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RESEARCH ARTICLE

COMPARATIVE EXERGY ANALYSES OF GASOLINE AND ALTERNATIVE FUELLED SI ENGINES

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ABSTRACT

The current works examines the detailed thermodynamics models for naturally aspirated gasoline and alternative fuel to spark ignition internal combustion engines. A comparative study based on the first and second laws of thermodynamics are discussed here. The key parameters for analysis were considered as mean effective pressure (MEP), power, torque, exergetic efficiency, second law efficiency, and irreversibility. Air standard assumptions were taken consideration for the analyses. MEP, power output and torque for all alternative fuelled engines, are higher compared to that of a gasoline engine. Exergy due to heat and work were also discussed. For heat exergy, only hydrogen exceeds gasoline while other alternative fuels have lower heat exergy than gasoline. But work (mechanical) exergy for all the alternative fuelled engines are higher than the gasoline engine. The Irreversibility or losses for the alternative fuelled engines are significantly lower than a gasoline engine. Alternative fuel engines have lower specific fuel consumption than the gasoline engine. Hence the 1st law and second law efficiency of the alternative fuelled engines are higher compared to that of gasoline. This is also due to having a high compression ratio associated with alternative fuelled internal combustion engine. Exergy by heat transfer of alternative fuelled internal combustion engine is higher due to having high heat generation during combustion.

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INTRODUCTION

The use of various fuels for the internal combustion engines started as early as the late 1800s while the development of the IC engines started well. Over the years, demand and uses of energy are increasing throughout the world. Environmental pollutions are also increased. Current energy sources are depleting. In recent years, the economy of Malaysia grew rapidly. The private vehicle populations grew rapidly. This rise of the vehicle 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 (Saidur *et al.,* 2007). Valero and Valero (2012) indicated that there might not be enough available resources to satisfy the predicted future mineral demand.

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Therefore, studies were conducted in the area of renewable energy to overcome these challenges (Faizal *et al.,* 2013, 2014 & 2017). The changing of fuel from gasoline to alternative fuels 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 the energy system (Dince *et al.,* 2004). Thermodynamics model will be developed according to Ideal Otto cycle (Cengel and Bole, 2007). Analysis of mean effective pressure, power, torque, exergy due to heat transfer, exergy due to work, and irreversibility will be determined, displayed, commented, and reasoned. First and second law efficiencies for both gasoline and hydrogen fuelled will be derived from this analysis. Studies have been made in applying the second law of thermodynamics to internal combustion engines to diagnose losses and to suggest solutions for improving engine performance and efficiency. A lot of works have been done also for alternative fuelled engines. Aydin and Acaroglu (2012), Bayraktar and Durgun (2005) (Shehata, 2001) has developed and validated an engine simulator to compare performance and emission characteristics of an engine working on LPG and gasoline. Yan, Xu (2018) compared power-gas with gasoline and natural gas (NG). Duque Amaya, Díaz Torres (2016) and Rakopoulos and Giakoumis (2006) shown that exergy of methane and methanol is lower than dodecane but the pollutant emissions are decreased. Caton (2000), 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 as fuels are remained without reaction. 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 (Escalante Soberanis *et al.,* 2010). 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%. Soma & Dattab (2018) has recognized that, in almost all situations, the major source of irreversibility 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. The optimum operating condition in this context can be determined from the parametric studies on combustion irreversibility with operating parameters in different types of flames. The objective of the current work is to compare the thermodynamics performance of gasoline and alternative fuelled internal combustion engines (ICE) based on First law and second law analysis of an SI engine. The SI engines are operated with gasoline, methanol, ethanol, propane, methane, hydrogen as fuel.

Table 1. The gasoline and other fuel properties

Fuel type	RON	Formula	Molecular weight	Density (kg/m^3)	Heat of vaporization at 298 K (kJ/kg)	Lower heating value (MJ/kg)	Stoichiometric air /fuel ratio
Gasoline	95.8	$C_{7.56}H_{15.5}$	106.22	750	305	44.0	14.60
Methane	120	CH_4	16	720	-	50.0	17.23
Propane	112	C_3H_8	44	545	426	46.4	15.67
Hydrogen	106	H_2	2	90	-	120.0	34.30

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

Fuel	Formula	Ignition Temperature (°C)	Compression ratio r_c
Octane/gasoline	C_8H_{18}	300 - 450	8.0
Hydrogen	H_2	858	14.5
Methane	CH_4	813	15.0
Propane	C_3H_8	457	10.0
Methanol	CH_4O	574	11.0
Ethanol	C_2H_6O	537	10.0

To model the performance of an internal combustion engine using alternative fuels, the second law of thermodynamics has proven to be a very powerful tool in the optimization of complex thermodynamic systems. Firstly, we need to be familiar with some of the terms. Exergy is the maximum useful work that could be obtained from the system at a given state in a specified environment. Reversible work is the maximum useful work that can be obtained as a system undergoes a process between two specified states. Irreversibility is the exergy destruction or lost work, which is the wasted work potential during a process pursuant to irreversibility (Cengel and Bole, 2007). All the fuels that are discussed in this study have widely used as an alternative fuel. Rakopoulos and Kyritsis (2001) shown that exergy of methane and methanol is lower than dodecane but the pollutant emissions decreased. Anangapal (2014) 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. The amount of the availability that is destroyed increases for lower final temperatures.

Thermodynamic Analysis

Thermodynamic analyses for gasoline and alternative fuelled engine were conducted based on air-standard Ideal Otto cycle (Pulkrabek, 2004) at 3000 rpm. All engines were considered as four-cylinder, 2-liter, spark ignition, square engine. Combustion efficiency is assumed to be 100%. It can be assumed that the initial conditions in the cylinder before compression stroke are 100 kPa and 30°C. The processes in an air standard Otto cycle are shown in Fig. 1

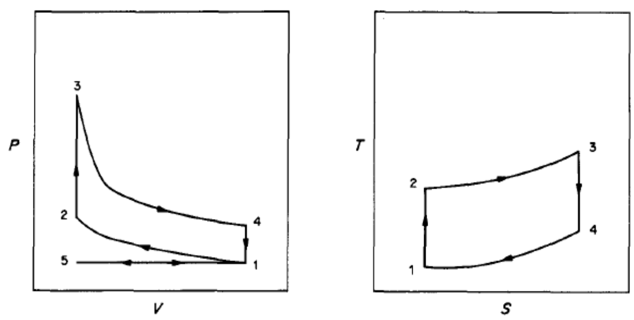

Fig. 1. P-V and T-s Diagram for ideal Otto cycle

Process 1-2 – isentropic compression stroke:

$$T_2 = T_1(r_c)^{k-1} \text{ and } \quad P_2 = P_1(r_c)^k \qquad (1)$$

and

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

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

$$Q_{in} = m_f Q_{HV} \eta_c = m_m C_v (T_3 - T_2) \qquad (3)$$

Where,

$$P_3 = P_2\left(\frac{T_3}{T_2}\right) \qquad (4)$$

Process 3-4 – Isentropic power stroke:

$$T_4 = T_3\left(\frac{1}{r_c}\right)^{k-1} \text{and } P_4 = P_3\left(\frac{1}{r_c}\right)^k \qquad (5)$$

and

$$W_{3-4} = \frac{mR(T_4-T_3)}{1-k} \qquad (6)$$

Horsepower and Torque output of the Engine

Power is defined as the rate of work of the engine. If n = number of revolutions per cycle and N = engine speed (rpm), then power (W) can be written as:

$$\dot{W} = W\frac{N}{n} \quad (7) \text{ where } 1kW = 1.341hp \qquad (7)$$

where $1kW = 1.341hp$

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 as follows (Pulkrabek, 2004):

$$\tau = \frac{\dot{W}}{2\pi N} \qquad (8)$$

Exergy by Heat Transfer and Exergy Transfer Work

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 (Cengel and Bole, 2007)

$$X_{heat} = \left(1 - \frac{To}{T}\right)Q \qquad (8)$$

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 polytrophic and as a function of cylinder volume (Cengel and Bole, 2007). Finally the exergy due to work can be given by:

$$X_{work} = \begin{cases} W - Wsurr \ (for\ boundary\ work) \\ W \qquad (for\ other\ form\ of\ work) \end{cases} \qquad (10)$$

Where, $W_{surr} = P_0 (V_2 - V_1)$ (11)

Irreversibility (I)

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

$$I = W_{rev,out} - W_{u,out} \qquad (12)$$

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% (Hongqing and Huijie, 2010). 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 and 2nd Law Efficiency

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 (Hongqing and Huijie, 2010)

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \qquad (13)$$

Or, thermal efficiency of the Otto cycle at WOT can be determine by follows (Pulkrabek, 2004)

$$\eta_{th,Otto} = 1 - \frac{1}{r_c^{\,k-1}} \qquad (14)$$

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 (Cengel and Bole, 2007). From irreversibility Eq. (12), the second-law efficiency can be expressed as the ratio of the useful work output and the maximum possible (reversible) work output:

$$\eta_{II} = \frac{W_u}{W_{rev}} \qquad (15)$$

Based on the above models, the first and second law efficiency can be calculated and graphed for alternative and gasoline fuelled engines.

RESULTS AND DISCUSSION

Horsepower and Torque

Fig 2 illustrates that alternative fuels has higher power output compared to gasoline. The results are relatively consistent with report from (Pourkhesalian *et al.,* 2010; Szwaja *et al.,* 2007; Jahirul *et al.,* 2010 Sopena *et al.,* 2010) which also indicated that alternative fuels can have higher power output than gasoline.

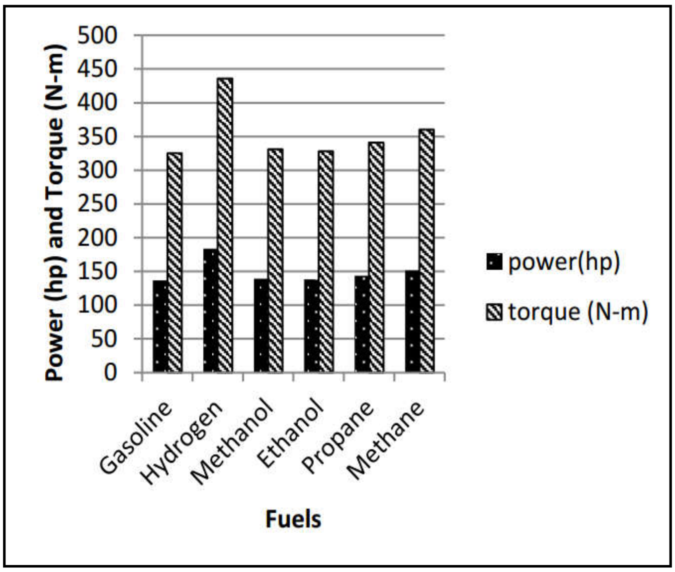

Fig 2. Comparison of horsepower (hp) and torque (N. m) of different fuels

Higher horsepower also means that the torque will be higher or vice versa. Fig 2 shows that, torque of alternative fuelled engines are higher compared to gasoline fuelled engine. Higher compression ratio (Verhelst *et al.,* 2009) and higher pressure due to combustion of hydrogen fuelled engine are the major factors for the higher torque of hydrogen engine. Yamin and Badran (2002) states that engines run on LPG tend to produce 3-5% less power than gasoline. However, by offsetting the heat in the inlet manifold, volumetric efficiency of LPG will rise up to 8% and increased the engine power output. Balki and Sayin (2014) states that ethanol has higher volumetric efficiency and torque because of ethanol evaporation decreases the air intake temperature.

Exergy by Heat Transfer, Exergy Transfer by Work and Irreversibility

Fig 3 shows that greater heat exergy for hydrogen engine compared to gasoline engine was due to higher combustion temperature associated with the hydrogen fuelled engine. 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 (Shudo, 2007). The results obtained were consistent with studies by Nieminen and Dincer (2010) which illustrates the variation of exergy due to heat transfer as a function of crank angle. Lower combustion temperature for other alternative fuels like alcohol, LPG and CNG leads to lower heat exergy compared to gasoline engine. All alternative fuels have higher 'Exergy due to Work' than gasoline fuelled engine due to higher temperature and pressure from combustion of fuel. However, Nieminen and Dincer (2010) studies stated that hydrogen has lower work exergy due to higher compression stroke associated with hydrogen fuelled engine and this also applied to CNG because of the higher compression ratio. An irreversibility analysis is done for all fuel combustion reactions using the approach based on Eq. (12). It is observed in Fig 4 that the combustion of alternative fuels is less irreversible than that of gasoline. The results are consistent with the results reported by Nieminen and Dincer (2010) for hydrogen fuel. Less irreversibility means fewer losses of exergy will occur during the operation of an engine.

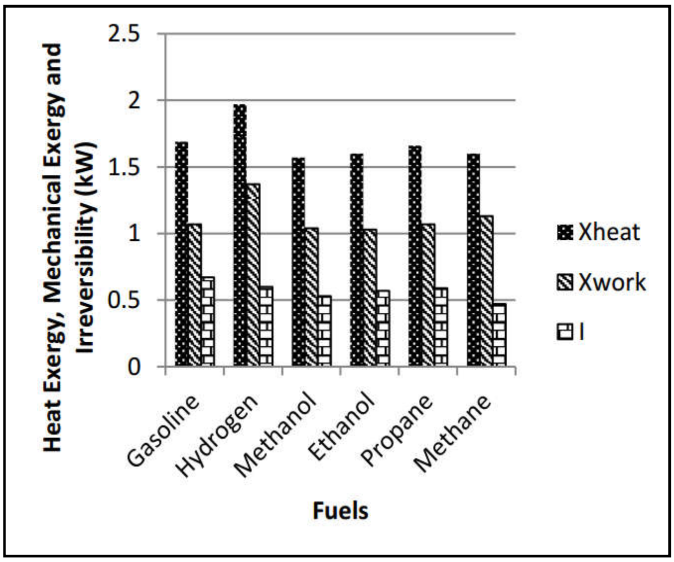

Fig. 3. Comparison of heat exergy, mechanical exergy and irreversibility (kJ) of different fuels

First and Second Law Efficiency of the Systems for Different Fuels

Fig 4 shows that 1st law and second law efficiencies for all alternatives fuelled engines are higher than that of the gasoline engine. The results are consistent with (Nieminen and Dincer, 2010) where the authors found that the hydrogen fuelled engine had a greater proportion of its chemical exergy converted into work. The first law efficiency alternative fuels (Ozcan and Yamin *et al.,* 2008; Park *et al.,* 2010; Verhelst *et al.,* 2009) engine were higher than gasoline due to the higher compression ratio. Second law efficiency associated with the alternative fuelled engine also higher due to significantly lower irreversibility than that of a hydrogen engine.

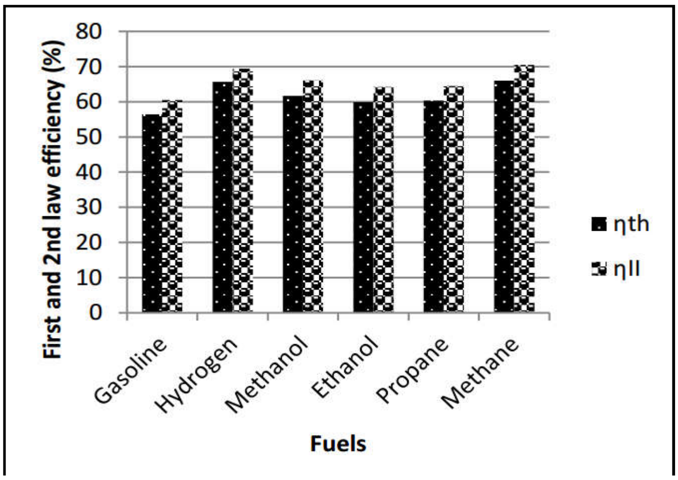

Fig. 4. Comparison of 1st and 2nd law efficiency of the fuels

Exergy Efficiency of the Different Fuels

Based on the concept of second law analysis, exergetic parameters of the fuels are calculated and shown in Fig 5. Alternative fuelled engines show higher exergetic efficiency than gasoline engine. Most of the useful energy is wasted for the gasoline engine. As hydrogen has the highest chemical exergy of the fuels, so it shows the highest exergetic efficiency. Gasoline engine shows the least exergetic efficiency of the engines. Most of the useful work is lost in the case of gasoline engine. Hydrogen has higher heating value compared to other fuels. So it needs less amount charge. Hence it causes higher exergetic efficiency compared to other fuels and gasoline also. After all, the alternative fuels show higher exergetic efficiency than gasoline. Hydrogen is the most efficient fuel. Similar results are obtained for hydrogen from the study by Caton (Caton *et al.,* 2000). There the author showed that hydrogen and carbon monoxide have highest exergy efficiency i.e. lowest exergy destruction.

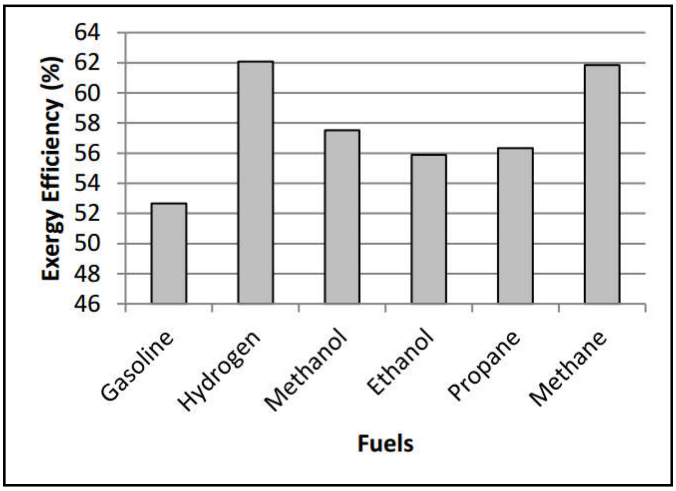

Fig. 5. Exergetic efficiency of the fuels

Conclusion

This comparative thermodynamics analysis between gasoline and alternative fuelled internal combustion engines has indicated that alternative fuelled engine is more efficient than a gasoline fuelled engine based on first law and the second law efficiency. The reasons include higher compression ratio and lower irreversibility associated with the alternative fuelled engine. Finally, the analysis conducted in this study shows that alternative fuelled engine indicates higher mean effective pressure, torque, power output, heat exergy and work exergy compared to that of the gasoline engine because of higher temperature and pressure during combustion and compression. Another thing is that, only hydrogen has the highest heating value of the alternative refrigerants. However, this study is a theoretical prediction of the performance analysis of alternative fuels using the thermodynamics model. The actual data might be different from theoretical data. But from many literatures, it is also proved that gasoline has the lowest performance among the other fuels.

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