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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

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ABSTRACT

In the current work, the variation of EGR rates is investigated in a hydrogen-fueled, spark-ignition 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 non-conventional 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 measured data.

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Nomenclature

A	calibration constant in turbulent flame speed expression
$D_{T,u}$	thermal diffusivity of the unburned mixture, m^2/s
f	residual gas fraction by volume, %
F	residual gas correction expression
k	turbulent kinetic energy (per unit mass), m^2/s^2
LHV_{H_2}	lower heating value of hydrogen, kJ/kg
L_t	turbulent integral length scale, m
m_{H_2}	inlet hydrogen mass, kg
$\dot{m}_{EGR}$	EGR mass flow rate, kg/s
$\dot{m}_{air}$	air mass flow rate, kg/s
$\dot{m}_{H_2}$	hydrogen mass flow rate, kg/s
n_{gi}	gross indicated efficiency, %
P	pressure, N/m^2
P_{IVC}	pressure at inlet valve closure, N/m^2
P_0	reference pressure, N/m^2
Q_{H_2}	heat of combustion, J
r_k	local flame kernel radius, m
S_{cr}	source term due to crevice flows
S_φ	source term
t	time, s
T	temperature, K
T_0	reference temperature, K
T_u	unburned gas temperature, K
u_f	flame propagation velocity, m/s
u_l	laminar flame speed, m/s
u_{l0}	laminar flame speed at reference conditions, m/s
u_t	turbulent flame speed, m/s
u'	rms turbulent velocity, m/s
$\vec{u}$	velocity vector, m/s
V	cylinder volume, m^3
V_s	swept volume, m^3
W_{gi}	gross indicated work, J
W_i	indicated work, J

Greek symbols

Γ_ϕ	diffusion coefficient, kg/m s
ε	turbulent dissipation rate (per unit mass), m^2/s^3
λ	relative air-to-fuel ratio
ρ	density, kg/m^3
ρ_b	burned gas density, kg/m^3
ρ_u	unburned gas density, kg/m^3
τ_c	characteristic conversion time, s
τ_l	laminar kinetics time, s
τ_t	turbulent mixing time, s
φ	fuel-to-air equivalence ratio or (simply) equivalence ratio
ϕ	generalized variable

Abbreviations

ABDC	after bottom dead center
ATDC	after top dead center
BBDC	before bottom dead center
BDC	bottom dead center
CFD	computational fluid dynamics
CFR	cooperative fuel research
COV	coefficient of variance
CR	compression ratio
°CA	degrees of crank angle
EGR	exhaust gas recirculation
EOI	end of injection
EVC	exhaust valve closing
EVO	exhaust valve opening
HCCI	homogeneous charge compression ignition
IMEP	indicated mean effective pressure
IT	ignition timing
IVC	inlet valve closure
IVO	inlet valve opening
MBT	minimum spark advance for best torque
MFB	mass fraction burned
NO	nitric oxide
NO_x	nitrogen oxides
PFI	port-fuel injection
PISO	pressure implicit splitting of operators
rms	root mean square
rpm	revolutions per minute
SI	spark-ignition
TDC	top dead center
TWC	three-way catalyst
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 (NO_x), 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_x) 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