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A combined experimental and numerical study of thermal processes, performance and nitric oxide emissions in a hydrogen-fueled spark-ignition engine

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ARTICLE INFO

Article history:
Received 22 November 2010
Received in revised form
17 January 2011
Accepted 19 January 2011
Available online 17 February 2011

Keywords:
Hydrogen
Spark-ignition engine
Combustion efficiency
Heat transfer
NO emissions

ABSTRACT

This work concerns the study of a spark-ignition engine fueled with hydrogen, using both measured and numerical data at various conditions, focusing on the combustion efficiency, the heat transfer phenomena and heat loss to the cylinder walls, the performance, as well as the nitric oxide (NO) emissions formed, when the fuel/air and compression ratio are varied. For the investigation of the heat transfer mechanism, the local wall temperatures and heat flux rates were measured at three locations of the cylinder liner in a CFR engine. These fluxes can provide a reliable estimation of the total heat loss through the cylinder walls and of the hydrogen flame arrival at specific locations. Together with the experimental analysis, the numerical results obtained from a validated in-house CFD code were utilized for gaining a more complete view of the heat transfer mechanism and the hydrogen combustion efficiency for the various cases examined. The performance of the CFR engine is then identified, since the calculated cylinder pressures are compared with the measured ones, from which performance and heat release rates are calculated and discussed. Further, NO emission studies have been accomplished, with the calculated results not only being compared with the measured exhaust NO ones, but also further processed for conducting an in-depth investigation of the dependence of NO production on the spatial distribution of in-cylinder gas temperature. It is revealed that for lower fuel/air ratio the burned gas temperature is held at low level and the heat loss ratio is quite low. As the load increases and stoichiometric mixtures are used, the wall and in-cylinder gas temperatures increase substantially, together with the heat loss and the NO emissions, owing to the high hydrogen combustion velocity and the consequent high rate of temperature rise. The combustion efficiency is slightly increased, but the indicated efficiency is decreased due to higher heat loss.

1. Introduction

One important research aspect of the automotive industry is the improvement of the engine efficiency and the exploitation of the use of alternative fuels. Within this field, appropriate experimental test-benches are constructed, in order to investigate the combustion process and performance of the promising spark-ignition engines running on hydrogen under different operating conditions and strategies [1–6], together with the various in-cylinder processes taking place [7]. For this

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doi:10.1016/j.ijhydene.2011.01.103

Nomenclature

A	calibration constant in turbulent flame speed expression
c_p	specific heat capacity under constant pressure, J/kg K
k	turbulent kinetic energy (per unit mass), m^2/s^2
LHV_{H_2}	lower heating value of hydrogen, kJ/kg
m_{H_2}	inlet hydrogen mass, kg
n_{ex}	exhaust heat ratio
n_i	indicated efficiency (gross)
n_u	combustion efficiency
n_w	heat loss (to the walls) ratio
P	pressure, N/m^2
Pr	Prandtl number
q_w	wall heat flux, W/m^2
Q_B	real heat of combustion, J
Q_{ex}	exhaust heat, J
Q_n	net heat release, J
Q_{H_2}	theoretical heat of combustion, J
Q_w	wall heat loss, J
$\dot{Q}_c'''$	volumetric heat release rate due to combustion, J/s m^3
S_{cr}	source term due to crevice flows
S_h	source term of the enthalpy equation
$S\varphi$	source term
t	time, s
T	temperature, K
T_w	wall temperature, K
u_l	laminar flame speed, m/s
u_t	turbulent flame speed, m/s
u_T	friction velocity, m/s
u'	rms turbulent velocity, m/s
$\vec{u}$	velocity vector, m/s
V	cylinder volume, m^3
W_{gi}	gross indicated work, J
W_P	pumping losses, J
y	distance of the computational node from the wall, m
y^+	non-dimensional distance from the wall

Greek symbols

$\Gamma\phi$	diffusion coefficient, kg/m s
γ	ratio of specific heat capacities
λ	relative air-to-fuel ratio
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ_c	characteristic conversion time, s
τ_l	laminar kinetics time, s
τ_t	turbulent mixing time, s
τ_w	local wall shear stress, kg/m s^2
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
BTDC	before top dead center
CFD	computational fluid dynamics
CFR	Cooperative Fuel Research
CR	compression ratio
°CA	degrees of crank angle
EVO	exhaust valve opening
IT	ignition timing
IVC	inlet valve closure
MBT	minimum spark advance for best torque
NO	nitric oxide
NO_x	nitrogen oxides
PFI	port fuel injection
PISO	pressure implicit splitting of operators
rpm	revolutions per minute
SI	spark-ignition
TDC	top dead center
WOT	wide-open throttle

task many important parameters are measured, such as the cylinder pressure, emissions, wall temperatures etc., and processed to evaluate the engine performance [8,9].

Apart from the experimental investigations of hydrogen-fueled spark-ignition engines, numerical tools are also developed [7,10–13] in order to constitute an additional weapon in the detailed investigation of the various processes on those kind of engines. Especially, the results obtained from computational fluid dynamics (CFD) codes [7,13] can further assist to appraise the engine performance, since they can describe in a more fundamental way the in-cylinder phenomena [14], such as the flame kernel development, and the heat and mass transfer.

In the present study both experimental and numerical investigations have been accomplished simultaneously, in order to identify with detail some critical processes taking place in a hydrogen-fueled, spark-ignition engine. More specifically, measurements have been conducted on a Cooperative Fuel Research (CFR) engine at two compression ratios and three equivalence ratios at minimum spark advance for best torque (MBT), in order to appraise the heat transfer through the cylinder boundaries together with the engine's performance and emissions. Also, a validated in-house CFD code has been applied to simulate the functioning of that engine under the same operating conditions, in order to have a more detailed view of the in-cylinder processes. Both results (experimental and numerical) are combined, with a final task to examine the combustion efficiency, the thermal processes, the performance, and the spatial production of nitric oxide emissions for this engine.

2. Experimental data

2.1. Test engine

The experimental data used in the present study concern measurements on a CFR engine, operating at a constant