**Comparative exergy analyses of gasoline, hydrogen, methanol, ethanol, LPG (propane) and CNG (methane) fuelled SI Engines**

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**Abstract**

The current works examines the detailed thermodynamics models for naturally aspirated gasoline and alternative fuelled to spark ignition internal combustion engines on the basis of ideal Otto cycle. A comparative study based on the first and second laws of thermodynamics are discussed here. The key parameters for analysis are 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 are also discussed here. 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 heat transfer of alternative fuelled internal combustion engine is higher due to having high heat generation during combustion.

***Keywords:*** Hydrogen, Gasoline, fuel, exergy, spark engine

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1. **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 [1]. Valero et al. [2] indicate that there might not be enough available resources to satisfy the predicted future mineral demand. 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 [3]. Thermodynamics model will be developed according to Ideal Otto cycle [4]. Analysis of mean effective pressure, power, torque, exergy due to heat transfer, exergy due to work, and irreversibility will be determined, displayed, commented, and reasoning provided. First and second law efficiencies for both gasoline and hydrogen fuelled will be derived from this analysis.

Some studies have 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 works have been done also for alternative fuelled engines. Bayraktar and Durgun [5] has developed and validated an engine simulator to compare performance and emission characteristics of an engine working on LPG and gasoline. Mustafi et al. [6] compared power-gas with gasoline and natural gas (NG). Rakopoulos and Giakoumis [7] shown that exergy of methane and methanol is lower than dodecane but the pollutant emissions are decreased. Caton [8], state 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 [9].

**Table 1: The gasoline and other fuel properties [10]**

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 [4]. All the fuels that are discussed in the presented paper have widely used as an alternative fuel. Rakopoulos and Kyritsis [11] shown that exergy of methane and methanol is lower than dodecane but the pollutant emissions decreased. Schnoor [12], state 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. 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 [13] 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.

**Table 2: Ignition temperature and compression ratio used for various fuels [4, 14-18]**

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 a SI engine. The SI engines are operated with gasoline, methanol, ethanol, propane, methane, hydrogen, etc. These results are carried out and analyzed.

1. **Thermodynamic Analysis**

Thermodynamic analyses for gasoline and alternative fuelled engine are going to be made based on air-standard Ideal Otto cycle [19] at 3000 rpm. All engines will be 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:

and (1)

(2)

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

(3)

Where, (4)

Process 3-4 – Isentropic power stroke:

and (5)

(6)

**2.1 *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 () can be written as [19]:

(7) and where

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 [19]:

(8)

**2.3 *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)[20, 21]. 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 Xheat in the amount of [4]

Xheat = (9)

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 [4]. Finally the exergy due to work can be given by:

Xwork = (10)

Where, Wsurr = P0 (V2 – V1) (11)

**2.4 *Irreversibility (I)***

Any difference between the reversible work Wrev and the useful work Wu is due to the irreversibility present during the process, and this difference is called irreversibility *I.* It is expressed as

*I =* Wrev,out – Wu,out (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% [22]. Soma and Dattab [13] 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.

**2.5 *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 [4]

(13)

Or, thermal efficiency of the Otto cycle at WOT can be determine by [19]

(14)

Second-law efficiency ηII is defined as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same condition [4]. 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:

(15)

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

1. **Results and Discussion**

**3.1 *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. [23] for LPG, Sorensen [24] for hydrogen, Szwaja et al. [25] for alcohols, Hollnagel et al. [26] for CNG and Jahirul et al. [27] for CNG which also indicate 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 [14] and higher pressure due to combustion of hydrogen fuelled engine are the major factors for the higher torque of hydrogen engine.

Yamin & Badral [28] 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. Rovai et al. [29], states that ethanol has higher volumetric efficiency and torque because of ethanol evaporation decreases the air intake temperature.

**3.2 *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 [4]. 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 [30].

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

The results obtained were consistent with studies by Nieminen and Dincer [31] which illustrate 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 [4]. However, Nieminen and Dincer [31] in his 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 [31] for hydrogen fuel. Less irreversibility means fewer losses of exergy will occur during the operation of an engine.

**3.3 *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 [31] where the authors found that the hydrogen fuelled engine had a greater proportion of its chemical exergy converted into work. The first law efficiency of hydrogen [14], CNG [15], LPG [16], Methanol [17] and Ethanol [18] 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 5: Comparison of 1st and 2nd law efficiency of the fuels.**

**3.4 *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 [32].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**

1. **Conclusions**

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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**Nomenclature**

0 Dead state

Cv Specific heat at constant volume (Cv = 0.718 kJ/kg ·K)

k Ratio of specific heats (k=1.4)

mf Mass of fuel (kg)

mm Mass of mixture (kg)

N Engine speed (m/s)

n Revolutions per cycle

R Gas Constant (R=0.287 kJ/kg·K)

rc Compression ratio

Rev Revolution

rev Reversible

surr Surrounding

th Thermal

u Useful

V Volume (m3)

Vd Displacement volume (m3)

X Exergy (J)

ηc Combustion efficiency