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Energetic and exergetic analyses of a variable compression ratio spark ignition gas engine

A. Javaheri [a], V. Esfahanian [a,*], A. Salavati-Zadeh [b], M. Darzi [b]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, Iran
[b] Vehicle, Fuel and Environment Research Institute, University of Tehran, Iran

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ABSTRACT

Considering the significance of obtaining higher efficiencies from internal combustion engines (ICE) along with the growing role of natural gas as a fuel, the present work is set to explore the effects of compression ratio (CR hereafter) and air/fuel equivalence ratio (AFER hereafter) on the energy and exergy potentials in a gas-fueled spark ignition internal combustion engine. Experiments are carried out using a single cylinder, port injection, water cooled, variable compression ratio (VCR hereafter), spark ignition engine at a constant engine speed of 2000 rpm. The study involves CRs of 12, 14 and 16 and 10 AFERs between 0.8 and 1.25. Pure methane is utilized for the analysis. In addition, a natural gas blend with the minimum methane content among Iranian gas sources is also tested in order to investigate the effect of real natural gas on findings. The energy analysis involves input fuel power, indicated power and losses due to high temperature of exhaust gases and their unburned content, blow-by and heat loss. The exergy analysis is carried out for availability input and piston, exhaust, and losses availabilities along with destructed entropy. The analysis indicates an increase in the ratio of thermo-mechanical exhaust availability to fuel availability by CR with a maximum near stoichiometry, whereas it is shown that chemical exhaust exergy is not dependent on CR and reduces with AFER. In addition, it is indicated that the ratio of actual cycle to Otto cycle thermal efficiencies is about constant (about 0.784) with changing CR, AFER and CNG fuel used.

1. Introduction

Today, the ICE designers are facing the strict limitations obliged by regulatory agenda concerning engine efficiencies and fuel consumption. The energy and exergy balance analyses are attractive and efficient tools for optimizing the ICEs performance. These analyses pave the way to estimate the energy and availability balances in engines and hence, to find better approaches for achieving higher efficiencies.

The input energy is apportioned into different categories: useful work, transferred heat to coolant and wasted energy from exhaust. As long as these conversions take place, the energy equation, i.e., the first law of thermodynamics is satisfied regardless of the possibility of the phenomena. The latter is taken into account by the exergy analysis, i.e., the second law of thermodynamics. Hence, in order to analyze the engine performance, i.e., to evaluate the irreversibilities associated with different phenomena such as combustion, mixing, heat transfer, and so, the first law fails to give a comprehensive insight and should therefore be supplemented with the second law, for which the key parameter is availability or exergy, the maximum theoretical work that can be obtained from a system as it comes to equilibrium with the reference environment.

The energy and exergy balances in ICEs for optimizing the performance have been the topic of many previous studies. Several researches considered CI engines [1–8], while others addressed SI engines [9–14]. Rakopoulos [9] investigated first and second laws of thermodynamics in a gasoline spark ignition engine using numerical simulation and experimental observations in different CRs, AFERs spark advances for an engine cycle. Sayin et al. [10] performed energy and exergy analyses for a four-stroke gasoline engine using fuels with different octane numbers in different engine speeds and torques. Sezer and Bilgin [11] studied the effect of air/fuel mixture properties on the exergy balance in gasoline SI engines. Fu et al. [12] also studied the distributions of energy and exergy in gasoline engines by investigating the influence of engine load and speed on the useful work, wasted exhaust energy and exergy losses. Li et al. [13] examined the effects of cooled EGR on the fuel conversion efficiency in a boosted, spark ignition (SI), direct injection (DI) gasoline engine at various loads using experimental observation and engine 1-D simulation. Rakopoulos and Giakoumis [15] reported a review related to the application of 2nd law analysis

* Corresponding author. Tel./fax: +98 21 88020741.
E-mail address: evahid@ut.ac.ir (V. Esfahanian).

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Nomenclature

Notation

C_p	constant pressure specific heat capacity
h	enthalpy
IP	indicated power
$\dot{m}$	mass flow rate
$\dot{n}$	gas mole flow rate
N	engine RPM
P	pressure
$\dot{Q}$	energy rate
R_u	universal gas constant
s	enthropy
T	temperature
$\dot{X}$	availability rate

Acronyms

AFER	air/fuel equivalence ratio
CR	compression ratio
ETU	engine timing unit
EVC	exhaust valve close
EVO	exhaust valve open
IMEP	indicated mean effective pressure
IP	indicated power
IVO	intake valve open
IVC	intake valve close
KI	knock intensity
MBT	minimum advance for best torque
MFB	mass fuel burned
LHV	lower heating value
VCR	variable compression ratio

Subscripts

amb	ambient
d	destructed
ex	exhaust
in	intake
l	loss
p	piston

Superscripts

ch	chemical
comb	combustion
th	thermal
ub	unburned

Greek letters

η	efficiency

to ICEs, which was comprised of the chemical and thermo-mechanical exergy balances in the engine and its subsystems.

On the other hand, compressed natural gas (CNG) seems to be a promising alternative fuel in many countries. The market demand for developing new gas engines in stationary and automotive applications is increasing due to its advantages concerning resources and its potential to meet strict engine emission regulations. Nevertheless, employment of CNG as fuel brings a new challenge in front of ICE designers, i.e. the severe diversity which exist in composition of different CNGs and therefore, causes changes in combustion rates and heating values and hence deviation in the performance of gas engines.

Despite the fact that many researches are devoted to the first and second law analyses in gasoline SI engines, CNG fueled SI engines have been addressed less, unlike the work of Gharehghani et al. [14] in which an experimental investigation on the thermal balance and performance of a turbocharged gas SI engine is carried out. Hence, there exist still numerous unclear facts about gas-fueled engines and their dependency on fuel composition and other performance parameters. In line with these concerns, the present research aims to investigate the influence of CR and AFER on the energy and exergy balances in a CNG-fuelled SI engine theoretically and experimentally using two different fuels. Pure methane is used since it is the most favored surrogate for CNG in researches. In addition, the test procedure and thermodynamic analyses are repeated for a real CNG fuel with minimum methane content among natural gas sources in Iran, and the observations on energy and exergy balances are compared to ensure if considering pure methane could give us a correct insight about the energy and availability distribution inside the engine.

All the tests are carried out in 2000 rpm and full load situation to eliminate the effects of engine load and speed. Considering higher resistance of CNG to knock, the engine CR of 16 is studied along with the engine CRs of 12 and 14 to investigate the situations with higher efficiencies. The equivalence ratios lie between AFER = 0.8 to AFER = 1.25.

2. Experimental setup and procedure

The schematic diagram of the experimental setup is depicted in Fig. 1. Meanwhile, Fig. 2 shows the single cylinder test bed including VCR single cylinder engine, the specifications of which are given in Table 1.

The CR is changed by altering the clearance shims between liner and lower part of engine. The engine management system is an open engine timing unit (ETU) which controls the spark and injection timings as well as injection duration. An AC dynamometer controls the engine speed. The test bed conditioning system controls the engine inlet water and inlet oil temperatures and the oil pressure. An AVL Indimicro with AVL GU22C pressure sensor is used for the in-cylinder pressure indicating. A crank based data with resolution of 7200 points is measured for each engine cycle. The data analysis is performed with an Indicom script program. The exhaust gas composition is measured with AVL-Dicom 4000, which measures the volumetric percentage of CO_2, CO, HC, O_2 and NO_X. This instrument measures the total amount of hydrocarbons present in the engine emission including methane and other ones. A Micro Motion coriolis flowmeter measures the fuel mass flow rate. An Innovate LM1 wide band AFER sensor system is used for AFER measurement.

The characteristics of the fuels used are brought in Table 2. Pure methane (CNG1) is considered as surrogate for natural gas. Additionally, all the tests are repeated utilizing a real natural gas (CNG2), which has the minimum methane content among gas sources in Iran.

Six test sets are performed for three CRs and two CNG compositions. All experiments are carried out at 2000 rpm and full load condition. In all the tests, the spark advance is set such that the engine runs at MBT (Minimum advance for Best Torque). To this end, the spark advance is adjusted so that the crank angle at which 50% of the fuel is burned (MFB50%) remains constant, which for the present research is 10.5 ± 0.5 ATDC. Meanwhile, it is assured that the knock intensity remains under threshold, i.e., 1 < KI < 2. In each test, after the engine stabilization, 300 cycles of in-cylinder