Taguchi Method for Investigating the Performance Parameters and Exergy of a Diesel Engine Using Four Types of Diesel Fuels

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***Abstract*—The effects of changes in engine operating parameters, i.e., engine speed, throttle and water temperature, for four types of diesel fuel (A, B, C and D) of different specific gravities, as supplied from local market and refineries, were studied and simultaneously optimized. The experiment design was based on Taguchi's "L' 16" orthogonal table, and the engine was put to test at different engine speeds, throttling opening percentages and water temperatures, using different fuels. The data were analyzed using S/N (signal to noise ratio) for each factor. The obtained results show that the optimum operating conditions for minimum BSFC (brake specific fuel consumption) are achieved when the engine speed is 2500 rpm, the throttle is placed at 75% of full throttling, the water temperature is 80 °C and the engine is using fuel type D. Also, results of S/N ratio reveal that the throttle has significant influence on brake thermal and exergic efficiencies. Water temperature is the second most effective factor and then comes the influence of engine speed. The least effective factor among the studied parameters for the types of fuel considered in this experiment is the fuel type.**

***Index Terms*—Compression ignition engines, exergy, Taguchi, performance.**

I. Introduction

A charge of compressed air and a diffused spray of liquid fuel operate the compression ignition engine. The combustion pressure in the cylinder of a diesel engine is the result of a larger compression ratio which, combined with better combustion efficiency, gives it a higher indicated thermal efficiency when compared to spark ignition engine. The diesel engine is still recognized as a promising power train for the foreseeable future due to superior thermal efficiency and reliability (Xin, 2011).

This work is based on experimental observations to improve our understanding of the parameters affecting the performance of a diesel engine. To select the range of parameters to work with, it was necessary to run a review over the working parameters and check their effect on the performance of the compression ignition test rig.

Engine characteristics such as; engine speed, reduction in intake throttle pumping loss, equivalence ratio balance and its effect on leaner mixture of air and fuel, and higher compression ratio, prove that the diesel engine can run at a higher brake thermal efficiency than its gasoline engine counterpart (Xin, 2011; Mollenhauer and Tschoeke, 2010; Doe, 1993).

It is estimated that for diesel engine, the specific fuel consumption is about 80% of that of petrol engine. The lowest specific fuel consumption of compression ignition engine is attained as the fuel-air ratio approaches the stoichiometric ratio and a speed at which volumetric efficiency is at the optimum. It is also estimated that the highest thermal efficiency and lowest fuel consumption of diesel engines occur at approximately 50-85% of maximum brake mean effective pressure (Garrett, 2001; Rajput, 2008).

To improve our understanding of the significance of diesel fuels and their influence on the engine itself, it is important to have a basic understanding of fuel characteristics, properties and contaminants that impact the operation of such an engine. The quality of fuel plays an important role in diesel engine performance. It also affects the durability of operation and maintenance intervals. A fuel property is considered to be a characteristic occurring in the fuel carried over from its crude source or the result of the refining processes by which it was produced. Fuel characteristics are affected by fuel delivery temperatures and excessive evaporation of fuel during its transport to the combustion chamber can disturb the performance of the fuel injectors.

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Cooling systems are designed to maintain engines at optimum temperatures, allowing the design of components that expand on heating to form very tight fits and running tolerances. The calibration of ignition and fuel settings is balanced against the operating temperature imposed for the clean and efficient combustion of fuel. Temperatures inside the combustion chamber of an engine, during combustion, reach the order of 2427 ^{o}C and up (Pulkrabek, 2004). Engine components may not be able to tolerate this kind of temperature and can fail if proper heat transfer does not occur. Cooling the combustion chamber is highly critical in keeping an engine and engine lubricant from thermal failure. This is balanced against the principle that it is desirable to operate an engine as hot as possible to maximize thermal efficiency (Pulkrabek, 2004; Denton, 2011).

Many researchers studied the performance of CI engines, using Taguchi method. An experimental study has been carried out by Nataraj, Arunachalam and Dhandapani (2005), to simultaneously optimize several diesel engine designs and operating parameters for low exhaust emissions using, Taguchi method. Kanogˇlu, Isık, and Abuşogˇlu (2005) studied the characteristics and performance parameters of the internal combustion engines of the power plant. The mass, energy and exergy balances are verified for each flow stream in the power plant. The work and heat interactions, the exergy losses and the efficiencies of various components based on both energy and exergy concepts are evaluated and the thermal and the exergy efficiencies of the plant are determined. Tamilvendhan, et al. (2011) based their experiment on diesel fuel blends and studied fuel replacing ability, performance and emission behavior with respect to blend proportions, injection timing and pressure, using Taguchi's nine trials for optimization. The trials were based on studying the main effect of each of the above three parameters. The measured performance figures from these trials were used to analyze the effect of the studied factors. The results indicated improved brake thermal efficiency without excessive deterioration of the exhaust emission.

Wu and Wu (2013) used Taguchi method to determine the optimal concentration of diesel/biodiesel blend using cooled exhaust gas recirculation (EGR) at the inlet port. They researched the optimal operating factors for achieving good combustion performance and low emissions at various engine loads and 1500 rpm.

Sekmen and Yılbaşı (2010) conducted experimental investigation of diesel engine performance including, specific fuel consumption and brake horse power, based on energy and a number of exergy balances such as; exergy destruction and exergetic efficiency, with different fuel. They arrived at the conclusion that a combined energy and exergy analysis provides a much better and more realistic answer.

ANOVA (analysis of variance) is an approach based on analysis related to sums of squares for each effective factor to express dispersion of characteristics, (Lee, et al., 2013). It finds the factors with significantly effective impact, when compared to the others. This helps in reducing the number of considered parameters.

Xiao, et al. (2014) conducted a simulation investigation using, CFD (computation fluid dynamics) with Taguchi method and ANOVA to understand the combined effect of a number of combustion parameters such as EGR (exhaust gas recirculation), fuel quality and injection timing on NOx (oxides of nitrogen). They concluded that EGR is the most effective factor in estimation of the amount of produced NOx.

There are a large number of parameters to be considered for every experimental investigation. An approach based on Taguchi method is adopted in this work with the aim of optimizing the experimental parameters with a reduced number of attempts. Larger number of parameters leads to larger number of trials and consumes more time to complete the experiment.

Taguchi method depends on orthogonal arrays, which are statistically analyzed, leading to a thorough investigation of the results. Based on this approach the considered data is assessed and optimized taking into account a more universal view when considering the mean and the variation through signal to noise ratio. The strength of the influence of parameters is based on the outcome of signal to noise ratio evaluation.

The concept of signal (product quality) to noise (uncontrollable factors) ratio are log functions based on Larger the better, Smaller the better and Nominal the better.

In this work the effective parameters to be investigated are pre-defined as engine speed, throttle position, cooling water temperature and the fuel type. ANOVA was not applied to optimize the selection process due to limited number of considered parameters. At one stage, Taguchi method is applied to indicate the order of significance of these parameters.

II. Theoretical Approach

A. Fuel Consumption

Specific fuel consumption is defined as the amount of fuel consumed for each unit of brake power developed per hour. It is a clear indication of the efficiency with which the engine develops power from fuel, (Rajput, 2008).

$$BSFC = 3600\, \dot{m_f}\ \ BP \tag{1}$$

B. Volumetric Efficiency

This is equal to the ratio of mass of air, which enters or is forced into the cylinder in intake stroke, to the mass of air equivalent to the piston displacement at intake temperature and pressure conditions, (Rajput, 2008).

$$\eta_v = \dot{m_a} / \dot{m_f} \tag{2}$$

Air volumetric flow-rate is measured with air box manometer head by the relation, (Cussons Technology Ltd, 1989):

$$V_{actual} = 0.1244\, d^2 (\mathrm{hh}/\rho_{\mathrm{air}})^{0.5} \tag{3}$$

C. Energy Analysis of Diesel Engine

Most transient-flow processes can be modeled as uniform flow. The following assumptions were made to simplify the first law calculation; the engine operates at steady state and the whole engine, including the dynamometer, is selected as a control volume. This excludes the work transfer between the engine and the dynamometer. Also the combustion air and the exhaust gas each form ideal gas mixtures and potential and kinetic energy effects of the incoming and outgoing fluid streams are ignored.
Fuel energy rate to the control volume is given by Equation:

$$Q_f = \dot{m_f}\ LHV \quad (4)$$

Brake power of the engine is determined by:

$$Pb = \mathrm{T_r}.\omega = 2\pi N T_r/60 \quad (5)$$

Brake thermal efficiency of the control volume (η_b) is usually determined as the ratio of the power output (net work) to the fuel energy input and is represented by:

$$BTE = P_b/Q_f = P_b/\,(\dot{m}_f\ \ LHV\ ) \quad (6)$$

D. Exergy Analysis

Exergy is the maximum theoretical work obtainable from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment. The order of exergy destruction and losses in the processes and components of a thermal system can be revealed by the exergy analysis of the system. The results of exergy analysis can be used for identifying certain processes in a thermal system, on which further studies must be conducted to achieve better energy source utilization. The specific chemical exergies of liquid fuels can be evaluated from the following expression on a unit mass basis (Sayin, 2006; Rakopoulos, 2004).

$$a_{fch} = LHV\ (1.04224 + 0.011925\, m_1/m_2 - 0.042\, m_2) \quad (7)$$

On the other hand, assuming the ideal solution assumption is valid; the specific chemical exergy for a multi component stream can be calculated as:

$$e_{ch} = R\ To \sum_{i=1}^{n} a_i\ ln(yi/yio) \quad (8)$$

When R is gas constant (kJ/(kmol.K)) and To is the ambient temperature as indicated in the nomenclature.

Diesel fuel can be modeled as $C_{14.4}H_{24.9}$ (Rakopoulos, 2004). When computing the rate of exergy transfer accompanying heat transfer, it was assumed that $\dot{Q}_{cv}$ is rejected into the ambient air from the boundary having the same temperature as the engine coolant circulating in the engine block. Inserting values for the exergy transfer accompanying heat, mass flow, and power transfers, used in calculation of fuel and work exergies, the rate of exergy destruction in the engine can be determined by (12), indicated below. Exergetic efficiencies also can be used to evaluate the effectiveness of engineering measures taken to improve the performance of a thermal system. Finally, the exergetic efficiency of the engine (13) can be evaluated from the ratio of the power output to the fuel exergy input. Exergy destruction can be calculated from the difference between the exergy input and the net work produced. If the proportion of exergy destruction to the entered fuel exergy decreased, then the exergic efficiency is increased. The relevant exergy relations are defined below (Sorathia and Yadav, 2012):

$$Fuel\ Exergy: E_f\ = m_f\ e_{ch} \quad (9)$$

$$Heat\ Exergy: E_Q\ = \textstyle\sum_s (1 - T_o/T) \quad (10)$$

$$Work\ Exergy: E_w = W = Pb \quad (11)$$

$$Destroyed\ Exergy: E_d = E_f - E_w \quad (12)$$

$$Exergetic\ Efficiency: \eta_{II} = E_w/E_f = 1 - E_d/E_f \quad (13)$$

III. Experimental work

In this study the experimental set up consists of a compression ignition engine test bed connected directly to an eddy current dynamometer as indicated in Fig. 1.

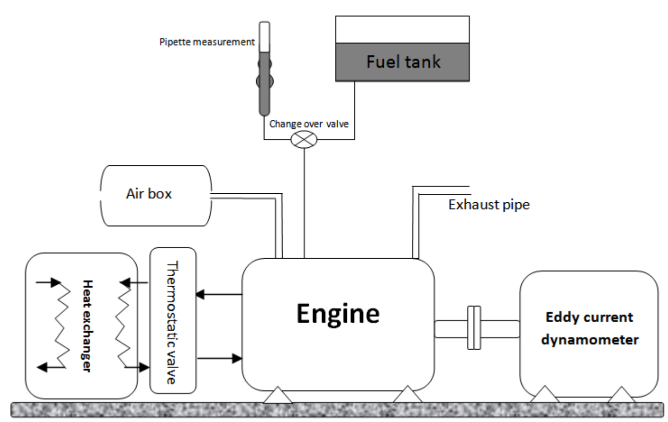

Fig. 1. Test rig schematic

For this layout the specifications are shown below:
Engine type: Ford XLD 416, four stroke, water cooled, indirect injection compression ignition engine, 1.6 liter engine. Number of cylinders: 4 in-Line, Bore: 80 mm and stroke: 80 mm. Compression ratio: 21.5:1. Dynamometer: Froude EC38 TD eddy current dynamometer. The rig is used for testing, based on Taguchi's (L'16) table, with four types of locally available fuels with the specifications shown in Table I. The fuel types shown in this table represent four types of fuel available in the region.

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TABLE I
PROPERTIES OF FOUR TYPES OF DIESEL FUELS

Type	SG AT 15.5 °C	LHV (MJ/Kg)
A	0.8118	43.188
B	0.8318	43.154
C	0.8284	43.265
D	0.8322	43.364

The succession of tests is listed in Table II. This table shows throttle openings of (55%, 65%, 75% and 85%), engine speed variations of (2000 rpm, 2250 rpm, 2500 rpm and 2750 rpm) and water temperatures of (65 ^{o}C, 70 ^{o}C, 75 ^{o}C and 80 ^{o}C) for four fuel types.

IV. RESULTS AND DISCUSSION

The present work uses four factors at four levels. Hence, an L'16 orthogonal array, Table II, with four columns and sixteen rows were used to design Taguchi's experiment with Minitab 16 software. The factors considered for experiment and levels are shown in Table II. Sixteen independent experiments were conducted in an attempt to obtain high accuracy and research quality results. All the parametric variations were done on the same fuel to avoid mixing between the fuels during experimentations. To ensure the correct throttle position, the gap between the throttle lever and its stop was measured with a set of spacers for each similar throttle positions.

TABLE II
TEST ARRANGEMENTS

Experiment no.	L'16 ORTHOGONAL ARRAY				Obtained Data		
	Fuel Type	Engine Speed (rpm)	Throttle (%)	Water Temperature (°C)	Torque	Head of Air Box Manometer (mm) [converted to air flow rate (l/min)]	Time for Fuel Consumption (sec) [converted to fuel flow rate (g/sec)]
1	A	2000	55	65	40.1	7.75 [1183.15]	29.1 [0.821]
2	A	2250	65	70	53	9.75 [1327.062]	22.05 [1.083]
3	A	2500	75	75	65.3	12.25 [1487.5]	19.55 [1.221]
4	A	2750	85	80	72.4	14 [1590.204]	15.25 [1.566]
5	B	2000	55	65	37.9	7.5 [1163.91]	32.1 [0.752]
6	B	2250	65	70	59.9	9.5 [1309.938]	22.6 [1.069]
7	B	2500	75	75	63.9	12.75 [1517.554]	18.08 [1.336]
8	B	2750	85	80	72.1	14.25 [1604.34]	15.1 [1.599]
9	C	2000	55	65	31.2	7.5 [1163.91]	33.03 [0.738]
10	C	2250	65	70	44.6	9.75 [1327.062]	24.23 [1.005]
11	C	2500	75	75	73	12.25 [1487.5]	20.33 [1.198]
12	C	2750	85	80	73	14.25 [1604.34]	18.332 [1.33]
13	D	2000	55	65	22.6	7.5 [1163.91]	37.98 [0.644]
14	D	2250	65	70	51.7	10 [1343.968]	24.3 [1.006]
15	D	2500	75	75	72.2	12 [1472.243]	20.29 [1.205]
16	D	2750	85	80	74	14 [1590.204]	19.11 [1.279]

All data are taken after the engine coolant temperature, coming out of the engine, reached the desired temperature. The results of the experimental layout of L'16 orthogonal array were calculated. The data is analyzed with Minitab 16 software, which simplifies the Taguchi procedure and results and S/N ratios are calculated. The software was checked for accuracy using stepwise hand calculations. S/N ratio represents the transformation of repetition data to measure of present variation. There are several S/N ratios available depending on the type of characteristic, the equations for calculating S/N ratios give negative values as is indicated from the format of these equations (Ross, 1996):

- Lower is better:

$$s/N_{LB} = -10\,LOG(1/n\ \sum_{i=1}^{n} Y_i^2) \qquad (14)$$

- Higher is better:

$$s/N_{HB} = -10\,LOG(1/n \sum_{i=1}^{n} 1/Y_i^2) \qquad (15)$$

- Nominal is better:

$$s/N_{nominal} = -10\,LOG(1/\,n \sum_{i=1}^{n} Y_i - Y_m) \qquad (16)$$

Once the experimental design was determined and the trials were carried out, the measured performance characteristic from each trial was used to analyze the relative effect of the different parameters.

Fig. 2 and Fig. 3 show the obtained graphs of Taguchi experiments for the value of the means and the mean of S/N ratios, ranging from smaller is better for SFC (Fig. 2) which explains the opposite projection of the graph of mean of means, which is an engine characteristic that is optimum when smallest to larger is better for volumetric efficiency (Fig. 3) which is best when largest and is projected comparably by mean of means graphs. They were used for selecting the optimum level of the parameters.

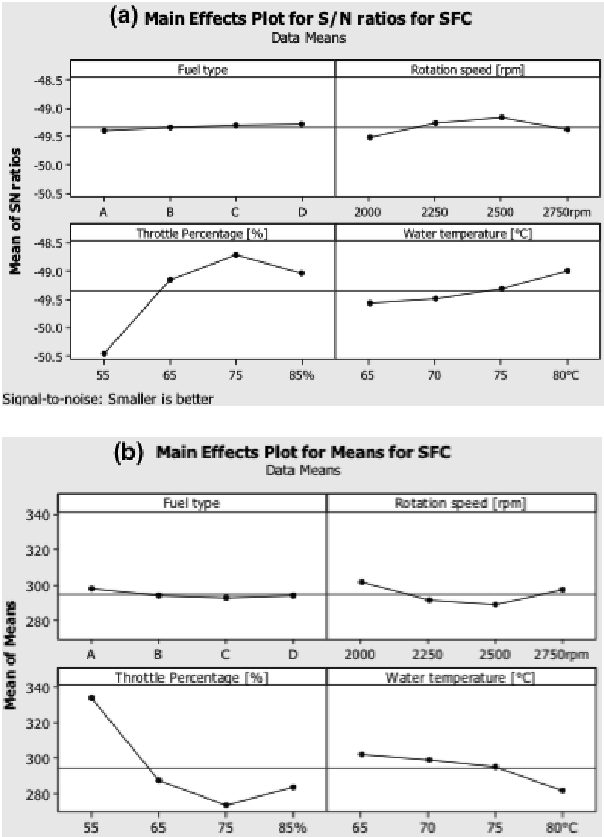

Fig. 2. Main effects plot of the S/N ratios and means for BSFC.

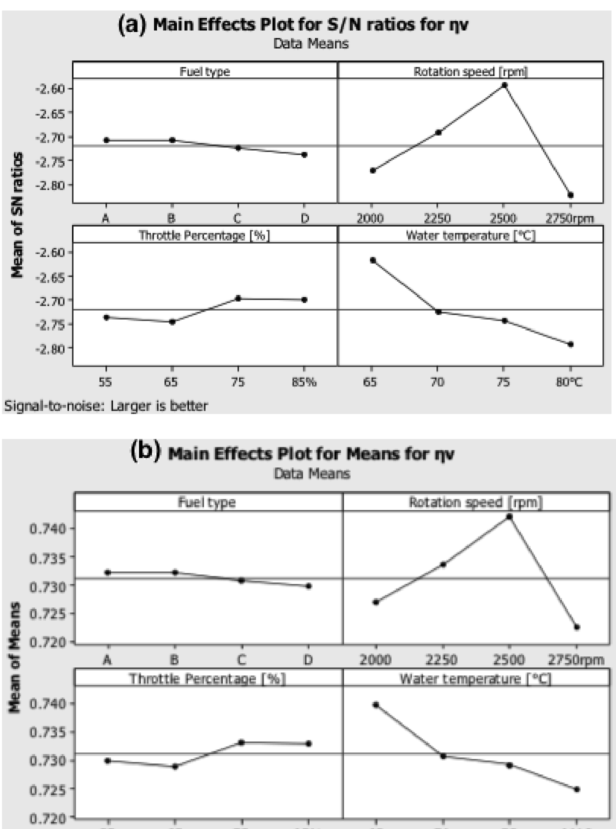

Fig. 3. Main effects plot of the S/N ratios and means for volumetric efficiency.

The peak value of each graph is considered as the optimum point, as these points are offering highest S/N ratios. The horizontal line in the middle of each figure indicates the mean of the projected values. The mean of means indicates the average of the highest and lowest averages for each factor and the graphs are limited in presentation by the software mini tab (5) grapher and this has partially affected the presentation of the throttle contribution as the highest value of the graph falls outside the y-axis limit.

The confirmation tests were later conducted with the optimum combination of results showing that the obtained parameters have prime values compared to the other tested experiments. The obtained results are discussed below:

A. Brake Specific Fuel Consumption (BSFC)

Results reveal that the specific fuel consumption is strongly affected by the throttle position because of the highest range between maximum to minimum S/N ratio. Fig. 2 shows that the minimum point of consumption occurs at %75 of the full throttle. The second most effective factor is the water temperature of the engine. The plot profile reveals that BSFC decreases as the water temperate is increased, reaching the minimum at a water temperature of 80°C. The third effective factor over the output of BSFC characteristic is rotation speed of the engine. The minimum fuel consumption is achieved at an engine speed of 2500 rpm. And it is at this speed that the engine attains maximum volumetric efficiency. The contours of the diesel fuel type curves are almost unremitting. The results reveal approximated output. As specific gravity (SG) is increased, BSFC is slightly decreased and it indicates the minimum value with diesel fuel type (D), which has the highest specific gravity ($SG_{15.5}$= 0.833). If BSFC is expressed in [liter/kW.hr], the consumption differences become more observable.

B. Volumetric Efficiency

The engine speed (N) has a major effect on volumetric efficiency. Fig. 3 shows that (η_v) has maximum value at an engine speed of 2500 rpm. The temperature of water is the second most effective factor on the volumetric efficiency. As the temperature is increased, the volumetric efficiency is decreased as a result of the decreasing density of the air entering the combustion chamber. It is concluded that the volumetric efficiency reaches the maximum value at a temperature of (65°C).

As normally aspirated diesel engines receive almost equal amounts of air and the power is controlled by the injection pulses and duration, then the throttle has no significant effect on the volumetric efficiency and the indicated differences are related to errors in the precision of the measurement of the manometer inside the air box. The fuel type has no substantial effect on the volumetric efficiency because the mixing of fuel and air takes place inside the cylinder and there is no visible influence for the evaporation of fuel after injection, on the induction of air.

C. Brake Thermal Efficiency (BTE)

The energy converted into power output was measured by the dynamometer. The dynamometer was also used to keep the engine speed at a constant value.

The torque was measured from the force imposed by the dynamometer. The recorded engine speed and the measured torque lead to the calculation of the output power, (5). To measure the energy transferred from the fuel to the engine, the mass flow rate of fuel was calculated, the net heating value (LHV) was obtained from an empirical relation (Mollenhauer and Tschoeke, 2010):

$LHV = 46.22 - 9.13 \times (SG)^2 + 3.68 \times (SG)$, and then (BTE) was found. In order to efficiently study the factors and find their optimum impact point, Taguchi techniques are employed. Results reveal that the throttle has a significant effect on the brake thermal efficiency (BTE) and Fig. 4 shows that (BTE) reaches its optimum point at 75% of the maximum throttle. The second significant factor affecting (BTE) is the water temperature. Within the operating range, (BTE) is directly increased as the water temperature is increased. From the test it is established that η_b has the optimum point at 80°C. The engine speed is the third effective factor on (BTE). (BTE) reaches the optimum point at an engine speed of 2500 rpm. Diesel fuel type has a minor effect on (BTE). However, increasing the specific gravity (SG) of the diesel fuel slightly increases (BTE). From the experiments, it is concluded that (BTE) is optimum for the diesel fuel type D which has $SG_{15.5\,°C} = 0.833$.

The optimal values are obtained from using Taguchi method on the samples of test results for the variables indicated above as shown in Fig. 4. After conducting the confirmation test with the optimum combination (water temperature = 80 °C, throttle = 75%, N = 2500 rpm, fuel type (D)), the results show a value of 0.331 for (BTE). This value, which is obtained with the optimal data, as explained above, represents the maximum value which is confirmed though using only the optimized values of above mentioned parameters and it is the maximum value when compared to the other experiments. Therefore, the validity of this value is confirmed using Taguchi method, which is the case for this work.

D. Exergetic Efficiency

Since the exergetic efficiency takes into account not only the first but also the second law of thermodynamics, it provides a better measure of the performance for a thermal system. The fuel exergy (based on chemical exergy), expressed in (7), (8) and (9) for the four fuel types is calculated with procedures involving lower heating value (LHV). Exergetic efficiency (η_{II}) and S/N ratios for all experiments are calculated and the effects of factors are investigated as shown in Fig. 5. The throttle has a significant effect on the exergic efficiency (η_{II}) and it has the optimum value at %75 of full throttle. Temperature of water is the second significant factor for (η_{II}). The pattern of the curve of (η_{II}) is increased as the temperature is increased and it has a maximum value at 80 °C.

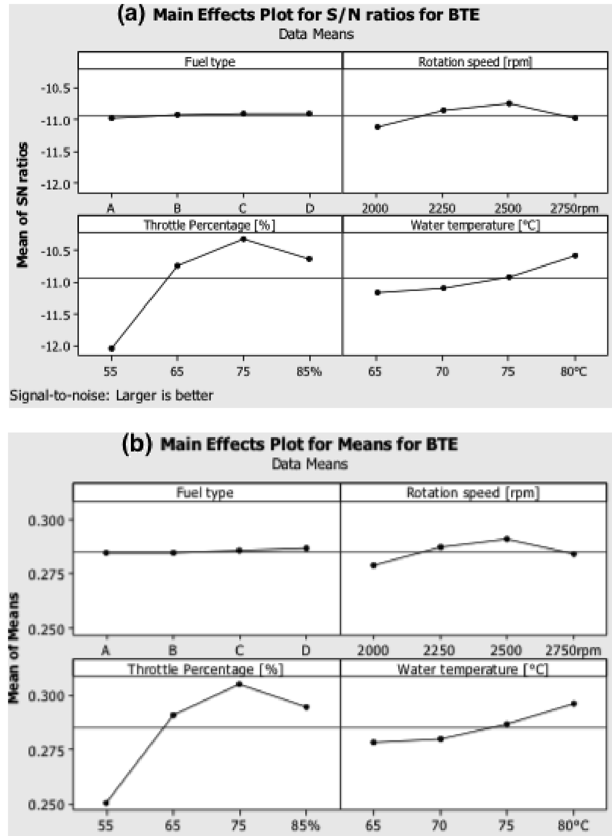

Fig. 4. Main effects plot of the S/N ratios and means for (η_b).

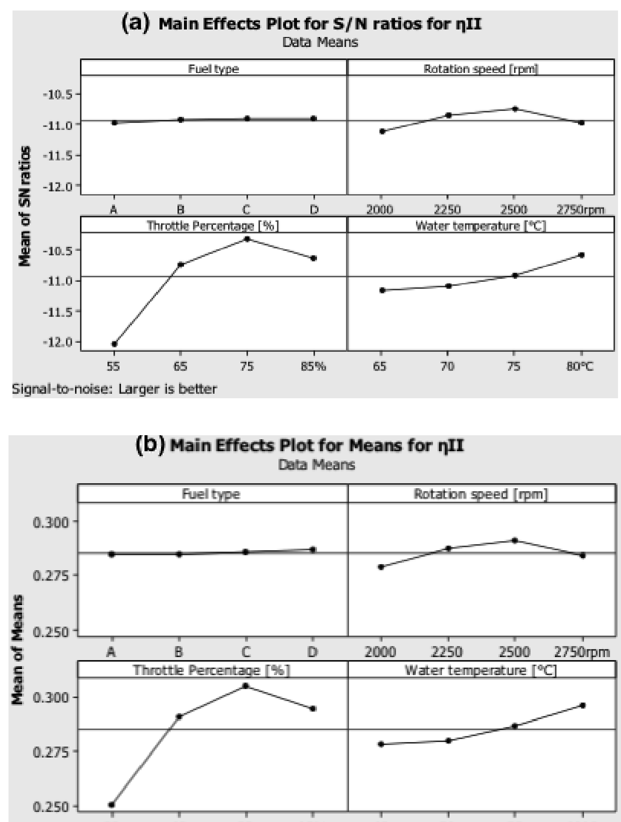

Fig. 5. Main effects plot of the S/N ratios and means for the exergetic efficiency.

Engine speed is the third effective factor for (η_{II}) and it has the peak value at 2500 rpm. Diesel fuel type has a minor effect on (η_{II}). However fuel type D achieves the optimum value of (η_{II}). Due to the fact that both exergic efficiency and BTE are inherently expressing deviation from the ideal performance, their trends are also similar. However, the exergic efficiencies are lower than the corresponding (BTE) because a higher amount of deviations are expressed in fuel exergy, compared to the fuel energy.

V. Conclusion

a) The effectiveness of Taguchi methodology is underlined by replacing the required (4^4 = 256) tests, needed to decide the effect of parameters: engine speed, throttle and water temperature for four types of fuel by only 16 deciding experiments as indicated in Table II.
b) The throttle has a proportional relation to break mean effective pressure as a result of the increase in the quantity of injected fuel. The best operating point was accomplished at 75% of full throttle.
c) Throttle position has no effect on volumetric efficiency of test engine.
d) Water temperature is second most effective parameter on engine operation for minimum BSFC. The optimum temperature for improved brake thermal and exergic efficiencies is found to be 80°C.
e) As the water temperature was increased the volumetric efficiency dropped. During the experiments, the maximum volumetric efficiency was recorded at a water temperature of 65°C.
f) The optimum engine speed for the test engine, based on maximum volumetric efficiency, minimum BSFC and improved values of thermal and exergic efficiencies was 2500 rpm.
g) Fuel specific gravity has a limited effect on BSFC. It is shown from the results that the reduction in power caused by the reduction in volumetric flow rate is compensated by increasing the fuel density.

Future work can focus on applying a similar procedure to a direct injection diesel test rig, which is more susceptible to variation in diesel engine fuel type.

Nomenclature

Symbol	Definition	Unit
Ai	Coefficient of the component *i* in the reaction equation	-
a_{fch}	Specific chemical exergy	kJ/kg
BSFC	Brake specific fuel consumption	g/kW.hr
BP	Brake power	kW
D	Orifice diameter	mm
E_d	Destroyed exergy	kJ
E_f	Fuel exergy	kJ
E_Q	Heat exergy	kJ
Ew	Work exergy	kJ
Ech	Specific chemical exergy for a multicomponent stream	kJ/kg
h_e	Exit enthalpy	kJ/kg
h_i	Inlet enthalpy	kJ/kg
Hh	Manometer reading	mm
LHV	Lower heating value	kJ/kg
$\dot{m}_e$	Exit mass flow rate	kg/sec
$\dot{m}_i$	Inlet mass flow rate	kg/sec
N	Number of tests in a trial	-
N	Engine speed	Rpm
Q	Heat rate	Watt
Q_{cv}	Heat rejection	Watt
$Q^o{}_f$	Fuel energy rate	Watt
Pb	Brake power	Watt
R	Gas constant	kJ/kmole.K
SG	Specific gravity	-
S/N	Signal to noise ratio	-
T	Temperature	°C
T_o	Ambient temperature	°C
Tr	Torque	N.m
V^o	Volumetric flow rate	m^3/sec
W^o	Rate of work	Watt
y_i	Molar ratio of i^{th} component in exhaust	-
$y_i{}^o$	Molar ratio of ith component in the environment	-
Yi	Value of the performance characteristic for a given experiment	-
Ym	Nominal value of results	-
	Greek letters	
η_b	*Brake thermal efficiency*	-
η_{II}	*Exergetic efficiency*	-
η_v	*Volumetric efficiency*	-
ρ	*Density*	kg/m^3
ω	*Angular velocity*	rad/sec
π	*3.14*	-

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