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Comparative thermodynamics analysis of gasoline and hydrogen fuelled Internal Combustion Engines

M. Faizal[1,2] and R. Saidur[3]

[1] ADP, Taylor's University Lakeside Campus, 47500 Selangor, Malaysia

[2] Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

[3] Center of Research Excellence in Renewable Energy (CoRERE), King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

Abstract

Comparative thermodynamics models for naturally aspirated gasoline and hydrogen fuelled spark ignition internal combustion engines were developed according to the first and second law of thermodynamics. Analysis of mean effective pressure, power, torque, exergy due to heat transfer, exergy due to work, and irreversibility were made. Thermodynamics model was developed according to Ideal Otto cycle. Assumptions were made according to air standard assumptions. First law efficiency, mean effective pressure, power, and torque of hydrogen fuelled engine are higher than gasoline fuelled engine due to higher compression ratio associated with hydrogen fuelled engine, 14.5:1 compared to 8:1 of gasoline fueled engine. Hydrogen fueled internal combustion engine can have higher compression ratio because of higher auto-ignition temperature, 858°C compared to 300-450°C for gasoline fuel. A second law analysis shown that hydrogen fuelled engine had higher second law efficiency of 69.40% compared to 60.49% for a gasoline fuelled engine due to significantly lower irreversibilities and lower specific fuel consumption. The greater heat transfer exergy of hydrogen fuelled occurs due to a greater amount of heat generated from hydrogen combustion. However, the high available thermal energy of hydrogen fuelled engine needs higher cooling load which decreases the power of the engine.

Keywords: Exergy; Thermodynamics; 1st and 2nd law analysis; hydrogen fuel; internal combustion engine

1. Introduction

Demand and usage of energy is increasing throughout the world. Pollution increased. Current energy sources are depleting. In recent years, the economy of Malaysia grew rapidly. The private vehicle populations grew rather in an escalating manner. This phenomenal rise of vehicles number has increased energy consumption, especially fossil fuels. Consequently air pollution has increased to a remarkable extent. In 2002, the transportation sector of Malaysia used about 40% of the total energy consumed [1]. Valero and Valero [2] indicate that there might not be enough available resources to satisfy the predicted future mineral demand. The changing of fuel from gasoline to hydrogen demands a thermodynamic analysis to determine and predict changes in performance and efficiency. Exergy is an effective method using the conversion of mass and conversion of energy principles together with the second law of thermodynamics for the design and analysis of energy system [3]. Analysis of mean effective pressure, power, torque, exergy due to heat transfer, exergy due to work, and irreversibilities will be provided. First and second law efficiencies for both gasoline and hydrogen fuelled will be derived from this analysis.

Studies had been made applying the second law of thermodynamics to internal combustion engines to diagnose losses and suggest solutions for improving engine performance and efficiency. A lot of work has been done for alternative fueled engines. Bayraktar [4] has developed and validated an engine simulator to compare performance and emission characteristics of an engine working on LPG and gasoline. Mustafi,

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Miraglia [5], in their work compared power-gas with gasoline and natural gas (NG). Rakopoulos and Giakoumis [6] shown that exergy of methane and methanol is lower than dodecane but the pollutant emissions decreased. Caton [7], stated that the destruction of the fuel's available energy due to the combustion process decreases for operation at higher temperatures. The highest availability was found to exist for the unreacted fuel. This represents a maximum potential to perform work. When this chemical energy is transformed into thermal energy, some portion (which depends on the final temperature) of the original availability is destroyed.
Hydrogen, being highly reactive, offers wide range of advantages in performance. One of the principal advantages that hydrogen has a fuel is the wide flammability limits (see Table 1). These wide limits allow that the combustion occurs with different equivalence ratios, in particular with slight mixtures, which makes relatively easy to operate an engine with hydrogen [8].

Table 1: The gasoline and other fuel properties [9]

Fuel type	RON	Formula	Molecular weight	Density (kg/m3)	Heat of vaporization (kJ/kg)	Lower heating value (Mj/kg)	Stoichiometric air /fuel ratio
Gasoline	95.8	C8H16	106	750	305	44.0	14.60
Methane	120	CH4	16	720	-	50.0	17.23
Propane	112	C3H8	44	545	426	46.4	15.67
Hydrogen	106	H2	2	90	-	120.0	34.30

The minimum ignition energy and the wide range of flammability of hydrogen allow the presence of combustion at lower equivalence ratios than those with gasoline, and it can obtain a higher power at specific equivalence ratios. The higher power output of the engine, running with hydrogen, was about 80% of the power reached with gasoline. From the experiment conducted by Hari Ganesh, Subramanian [10], volumetric efficiency was plotted versus power output and thermal efficiency versus equivalence ratio. In the first case, a higher volumetric efficiency, compared with that of gasoline, with a power output between 2 and 7 kW, was observed. In the case of thermal efficiency, it was reached a maximum of about 27%, at different speeds, over that with gasoline which is about 25%. Yousufuddin and Masood [11], made experimental and computational work on a hydrogen diesel dual fuel engine, with hydrogen presence from 10 to 80% Vol. It was noticed that with the increase of hydrogen load the pressure increases at high compression ratios due to the high flammability and rate of combustion of hydrogen. Moreover, hydrogen has a major flame velocity at stoichiometric conditions, which makes the engine getting closer to the thermodynamically ideal engine. Hydrogen injection during compression stroke prevents knocking, increases thermal efficiency and maximizes the power output [12]. Knock, or spark knock, is defined as autoignition of the hydrogen–air end-gas ahead of the flame front that has originated from the spark. The high autoignition temperature, finite ignition delay and the high flame velocity of hydrogen means that knock, as defined, is less likely for hydrogen relative to gasoline, and hence the higher research octane number (RON) for hydrogen (RON>120) [13], in comparison to gasoline (RON=91−99) [14].

Table 2: Ignition temperature and compression ratio used for various fuels

Fuel	Formula	Ignition Temperature (°C)	Compression ratio CR	Reference
Octane	C8H18	300 - 450	8.0	Cengel and Bole [15]
Hydrogen	H2	858	14.5	Verhelst, Maesschalck [16]
Methane	CH4	813	15.0	Gupta [17]
Propane	C3H8	457	10.0	Ozcan and Yamin [18]
Methanol	CH4O	574	11.0	Li, Fan [19]
Ethanol	C2H6O	537	10.0	Park, Choi [20]

2. Analysis

Thermodynamic analyses for both gasoline and hydrogen fuelled engine are going to be made based on air-standard Ideal Otto cycle [21] at 3000 RPM. Both engines will be four-cylinder, 2-liter, spark ignition, square engine. Combustion efficiency is assumed as 100%. It can be assumed that the initial conditions in the cylinder before compression stroke are 100 kPa and 30°C.
Process 1-2 – isentropic compression stroke:

$$T_2 = T_1(r_c)^{k-1} \quad (1)$$

$$P_2 = P_1(r_c)^k \quad (2)$$

$$W_{1-2} = \frac{mR(T_2-T_1)}{1-k} \quad (3)$$

Process 2-3 – constant-volume heat input (combustion):

$$Q_{in} = m_f Q_{HV}\eta_c = m_m C_v(T_3 - T_2) \quad (4)$$

$$P_3 = P_2\left(\frac{T_3}{T_2}\right) \quad (5)$$

$$T_3 = T_{max} \quad (6)$$

$$P_3 = P_{max} \quad (7)$$

Process 3-4 – Isentropic power stroke:

$$T_4 = T_3\left(\frac{1}{r_c}\right)^{k-1} \quad (8)$$

$$P_4 = P_3\left(\frac{1}{r_c}\right)^k \quad (9)$$

$$W_{3-4} = \frac{mR(T_4-T_3)}{1-k} \quad (10)$$

Pressure in the cylinder of an engine is continuously changing during the cycle. An average or mean effective pressure (mep) for both gasoline and hydrogen fuelled engine is defined by [21]

$$mep = \frac{W}{V_d} \quad (11)$$

Power is defined as the rate of work of the engine. If n = number of revolutions per cycle and N = engine speed, then [21]

$$\dot{W} = W\frac{N}{n} \quad (12)$$

Power is commonly measured in horsepower (hp)

$$1kW = 1.341hp \quad (13)$$

Torque is a good indicator of an engine's ability to do work. It is defined as force acting at a moment distance and has units of N-m. Torque τ is related to power by [21]

$$\tau = \frac{\dot{W}}{2\pi N} \quad (14)$$

Exergy by heat transfer is the work potential of the energy transferred from a heat source in a system taken from its initial temperature to temperature of the environment or dead state. Heat is a form of disorganized energy, and thus only a portion of it can be converted to work, which is a form of organized energy (the second law). Work can always be produced from heat at a temperature above the environment temperature by transferring it to a heat engine that rejects the waste heat to the environment. Therefore, heat transfer is always accompanied by exergy transfer. Heat transfer Q at a location at thermodynamic temperature T is always accompanied by exergy transfer X_{heat} in the amount of [15]:

$$X_{heat} = \left(1 - \frac{To}{T}\right)Q \quad (15)$$

Work exergy is defined as the availability of the system to do actual work on the changing control volume against its surroundings. With respect to a piston-cylinder device, boundary work is the work required to move the piston against the boundary conditions and change the cylinder volume. The compression and expansion processes are assumed to be polytropic and as a function of cylinder volume [21]. Finally the exergy due to work can be given by:

$$X_{work} = \begin{cases} W - Wsurr\ (for\ boundary\ work) \\ W \qquad (for\ other\ form\ of\ work) \end{cases} \quad (16)$$

Where

$$W_{surr} = P_0\,(V_2 - V_1) \quad (17)$$

Any difference between the reversible work W_{rev} and the useful work W_u is due to the irreversibilities present during the process, and this difference is called irreversibility *I*. It is expressed as

$$I = W_{rev,out} - W_{u,out} \quad (18)$$

The amount of the availability that is destroyed increases for lower final temperatures. During the combustion process, the availability destroyed by combustion is about 18.9%, and the availability destroyed by the heat transfer is about 12.0% [22]. In almost all situations, the major source of irreversibilities is the internal thermal energy exchange associated with high temperature gradients caused by heat release in combustion reactions. The primary way of keeping the exergy destruction in a combustion process within a reasonable limit is to reduce the irreversibility in heat conduction through proper control of physical processes and chemical reactions resulting in a high value of flame temperature but lower values of temperature gradients within the system.

First Law efficiency is a measure of the performance of a heat engine according to the fraction of the heat input that is converted to net-work output. The 1st Law efficiency of an engine can be expressed as

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \quad (19)$$

Or

Thermal efficiency of the Otto cycle at WOT can be determine by

$$\eta_{th,Otto} = 1 - \frac{1}{{r_c}^{k-1}} \quad (20)$$

Second-law efficiency η_{II} is defined as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same condition. From irreversibility equation (3.19), the second-law efficiency can be expressed as the ratio of the useful work output and the maximum possible (reversible) work output:

$$\eta_{II} = \frac{W_u}{W_{rev}} \quad (21)$$

Based on the above models, the first and second law efficiency can be calculated for both hydrogen and gasoline fueled engines.

3. Results and Discussion

Figure 1 shown that mep for hydrogen fuelled engine is higher, 2740 kPa compared to gasoline, 2040 kPa. This result was due to higher work output associated with hydrogen fuelled engine. The higher work output of hydrogen fuelled engine was caused by higher heat energy input from combustion because of higher heating value of hydrogen fuel, 120 MJ/kg compared to gasoline fuel, 44 MJ/kg [9]. Figure 2 illustrate that hydrogen has higher power output, 183.7 hp compared to gasoline, 136.76 hp. The results are relatively consistent with report from Sørensen [23], which also indicated that hydrogen can have higher power output than gasoline. Higher horsepower also means that the torque will be higher. Figure 3 shown that torque of hydrogen fuelled engine is higher, 436 N-m compared to 325 N-m associated with gasoline fuelled engine. Higher compression ratio [16] and higher pressure due to combustion of hydrogen fuelled engine are the major factors for the higher torque of hydrogen engine. Figure 4 shown that greater heat exergy for hydrogen engine compared to gasoline engine was due to higher combustion temperature associated with the hydrogen fuelled engine [15]. However, the high available thermal energy or thermal exergy of hydrogen fuelled internal combustion engine needs higher cooling load which decreases the power of hydrogen fuelled internal combustion engine [24]. The results obtained were consistent with studies by Nieminen and Dincer [3] which illustrate the variation of exergy due to heat transfer as a function of crank angle.

Figure 5 shown that hydrogen have higher exergy due to work than gasoline fuelled engine due to higher temperature and pressure from combustion of hydrogen fuel [15]. However, Nieminen and Dincer [3] in his studies stated that hydrogen has lower work exergy due to higher compression stroke associated with hydrogen fuelled engine.

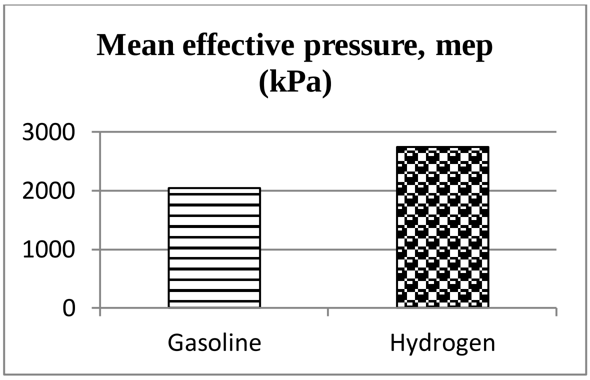

Figure 1: Comparison of mean effective pressure for gasoline and hydrogen fuelled engine

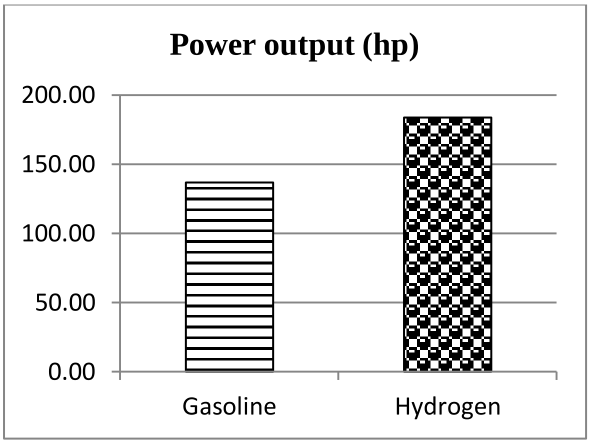

Figure 2: Comparison of horsepower for gasoline and hydrogen fuelled engine

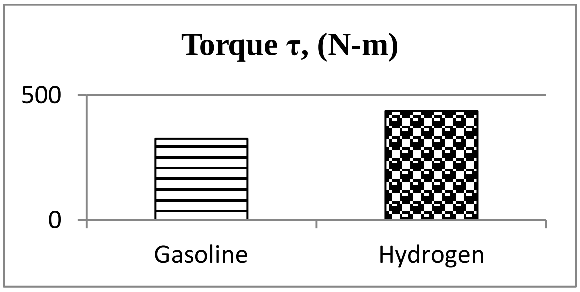

Figure 3: Comparison of torque for gasoline and hydrogen fuelled engine

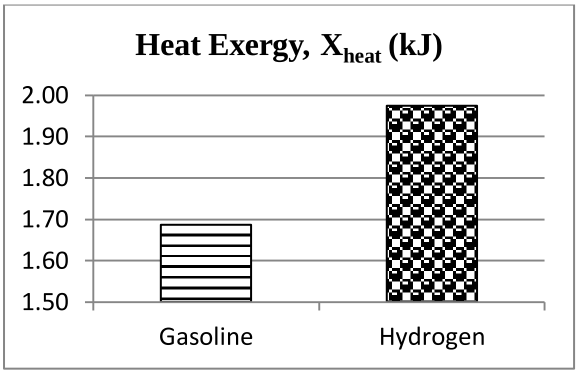

Figure 4: Comparison of heat exergy for gasoline and hydrogen fuelled engine

The transfer of exergy via compression work is the reason for the negative value of exergy. An irreversibility analysis is done for both gasoline and hydrogen combustion reactions using the approach from eq. 18. It was found that the combustion of hydrogen is less irreversible than the combustion of gasoline. The results are consistent with results reported by Nieminen and Dincer [3]. Figure 7 shown that both 1st law and second law efficiency for hydrogen engine is higher than gasoline engine 65.64, 69.4 % and 56.4, 60.5 % respectively. Nieminen and Dincer [3] also found that the hydrogen fuelled engine had a greater proportion of its chemical exergy converted into work, indicating a second law efficiency of 41.37% as opposed to 35.74% for a gasoline fuelled engine.

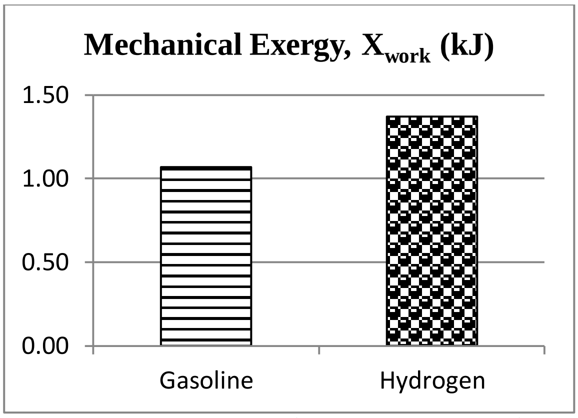

Figure 5: Comparison of mechanical exergy for gasoline and hydrogen fuelled engine

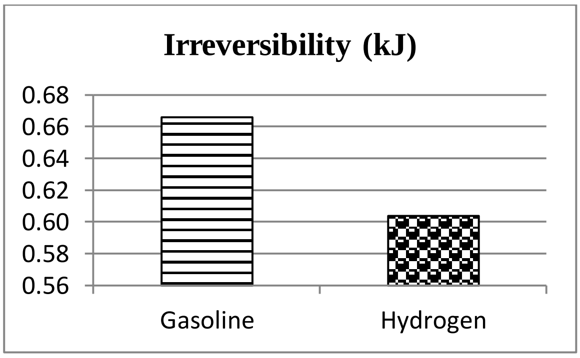

Figure 6: Comparison of irreversibility for gasoline and hydrogen fuelled engine

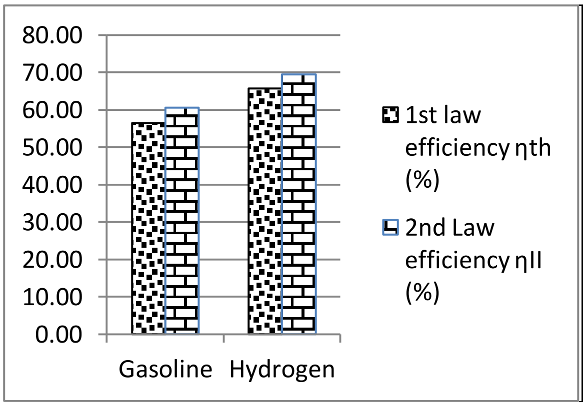

Figure 7: Comparison of 1st and 2nd law efficiency for gasoline and hydrogen fuelled engine

The higher first law efficiency of hydrogen engine was due to higher compression ratio [16] and the higher second law efficiency associated with hydrogen engine is due to significantly lower irreversibilities of hydrogen engine [15].

4. Conclusions

This comparative thermodynamics analysis between gasoline and hydrogen fuelled internal combustion engines has indicated that a hydrogen fuelled engine is more efficient than a gasoline fuelled engine from the first law perspective, 65.64% to 56.4% and the second law efficiency, 69.4% to 60.5% respectively. The reasons include higher compression ratio and lower irreversibility associated with hydrogen engine. Finally, the analysis conducted in this study shows that a hydrogen fuelled engine gives higher mean effective pressure, torque, power output, heat exergy and work exergy compared to gasoline engine because of higher temperature and pressure from hydrogen combustion.

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