Theoretical and Experimental Investigation on Exergy Analysis of Internal Combustion Engine

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Abstract—This study presents energy and exergy analysis of a three cylinders four-stroke naturally aspirated spark ignition engine using gasoline fuel. Each test was performed by varying the engine speed between 1100 rpm to 3200 rpm with the interval of 300 rpm at 0.5 Kg load. The load was also varied from 0.5 Kg to 2 Kg with the interval of 0.5 Kg. and at each load the engine speed was varied. Then using the steady state data along with the energy and exergy rate balance equations various performance parameters of the engine were evaluated for each load case. It was found that almost all the performance parameters increased with increasing engine speed.

Key words: Exergy, Internal combustion Engine, Load conditions

I. INTRODUCTION

The increased importance of efficient utilization of fossil fuels in engines with reduced emissions requires thorough understanding of thermodynamics of internal combustion engines. The performance, fuel consumption and exhaust emissions of internal combustion (IC) engines have been improved considerably since the introduction of these engines. These improvements have been brought about by advancing the engine design and adopting best operating parameters. Different load conditions affect the performance and exhaust emissions of internal combustion engine. It can be seen from the literature survey that there are only a few studies investigating the effect of load conditions on the gasoline engines. Therefore, in the current study, the effect of different load conditions on performance is investigated using the second law of thermodynamics.

An exergy-based analysis is the analysis of a system based on the second law of thermodynamics that overcomes the limit of an energy-based analysis. Exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. Exergy is generally not conserved as energy but destroyed in the system. Exergy destruction is a measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system. This provides useful information to improve the overall efficiency and cost effectiveness of a system.


In this study, energy and exergy analyses of a three-cylinder, four-stroke gasoline engine are investigated. The test engine was powered with gasoline fuel and operated at different load conditions. The tests for each load condition were conducted by varying the engine speed. Using the experimental data, the reaction equations, the energy rate balance and the exergy rate balance for the engine were determined. Consequently, various energetic and exergetic performance parameters of the engine were evaluated for each load condition and compared with each other’s.

II. EXPERIMENTAL SET-UP AND TESTING PROCEDURE

A. Experimental Procedure

1) The engine was started and it was allowed to run for 10 - 15 minutes at to load and at idling speed of 900 - 1000
rpm. During this period it was checked that all systems of the fig were working normal.

2) The engine was accelerated with the help of accelerator drive. The speed and load on the Engine were set according to the requirement of the measurement, using a good quality hand tachometer and the driving wheel of the dynamometer respectively.

3) Locked the accelerator level and the dynamometer level in the position so that the load and speed of engine do not change due to vibrations.

4) Note Down the readings of Temperatures at various points, orifice meter, rota meter.

5) Stopped the fuel supply form the tank to the engine by operating the cock provided so that the fuel is supplied by the pipette.

6) Noted down the time required for consumption of 5 ml of fuel with the help of stop watch.

7) The exhaust gas analyser was started and allowed to run for HC residual check and allowed to initialize and allowed to get ready for the measurement.

8) The cap of the probe was removed and it was placed in the flow of exhaust gas coming out of the exhaust gas calorimeter.

9) Noted down the percentage of the different gases which were displayed on the screen of the exhaust gas analyser.

10) Repeated this procedure for 0.5 Kg load and speed of 1100, 1400, 1700, 2000, 2300, 2600, 2900, 3200 rpm, 1 Kg load and all the speeds. 1.5 kg load and all the speeds 2 Kg load and all the speeds.

B. Determination of combustion equation

Energy and exergy analysis of the test engine for each test operation can be performed after determining the reaction equation for the considered operation. For this purpose, it is necessary to make some simplifying assumptions. Accordingly, it is assumed that there is no water vapour in the combustion air, and the air contains 21% oxygen and 79% nitrogen on a molar basis. Moreover, it is also assumed that the nitrogen in the air cannot undergo chemical reactions to form NO and NO2. After these assumptions, the general form of the reaction equation is

\[ C_8H_{18} + a(O_2 + 3.76N_2) = bC_2O_3 + cCO + dO_2 + fN_2 + gH_2O \]  

(1)

In all test operations, the fuel chemical formulas, fuel and air flow rates and the flow rate of Co, Co2 and O2 are known. Thus by applying conservation of mass principle to the carbon, hydrogen, oxygen and nitrogen, the unknown coefficients in equation (1) can be determined.

III. ENERGY ANALYSIS

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

The engine runs at steady state. The combustion air and exhaust gas each forms ideal gas mixture. Potential and kinetic energy effects of the combustion air, fuel stream and exhaust gas are ignored.

After the assumptions the energy rate balance for a control volume consisting of the entire engine including the dynamometer can be written as

A. Energy rate balance

(energy supplied in the form of fuel) = (Brake Power) + (Heat energy lost in engine cooling) + (Heat energy lost in exhaust gas calorimeter) + (Heat energy lost in exhaust gas leaving the calorimeter)

Energy supplied in the form of fuel can be determined as follows.

B. Energy supplied to the engine (H1)

Energy supplied (H1) =  \( \dot{m}_f \times \text{calorific value of fuel} \) KJ/s

(2)

Here \( \dot{m}_f \) represents the mass flow rate of the fuel which is measured by measuring the time required for consumption of 5 ml fuel. Here density of the gasoline (0.74 kg/litter) is multiplied to convert volume flow rate into mass flow rate.

\[ \dot{m}_f = \frac{0.74 \times 0.005}{s} \]  

Kg/s

(3)

Energy supplied (H1) = \( \dot{m}_f \times \text{fuel calorival value} \)

C. Work Rate

\[ \text{Work Rate} = \frac{W \times N}{2000} \]  

KJ/s

(4)

D. Heat energy lost in engine cooling

\[ H_2 = m_w C_{pw}(T_{woc} - T_{wic}) \]

(5)

E. Heat energy lost in exhaust gas calorimeter

\[ H_3 = m_g C_{pg}(T_{gic} - T_{goc}) \]

(6)

\[ H_4 = m_g C_{pg}(T_{gic} - T_o) \]

(7)

(8)

(9)

G. Break Thermal efficiency (\( \eta \))

\[ \eta = \frac{\dot{W}_p}{\text{heat supplied}} \times 100\% \]  

(10)

IV. EXERGY ANALYSIS

The specific flow exergy of a fluid stream can be found by summing thermo mechanical and chemical exergies, i.e.:

\[ \dot{e} = \dot{e}^{th} + \dot{e}^{ch} \]

(11)

The thermo mechanical exergy can be defined as

\[ \dot{e}^{th} = \dot{h} - \dot{h}_o - T_0(\dot{s} - \dot{s}_o) \]

(12)

Where \( \dot{h} \) and \( \dot{s} \) signify the specific enthalpy and entropy of the fluid, respectively, whereas \( \dot{h}_o \) and \( \dot{s}_o \) stand for the corresponding values of these properties when the fluid comes to equilibrium with the reference environment.

A. Fuel Exergy

Estimation of chemical exergy of fuel with complex but known compositions is performed as for other chemicals. The exergy of fuel can be calculated from the relation

\[ e_f = \sum m_j e_{ch_j} \]

(13)

Where \( m_j \) = mass fraction of compound \( j \) and \( e_{ch_j} \) = specific chemical exergy of the compound.

Since many solid and liquid fuels have unknown structures with known chemical compositions. We cannot estimate exergy because of lack of standard enthalpies of formation and absolute entropies.
Rant was one of the early workers to suggest use of analogies for homogeneous organic fuels. After estimating chemical exergies of many homogeneous organic fuels, he calculated the ratios of exergies to heating values and then estimated average values of these ratios for both liquid and gaseous fuels.

Assuming that these ratios are also valid for fuels with unknown structures, he proposed to estimate the chemical exergy of a liquid fuel if its molecule contains more than one atom of carbon. He gave the relation as

$$e_{ch} = 0.975 Q_h$$ ........................................(14)

here $e_{ch}$ is the chemical exergy of fuel and $Q_h$ is the higher heating value of the fuel.

From the calculations it was found that chemical exergy of fuel exceeds their lower heating value. (for liquid fuels it exceeds by 5 to 6%).

B. Exergy accompanying Exhaust gas

The exhaust gas can be assumed as a mixture of ideal gases. Then, the thermo mechanical exergy of the exhaust gas at the temperature $T$ and pressure $p$, and containing $n$ components can be obtained from

$$e = \sum_{i=1}^{n} a_i \left[ \bar{h}_i(T) - \bar{h}_i(T_0) - T_0 s^0(T) - s^0(T_0) - \frac{R}{p} \bar{s}_i \right]$$ ..................................................(15)

Where $a_i$ is the molar amount of the component $i$, $s^0$ is the absolute entropy at the standard pressure and $R$ is the universal gas constant.

Both thermo mechanical and chemical exergies of the combustion air can be ignored since the intake air was very close to the reference state in the all test operations. As its properties were almost equal to those in the reference conditions, the thermo mechanical exergy of the fuel can also be ignored.

The exergy rate balance for the engine operating at a steady state can be expressed as

$$0 = \sum_j \left( 1 - \frac{T_j}{T} \right) \dot{Q}_{cv} - \dot{w}_{cv} + \dot{n}_f e_f - \dot{n}_f e_{cx} - \dot{e}_d$$ ........................................(16)

C. Exergy Destruction

Here the value of exergy destruction is calculated by calculating the total exergy transfer in the engine with the help of equations given above.

D. Exergy Accompanying Heat Transfer

The heat transfer takes place in the engine cylinder wall to cooling water and in the exhaust gas calorimeter this can be found out by the following equation.

$$\sum_j \left( 1 - \frac{T_j}{T} \right) \dot{Q}_{cv} = \left( 1 - \frac{T_0}{T_{goc}} \right) \dot{m}_w c_p (T_{goc} - T_0) + \left( 1 - \frac{T_0}{T_{gic}} \right) \dot{m}_w c_p (T_{gic} - T_0)$$ ........................................(17)

E. Exergy accompanying work transfer

$$\dot{w}_{cv} = \frac{2\pi NT}{60}$$ ..................................................(18)

F. Break Thermal efficiency ($\eta$)

$$\eta = \frac{\text{Work rate}}{\text{Heat supplied}} \times 100\%$$ ........................................(19)

V. RESULTS AND DISCUSSION

A. Energy Analysis

1) Fuel Energy

From the reading taken for the fuel energy which are in the observation table of appendix, the values of fuel energy for all the speed and load conditions are calculated which is shown in table 2. Figure 16 shows the variation of fuel energy with speed and load conditions.
3) **Heat Transfer:**

![HEAT TRANSFER](image1)

Fig. 4: Graph between Heat transfer Vs Speed

From figure it can be seen that with increasing the speed the heat transfer loss is increasing for all the load conditions. At 2 Kg load there is maximum heat transfer loss and at 1 Kg load there is minimum heat transfer loss.

4) **Exhaust Gas**

![EXHAUST GAS](image2)

Fig. 5: Graph between Energy in exhaust gas Vs Speed

From figure it can be seen that with increasing speed Energy lost in the exhaust gas is also increasing. It can also be seen that at 0.5 load condition there is maximum heat lost by the gas among all the loads. And at 1.5 Kg load there is minimum heat loss by the exhaust gas.

5) **Efficiency**

![Efficiency](image3)

Figure: 6 Graph between Efficiency Vs Speed

From figure it can be seen that with increasing the load the efficiency is increasing. It can also be seen that the maximum efficiency is shifting in increasing speed direction. Which means the maximum efficiency is increasing with increasing the speed and load.

**B. Exergy Analysis**

From the reading taken for the calculation of fuel exergy which are in appendix, the fuel exergy at all the speed and load conditions are calculated which is tabulated in table 7 as shown below

5) **Fuel Exergy**

![Fuel Exergy](image4)

Fig. 8: Graph between Work rate Vs Speed

From figure it can be seen that with increasing the speed the work done by the engine is increasing at all the loads. With increasing the load on the engine the work done is also increasing.
2) Exergy accompanying heat transfer

Fig. 9: Graph between Exergy accompanying heat transfer Vs Speed

It can be seen that with increasing speed the exergy accompanying heat transfer is increasing for all the load conditions.

It can also be seen that the maximum exergy accompanying heat transfer loss occurs at 2 kg load and minimum exergy accompanying heat transfer loss occurs at 1 kg Load condition

3) Exergy Accompanying Exhaust Gas

Fig. 10: Graph between Exergy accompanying exhaust gas Vs Speed

It can be seen from the figure that with increasing speed the exergy accompanying exhaust gas is increasing and it can also be seen that it is also increasing with increasing the loads.

At 0.5 kg load there is minimum exergy loss and at 2 kg load there is maximum exergy loss.

4) Exergy Destruction

Fig. 11: Graph between Exergy Distruiction Vs Speed

From figure it can be seen that with increasing speed the exergy distruction is also increasing. It can be seen that at 0.5 kg load there is maximum exergy distruction occurs and at 1.5 kg load it is minimum.

5) Efficiency

Fig. 12: Graph between Efficiency Vs Speed

From figure it can be seen that with increasing the load the efficiency is increasing. It can also be seen that the maximum efficiency is shifting in increasing speed direction.

VI. CONCLUSION

Experimental investigation has been carried out for the energy and exergy analysis of a three cylinder four stroke gasoline engine using different load conditions. The tests were conducted by varying the engine speed and load. From the experimental reading using the reaction equation, the energy rate balance and the exergy balance for each test operation were determined. Finally various energetic and exergetic performance parameters of the engine were evaluated and compared with each other’s. Following conclusions can be drawn from the present study.

- Operations with low loading lead to lower efficiency, usually a higher exhaust energy loss and higher exergy loss due to heat loss.
All energetic and exergetic performance parameters increase with increasing engine speed as high engine speeds cause a more homogenous mixture and a boosted turbulence in the combustion chamber, almost.

The system inefficiency is mainly caused by the exergy destruction due to irreversible process such as combustion. The exergy losses due to the exhaust gas and heat flow from the control volume are other contributors to inefficiency. The energy lost by the Exhaust gas is maximum at 0.5 kg load and minimum at 1.5 kg load.

From energy analysis and exergy analysis it is found that with increasing the speed all the performance parameters are increasing. With increasing the load fuel consumption is increasing, it is Minimum at 1.5 kg load. Loss of energy and exergy in heat transfer is also increasing. The useful work obtained by the engine is also increasing with increasing speed and load.

The efficiency is increasing with increasing speed and reaches the pick position and then decreases with increasing speed. With increasing the load the maximum efficiency is shifting in increasing speed direction.

NOMENCLATURE

- \( m_f \) = mass flow rate of fuel (Kg/s)
- \( m_a \) = mass flow rate of air (Kg/s)
- \( m_e \) = mass flow rate of exhaust gas (Kg/s)
- \( m_w \) = mass flow rate of water (Kg/s)
- \( c_{pw} \) = Specific heat of water (KJ/Kg K)
- \( c_{pg} \) = Specific heat of exhaust gas (KJ/Kg K)
- \( T_{wi} \) = Temperature of water inlet to engine (K)
- \( T_{woe} \) = Temperature of water outlet from engine (K)
- \( T_{wic} \) = Temperature of water inlet to calorimeter (K)
- \( T_{woc} \) = Temperature of water outlet from calorimeter (K)
- \( T_{goc} \) = Temperature of gas outlet from engine (K)
- \( T_{bic} \) = Temperature of gas inlet to calorimeter (K)
- \( T_{boc} \) = Temperature of gas outlet from calorimeter (K)
- \( T_o \) = Temperature of environment (K)
- \( H_1 \) = Energy supplied to engine (KJ/Kg)
- \( H_2 \) = Energy lost in engine cooling (KJ/Kg)
- \( H_3 \) = Energy lost in exhaust gas calorimeter (KJ/Kg)
- \( H_4 \) = Energy lost in Exhaust gas (KJ/Kg)
- \( h \) = Enthalpy (KJ/Kg)
- \( h_0 \) = Enthalpy at reference environment(KJ/Kg)
- \( s \) = Entropy(KJ/Kg k)
- \( s_0 \) = entropy at reference environment (KJ/Kg k)
- \( p \) = pressure (kPa)
- \( p_0 \) = pressure of reference environment (kPa)
- \( R \) = universal gas constant (kJ/kmol K)
- \( e \) = Exergy (KJ/Kg)
- [LHV] = Lower heating value
- \( a_i \) = molar amount of component I
- \( W \) = power obtained from the control volume (kW)

REFERENCES


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