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EXERGY ANALYSIS OF A SINGLE-CYLINDER FOUR-STROKE GASOLINE ENGINE

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ABSTRACT: In developing countries, the four-stroke single-cylinder gasoline engine finds wide use. Motorcycles, tricycles and household machines like vegetable grinding machines are but a few of the machinery which run on this engine. Researchers have found that this engine is inefficient and consumes a lot of fuel, in light of sustainability and energy efficiency, this study aimed to perform an exergy analysis of a single-cylinder 4-stroke gasoline engine to determine how best its efficiency can be improved. Parameters such as brake thermal power, exergy efficiency, the quantity of exergy destruction and the component of the engine which is the most influential on its efficiency were determined while varying the engine's torque. A G200K1 Honda engine was used as the study material. At the lowest tested torque of 9.4Nm, a corresponding brake power output of 2.4609kW and efficiency of 17.07% was measured, while at a higher torque 9.70Nm, a corresponding brake power output of 2.5395kW and efficiency of 17.62% was measured. It was also found that for every 1.06% rise in torque there is a corresponding 1.80% rise in brake power and exergy efficiency. It was concluded from the findings that the bulk of energy waste in the system comes from the high-temperature gas released from the engine's exhaust. For the overall efficiency of four-stroke single-cylinder gasoline engines to be improved, the exergy destruction due to combustion should be minimised by optimizing the combustion temperature and reducing heat loss from the combustion chamber.

Keywords: *Exergy, Exergy Analysis, Internal Combustion Engines, Energy*

1. INTRODUCTION

There is no doubt that the world's quest for energy has increased, this is largely because of the rise in population, technological advancement and increased earning powers. The increased quest for energy has made most countries develop policies that encourage energy conservation and energy efficiency (Aliu, 2020; Xu *et al*., 2021). The ability to detect energy losses is key to designing new systems that will minimize losses. In the field of thermodynamics, the ability to determine the quality of energy (exergy) in any thermodynamic system has made it easy for scientists and engineers to design systems that minimise energy losses and reduce wastages.

In practice, complete equilibrium is unattainable, any system whose parameters such as chemical composition, pressure and temperature are above that of its surroundings is not in equilibrium and possesses the capacity to carry out work, this potential is referred to as the exergy of the system. Exergy encapsulates the quality (usefulness) of energy in addition to what is destroyed during conversion from one form of energy to another (Arango-Miranda *et al.,* 2018). Exergy is commonly referred to as useful energy or available energy. In recent years, engineers have relied on performing exergy analysis to determine the thermodynamic performance of a system/process, this has proven to be more effective than the conventional energy analysis which was previously used to determine the thermodynamic performance of systems, this is so because exergy analysis more details and it is more useful in improving the efficiency of a system compared to relying solely on energy analysis (Ameri *et al.*, 2010; Rosen, 2021).

The four-stroke, single-cylinder gasoline engine has popular usage in developing countries, it finds use in diverse machinery and vehicles. In Nigeria, motorcycles and tricycles which are among the most common modes of transportation in cities and townships (Modibbo and Mary, 2017) run on 4-stroke single-cylinder gasoline engines.

The high combustion chamber temperature, heat transfer and friction in the cylinder of a typical single-cylinder four-stroke gasoline engine greatly reduce its efficiency thereby leading to high fuel (gasoline) consumption and unusually high release of greenhouse gases into the atmosphere (Liu *et al.*, 2018; Shaheen and Lipman, 2007). This study aims to perform exergy analysis of a single-cylinder four-stroke gasoline engine to determine the most influential factor on its efficiency and how best it can be improved upon, a Honda G200K1 single-cylinder four-stroke gasoline engine located in the thermodynamics laboratory of the Department of Mechanical Engineering, Bayero University, Kano will be used for the study.

2. MATERIALS AND METHOD

2.1. Experimental equipment and their uses

An exhaust gas analyser is a equipment used to analyse the proportions of emission gases from internal combustion engines measures the proportions of CO, CO_2 and O_2 gases in the exhaust of an IC engine while also measuring the flue and net temperatures. A Kane 900 Plus Multi-Gas Emissions Analyser was used for this study, it has a resolution of 0.10℃/°F (Flue Temperature), 0.1℃/°F (Inlet Temperature), 0.1mbar (pressure), 0.1% oxygen, 1ppm Carbon Monoxide (standard H compensated), 0.01%Carbon Monoxide, 1ppm Nitric Oxide (standard), 1ppm Nitrogen Oxide (low range). A Vernier calliper was used for measuring the internal and external diameters of the air inlet, exhaust and fuel pipes. A Starnic calliper with a measuring range of 0-20cm and a precision of ±0.05mm was used for this research. A hygrometer with a measurement range of 0 –100%, resolution of 0.1%RH and accuracy of 97.5%, temperature range -20 – 60^{0}C was used to measure the humidity of the generator house. For temperature measurements, a digital thermometer with a K-type thermocouple which has a measurement range of -50^{0}C to 1,300^{0}C, with an accuracy of ± 99.7% and a resolution of 1^{0}C and 0.1^{0}C was used for all temperature readings. To measure the speed of air at the inlet and exhaust, a TA430/TA430 anemometer with a measuring range of 0 to 6000 ft/min (0 to 30 m/s) and an accuracy of ±0.015m/s was used. A TD 115 hydraulic dynamometer made by TecQuipment with a maximum load of 5000g/49N, resolution of 1g/0.01 and accuracy of ±0.4% was used to measure the engine torque. The speed of the engine was measured using a tachometer, the tachometer in the laboratory is a Microtech 8300 model which has an LCD screen and a measurement range of 0.3 – 99999 RPM with an accuracy of ±0.008%. To accurately measure the volume of gasoline used for the experiment, a 500ml measuring cylinder with readability of 0.5ml and accuracy of ±0.5ml was used.

Tests were performed on the G200K1 gasoline engine, specifications of the engine are outlined in Table 1 while its image can be seen in Figure 1.

Table 1. Details of the Engine Used for the experiment

Engine type	4-stroke single cylinder Overhead Valve gasoline engine 25° inclined cylinder horizontal shaft
Cylinder sleeve type	Cast iron sleeve
Bore x Stroke	60 x 42 mm
Displacement	118 cm^3
Compression ratio	8.5: 1
Net power	2.6 kW (3.5 HP) / 3600 rpm
Continuous rated power	1.8 kW (2.4 HP) / 3000 rpm 2.1 kW (2.8 HP) / 3600 rpm
Maximum net torque	9.3 Nm / 0.74 kgfm / 2500 rpm
Ignition system	Transistorised
Starter	Recoil
Fuel tank capacity	2.0 Litre
Fuel consumption at continuous rated power	1.0 L/h - 3600 rpm
Engine oil capacity	0.6 Litre
Dimensions (L x W x H)	305 x 346 x 329 mm
Dry weight	13 kg

Figure 1. Honda G200K1 single-cylinder four-stroke gasoline engine

2.2. Determination of brake power and the exergy efficiency at different torques

This particular experiment was carried out to investigate the performance of the single-cylinder four-stroke gasoline engine run on different torques. It was firstly assumed that the reference environment is an ideal gas mixture whose composition on molar basis is thus: CO_2 = 0.03%; N_2 = 75.6%; O_2 = 20.35%; H_2O = 3.12%; other gases= 0.83% (Ibrahim *et al.*, 2017). Before starting the tests, the engine was started and left to idle for about 10 minutes. It was then tested under 9.40, 9.50, 9.60 and 9.70 Newton-metre (Nm) torque conditions at a constant speed of 2500 rpm.

The brake power was thereafter estimated using equation 1:

$$\acute{W} = \frac{2\pi TN}{60} \quad (1)$$

T= Torque
N=Engine Speed

Thereafter, the time taken for 3 litres of gasoline to be consumed was noted for the whole experiment. The engine was mounted on a test bench and its output shaft was connected to the rotor of a dynamometer which measures its torque, mechanical friction was used to brake the rotor.

During the engine test, the time taken for 3 litres of fuel to be completely exhausted was noted, this was then used to calculate the mass flow rate of the system. For that to be done, the volumetric flow rate (V̤) was first determined by dividing the volume (v) of gasoline consumed within the experimentation time, see equation 2. The mass flow rate was thereafter estimated by multiplying the density of the fuel (obtained from table) with the estimated volumetric flow rate (equation 3).

$$\underset{\cdot}{V} = \frac{v}{t} \quad (2)$$

Hence,

$$\dot{m}_f = \rho_{avg}\underset{\cdot}{V} \quad (3)$$

For the determination of the exergetic efficiency of the engine, which the ratio of the engine's power output to its fuel exergy input for each torque was determined thus (Hacatoglu *et al.*, 2014):

$$\varepsilon_1 = \frac{\dot{W}}{\dot{m}_f e_f} \quad (4)$$

Where

$$ef = e_{tm} + e_{ch} \quad (5)$$

ef = specific exergy of steam
e_{tm} = Thermomechanical exergy
e_{ch} = Thermochemical exergy

The thermomechanical exergy can be determined thus (Sayin *et al.*, 2007):

$$e_{tm} = \bar{h} - \overline{h_o} - T_0(\bar{s} - \overline{s_0}) \quad (6)$$

Where $\bar{h}$ and $\bar{s}$ signify the specific enthalpy and specific entropy of the fluid, respectively; $\bar{h}_0$ and $\overline{s_0}$ stand for the corresponding values of these properties when the fluid comes to equilibrium with the reference environment.

The specific chemical exergies also thermochemical exergy (e_{ch}) of liquid fuels on a unit mass basis can be determined from the following relation (Seyedkavoosi *et al.*, 2017).

$$e_{ch} = \left[1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right)\right] \times LHV \quad (7)$$

Where h, c, o and s are the mass fractions of Hydrogen, Carbon, Oxygen and Sulphur, respectively.
LHV = 44240kJ/kg = Lower heating value of gasoline ($C_{10}H_{22}$) (Hudzik *et al.*, 2014).

Brake thermal efficiency (BTE) is the ratio of the brake power obtained from the engine to the fuel energy supplied to the engine. The BTE will determine how efficiently the heat is converted into work (Ramalingam and Rajendran, 2019). BTE is estimated thus:

The brake thermal efficiency for this engine was obtained using equation 8

$$BTE = \frac{\dot{W}_{cv2}}{\dot{Q}_{cv}} \quad (8)$$

Where

$\dot{W}_{cv2} = brake\ output\ power$

$\dot{Q}_{cv}$ = The input energy to the gasoline engine

2.3. Determination exergy destruction at different torques

The relative humidity of the laboratory was first measured, the engine was loaded up to a certain torque while the speed remained constant, parameters like airspeed, temperature of fuel and exhaust gas, flow rate of the intake air were then measured and noted. The parameters obtained were used to determine the destruction at different torques when compared with the initial content of the fuel. The fuel content was obtained in the following manner: The empty measuring cylinder was taken for measurement on mass balance, gasoline was poured to 800ml level of the cylinder, and gasoline in the cylinder was taken to mass balance and the mass reading of gasoline together with the cylinder was taken. This experiment was repeated several times, and the average mass of the gasoline together with the cylinder was taken. The density of gasoline was then estimated, when compared to the density of gasoline in literature (Anuchi and Chukwu, 2017; Obodeh and Akhere, 2010), it was found that the gasoline is decane ($C_{10}H_{22}$). Table 2 shows the thermophysical properties of decane (Nourozieh *et al.*, 2013).

The exergy destruction using these thermophysical properties was calculated using the exergy balance equation:

$$0 = \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_f e_f - \dot{m}_f e_{ex} - \dot{E}d \quad (9)$$

Table 2. Thermophysical Properties

Substance	$\bar{h}_f^0$ (kJ/kmol)	$\bar{h}_{298K}$ (kJ/kmol)
$C_{10}H_{22}$	-249,659	
O_2	0	8682
N_2	0	8669
H_2O	-241,820	9904
CO_2	-393,520	9364

2.4. Determination component of the G200K1 that is most influential on its efficiency

Calculations for the exergy of the engine were done relative to the reference environment which had ideal gas properties: temperature (T_0) = 298.15K, pressure (P_0) = 1atm. Moreover, it is assumed that the reference point has an ideal gas mixture properties with the following composition on a molar basis: N_2= 75.6%; O_2= 20.35%; CO_2=0.03%; H_2O=3.12%; other gases= 0.83% (Barelli *et al.*, 2011; Moran *et al.*, 2010). The exhaust gas is assumed to be a mixture of ideal gases, the thermomechanical exergy of the exhaust gas at the temperature T and pressure p, and containing n components can be obtained from equation 10 (Sayin *et al.*, 2007).

$$e_{tmg} = \sum_{i=1}^{n} a_i \left\{\bar{h}_i(T) - \bar{h}_i(T_0) - T_0\left[\bar{S}^0(T) - \bar{S}^0(T_0) - R ln\frac{p}{p_0}\right]\right\} \quad (10)$$

Where: R = Gas constant; T_o =Environment temperature; p = pressure of exhaust gases; a_i= Molar amount of the gases; $\bar{h}_i(T)$ = Enthalpies at temperature of gases; $\bar{h}_i(T_o)$ = Enthalpies at environment temperature; $\bar{S}^o(T)$ = Entropies at temperature of gases; $\bar{S}^o(T_o)$ = Entropies at environment temperature.

3. RESULT AND DISCUSSION

3.1. Average brake power and exergy efficiency

Since brake power is a function of torque and speed, the speed of the engine was maintained at 2500 rpm throughout the engine test. Hence, different power values of brake power corresponding to the torques of 9.4, 9.5, 9.6 and 9.7 Nm were obtained as 2.46, 2.49, 2.51 and 2.52 kW. The brake power (kW) and exergy efficiency (%) at different torque values (Nm) and airspeeds (m/s) were obtained (see table 3). From the table, it can be seen that as torque increases, other parameters like air velocity, brake power and exergy efficiency also increase. Since higher exergy efficiency means higher energy quality used in a thermodynamic system which then makes the system more sustainable (Caliskan and Hepbasli, 2011), therefore, can be said that the single cylinder 4 stroke gasoline engine is more efficient when loaded. To buttress this point, the effect of engine load and reversible work on the rate of efficiency was estimated, the engine loads were varied from 20% to 100% at increments of 10%. The result shows that for every 10% change in torque there is at least 2.62% change in brake power output at a constant speed of 2500rpm, the relationship is a straight-line graph with equation y = 3.8168x + 0.0073.

Table 3. Brake power and exergy efficiency

Torque (Nm)	Air Velocity (m/s)	Brake Power (kw)	Exergy Efficiency (%)
9.40	0.50	2.4609	17.07
9.50	0.51	2.4871	17.25
9.60	0.51	2.5133	17.43
9.70	0.52	2.5395	17.62

3.2. Brake thermal efficiency and exergy efficiency

The brake thermal efficiency (%) and exergy efficiency (%) at toque values (N/m) and airspeeds are presented in table 4. It can be seen that as torque increases, other parameters like air velocity, brake thermal and exergy efficiency increase too. This is an indication that torque is the most influential parameter affecting the efficiency of a single-cylinder four-stroke gasoline engine, this finding concurs with that of other researchers who have worked on other types of engines (Ghazikhani *et al.*, 2014; Parlak, 2005; Yamin *et al.*, 2018).

Table 4. Brake thermal and exergy efficiency

Torque (Nm)	Air Velocity (m/s)	Exergy Efficiency (%)	Brake Thermal Efficiency (%)
9.40	0.50	17.07	27.46
9.50	0.51	17.25	27.76
9.60	0.51	17.43	28.05
9.70	0.52	17.62	28.35

Figure 2 is a graph of torque against brake thermal efficiency, the relationship between the two is linear with equations y = 0.3378x + 0.1231. The highest brake thermal efficiency (28.35kw) is obtained at a torque of 9.70Nm at a constant 2500rpm. For every 10% rise in torque, there is a 30% rise in brake thermal efficiency.

It can be seen that the exergy transferred out of the system by the exhaust gases is very high as a result of the very high temperature of the flue gases, and the higher the temperature of the engine surface from where the heat is rejected thus a high exergy loss (thermochemical exergy of exhaust gases) because of this. The uncounted exergy shows the proportion of the exergy destroyed as a result of unrecoverable and uncounted losses in the whole engine such as combustion losses, friction loss, heat loss to lubricating oil, power consumed by auxiliary equipment e.g. pumps, radiation losses, thermal mixing losses etc. Exergy loss caused by irreversible combustion has a large proportion. Fuel combustion is a strongly irreversible process, although chemical energy is converted into thermal energy in the combustion process, and the quantity of energy is constant in conversion and transfer processes, exergy is reduced greatly. Furthermore, the higher the combustion temperature, the higher the potential for NOx formation in the combustion process is.

In addition, high temperatures of combustion cause increased heat transfer from the engine cylinder, consequently increasing the exergy lost as a result of the high heat transfer rate/heat loss. Temperature gradient is the driving force of heat transfer, it is an irreversible process where heat is transferred due to temperature difference, hence, exergy is lost in the process. Loss in exergy due to heat transfer is as a result of temperature gradient, the greater the gradient, the greater the exergy loss. The smaller the temperature gradient, the smaller the exergy loss.

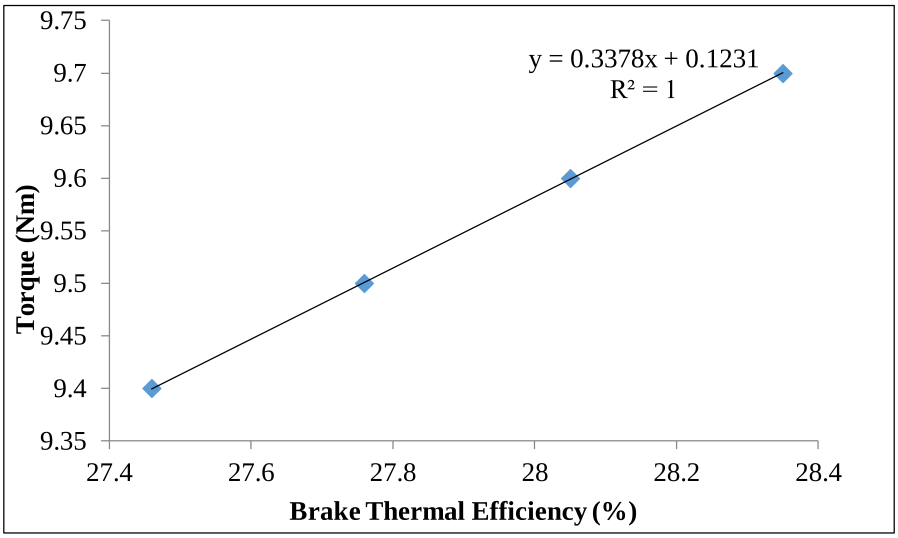

Figure 2. Graph of Torque against Brake thermal efficiency

3.3. Torque and exergy destruction

The exergy destruction (kW) at different values of torques and airspeeds are presented in table 5. From the table, as torque increases, other parameters like air velocity, exergy destruction (kW) increases too. The higher the value of torque, the higher the exergy destruction in the system, this is because the useful energy contained in the fuel is being converted to mechanical work (movement of the piston) and heat. This finding is further expatiated graphically by the illustration in Figure 3. It can be seen that torque has a direct impact on exhaust exergy, at the lowest torque of this research work (2.40Nm) the exhaust exergy lost is 29.779kW at constant speed 2500rpm. While at the highest torque of 2.70Nm, the exhaust exergy lost is 29.857kW. The relationship is a straight-line graph with equation y = 3.8462x - 105.13 which tells us that as torque increases exhaust exergy loss increases too. To minimise exhaust exergy loss, lower torque is required.

Comparing the exergetic efficiency (rate of exergy loss accompanying heat loss) of the system to the variation in torque, a similar pattern was noticed – the exergetic efficiency increases as torque increases. The linear graph relationship with equation y = 0.5464x + 0.0749 is represented in Figure 4. It was found that maximum exergetic efficiency (17.62%) is obtained at 9.70Nm torque and that for every 10% rise in torque there is an 18% rise in exergetic efficiency at 2500rpm but this value may change at different speed operations.

Table 5. Exergy destruction

Torque (Nm)	Air Velocity (m/s)	Exergy Destruction (kW)
9.40	0.50	-29.779
9.50	0.51	-29.805
9.60	0.51	-29.830
9.70	0.52	-29.857

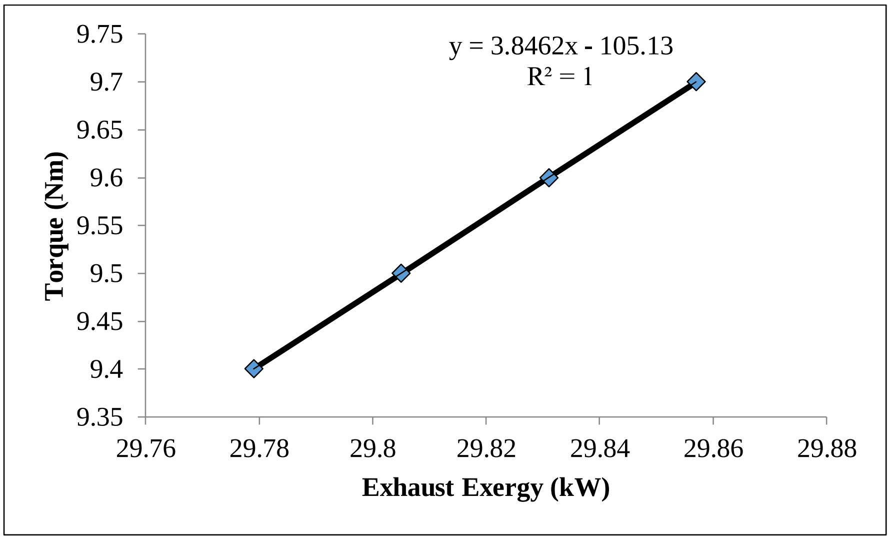

Figure 3. Graph of Torque against Exhaust Exergy

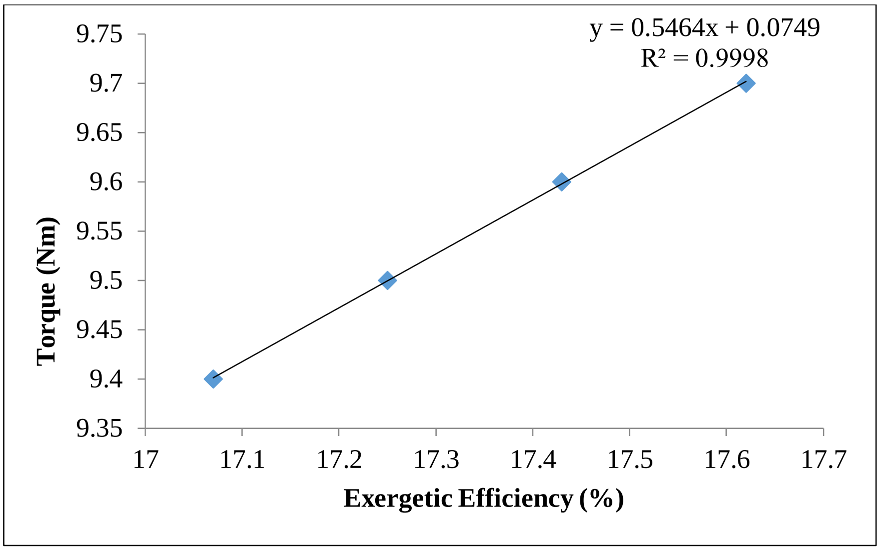

Figure 4. Graph of Torque against Exergetic efficiency

4. CONCLUSION

An exergy analysis was carried out on a Single-cylinder, four-stroke G200K1 gasoline engine at the Mechanical Engineering thermodynamic laboratory of Bayero University, Kano. Using the data gathered, the exergy balance relationship and exergetic efficiency were determined. It was found that the reversible work, irreversibility and exergy efficiency of a single-cylinder four-stroke engine increases with an increase in torque, this was demonstrated when the engine load was varied from 20% to 100%. It was also found that for every 10% rise in torque, there is a corresponding increase in other parameters such as exergy destroyed, and exergy efficiency. On the efficiency of the engine, it was found that the major part of wasted energy is the high-temperature gas released through the exhaust.

To improve the overall efficiency of a four-stroke single-cylinder gasoline engine, the exergy destruction due to combustion can be reduced by optimizing the combustion temperature, this can be done by using a material with low thermal conductivity to reduce heat loss from the combustion chamber.

5. ACKNOWLEDGEMENT

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NOMENCLATURE

a_i= Molar amount of the gases
BTE = Brake thermal efficiency
ε_1 = exergetic effciency
e_{ch} = Thermochemical exergy
$\dot{E}d$ = Exergy destruction
e_f = Specific exergies of the fuel
e_{tm} = Thermomechanical exergy
e_{tmg} = Thermomechanical exergy of exhaust gases
$\bar{h}_0$ = Specific enthalpy when fluid is at equilibrium with the reference environment
$\bar{h}$ = specific enthalpy
$\dot{m}_f = Mass\ flow\ into\ the\ system$
N = Engine Speed

LHV = Lower heating value
p = pressure of exhaust gases
R = Gas constant
$\dot{Q}_{cv}$ = The input energy to the gasoline engine
$\bar{s}$ = Specific entropy
$\bar{s}_0$ = Specific entropy when fluid is at equilibrium with the reference environment
t = time
T_o =Environment temperature
T = Torque
v = volume of gasoline consumed
$\dot{V}$ = volumetric flow rate
$\dot{W}_{cv2}$ = brake power output
ρ_{avg} = average density

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