high EGR rates, focusing on the combustion phenomena. At the same time, the CFD results are compared with the corresponding measured ones, in order to evaluate the CFD code under such nonconventional operating conditions and to test a recent expression for the residual gas term included in the hydrogen laminar flame speed expression. It is revealed that the combustion takes place in few degrees of crank angle, especially at high engine loads (low EGR rates), whereas the exhaust nitrogen oxides emissions are significantly decreased in comparison to the use of lean mixtures for controlling the engine load. Additionally, the recent expression of the residual gas term, which has been tested and incorporated in the CFD code, seems to be adequate for the calculation of combustion phenomena in highly diluted, with EGR, hydrogen-fueled spark-ignition engines, as for every EGR rate tested (even for the higher ones) the computational results are compared in good terms with the

Copyright © 2012, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.

 <sup>&</sup>lt;sup>a</sup> Internal Combustion Engines Laboratory, Thermal Engineering Department, School of Mechanical Engineering,
 National Technical University of Athens, 9 Heroon Polytechniou St., Zografou Campus, 15780 Athens, Greece
 <sup>b</sup> Department of Flow, Heat and Combustion Mechanics, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

<sup>\*</sup> Corresponding author. Tel.:  $+30\ 2107723529$ ; fax:  $+30\ 2107723531$ .

| Nomenclature         |  | $\rho$            | density, kg/m <sup>3</sup>                |
|----------------------|--|-------------------|---|
| Α                    | calibration constant in turbulent flame speed                              | $ ho_{ m b}$      | burned gas density, kg/m³                 |
|                      | expression   | $ ho_{ m u}$      | unburned gas density, kg/m³               |
| $D_{T,u}$            | thermal diffusivity of the unburned mixture, m <sup>2</sup> /s             | $	au_{	extsf{c}}$ | characteristic conversion time, s         |
| f f                  | residual gas fraction by volume, %   | $	au_1$           | laminar kinetics time, s                  |
| F                    | residual gas correction expression   | $	au_{t}$         | turbulent mixing time, s                  |
| k                    | turbulent kinetic energy (per unit mass), m <sup>2</sup> /s <sup>2</sup>   | $\varphi$         | fuel-to-air equivalence ratio or (simply) |
| $LHV_{H_2}$          | lower heating value of hydrogen, kJ/kg                                     |                   | equivalence ratio                         |
| L <sub>t</sub>       | turbulent integral length scale, m   | $\phi$            | generalized variable                      |
| $m_{\rm H_2}$        | inlet hydrogen mass, kg  | Abbreviations     |   |
| $\dot{m}_{\rm EGR}$  | EGR mass flow rate, kg/s   | ABDC              | after bottom dead center                  |
| $\dot{m}_{ m air}$   | air mass flow rate, kg/s   | ATDC              | after top dead center                     |
| $\dot{m}_{ m H_2}$   | hydrogen mass flow rate, kg/s  | BBDC              | before bottom dead center                 |
| $n_{\rm gi}$         | gross indicated efficiency, %  | BDC               | bottom dead center                        |
| P P                  | pressure, N/m <sup>2</sup>   | CFD               | computational fluid dynamics              |
| $P_{IVC}$            | pressure at inlet valve closure, N/m <sup>2</sup>                          | CFR               | cooperative fuel research                 |
| $P_0$                | reference pressure, N/m <sup>2</sup>                                       | COV               | coefficient of variance                   |
| $Q_{H_2}$            | heat of combustion, J  | CR                | compression ratio                         |
| $r_k$                | local flame kernel radius, m   | °CA               | degrees of crank angle                    |
| S <sub>cr</sub>      | source term due to crevice flows   | EGR               | exhaust gas recirculation                 |
| $S_{\varphi}$        | source term  | EOI               | end of injection                          |
| t t                  | time, s  | EVC               | exhaust valve closing                     |
| T                    | temperature, K   | EVO               | exhaust valve opening                     |
| To                   | reference temperature, K   | HCCI              | homogeneous charge compression ignition   |
| $T_{\rm u}$          | unburned gas temperature, K  | IMEP              | indicated mean effective pressure         |
| uf                   | flame propagation velocity, m/s  | IT                | ignition timing                           |
| $u_1$                | laminar flame speed, m/s   | IVC               | inlet valve closure                       |
| $u_{l0}$             | laminar flame speed at reference conditions, m/s                           | IVO               | inlet valve opening                       |
| $u_{t}$              | turbulent flame speed, m/s   | MBT               | minimum spark advance for best torque     |
| u'                   | rms turbulent velocity, m/s  | MFB               | mass fraction burned                      |
| $\overrightarrow{u}$ | velocity vector, m/s   | NO                | nitric oxide                              |
| V                    | cylinder volume, m <sup>3</sup>  | $NO_x$            | nitrogen oxides                           |
| $V_s$                | swept volume, m <sup>3</sup>   | PFI               | port-fuel injection                       |
| $W_{gi}$             | gross indicated work, J  | PISO              | pressure implicit splitting of operators  |
| $W_i$                | indicated work, J  | rms               | root mean square                          |
| Crack or             | Greek symbols  |                   | revolutions per minute                    |
|                      | diffusion coefficient, kg/m s  | SI                | spark-ignition                            |
| $\Gamma_{\phi}$      | turbulent dissipation rate (per unit mass), m <sup>2</sup> /s <sup>3</sup> | TDC               | top dead center                           |
| $\epsilon$           | relative air-to-fuel ratio   | TWC               | three-way catalyst                        |
| λ                    | relative all-to-luel latio   | UEGO              | universal exhaust gas oxygen              |
|                      |  |                   |   |

## 1. Introduction

One type of engine showing high research interest is the spark-ignition engine running on hydrogen, for which appropriate experimental test-benches are developed, in order to investigate the combustion processes and their performance under different operating conditions and strategies [1–7], as well as the various in-cylinder processes taking place [8–12]. Apart from these experimental investigations, numerical tools are also developed [8,13–16], which can further assist in the understanding of the various processes taking place in those engines. Especially, the results obtained from computational fluid dynamics (CFD) codes [8,16], which describe in a more fundamental way the in-cylinder processes [17,18], can identify at a local level the coupling of the relevant transport phenomena.

One method of regulating the engine load and decreasing the exhaust nitrogen oxides (NOx), is the use of exhaust gas recirculation (EGR). While in diesel and HCCI engines the use of large quantities of EGR is a common practice [19-23], in gasoline spark-ignition (SI) engines significantly lower EGR rates are used, due to the severe decrease of flame speed. Recently, attention is paid to the use of larger EGR rates in spark-ignition engines using fuels other than gasoline, such as natural gas, hydrogen etc. [24-27]. More specifically, in hydrogen-fueled spark-ignition engines the use of EGR aims at decreasing the exhaust nitrogen oxides (NO<sub>x</sub>) and regulating the engine load without the need of throttling. The first target can be directly achieved, since the fresh mixture diluted with exhaust gases possesses a higher specific heat capacity, thus decreasing the maximum combustion temperature. On the other hand, the second target (control of engine load) can be

## Download English Version:

# https://daneshyari.com/en/article/1276375

Download Persian Version:

https://daneshyari.com/article/1276375

Daneshyari.com