MULTI-RESPONSE OPTIMIZATION OF DIESEL ENGINE OPERATING PARAMETERS RUNNING WITH WATER-IN-DIESEL EMULSION FUEL

by

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Water-in-diesel emulsion fuel is a promising alternative diesel fuel, which has the potential to promote better performance and emission characteristics in an existing Diesel engine without engine modification and added cost. The key factor that has to be focused with the introduction of such fuel in existing Diesel engine is desired engine-operating conditions. The present study attempts to address the previous issue with two-phases of experiments. In the first phase, stable water-in-diesel emulsion fuels (5, 10, 15, and 20 water-in-diesel) are prepared and their stability period and physico-chemical properties are measured. In the second phase, experiments are conducted in a single cylinder, 4-stroke Diesel engine with prepared water-in-diesel emulsion fuel blends based on L_{16} orthogonal array suggested in Taguchi's quality control concept to record the output responses (performance and emission levels). Based on signal-to-noise ratio and grey relational analysis, optimal level of operating factors are determined to obtain better response and verified through confirmation experiments. A statistical analysis of variance is applied to measure the significance of individual operating parameters on overall engine performance. Results indicate that the emulsion fuel prepared by Sorbitan monolaurate surfactant at high stirrer speed endows with better emulsion stability and acceptable variation in physico-chemical properties. Results of this study also reveal that the optimal parametric setting effectively improves the combustion, performance, and emission characteristics of Diesel engine.

Key words: *water-in-diesel emulsion, emulsion fuel formulation,
emulsion fuel properties, Taguchi-grey relational analysis,
analysis of variance*

Introduction

Air pollution caused by the Diesel engines has thrown much interest in the domain of eco-friendly diesel fuel since environmental improvement and human health are of concern. In order to obtain better emission characteristics in existing Diesel engines, considerable efforts have gone into the research and development of fuel modifications and alternative fuels. As a consequence, the introduction of water in Diesel engine has been preferred for the existing Diesel engine since the desired emission characteristics can be achieved without any added cost and engine modification [1, 2].

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The introduction of water in Diesel engine was initially proposed by Hopkinson to promote better inter cooling and reduce emission levels in gas engines. There are generally three approaches to introduce water in Diesel engine: (1) direct injection of water into the combustion chamber, (2) fumigating the water into the engine intake air, and (3) water-to-diesel (W/D) emulsion fuel. Out of these, W/D emulsion fuel has the favorable fuel characteristics such as large fragmentation, less change in viscosity, and better micro-explosion phenomena of the water droplets [3].

The formation of stable W/D emulsion fuel for a long period is the critical issue in emulsion fuel preparation. In order to avoid the phase separation of emulsion fuels, surfactants are used to lower the surface tension between the water and diesel molecules [4]. Non--ionic surfactants are generally used in emulsion fuel, which are having the positive fuel characteristics such as, burn with no soot and free of sulfur and nitrogen [5]. Sorbitan monolaurate, a non-ionic surfactant with HLB 8.6 is used as a surfactant in this study, since it provides better W/D emulsion stability with minor occurrence of creamy layer and the coalescence zone [1].

In emulsification process, W/D emulsion with droplet size of 50-200 nm is formed at the occurrence of a high-energy emulsification. This high-energy method includes high-shear stirring, high-pressure homogenizers, ultrasonic, and supersonic vibration. As far as the smoke and NO_x emissions are concerned, ultrasonic, and supersonic vibrations have negative impact compared to the emulsions prepared by mechanical homogenization [6]. Consequently, a mechanical agitator with variable stirrer speed (0-15000 rpm) is fabricated to prepare W/D emulsion fuel in the present study.

Several investigations have been carried out to study the performance and emission characteristics of W/D emulsion fuel in Diesel engine. As far as the performance characteristics are concerned, the complexity to analyze the combustion phenomena leads to inconsistent report in the domain of W/D emulsion fuel [7]. However, majority of the studies reported that the consistent improvement in emission characteristics of Diesel engine with W/D emulsion fuel is due to better mixing and enhanced atomization at lower burning gas temperature [8-11].

Taguchi method is a useful tool for the design of experiments, which provides efficient and systematic approach for optimization. The Taguchi method uses an orthogonal array to read the essence of the effect of entire input parameters with minimal number of experiments. The Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to sources of variation [12]. Several optimization processes have been conducted to obtain better engine performance based on Taguchi's offline quality control concept. In order to optimize the control parameters such as clearance volume, valve opening pressure, nozzle-hole diameter, static injection timing, and load-torque of the Diesel engine with respect to NO_x and other emissions, Wilson and Udayakumar [13] conducted experiments based on Taguchi method and predicted the percentage contributions of the effect of parameters using statistical analysis of variance (ANOVA). Modi *et al.* [14] reported the parametric optimization for brake thermal efficiency (BTE) in single cylinder Diesel engine running with palm seed oil and diesel blend using Taguchi method. In order to determine the optimal combination of concentration for a Diesel engine with diesel/biodiesel blends, Wu and Wu [15] applied Taguchi method. Wu *et al.* [16] also applied Taguchi's concept to find optimal level of factors in diesel/biodiesel engine running with port-injection liquefied petroleum gas.

In the traditional Taguchi method, individual responses alone can be optimized within the experimental domain [17-19]. Multi-objective optimization problems can be solved by employing the Taguchi method integrated with other modern optimization tools such as genetic algorithm, response surface methodology, and grey relational analysis (GRA) [20, 21]. The Taguchi method coupled with GRA has a wide area of application in multi-objective problems, since the optimization of the complicated multiple performance characteristics can be simplified through Taguchi-grey relational analysis [15]. Karnwal *et al.* [22] have applied Taguchi method with grey relational analysis to obtain maximum multiple-performance of a Diesel engine with minimum multiple-emissions. Pohit and Misra [23] adopted the same concept to optimize the performance and emission characteristics of Diesel engine with biodiesel. However, very little number of studies has been reported by the researchers in the domain of multi-response optimization in Diesel engines. The existing investigation followed the Taguchi-grey relational based multi-response optimization method to obtain optimal level of engine operating factors running with W/D emulsion fuel. In addition, ANOVA is applied to analyze the influence of individual operating parameters on overall performance and emission levels.

Materials and methods

Materials

In this work, high-speed diesel (Bharath Petroleum Corporation Ltd., India) is used as continuous phase of the emulsion. Sorbitan monolaurate (HLB: 8.6) is used as the surfactant (Estelle Chemicals P. Ltd.). Double distilled filtered water is used as the dispersed phase of emulsion.

Emulsion fuel preparation and properties measurement

To prepare W/D emulsion fuel, the desired quantity of water (5%, 10%, 15%, and 20% of total volume) and surfactant (1% of total volume) are added drop by drop in the fuel mixing jar and stirred at high speed (15000 rpm) constantly for about 30 minutes. The experimental layout for emulsion fuel preparation is shown in fig.1.

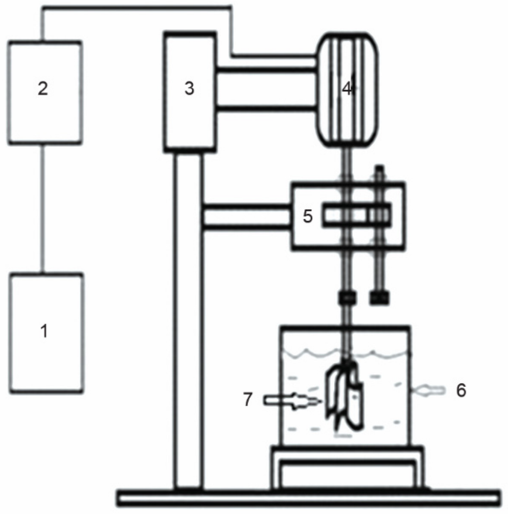

Figure 1. Experimental layout of emulsion fuel preparation
1 – power supply, 2 – auto transformer, 3 – frame, 4 – motor, 5 – gear box (gear ratio 2:1, speed ratio 1:2), 6 – mixing jar, 7 - stirrer

To measure the emulsion stability, laser beam associated photonic system that is developed by Suresh and Amirthagadeswaran [2] is adopted in this study. The properties of fuels are measured in accordance with EN 590:2009. The density [kgm^{-3}] is measured using a hydrometer (Avi. Chem. Industries, India) at a reference temperature of 15 °C (EN ISO 12185:2009) The kinematic viscosity [mm^2s^{-1}] is measured using a red wood Viscometer (M/S Mechtrix Engineers, India) at a reference temperature of 40 °C (EN ISO 3104:2009). The flash point of the fuels is measured by open cup Cleveland apparatus (EN 590:2009). The heating value of diesel and prepared emulsion fuels is found using a bomb calorimeter (M/S Mechtrix Engineers, India).

Engine test set-up

The engine used in this experiment is a computerized single cylinder, 4-stroke and variable compression ratio (CR) Diesel engine with an eddy current dynamometer. The fuel injection timing is maintained constantly at 23° before top dead center. ICEnginesoft_9.0 software is used to record the combustion parameters. As for the measurement of emissions, AVL di-gas gas analyzer is used. During the experiments, the measurements are recorded for every 10 second interval during the 100 seconds duration of engine running and the average data are calculated for consideration and discussion. The engine is initially run for 10-15 minutes and the corresponding exhaust temperature and speed are monitored. Once these parameters become steady, data are recorded.

The uncertainty percentage of various parameters such as, brake power (BP), brake specific fuel consumption (BSFC), and BTE are calculated:

If an estimated quantity, R, depends on independent variables like x_1, x_2, ... x_n, then the error in the value of R is given by:

$$R = f(x_1, x_2, \ldots x_n) \tag{1}$$

To get the realistic error limits, ΔR, the principle of root mean square method is used as explained by Holman [24]:

$$\Delta R = \sqrt{\left(\frac{\partial R}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\Delta x_2\right)^2 + \ldots . + \left(\frac{\partial R}{\partial x_n}\Delta x_n\right)^2} \tag{2}$$

The error limits for the estimated quantity is $R \pm \Delta R$.

The realistic error of BP is computed:

$$\text{BP} = f(N, T) \tag{3}$$

$$\Delta\text{BP} = \sqrt{\left(\frac{\partial \text{BP}}{\partial N}\Delta N\right)^2 + \left(\frac{\partial \text{BP}}{\partial T}\Delta T\right)^2} \tag{4}$$

where $\Delta N = 0.1$ and $\Delta T = 0.05$.

The realistic error of BSFC is computed:

$$\text{BSFC} = f(\text{TFC}, \text{BP}) \tag{5}$$

$$\Delta\text{BSFC} = \sqrt{\left(\frac{\partial \text{BSFC}}{\partial \text{TFC}}\Delta\text{TFC}\right)^2 + \left(\frac{\partial \text{BSFC}}{\partial \text{BP}}\Delta\text{BP}\right)^2} \tag{6}$$

The realistic error of BTE is computed:

$$\text{E} = f(\text{TFC}, \text{BP}) \tag{7}$$

$$\Delta\text{BTE} = \sqrt{\left(\frac{\partial \text{BTE}}{\partial \text{TFC}}\Delta\text{TFC}\right)^2 + \left(\frac{\partial \text{BTE}}{\partial \text{BP}}\Delta\text{BP}\right)^2} \tag{8}$$

where ΔTFC and ΔBP are calculated as 0.3% and 0.8%, respectively.

The detailed specifications of engine and gas analyzer, and its uncertainty values are listed in tab. 1. The schematic layout of engine test set-up is shown in fig. 2.

Table 1. Specification of the engine, emission analyzer, and uncertainty of calculated parameters

(a) Engine specifications		(b) Uncertainty percentage of calculated parameters	
Parameter	Specification	Parameter	Uncertainty percentage
Engine type	Computerized, 4-stroke, single cylinder, VCR Diesel engine	Brake power	±0.8
Bore × stroke [cm]	8.75 × 11	Brake specific fuel consumption	±0.9
Displacement volume [cm^3]	661.45	Brake thermal efficiency	±0.9
Maximal power	3.5 kW at 1500 rpm		
CR range	12-18		
Dynamometer	Eddy current dynamometer (max. load of 7.5 kW)		
(c) Gas analyzer specifications			
Measured quality	Measuring range	Resolution	Uncertainty percentage
NO	0-5000 ppm vol.	1 ppm vol.	±0.02
HC	0-20000 ppm vol.	≤ 2000: 1 ppm vol. > 2000: 10 ppm vol.	±0.05
CO	0-10% vol.	0.01% vol.	±0.1
CO_2	0-20% vol.	0.1% vol.	±0.05

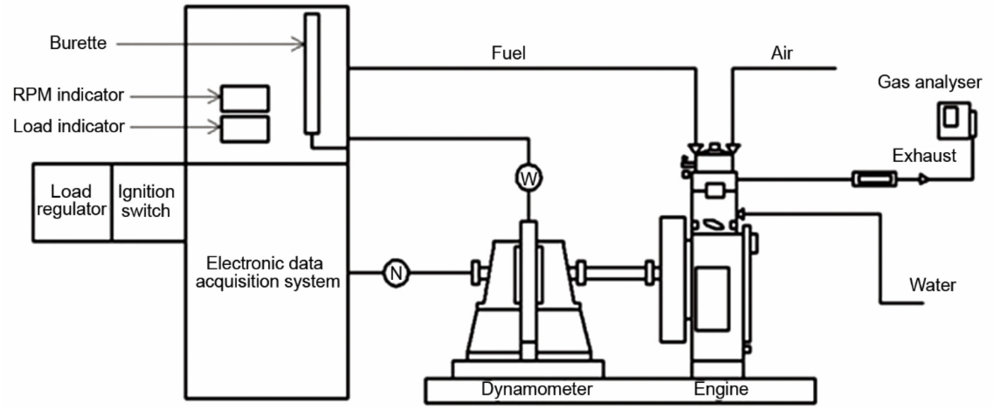

Figure 2. Schematic layout of experimental set-up: W – load sensor, N – engine speed sensor

Taguchi-grey analysis

The current study employs Taguchi's L_{16} orthogonal array to plan the experiments on the Diesel engine. Three factors, (1) engine load, (2) CR, and (3) water concentration

(WC) in diesel are identified as control parameters. Six experimental results, (1) BSFC, (2) BTE, (3) HC, (4) CO, (5) CO_2, and (6) NO are selected as output responses.

Combustion phases such as starting of combustion, mass fraction burned, and end of combustion are the crucial factors, which directly affect the performance and emission characteristics of Diesel engine [1]. All the previous selected factors have direct influence on engine combustion. Increase in engine load leads to shorter ignition delay and complete combustion, which contributes to better engine performance. Concurrently, the higher engine loads direct to high level of emissions such as HC, CO, and NO. Hence, the engine loads are chosen in all intervals (25%, 50%, 75%, and 100%). Similarly, high CR leads to high level of emissions, while it reduces the ignition delay and support to better engine performance [24]. Besides, the longer ignition delay with low CR makes the engine to fail to run. Hence, the parameter levels for CR are chosen to be 15, 16, 17, and 18. The parameter levels for WC are chosen as 5%, 10%, 15%, and 20% of total volume of fuel. Increase in WC provides better engine performance and low level of NO emissions. At the same time, the higher WC in diesel (above 20%) leads to pro-longed ignition delay and longer combustion duration, resulting in rough engine operation [24].

In this study, BTE has been characterized as *the larger-the better* and the characteristic are computed:

$$x_{(i)}k = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{9}$$

The BSFC and emission parameters (HC, CO, CO_2, and NO) have been characterized as *the smaller-the better* and computed:

$$x_{(i)}k = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{10}$$

where $x_i(k)$ is the sequence for comparison, $y_i(k)$ – the original reference sequence, $i = 1, 2, \dots m$, $k = 1, 2, \dots n$, where, m and n being the total number of experiments and response. The values $\min y_i(k)$ and $\max y_i(k)$ are the smallest and the highest values of $y_i(k)$, respectively.

The grey relational coefficient $\xi_i(k)$ is calculated:

$$\xi_i(k) = \frac{\Delta_{\min} + \Psi\Delta_{\max}}{\Delta_{0i}(k) + \Psi\Delta_{\max}} \tag{11}$$

$$\Delta_{0i}(k) = \left\| x_0(k) - x_i(k) \right\| \tag{12}$$

where Δ_{0i} is the value of absolute difference, $\Delta_{\min}$, $\Delta_{\max}$ are the minimum and maximum values among the absolute differences. The purpose of distinguishing coefficient ψ $(0 \leq \psi \leq 1)$ is to weaken the effect of $\Delta_{\max}$ when it becomes too large. In the present study, the value of ψ was taken as 0.5. The grey relational grade (GRG) y_0 is calculated:

$$y_0 = \sum_{k=1}^{n} \xi_i(k)\beta y_i, \; \dots, \; \sum \beta = 1 \tag{13}$$

where β is the weighing factor.

While converting overall GRG from multiple grey relational coefficients, critical factors have to be assigned for more weightages [20]. The following value of weightage factor, β, (wei. factor) is adopted in this study for different responses: BSFC = 0.25, BTE = 0.25, HC = 0.1, NO = 0.3, CO = 0.05, and CO_2 = 0.05. The performance and emission parameters are assigned with equal weightage (0.5 each). In emission factors, NO is the major constrain and is assigned more weightage followed by HC. The magnitude of CO emission is normally low in Diesel engine due to lean mixture. The higher magnitude in CO_2 emission indicates the efficient combustion. Hence, these two factors weightage are assigned as low (0.05 each).

Results and discussion

Emulsion fuel stability and its property

The stability period of emulsion fuels and physico-chemical properties of base diesel (BD) and W/D emulsion fuels are measured and listed in tab. 2. It is observed that at low levels of WC, dispersed water droplets are so far spaced out to interact among each other and improve the emulsion stability. Increase in WC, reduces the emulsion stability since the droplet interactions become high. From the measured values, it is observed that the density and viscosity of emulsion fuels increase with the addition of WC due to the higher density of water. Increase in flash point is observed with increase in WC, whereas the drop in heating value is noted. The WC at 20% in diesel reduces the heating value by 7.7% over BD due to the heat absorption of inner phase water in emulsion fuel during combustion

Table 2. Properties of BD and W/D emulsion fuels

	Fuel properties				
Fuels	Stability period [hours]	Density at 15 °C [kgm^{-3}]	Viscosity at 40 °C [mm^2s^{-1}]	Flash point [°C]	Heating value [$MJkg^{-1}$]
BD	–	831.4	2.4	62	43.8
5 W/D	320	839.8	4.2	69	42.9
10 W/D	306	845.1	4.4	74	42.1
15 W/D	294	853.4	4.7	78	41.2
20 W/D	288	857.2	4.9	83	40.4

Experimental observation for L_{16} orthogonal array

Table 3 shows the input process parameter combinations and experimental results.

From the experimental results, it is observed that the increase in engine load increases the BTE, CO_2, and NO emissions. This is due to the efficient combustion and high rate of heat release at high load conditions. In addition, high engine load leads to drop in BSFC and HC emission. The performance characteristics are improved at high CR and high WC due to efficient burning of fuel and micro-explosion behavior of water droplets. The emission characteristics of NO and CO_2 are significantly improved by W/D emulsion fuels at all CR. Meanwhile, negative effects are observed in HC and CO emissions.

Optimization of process parameters and analysis of variance

To optimize the process parameters, the experimental data are normalized to obtain GRG. The signal-to-noise (S/N) ratio (larger-the-better) for overall GRG is found from the following equation:

Table 3. Orthogonal array, L_{16}, of the experimental runs and results

Run No.	Input process parameters			Output responses					
	Load [%]	CR	WC [%]	BSFC [kgkW^{-1} per hour]	BTE [%]	HC [ppm vol.]	CO [% vol.]	CO_2 [% vol.]	NO [ppm vol.]
1	25	15	5	0.6134	13.68	33	0.1	2.5	332
2	25	16	10	0.6032	14.18	34	0.09	3	266
3	25	17	15	0.5842	14.96	31	0.08	2.8	260
4	25	18	20	0.5767	15.45	26	0.07	2.9	248
5	50	15	10	0.395	21.65	33	0.09	4	398
6	50	16	5	0.3925	21.38	26	0.08	4.4	556
7	50	17	20	0.4259	20.92	27	0.07	4.2	483
8	50	18	15	0.3281	26.63	23	0.04	4.8	499
9	75	15	15	0.3179	27.49	33	0.1	4.8	615
10	75	16	20	0.3217	27.7	25	0.12	5.6	638
11	75	17	5	0.3023	27.76	20	0.03	6.2	941
12	75	18	10	0.294	29.09	20	0.04	6.6	785
13	100	15	20	0.2884	30.9	47	0.14	6.5	740
14	100	16	15	0.2861	30.55	34	0.13	6.6	816
15	100	17	10	0.2745	30.8	31	0.07	7.1	857
16	100	18	5	0.2705	31.03	25	0.07	8	1118

$$\frac{S}{N} = -10 \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \tag{14}$$

Table 4 shows the grey relational coefficient of all responses, GRG with weightage and S/N ratio. From the results, it is observed that run number 16 *i. e.* 5% of W/D emulsion fuel with CR of 18 under full load condition indicates a better performance level. As far as emission levels are concerned, 10% of W/D emulsion fuel at CR of 18 with 75% load condition (run number 11) indicates the best level of HC and CO emissions with a small drop in performance level. The drop in performance level is due to the low load condition. Improved NO level is observed at 25% of load with 18 CR for 20% of W/D emulsion fuel (run number 4). This is due to the lower mean gas temperature of W/D emulsion fuels under low load conditions even at high CR. The WC of 5% in diesel at 25% engine load with CR of 15 exhibits low level of CO_2 within the experimental runs. It is obvious that at low CR the combustion is incomplete and forms less magnitude of CO_2 under all load conditions irrespective of WC.

Figure 3 shows the main effects plot for S/N ratios of engine operating factors. Significant variation in S/N ratio for different loads and CR is noted, whereas, marginal variation is observed with WC. The variations in S/N ratio also imply the influence of process parameters. From the obtained results, it can be concluded that the optimum parametric setting is $A_4B_4C_2$ *i. e.* engine load = 100%, CR = 18, and WC = 10%. In order to predict the signifi-

Table 4. Calculated grey relational coefficient of all responses, GRG with weightage and S/N ratio

Weighting factor	0.25	0.25	0.1	0.05	0.05	0.3	Grey relational grade	S/N ratio	Rank
Run No.	Grey relational coefficient								
	BSFC	BTE	HC	CO	CO_2	NO			
1	0.3333	0.3333	0.5094	0.44	1	0.8382	0.5411	–5.3345	16
2	0.3400	0.3398	0.4909	0.4782	0.8461	0.9603	0.5839	–4.6732	13
3	0.3533	0.3505	0.5510	0.5238	0.9016	0.9731	0.5943	–4.5199	12
4	0.3589	0.3576	0.6923	0.5789	0.8730	1	0.6210	–4.1382	10
5	0.5793	0.4804	0.5094	0.4782	0.6470	0.7436	0.6161	–4.2070	11
6	0.5842	0.4733	0.6923	0.5238	0.5913	0.5855	0.5650	–4.9590	15
7	0.5245	0.4618	0.6585	0.5789	0.6179	0.6492	0.5671	–4.9268	14
8	0.7485	0.6634	0.8181	0.8461	0.5445	0.6341	0.6946	–3.1653	4
9	0.7834	0.7101	0.5094	0.44	0.5445	0.5424	0.6363	–3.9268	9
10	0.7700	0.7226	0.7297	0.3793	0.4700	0.5273	0.6468	–3.7846	8
11	0.8435	0.7262	1	1	0.4263	0.3857	0.6795	–3.3562	6
12	0.8794	0.8172	1	0.8461	0.4014	0.4475	0.7208	–2.8437	1
13	0.9054	0.9852	0.3333	0.3333	0.4074	0.4693	0.6619	–3.5842	7
14	0.9166	0.9475	0.4909	0.3548	0.4014	0.4337	0.6831	–3.3103	5
15	0.9772	0.9741	0.5510	0.5789	0.3741	0.4167	0.7202	–2.8509	2
16	1	1	0.7297	0.5789	0.3333	0.3333	0.7186	–2.8703	3

cance of process parameters, total variability of the GRG is separated by measuring the mean sum of squares. Total sum of square, SS_T, was determined by:

$$SS_T = \sum_{i=1}^{p}(y_i - y_m)^2 \tag{15}$$

where y_i is the mean response for i^{th} experiment, y_m – the grand mean of the response. The mean sum of square was determined based on SS_T and degree of freedom.

Table 5 shows the S/N ratio responses and the significance of the process parameters on overall performance. Based on these parameters, it can be predicted that the engine load has the maximum contribution (62.5%) on engine performance and emission levels. The CR of the engine contributes 28.2% on engine performance and emission levels, whereas, WC contributes 9.3%.

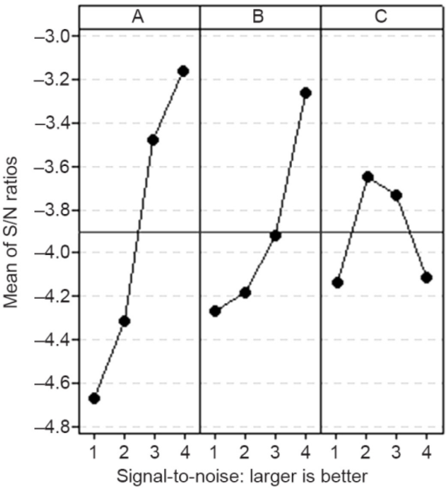

Figure 3. Main effects plot for S/N ratios of engine operating factors

Table 5. Overall responses of S/N ratio and significance of process parameters (ANOVA)

Level	Engine load (A)	CR (B)	WC (C)
1	–4.666	–4.263	–4.130
2	–4.315	–4.182	–3.644
3	–3.478	–3.913	–3.731
4	–3.154	–3.254	–4.108
Delta	1.513	1.009	0.486
Rank	1	2	3
Optimum level	A_4	B_4	C_2
Total sum of squares	0.0327	0.0147	0.0048
Degree of freedom	3	3	3
Mean sum of square	0.0109	0.0049	0.0016
% of contribution	62.5	28.2	9.3

Confirmation test

In order to verify the improvement and analyze the engine combustion behaviors at optimal condition, experiments are carried out at optimum parametric setting. The experimental values, GRG and S/N ratio for initial best setting ($A_3B_4C_2$) and optimum setting ($A_4B_4C_2$) are presented in tab. 6.

Table 6. Experimental result of optimum setting and its comparison with initial setting and BD

Experimental run	Output responses						Grey relational grade	S/N ratio
	BSFC [kgkW^{-1} per hour]	BTE [%]	HC [ppm vol.]	CO [% vol.]	CO_2 [% vol.]	NO [ppm vol.]		
Initial parametric setting – $A_3B_4C_2$	0.2944	29.09	20	0.04	6.6	785	0.7208	–2.843
Optimal parametric setting – A_4B_4 with BD	0.274	29.89	27	0.08	7.9	1320	–	–
Optimal parametric setting – $A_4B_4C_2$	0.255	33.49	26	0.07	8	890	0.7636	–2.2456
% of improvement in S/N ratio: 21								

From the experimental values, it is noted that the overall performance level at the optimum setting is improved over initial setting. The BSFC and BTE are improved by 13.3% and 15.1%, respectively. The emission characteristics are marginally increased with optimal setting. However, the better performance level with optimal setting can compensate the marginal increase in emission levels. It is also noted that the overall improvement in S/N ratio is 21%.

In addition, an experiment is conducted at optimum parametric setting (A_4B_4) with BD as fuel and results are presented in tab. 6. From the result, 6.9% improvement in BSFC is observed with W/D emulsion fuel over BD, whereas 12% increases in BTE is observed. Similar trends are arrived in emission levels and the improvements are noted as 3.7%, 12.5%, and 32.6% for HC, CO, and NO, respectively.

Figure 4 shows the in-cylinder pressure (ICP) rise and net heat release-rate (NHR) with respect to crank angle of BD and W/D emulsion fuel for the previous mentioned conditions. It is noted that W/D emulsion fuel has higher ICP and NHR over BD. This may be due to intensity of micro-explosion and elongated explosion duration, which promote better atomization of the air-fuel mixture. It is also observed that the crank angle of maximum ICP and NHR of W/D emulsion fuel is higher than BD. This is due to endothermic reaction of water particles present in the fuel during the combustion process, resulting in belated starting of combustion. Based on the previous discussions, it is clearly observed that W/D emulsion fuel has the potential to promote better performance and emission characteristics over BD.

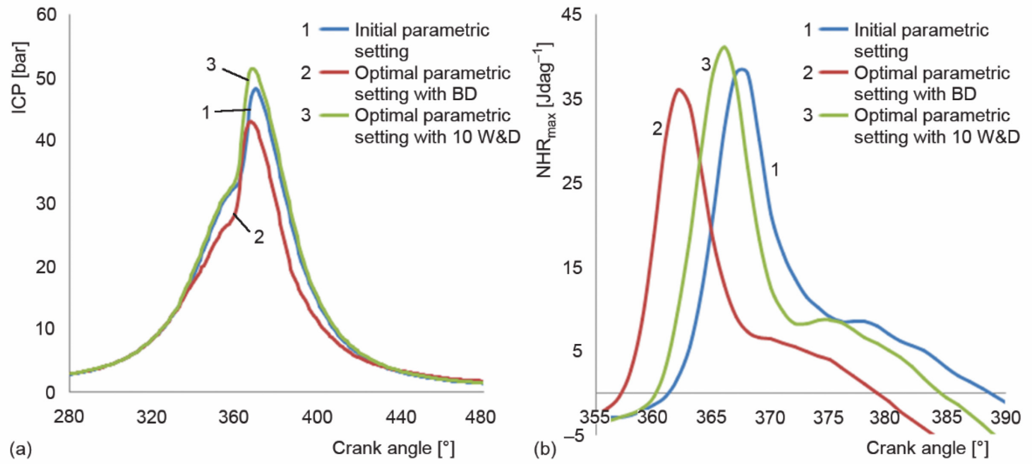

Figure 4. Combustion characteristics of BD and W/D emulsion fuels at optimal setting; (a) ICP, (b) NHR_{max}

Conclusions

To optimize the operating parameters of a Diesel engine running with W/D emulsion fuel, the Taguchi-grey relational analysis is applied and results presented. The conclusions of this experimental study are as follows:

- Sorbitan monolaurate surfactant promotes good emulsion stability and up to 20% WC with diesel the changes in physico-chemical properties are marginal.
- The optimal parametric setting is predicted as 100% engine load, CR of 18 and 10% W/D emulsion fuel and is confirmed through a set of experimental trials.
- The engine combustion, performance, and emission characteristics are considerably improved with optimal condition and overall improvement in S/N ratio is observed as 21%.
- The engine load has 62.5% influences on overall performance, whereas CR and WC contribute 28.2% and 9.3%, respectively.
- The finding of this experimental study and optimization models are expected to be positive guidelines for Diesel engines operating parameters' optimization running with different kind of emulsion fuels.

Nomenclature

BD – base diesel
BP – brake power
BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
CR – compression rate
GRA – grey relational analysis

GRG – grey relational grade
ICP – in-cylinder pressure
NHR – net heat release-rate
S/N – signal-to-noise
TFC – total fuel consumption
VCR – variable CR
WC – water concentration

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