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A comparative study on the first and second law analysis and performance characteristics of a spark ignition engine using either natural gas or gasoline

A. Gharehghani [a], R. Hosseini [a,*], M. Mirsalim [a], Talal F. Yusaf [b]

[a] Department of Mechanical Engineering, Amirkabir University of Technology, 424 Hafez Avenue, P.O. Box 15875-4413, Tehran, Iran
[b] University of Southern Queensland, Toowoomba, 4350 QLD, Australia

HIGHLIGHTS

- Effects of fuel on the energy and exergy balance in bi-fuel SI engine investigated.
- 1st and 2nd laws efficiency of CNG are 5.4% & 3.18% more than gasoline respectively.
- Destructed exergy in gasoline case is about 5.8% higher than CNG case, averagely.
- Gaseous fuel produces lower CO emission while its NOx is higher than gasoline.

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ABSTRACT

In this study, the effect of fuel type; gasoline or natural gas on the energy and exergy balance as well as the performance of spark ignition engine was experimentally investigated. The experiments were conducted using a four cylinder, naturally aspirated CNG–gasoline bi-fuel engine at wide open throttle (WOT) operating condition. The results showed that when engine was fed with gasoline, the output power was higher than that of gaseous fuel by 4.2 kW on average throughout the engine speed range. Thermal efficiency of the engine with natural gas was higher than that of the gasoline by approximately 5.4% throughout the engine speed range. In addition, CNG fuel showed higher exergetic efficiency than gasoline, and based on these results second law efficiency of CNG engine was higher than that of gasoline engine by 3.18% on average. This was largely due to combustion temperature increase in CNG case. For all operating points, the percentage of energy and exergy transfer through exhaust gases and the cooling system in gasoline are lower than CNG. However the destructed exergy of gasoline was higher than CNG by about 5.8%, averagely.

1. Introduction

The use of alternative fuels in IC engines has gained considerable attention lately due to the ever increasing conventional fossil fuel prices and the enforcement of strict emission regulations. Natural gas seems to be one of the promising substitutes for fossil fuels in the future owing to its availability, safety, clean combustion, and economic feasibility. However, thorough evaluation of energy and exergy of CNG–gasoline bi-fuel spark ignition engine is limited in the literature. Some of the related work to this topic only compared the performance of gasoline and natural gas fueled engines [1–3]. However, to optimize the performance of CNG–gasoline bi-fuel engines, the energy and exergy analyses are necessary.

To improve the first and second laws efficiencies in engine, energy and exergy destructions must be decreased. Therefore, it is important to know the fraction of each term which is the essential aim of the energy and exergy analysis. Energy and exergy balance investigation in compression ignition or spark ignition engines was studied previously [4–7]. Some efforts were made to compare the first and second laws for all types of engines and combustions [8–10]. Tsurushima et al. [9] compared the thermal balance for conventional diesel with HCCI and premixed diesel combustion and described the effect of Exhaust Gas Recirculation (EGR). They showed that by using EGR, heat losses decreased for both HCCI and premixed diesel combustion at lower load conditions. Also, the effect of fuel composition on heat balance in a

* Corresponding author. Tel.: +98 21 64543433; fax: +98 21 66419736.
E-mail address: hoseinir@aut.ac.ir (R. Hosseini).

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Nomenclature

$\dot{m}_a$	air mass flow (kg/s)	EGR	exhaust gas recirculation
$\dot{m}_c$	mass flow rate of cooling fluid (kg/s)	HCCI	homogeneous charge compression ignition
$\dot{m}_e$	mass flow rate of exhaust gas (kg/s)	IC	internal combustion
$\dot{m}_f$	fuel mass flow (kg/s)	LHV	lower heating value
T	absolute temperature (K)	LPG	liquefied petroleum gas
w_a	relative air humidity	MBT	maximum brake torque
AFR	air–fuel ratio	NA	naturally aspirated
BTDC	before top dead center	RPM	revolution per minute
CNG	compressed natural gas	VVT	variable valve timing
DI	direct injection	WOT	wide open throttle

single cylinder diesel engine operating on diesel, ethanol–diesel blends and fumigated ethanol demonstrated that for more than 15% blending, the thermal balance was significantly different compared to diesel [10].

The first and second laws analysis in a natural gas/diesel dual-fuel engine was investigated by Costa et al. [11] by developing an experimentally validated mathematical model to study the effect of air conditions, the type and quantity of fuel and the exhaustion gases on the engine performance. Recently, the exergetic and energetic evaluations of hybrid electric vehicle thermal management systems was done by Hamut et al. [12] to understand the effect of the operating parameters on the system performance. They showed that by optimizing the input parameters to the thermal management system, the performance of system could be enhanced especially from exergy point of view.

The results of energy and exergy analysis on a naturally aspirated gasoline engine showed that at low-speed and low-load, cooling fluid mainly contains the waste heat energy while at high-speed and high-load, exhaust gas energy is greater than the cooling fluid energy both in quantity and exergy percentage [13]. Another investigation on exergy balance in SI engines showed that a lean mixture gives the best first and second law efficiencies, and also increasing the initial charge temperature leads to a decrease in the first and second law efficiencies [14]. The effect of hydrogen enrichment on exergy analysis of a lean burn natural gas engine showed that with increasing hydrogen fraction, the irreversibility during the combustion decreases, and the second-law efficiency sharply increases close to the lean burn limit [15]. Another study on thermal balance of an LPG fueled SI engine with the addition of water reported that by increasing the water injection level, the percentage of output power increased, while the heat transferred to cooling fluid and exhaust gases decreased [16].

As mentioned above, many studies have been performed on energy and exergy analysis of diesel, diesel/natural gas dual fuel and gasoline engines, however only limited work has been done on bi-fuel (natural gas and gasoline) spark ignition engines. In this study, the effect of fuel type CNG and gasoline on the performance and efficiency of natural aspirated bi-fuel spark ignition engine was experimentally studied at different engine speed. For heat balance study, a control volume was assumed around the engine, and the first and second laws of thermodynamics were applied to calculate the input and output energies and exergies at the steady state condition.

2. Engine test setup

The engine used in this study was a bi-fuel (can be operated either with gasoline or CNG) four-cylinder, natural aspirated, water cooled, spark ignition, which was coupled to an AVL-190 kW dynamometer as shown in Fig. 1. The engine specifications are summarized in Table 1.

Fuel consumption was measured using an AVL-735 fuel meter. Analysis of the exhaust gas composition was undertaken using a Horiba-7170D (Gas Analyzer). K-type thermocouples were used to measure the temperature of exhaust gas, cooling fluid and the intake air. Table 2 summarizes the accuracy of the measurements and the uncertainty of the results for the tested parameters.

3. Energy balance analysis

To calculate the thermal balance in the engine, a control volume was assumed around the engine. The output energies consist of output power, energy consumed by the cooling fluid and the energy of exhaust gases.

The first law for control volume can be presented as follows:

$$\dot{Q}_f + \dot{Q}_a = \dot{W}_{sh} + \dot{Q}_e + \dot{Q}_c + \dot{Q}_u \quad (1)$$

where, $\dot{Q}_f$ is the fuel energy, $\dot{Q}_a$ is the energy of intake air, $\dot{W}_{sh}$ is the output power on shaft, $\dot{Q}_e$ is the energy of exhaust gases, $\dot{Q}_c$ is the energy consumed by the cooling fluid, and $\dot{Q}_u$ is the unaccounted losses to ambient.

The heat supplied by the fuel was calculated from Eq. (2):

$$\dot{Q}_f = Q_{LHV,f} \times \dot{m}_f \quad (2)$$

where $Q_{LHV,f}$ is the lower heating value of fuel (MJ/kg).

The energy of intake air is determined as follows [17]:

$$\dot{Q}_a = \dot{m}_a(\Delta h_a + w_a \Delta h_{H2O}) \quad (3)$$

where $\dot{m}_a$ is the mass flow rate of air (kg/s), Δh_a is the enthalpy difference with standard state (kJ/kg) and $w_a \Delta h_{H2O}$ is the enthalpy increment due to humidity of air (w_a is the relative humidity).

Energy transferred to the cooling fluid was calculated as below:

$$\dot{Q}_c = \dot{m}_c \times C_c \times \Delta T_{Engine} \quad (4)$$

In Eq. (4), $\dot{m}_c$ is the mass flow rate of the cooling fluid (kg/s), C_c is heat capacity of the cooling fluid which is 3.6 kJ/kg K and ΔT_{Engine} is the temperature difference between inlet and outlet cooling fluid.

An empirical equation was used to calculate the energy of exhaust gases [18] as shown below:

$$\dot{Q}_e = \dot{m}_e(A + B_1 T + B_2 T^2) \quad (5)$$

where

$$A = 8279.5 - 13744.4\lambda + 5160.9\lambda^2$$

$$B_1 = 1.35 - 0.6\lambda + 0.22\lambda^2$$

$$B_2 = 0.00002 - 0.00007\lambda + 0.00005\lambda^2$$