Energy and Exergy Analysis of Internal Combustion Engine with Injection of Hydrogen into the Intake Manifold

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Abstract- **In this article, first and second law analyses of a spark ignition engine was performed. The experimental data were obtained from a study of the effects of injection of bottled hydrogen gas on spark ignition engine performance that was conducted at the NASA Lewis Research Center in Cleveland, Ohio, in 1977. The tests were performed with two modes of fueling: gasoline mode and gasoline with hydrogen injection mode. The second law analysis determined the main exergy losses and destructions in the system. The objectives of this study are to evaluate the effect of hydrogen gas injection on the exergy destruction and exergy loss to the environment and apply performance assessment parameters. Engine energy and exergy rate balances were determined. For each mode of operation, energy and exergy efficiencies were calculated and compared to one another. Results indicate that the addition of hydrogen improved the thermal efficiency of very lean mixtures only (Φ=0.69). The results of tested gasoline with hydrogen mode demonstrated different energetic performance than the gasoline mode. Results indicate that with the hydrogen injection, the engine demonstrated lower exergetic efficiency and higher exergy destruction as compared to engines operating with gasoline only. Thus, more attention should be paid to the use of hydrogen from the exergy perspective. From the obtained results and the detailed study of previous works, it can be concluded that the addition of hydrogen can improve the performance of spark ignition engines with lean mixtures, in which case hydrogen injection improves the performance of the compression ignition engines at low loads.**

Keywords- Hydrogen; Thermal Efficiency; Energy; Exergy; Internal Combustion Engine

I. INTRODUCTION

Concerns regarding the limitations of energy resources and the lack of fossil fuels have become increasingly greater in recent years. For this reason, many countries are examining their energy policies and exerting great efforts to eliminate waste. Scientists have also developed a great interest in energy conversion devices to maximize the gain from energy conversion processes. The first and the second law of thermodynamics are very important tools used to evaluate energy conversion processes. The first law, which deals with the quantity of energy, serves as a tool for tracking energy during a process. The second law deals with the quality of energy, and focuses on the degradation of energy during a process, entropy generation, and lost work. The second law analysis help advise improvements [1].

Internal combustion engines used as energy conversion devices have experienced many changes in their design, materials, and operating characteristics. In recent decades, research focusing on reducing pollutants emission and fuel economy has become increasingly common [2].

Several researchers have investigated the use of alternative fuels to achieve this goal. One of the investigated fuels is hydrogen, which has been investigated to enhance the performance of diesel engines. The lean burning and better combustion properties of hydrogen make its use promising [2, 3].

Using the first law of thermodynamics to perform an energy analysis through determination of various performance parameters is not enough to fully evaluate energy resource utilization. Exergy (availability) analysis of the thermal systems help to explain the thermodynamic details of the system. Exergy is defined as the maximum useful work that can be obtained from the system in a given state in a specified environment. The exergy destruction (irreversibility or lost work) is defined as the wasted work potential during a process as the result of irreversibilities.

Exergy analysis enables the determination of the locations, causes and magnitude of energy resource waste in a system [4].Internal combustion engines used as energy conversion devices have experienced many changes in their design, materials, and operating characteristics. In recent decades, research focusing on the reduction of pollutant emissions and fuel economy have become increasingly prevalent [2].

When calculating exergetic efficiency, the actual performance of a process/system is compared to its ideal performance while the losses that affect performance are quantified by exergy destruction [5]. In internal combustion engines (ICE), exergy applications are significant [6]; the exergetic efficiency of diesel engines was determined to be approximately 39% [5, 7], while that of gasoline engines was determined to be 13% at low loads and 21% at high loads [4].

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In the present work, energetic and exergetic analysis is performed on spark ignition engine systems to investigate the effects of the injection of bottled hydrogen gas on performance. The experiment was conducted at the NASA Lewis Research Center in Cleveland, Ohio. The first and second laws of thermodynamics are employed to analyze the quantity and quality of energy in a spark ignition engine using gasoline fuel and hydrogen. Performance parameters of the engine for each fuel were computed and compared to one another, including the brake specific fuel consumption, fuel energy, brake thermal efficiency, heat and exhaust losses, fuel exergy, exergetic efficiency, exergy loss accompanying heat loss, exergy loss accompanying the exhaust gas, and exergy destroyed in the engine.

II. ENERGY ANALYSIS

With the purpose of simplifying first law calculations, the following assumptions are made:

1) The engine operates at a steady state;

2) The entire engine, including the dynamometer, is selected as a control volume;

3) The combustion air and exhaust gas each forms an ideal gas mixture;

4) Potential and kinetic energy effects of the combustion air, fuel stream and exhaust gas are not considered.

The energy input of any internal combustion (IC) engine is contained in its fuel. The energy input is then converted into other forms. In an engine, the input chemical energy of fuel is usually converted to the following forms:

1) Useful work output or shaft energy (Pshaft);

2) Energy transferred to cooling water ;

3) Energy transferred to the exhaust gases

4) Uncounted losses due to friction, radiation, heat transfer to surroundings, operating auxiliary equipment, etc.

The input energy to the engine is expressed as follows:

$$\overset{o}{Q}_f = \overset{o}{m}_f \times LHV \tag{1}$$

where LHV is the lower heating value (kJ/kg), and $\overset{o}{m}_f$ is the mass flow rate of fuel (kg/s).

The uncounted loss is determined by performing an energy balance, expressed as follows:

$$\overset{o}{Q}_f = \overset{o}{m}_f \times LHV \tag{2}$$

Thermal efficiency of the engine (energy percentage), is usually determined as the ratio of the power output (network) to the fuel energy input, expressed as follows:

$$\eta_{th} = \frac{p_{shaft}}{\overset{o}{Q}_f} \tag{3}$$

III. EXERGY ANALYSIS

The state of the environment and the state of the system are the primary factors which affect exergy. Therefore, exergy is a combination property. The exergy analysis of thermal systems is used to improve energy source utilization by determining the order of exergy destruction and loss in the processes and components of the system, and subsequently reducing them [7].

The second law analysis indicates various forms of energy which achieve various levels of useful mechanical work (exergy). In an IC engine, the exergy input (Ain) which is contained in the chemical exergy of fuel is converted into other forms of exergy [8].In an engine, the input fuel exergy is converted into the following forms:

1). Useful work output or shaft availability (Ashaft);

2). Availability transferred to cooling water (Acw);

3). Availability transferred to the exhaust gases (Aeg);

4). Uncounted availability destructions ($A_{destoyed}$) due to friction, radiation, heat transfer to surroundings, etc.

From the second law analysis, all transferred exergy can be calculated as follows [8]:Chemical availability of fuel or input exergy

For gasoline only:

$$A_{in} = A_{gasoline} = (1.0338)\overset{o}{m}_f \times LHV \tag{4}$$

For gasoline with hydrogen injection:

$$A_{in} = A_{gasoline} + A_{hydrogen} \tag{5}$$

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$$A_{igasoline} = (1.0338)\overset{o}{m}_f \times LHV$$
$$A_{hydrogen} = 0.9\overset{o}{m}_{hydrogen} * LHV \quad (6)$$

1). Shaft exergy:

A_{shaft} = Brake power outpu

t2). Exergy transferred to cooling water:

$$A_{cw} = \overset{o}{Q}_{cw} - T_o(s - s_o)$$
$$A_{cw} = \overset{o}{Q}_{cw} - \left[\overset{o}{m}_w \times Cp_w \times T_o \times \ln (T_2/T_1)\right] \quad (7)$$

3). Exergy transferred to the exhaust gases:

$$A_{eg} = \overset{o}{Q}_{eg} - T_o(s - s_o)$$
$$A_{eg} = \overset{o}{Q}_{eg} - \overset{o}{m} T_o\left[C_{pex} \ln \frac{T}{T_o} + R \ln \frac{p_o}{p_{ex}}\right] \quad (8)$$

4). Destroyed exergy:

$$A_{destroyed} = A_{in} - (A_{shaf} + A_{cw} + A_{eg}) \quad (9)$$

The exergy efficiency (η_{II}) is the ratio of total exergy recovered from the system to the total exergy input into the system. The recovered exergy includes A_{shaft}, A_{eg} and A_{cw}. Therefore:

$$\eta_{II} = \frac{\text{Recovered Exergy}}{\text{Input Exergy}}$$
$$\eta_{II} = 1 - \frac{A_{destroyed}}{A_{in}} \quad (10)$$

IV. RESULTS AND DISCUSSION

The locations of the available fuel energy losses or destructions are very important. Table I depicts the engine energy balance obtained from a study of the effects of injection of bottled hydrogen gas on spark ignition engine performance conducted at the NASA Lewis Research Center in Cleveland, Ohio, in 1977,[9]. Table II details important properties of gasoline and hydrogen fuel.

In this section, the first and second laws of thermodynamics are employed to analyze operation of a spark ignition engine with the injection of hydrogen into the intake manifold. Therefore, the effect of hydrogen injection on the energy and exergy balances of the engine operations are evaluated and compared to that of the gasoline mode. Tables III and IV show the calculated energies and exergies.

Table III shows the energy balance of the engine for all conducted tests. The output power for all tests was held constant and equal to 27 kW. Tests 1 and 2 were conducted with an equivalence ratio 0.69, indicating a very lean fuel to air mixture. As shown, in order to obtain an output power of 27 kW, the input fuel power was 131 kW for gasoline mode only, whereas the input fuel power was 118 kW for gasoline with hydrogen injection mode. This indicates the improvement of thermal efficiency, which may be explained as follows. In gasoline mode, when the mixture is made leaner above certain limits of the design features of the engine (Φ=0.69), the combustion process begins to develop differently. This change in the process of combustion is due to poorer ignition conditions induced by lean mixtures by the spark and flame propagation [10]. This causes a large portion of the fuel power to exit with the exhaust (0.39 %) due to burning of the fuel in the exhaust. Hence, the exhaust temperature is increased.

For gasoline with hydrogen injection mode, the high flame speed of hydrogen improves combustion of the lean gasoline air mixture and leads to a decrease in the portion of lost exhaust power (0.27%). Alternatively, the small quenching distance of hydrogen [11] causes the portion of heat lost by cooling to increase from 0.3 to 0.36. Figure 1 shows that the thermal efficiency increased from 20.61% to 22.8% at Φ=0.69 when hydrogen was injected with gasoline.

TABLE 1 ENGINE ENERGY BALANCE

Test No.	Hydrogen addition [a]	Equivalence ratio	Apparent flame speed		Input energy		Energy lost to cooling system		Energy lost to exhaust		Indicated horse power		Brake horse power		Exhaust manifold temperature	
			m/s	ft/s	kW	hp	kW	hp	kW	hp	kW	hp	kW	hp	K	F
1	No	0.69	22	71	131	175	39	52	51	68	35	47	27	36	989	1322

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2	Yes	[b]0.69	35	114	118	158	42	56	32	43	37	50	27	36	896	1153
3	No	[b]0.8	31	100	118	158	41	55	37	49	34	46	27	36	969	1286
4	Yes	0.80	40	132	122	163	45	60	33	44	37	50	27	36	943	1238
5	Yes	0.98	45	146	126	169	49	65	35	47	37	49	27	36	986	1315
6	No	0.96	34	113	122	164	46	62	34	46	37	49	27	36	981	1306

[a] Flow rate = 0.635 kg/hr (1.4 lb/hr)

b Minimum-energy-consumption equivalence ratio

TABLE 2 PROPERTIES OF GASOLINE AND HYDROGEN

Property	Hydrogen	Gasoline
Stoichiometric ratio for complete combustion (A/F by mass)	34:1	15:1
Auto ignition temperature (^{0}C)	585	260-460
Flame temperature (^{0}C)	2207	2307
Quenching distance (mm)	0.64	~ 2
Ignition energy @ stoich (mJ)	0.02	0.24
Flame speed @ stoich (m/s)	3.46	0.42
LHV (kJ/kg)	119810	44400

TABLE 3 ENERGY ANALYSIS OF GASOLINE AND HYDROGEN INJECTION MODES OF OPERATION

Equivalence ratio	Fuel type	Q_{in}		W_{shaft}		$Q_{cooling}$		$Q_{exhaust}$		$Q_{uncounted}$	
		kW	%	kW	%	kW	%	kW	%	kW	%
0.69	Gasoline	131	100	27	20.61	39	0.3	51	0.39	14	10.68
[b]0.69	Gasoline + hydrogen	118	100	27	22.88	42	0.36	32	0.27	17	14.40
[b]0.8	Gasoline	118	100	27	22.88	41	0.35	37	0.31	13	11.01
0.8	Gasoline + hydrogen	122	100	27	22.13	45	0.37	33	0.27	17	13.93
0.98	Gasoline + hydrogen	126	100	27	21.42	49	0.39	35	0.28	15	11.90
0.96	Gasoline	122	100	27	22.13	46	0.38	34	0.28	15	12.29

For Φ=0.8, 0.96, and 0.98, the burning of hydrogen results in increased maximum pressure due to the high flame speed of hydrogen speed [2]. Therefore, for these equivalence ratio values in the hydrogen injection mode, increasing the maximum pressure leads to increased mechanical losses. In order to obtain the same output brake power, the input power was increased. This leads to decreasing thermal efficiency, as shown in Figure 1.

Exergy analysis:

The exergy values of the gasoline and gasoline with hydrogen used in the test are presented in Table IV. It is observed that the exergy values of the tested fuels are similar to the fuel energy values. This is because the specific fuel exergy is related to the lower heating value.

TABLE 4 EXERGY ANALYSIS OF GASOLINE AND GASOLINE WITH HYDROGEN INJECTION MODES OF OPERATION

Equivalence ratio	Fuel type	A_{in}		A_{shaft}		$A_{coolsys}$		A_{ex}		Exergy dest.(I)		η_{II}	η_{th}
		kW	%	kW	%	kW	%	kW	%	kW	%		
0.69	Gasoline	135.43	100	27	19.9	4.21	1.98	33.36	24.6	66.42	53.4	46.55	20.61
[b]0.69	Gasoline + hydrogen	120.96	100	**27**	22.3	4.83	2.55	20.83	17.2	65.32	57.9	42.1	22.88
[b]0.8	Gasoline	121.99	100	27	22.1	4.62	2.42	24.17	19.8	62.20	55.6	44.37	22.88
0.8	Gasoline + hydrogen	125.09	100	27	21.6	5.49	2.81	21.52	17.2	67.97	58.4	41.61	22.13
0.98	Gasoline + hydrogen	129.23	100	27	20.9	6.42	3.2	22.89	17.7	69.68	58.2	41.81	21.42
0.96	Gasoline	126.12	100	27	21.4	5.71	2.91	22.23	17.6	67.04	58.1	41.94	22.13

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However, as shown in figure 2, the fuel exergy inputs are approximately 3.8% and 2.5% higher than that of gasoline and gasoline with hydrogen energy inputs, respectively. As shown in figure 3, calculation results indicate that the exergy lost in the cooling system of the engine in gasoline with hydrogen mode (2.55 %, 2.81%, and 3.2%) was higher than that lost in gasoline mode (1.98%, 2.42 %, and 2.91%). This may be due to increased heat transfer to the cylinder wall due to the lower quenching distance of hydrogen.

Figure 4 shows that the exergy loss due to the exhaust gases decreased in gasoline with hydrogen mode (17.2%, 17.2%, and 17.7%) as compared to gasoline mode (24.6%, 19.8%, and 17.6%). This reduction is due to the reduction of the exhaust gas temperature [7]. Figure 5 shows that the exergy destruction was higher in gasoline with hydrogen mode (57.9%, 58.4%, and 58.2%) as compared to gasoline mode (53.4%, 55.6%, and 82.1%).

A significant fraction of the fuel exergy is destroyed in engine irreversible processes such as heat transfer, combustion, the mixing of air and fuel, friction, etc., and exergy is not conservative. Results indicate that operation in gasoline with hydrogen mode yields higher exergy destructions. Consequently, exergetic efficiency for the gasoline with hydrogen mode of operation is lower compared to that of gasoline mode, as shown in Figure 6.

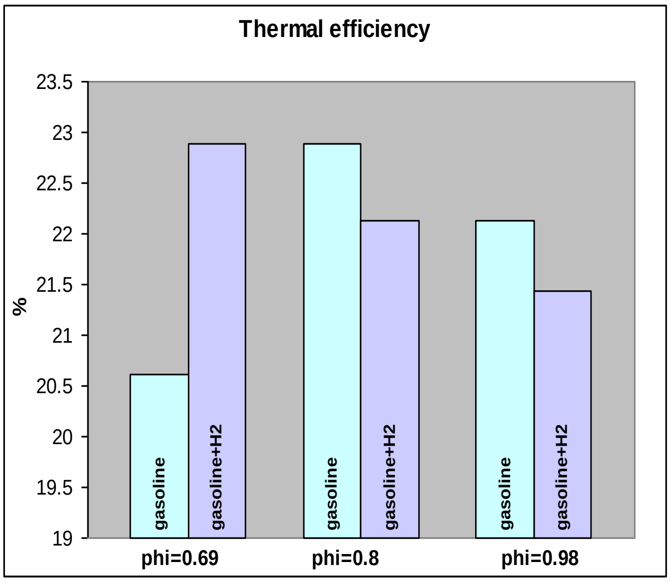

Fig. 1 Thermal efficiency at different equivalence ratios.

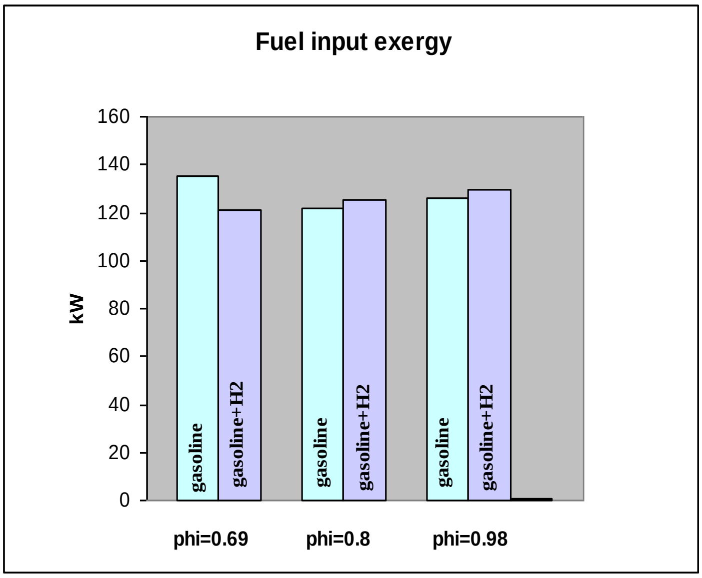

Fig. 2 Fuel input exergy at different equivalence ratios.

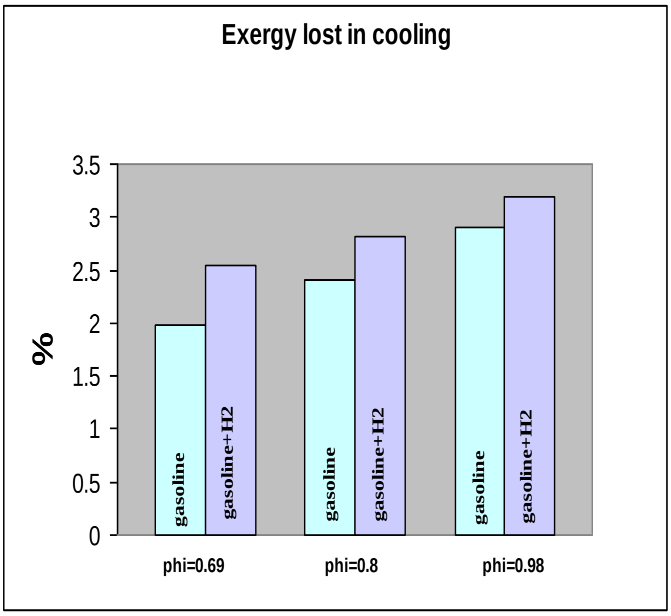

Fig. 3 Exergy lost in cooling at different equivalence ratios.

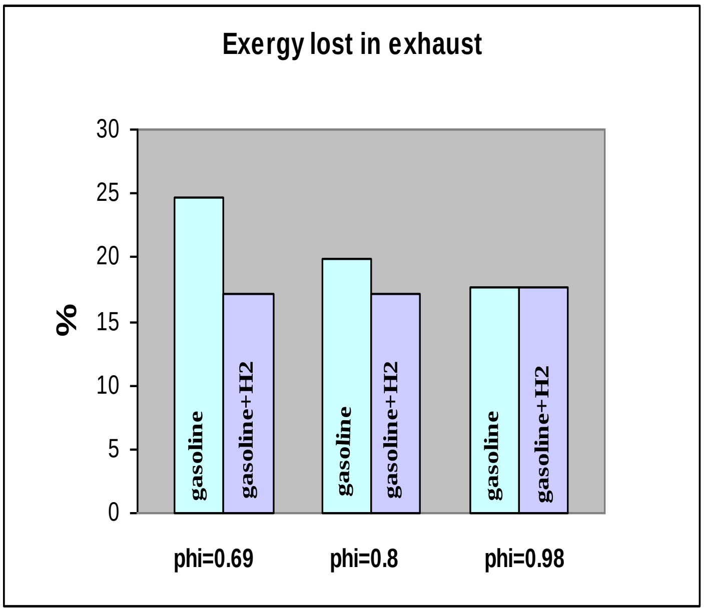

Fig. 4 Exergy lost in exhaust at different equivalence ratios.

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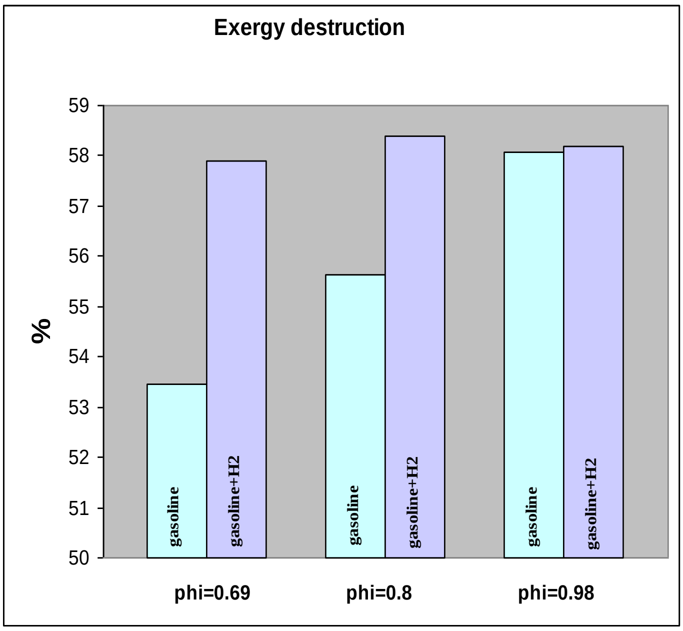

Fig. 5 Exergy destruction at different equivalence ratios.

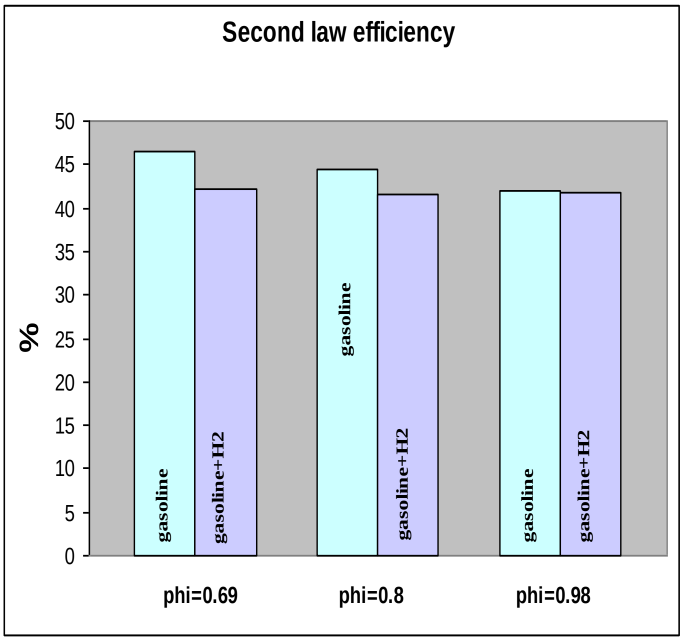

Fig. 6 Second law efficiency at different equivalence ratios.

V. CONCLUSIONS

The first and second law analyses of a spark ignition engine using gasoline and gasoline with injection of hydrogen have been conducted. The balance of energy rate and the exergy rate were determined using experimental data from a study of the effects of injection of bottled hydrogen gas on spark ignition engine performance that was conducted at the NASA Lewis Research Center in Cleveland, Ohio, in 1977. Considering the results of the present work, the following conclusions can be summarized:

1). The engine has lower thermal efficiency when a very lean mixture is introduced (Φ=0.69);

2). The thermal efficiency was improved when the hydrogen was injected with the very lean mixture due to the improvement of combustion;

3). Increasing the richness of the mixture (Φ=0.8, 0.96, 0.98) with injection of hydrogen decreases thermal efficiency;

4). Injection of hydrogen may be beneficial to efficiency in the case of a very lean mixtures only;

5). Second law analysis of the system indicates that the exergy loss in exhaust decreased in gasoline with hydrogen mode, which be due to the decrease of the exhaust temperature;

6). The exergy loss during cooling increased in gasoline with hydrogen mode, which may be due to increased heat transfer to the cylinder wall due to the lower quenching distance of hydrogen, and the total exergy loss (exhaust + cooling) decreased;

7). The exergy destruction increased in gasoline with hydrogen mode for all equivalence ratios, which may be due to irreversibility in engine processes such as heat transfer, combustion, friction in engine parts, the mixing of air and fuel, which destroy energy and is a primary factor of system inefficiency primarily caused by combustion [7];

8). The increase of the exergy destruction in gasoline with hydrogen mode leads to decreased second law efficiency.

9). Addition of hydrogen can improve the performance of spark ignition engines at lean mixtures, whereas it improves the performance of compression ignition engines at low loads [12, 13];

10). Hydrogen injection results in lower exergetic efficiency and higher exergy destruction compared to engines operating with gasoline only.

11) The results obtained by this study can be used as a basis for exergoeconomic analysis of systems.

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Nomenclature

A_{cw}	Exergy transferred to cooling water (kW)
$A_{destroyed}$	Destroyed exergy (kW)
A_{eg}	Exergy transferred to the exhaust gases (kW)
$A_{gasoline}$	Chemical exergy of gasoline fuel or input availability (kW)
$A_{hydrogen}$	Chemical exergy of hydrogen fuel or input availability (kW)
A_{in}	Chemical exergy of fuel or input availability (kW)
A_{shaftn}	Shaft exergy (kW)
C_{pex}	Specific heat of exhaust gases (J/kg K)
C_{pw}	Specific heat of water gases (J/kg K)
LHV	Lower heating value (J/kg)
$\overset{o}{m}_f$	Mass flow rate of fuel (kg/s)
p	Pressure (Pa)
p_o	Ambient pressure (Pa)
p_{ex}	Exhaust pressure (Pa)
$\overset{o}{Q}_{cw}$	Energy transferred to cooling water(kW)
$\overset{o}{Q}_{eg}$	Energy transferred to Exhaust gases(kW)
$\overset{o}{Q}_f$	Amount of fuel energy content (kW)

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$\overset{o}{Q}_{uncounted}$	Uncounted energy losses (kW)
s	Entropy (J/kg K)
s_o	Ambient entropy (J/kg K)
T_o	Ambient Temperature (K)
T_1	Cooling water inlet temperature (K)
T_2	Cooling water outlet temperature (K)
η_{II}	Second law efficiency %
η_{th}	Thermal efficiency %
Φ	Equivalence ratio

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