Performance of a Diesel Engine with Ethyl Levulinate-Diesel Blends: A Study using Grey Relational Analysis

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The combustion and emission characteristics of ethyl levulinate (EL)–diesel blended fuels were investigated using engine bench tests. Blended fuels properties, including the kinematic viscosity (KV), density, EL proportions, oxygen content, cetane number (CN), and lower heating value (LHV) were considered. The combustion and emission characteristics of brake-specific fuel consumption (BSFC), as well as hydrocarbon (HC), nitrogen oxide (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) emissions, as well as smoke opacity, were tested. The relationship between the blended fuel properties and the combustion–emission characteristics were analyzed using grey relational analysis (GRA). The correlation degree between the fuel properties and the combustion–emission results indicated that the BSFC was influenced most by the density of the blended fuels. NO_x, CO, and CO_2 emissions were influenced most by the oxygen content. The KV was the most influential parameter for HC emissions and the opacity of the blended fuels. The oxygen content was the foremost influential parameter. The results show that GRA could be used to increase the comprehensiveness of combustion–emission blended-fuel studies, by providing a reference for the reasonable use of biofuel-diesel mixtures.

Keywords: Blended fuels properties; Combustion and emission; Ethyl levulinate; Grey relational analysis

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INTRODUCTION

Levulinic acid (LA) contains a ketone group and a carboxylic acid group. These two functional groups make LA a potentially versatile building block for the synthesis of various organic (bulk) chemicals, such as levulinate esters (Girisuta *et al*. 2006; Lin *et al*. 2009). Ethyl levulinate (EL), one of the levulinate esters, is produced from LA and ethanol. Biomass materials, including wood, starch, cane sugar, grain sorghum, and agricultural wastes, have been used to produce LA (Lange *et al*. 2009; Fang and Hanna 2002; Chang *et al*. 2007) and ethanol (Villanueva Perales *et al*. 2011; Hamelinck *et al*. 2005). A new processing technique was developed that converts the carbohydrates found in plant biomass into EL (Mascal and Nikitin 2009), which could provide a possible oxygenate additive for diesel fuel. The Biofine process, for example, can convert ~50% of the mass of six-carbon sugars into LA, using an acid-hydrolysis reaction, with 20% being converted to formic acid and 30% to tars (Fitzpatrick 1990, 1997). Given these technologies, EL could be used as a possible additive in fossil diesel at a significantly reduced cost. EL has an oxygen content of 33%. The Development of Integrated Biomass

Approaches Network (DIBANET) reported that a blend of 20% EL, 79% petroleum diesel, and a 1% co-additive contained 6.9% oxygen, suggesting the feasibility of its use as an efficient, high-lubricity, low-sulfur fuel that burns significantly cleaner (Hayes 2009). Recently, Windom *et al.* (2011) analyzed the distillation curve of blends of EL–diesel and fatty acid–levulinate ester biodiesel. Joshi *et al.* (2011) investigated the cloud (CP), pour (PP), and cold-filter plugging points (CFPP) of biodiesels prepared from cottonseed oil and poultry fat, which were improved upon by the addition of EL (up to 20% by volume). Wang *et al.* (2012) investigated performances and exhaust emission levels of ethyl levulinate as an additive to conventional diesel fuel, with EL percentages of 5%, 10%, 15% (with 2% *n*-butanol), and 20% (with 5% *n*-butanol). NO_x and CO_2 emissions increased with engine power with greater fuel injections, but varied with changing EL content of the blends. CO emissions were similar for all of the fuel formulations. Smoke emissions decreased with increasing EL content.

Although the blended fuel properties (*e.g.*, kinematic viscosity (KV), density, EL proportions, oxygen content, cetane number (CN), and lower heating value (LHV)) and combustion–emission characteristics (*e.g.*, brake-specific fuel consumption (BSFC); emissions of hydrocarbons (HC), NO_x, CO, and CO_2; and fuel opacity) are related, quantitative analysis has proved difficult. Grey relational analysis (GRA) offers several advantages over traditional regression analysis, including minimal data requirements, simplicity of use, and reasonable projected outcomes (Lin *et al*. 2007). The grey theory has been applied previously to energy-related studies. Lu *et al.* (2008) used GRA to capture the dynamic characteristics of different factors affecting the transportation system, to evaluate the relative influence of fuel price, gross domestic product, number of motor vehicles, and travel distance. Lee and Lin (2011) proposed a perspective of multiple objective outputs to evaluate the energy performance of 47 office buildings, and then used the multiple-attribute decision-making approach of GRA to rank the energy performance of these buildings; this case study illustrated the effectiveness of GRA. Chang and Lin (1999) chose GRA to investigate how energy-induced CO_2 emissions from 34 industries were affected by the production and uses of coal, oil, gas, and electricity; sensitivity and stability tests, seldom discussed in most GRA studies, were conducted to enhance the reliability of the outcomes. Yuan *et al.* (2010) examined the relationship between China's energy consumption and economic growth. In the present study, we used GRA to investigate the inter-relationships among EL–diesel blended fuel properties and the engine's combustion–emissions characteristics. The purpose of this study was to provide a helpful reference for utilizing EL–diesel blended fuels.

EXPERIMENTAL

Experimental Apparatus

Engine performance was measured with an eddy current dynamometer (DW25, Chengbang, China) with 120 N•m torque and 25 kW of measurement capacity (accuracy of ±0.5 N•m torque). Engine speed and fuel consumption were measured with a tachometer (accuracy of ±1 rpm) and a digital intelligent fuel consumption meter (ET2500, accuracy of ±8 $g \cdot h^{-1}$). During the tests, all measured performance data and control parameters were exchanged between the test apparatus and the computer by an ET2000 intelligent measurement and control system (Chengbang, China). Engine exhaust gas components (CO_2, and NO_x) were measured with an exhaust gas analyzer (Testo360, Germany). Concentrations of HC and CO were measured with an exhaust gas analyzer (FGA-4100, China), and the light absorption coefficient (*k*) was measured with a smoke opacity analyzer (FTY-100, China). The emission test range and accuracies were as follows: CO_2: 0 to 20%, ±1.5%; NO_x: 0 to 1000 ppm, ±3.8%; HC: 0 to 10000 ppm, ±6%; CO: 0 to 9.99%, ±0.06%; and *k*: 0 to 16 m^{-1}, ±2.0%.

The apparatus used for fuel performances and emissions tests is shown in Fig. 1. A horizontal, single-cylinder, four-stroke diesel engine was used, and its specifics are listed in Table 1.

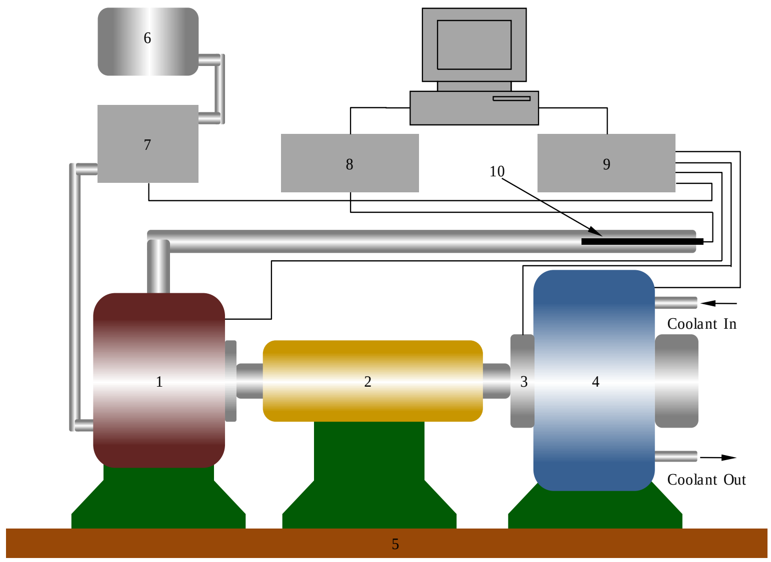

Fig. 1. Schematics of fuel test engine and setup. 1) Single-cylinder diesel engine, 2) Cardan shaft, 3) Tachometer, 4) Dynamometer, 5) Test chassis, 6) Fuel container, 7) Fuel consumption meter, 8) Exhaust gas analyzer, 9) Control unit, 10) Exhaust gas analyzing probe

Table 1. Specifics of the Tested Diesel Engine

Item	Description
Type	Horizontal four-stroke, single-cylinder
Combustion system	Direct injection
Bore × stroke (mm)	110 × 115
Displacement (L)	1.093
Compression ratio	17:1
Max power (kW)	14.7
Max speed (rpm)	2200
Cooling method	Water cooling system
Lubrication method	Combined pressure & splashing

Tested Fuels

Diesel fuel was obtained from China Petroleum and Chemical Corporation (Henan Branch). The EL (>99.9 wt %) was purchased from Shanghai Zhuorui Chemical Industry Co. The *n*-butanol (>99.9 wt %) was purchased from Tianjin Fuyu Fine Chemical Industry Co. The performances and emissions of the engine fueled with pure 0# diesel (solidifying point is 0 °C) were measured as the control (denoted as EL-0). Then subsequent tests were conducted when the engine was fueled with EL–diesel blends with

EL of 5%, 10%, 15%, and 20% in volume (labeled as EL-5, EL-10, EL-15, and EL-20, respectively). It should be noted that phase separation was observed when the EL volume percent in EL–diesel blend was ≥15% at room temperature (25 ºC); the co-additive *n*-butanol was mixed in EL-15 and EL-20 at 2% and 5% (by volume), respectively, to improve the solubility of the EL in diesel. EL-5, EL-10, EL-15, and EL-20 were enclosed in reagent bottles and put into a temperature test chamber (EL-04KA, Espec company, China). Phase separation was not observed in these mixtures for more than one month at 4 ºC, 10 ºC, 15 ºC, 20 ºC, and 25 ºC by temperature programmable controller of the chamber.

Tested Results

Prior to each test, the system was warmed up for at least 30 min. If the fuel was changed, 3 h was needed to ensure that the fuel was replaced completely throughout the engine's system. The maximum speed and power of the engine were 2200 rpm and 14.7 kW, respectively. Preliminary tests, using pure diesel fuel, were performed over the full engine speed range of 800 to 2200 rpm. The noise and system stability results indicated an optimal speed of 1200 rpm for the test conditions; this value was set for each test. The torque was then increased over the range of 3.0 to 57.0 Nm, in increments of 3.0 Nm. The system achieved the set conditions by adjusting the loads and throttle automatically. The average engine power, fuel consumption, and emission were recorded by a computer when the system became steady. The BSFC of different fuel formulas at different engine powers are shown in Fig. 2. The BSFC, or fuel consumption divided by the produced engine power, was significantly higher for smaller engine powers, with 5.3 kW at 1200 rpm giving the highest engine efficiency. The data for the GRA were provided under test conditions of 1200-rpm speed and 5.3-kW engine power.

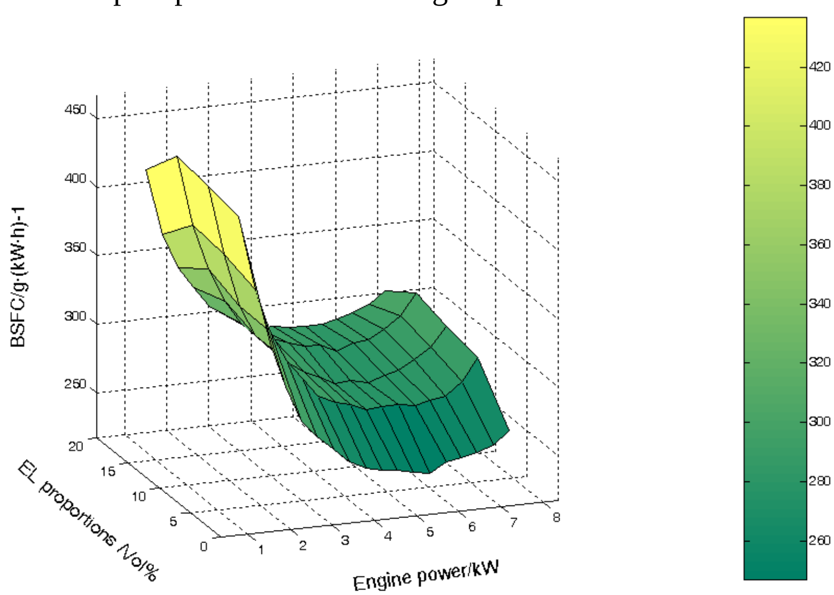

Fig. 2. Relationship between the BSFC of different fuels and engine power (1200 rpm)

The oxygen content of the blended fuel can be calculated as follows,

$$H_x = \frac{\sum m_i \cdot x_i}{\sum m_i} \times 100\% \tag{1}$$

where H_x is the oxygen content of the blended fuel in wt %, m_i is weight of the ith fuel in kg, and x_i is the oxygen content of the ith fuel in wt %. The oxygen content of diesel, EL, and *n*-butanol fuels were 0%, 33.3%, and 21.6%, respectively.

The measurements of the physical and chemical properties of EL–diesel blended fuels were determined according to the following standards.

- KV at 40 °C: Petroleum products: determination of kinematic viscosity and calculation of dynamic viscosity (China National Standards and Codes 1988);
- Density at 20 °C: Crude petroleum and liquid petroleum products: laboratory determination using the density-hydrometer method (China National Standards and Codes 2000);
- CN: Standard test method for cetane number of diesel fuel oil (China National Standards and Codes 2010);
- LHV: Petroleum products: determination of heat of combustion (China National Standards and Codes 1981).

Table 2. Properties of the Blends Fuels

Properties	Number of Blended Fuels					Note
	1	2	3	4	5	
	EL-0	EL-5	EL-10	EL-15	EL-20	
Composition/(vol %)	100% diesel	95% diesel + 5% EL	90% diesel + 10% EL	83% diesel + 15% EL + 2% *n*-butanol	75% diesel + 20% EL + 5% *n*-butanol	
Cold filter plugging point/(°C)	−2	−2	−3	−4	−3	Mean
Experimental data	-2	-2	-3	-4	-3	
	-2	-3	-3	-4	-3	
	-2	-2	-4	-4	-4	
Density(20 °C)/(g·cm^{-3})	0.836	0.845	0.853	0.862	0.870	Mean
Experimental data	0.836	0.846	0.853	0.862	0.871	
	0.836	0.845	0.853	0.861	0.870	
	0.837	0.845	0.854	0.862	0.870	
Kinematic viscosity (40 °C)/(mm^2·s^{-1})	2.83	2.68	2.63	2.56	2.25	Mean
Experimental data	2.83	2.68	2.63	2.55	2.25	
	2.83	2.67	2.63	2.56	2.26	
	2.83	2.68	2.62	2.56	2.25	
Closed-cup flash point /(°C)	61	62	63	50	48	Mean
Experimental data	61	62	63	50	48	
	61	62	64	50	48	
	62	62	63	50	47	
Oxygen content/(wt %)	0	1.98	3.92	6.23	8.71	Calculated
Cetane number	45.0	42.7	40.4	37.6	34.7	Mean
Experimental data	44.9	42.6	40.3	37.6	34.7	
	45.1	42.7	40.4	77.7	37.6	
	45.0	42.7	40.4	37.5	34.7	
Low heating value /(MJ·kg^{-1})	42.5	41.9	40.8	39.6	38.3	Mean
Experimental data	42.5	41.9	40.8	39.6	38.3	
	42.5	41.9	40.8	39.6	38.2	
	42.6	4.19	40.7	39.7	38.3	

Oxygen content was calculated on the basis of Zhang *et al.* (2010).

The test results of BSFC and emissions are shown in Fig. 3.

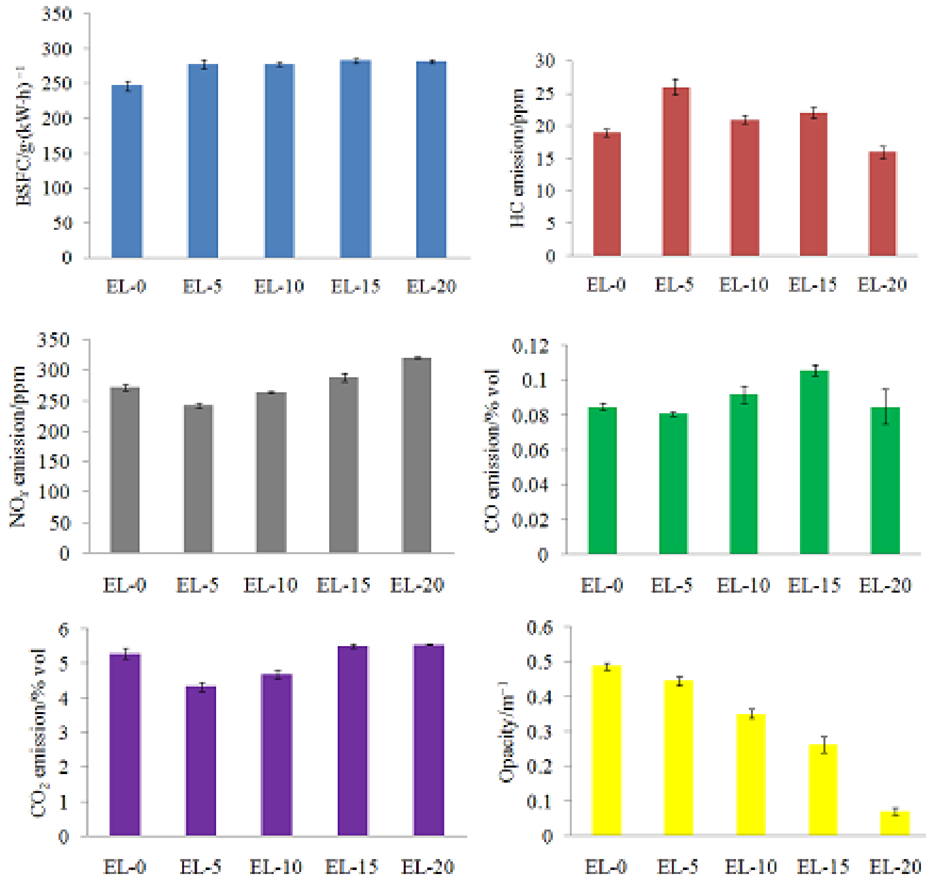

Fig. 3. Test results of BSFC and emissions (HC, NO, CO_x, CO_2, opacity)

The physical and chemical properties of the EL–diesel blended fuels and their test results are shown in Table 3.

Table 3. Characteristics and Test Results of Different EL–Diesel Blended Fuels

Correlation Parameters			Number of Blended Fuels				
			1	2	3	4	5
Properties	KV (40 °C)/mm^2·s^{-1}	X_1	2.83	2.68	2.63	2.56	2.25
	Density (20 °C)/g·cm^{-3}	X_2	0.836	0.845	0.853	0.862	0.870
	EL proportions/vol %	X_3	0	5	10	15	20
	Oxygen content/wt %	X_4	0	1.98	3.92	6.23	8.71
	CN	X_5	45.0	42.7	40.4	37.6	34.7
	LHV/MJ·kg^{-1}	X_6	42.5	41.9	40.8	39.6	38.3
Test result	BSFC/g·(kW·h)$^{-1}$	Y_1	247.2	277.7	277.6	282.9	282.2
	HC emission/ppm	Y_2	19	26	21	22	16
	NO_x emission/ppm	Y_3	272	242	264	289	321
	CO emission/% vol	Y_4	0.085	0.081	0.092	0.106	0.085
	CO_2 emission/% vol	Y_5	5.301	4.349	4.696	5.508	5.553
	Opacity/m^{-1}	Y_6	0.489	0.446	0.351	0.263	0.071

RESULTS AND DISCUSSION OF THE GREY RELATIONAL ANALYSIS

Methodology

The grey system is a system in which some of its information is clear and some of its information is not clear. The grey correlation, which is also known as the grey relation, is the uncertainty associated between things, or uncertainty associated between system factors and the main behavioral factors. Grey relational analysis, which is one of the important contents of grey system theory, is based on the degree of similarity or differences between factors of the main development trends and factors related to measurement. The purpose of GRA is to explore the qualitative and quantitative relationships among main development trends of factors and measure factors, to capture their dynamic characteristics during the development process, and to measure the relative influence of the compared series on the reference series (Deng 1996; Zhou 2007). In this paper, the main development trends of factors and measure factors represent fuel properties and test result, respectively. The dynamic characteristics represent test results, including BSFC and emissions of CO, CO_2, HC, and NO_x, as well as smoke opacity.

(1) Standardized treatment

Assume that $X_0 = \{x_0(k), k = 1, 2, \ldots, n\}$ is the sequence of parameters, $X_j = \{x_j(k), k = 1, 2, \ldots, n\}$ $(j = 1, 2, \ldots, m)$ is the sequence of sub-parameters, n is the length of the sequence, *i.e.*, the number of data points, and m is the number of sub-parameters. The dimensions and units of the original statistical data index are different; thus, the original data shall be subject to a dimensionless standardized treatment. The standardized treatment involves the use of an initial value, a mean, and a regional value. The regional value used in this paper is defined as follows:

$$x_j'\left(k\right) = \frac{x_j\left(k\right) - \min\left[x_j(k)\right]}{\max\left[x_j(k)\right] - \min\left[x_j(k)\right]} \tag{2}$$

(2) Calculation of the correlation coefficient

The grey correlation coefficient is defined as follows:

$$\xi_{0j}\left(k\right) = \frac{\min_j \min_k \left|x_0'\left(k\right) - x_j'\left(k\right)\right| + \rho \max_j \max_k \left|x_0'\left(k\right) - x_j'\left(k\right)\right|}{\left|x_0'\left(k\right) - x_j'\left(k\right)\right| + \rho \max_j \max_k \left|x_0'\left(k\right) - x_j'\left(k\right)\right|} \tag{3}$$

For the identification coefficient, $\rho \in \left[0,1\right]$; $\rho = 0.5$ is commonly used.

(3) Calculation of the correlation degree

The correlation degree indicates the correlation between two sequences, or the mean value of the correlation coefficients. The correlation degree (r_{0j}) between the sub-sequence (j) and sequence (0) is:

$$r_{0j} = \frac{1}{n}\sum_{k=1}^{n} \xi_{0j}\left(k\right) \tag{4}$$

(4) Sequencing of the correlation degree

The next step is to arrange the correlation degrees of m sub-sequences in the same sequence, to compose the correlation order and reflect the correlation degree of each sub-sequence to sequence. If there are t sequences $\{Y_1\}$, $\{Y_2\}$, …, $\{Y_t\}$ ($t \neq 1$) and m sub-sequences $\{X_1\}$, $\{X_2\}$, …, $\{X_m\}$ ($m \neq 1$), then the correlation degree of each sub-sequence to sequence $\{Y_1\}$ is $[r_{11}, r_{12}, \ldots, r_{1m}]$, and the correlation degree of each sub-sequence to sequence $\{Y_t\}$ is $[r_{t1}, r_{t2}, \ldots, r_{tm}]$, in which ($i = 1, 2, \ldots, t$; $j = 1, 2, \ldots, m$). The resulting correlation degree matrix, R, is given in Eq. 5:

$$R = \left(r_{ij}\right) = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{t1} & r_{t2} & \cdots & r_{tm} \end{bmatrix} \quad (5)$$

In the grey correlation matrix, the elements in row i are the grey correlation degrees of sequence (Y_i) to each sub-sequence $\{X_1\}$, $\{X_2\}$, …, $\{X_m\}$; the elements in line j are the grey correlation degrees of each sequence $\{Y_1\}$, $\{Y_2\}$, …, $\{Y_t\}$ to sub-parameter $\{X_j\}$. If every element in one line of R is higher than that in other lines, then the sub-parameter in this line is the superior sub-parameter. If every element in one row of R is higher than that in other rows, then the parameter in this row is the superior parameter.

Relational Analysis

According to Eqs. (2), (3), (4), and (5) and the above calculated data, the correlation degree of each fuel properties to the test result $\{Y_1\}$ was $[r_{11}, r_{12}, r_{13}, r_{14}, r_{15}, r_{16}]$ = [0.5445, 0.7377, 0.7338, 0.7195, 0.5200, 0.5493], where $r_{12} > r_{13} > r_{14} > r_{16} > r_{11} > r_{15}$ (r_{1j}, $j = 1 \ldots 6$ stand for the correlation degree of each fuel properties to the BSFC). This indicates that the influence of the density parameter of the blended fuels on the BSFC was the highest (*i.e.*, the influence of the blended fuel density on the fuel supply of the diesel engine required for one work cycle was higher).

The correlation degree of each fuel properties to test result $\{Y_2\}$ was $[r_{21}, r_{22}, r_{23}, r_{24}, r_{25}, r_{26}]$ = [0.7446, 0.6231, 0.6255, 0.6146, 0.7248, 0.7334], where $r_{21} > r_{26} > r_{25} > r_{23} > r_{22} > r_{24}$ (r_{2j}, $j = 1 \ldots 6$, stand for the correlation degree of each fuel properties to HC emissions), which shows that the influence of the KV of blended fuels on HC emissions was the highest. As KV increased, the fluidity of the fuel decreased. Under these conditions, fuel injection became difficult, or the diameter of the injected fuel drop became too large. In this case, the effective evaporation area of the fuel drop decreased, resulting in a non-uniform mixed-gas composition and incomplete combustion and emission of HC. As the viscosity decreased, the fluidity increased such that fuel flowed out from the gap between the plunger and the pump barrel of the fuel pump. In this case, the diameter of the atomized fuel droplet was too small, and the injection shot was too short for uniform mixing between the fuel and the gas. This resulted in incomplete combustion and the production of HC.

The correlation degree of each fuel properties to test result $\{Y_3\}$ was $[r_{31}, r_{32}, r_{33}, r_{34}, r_{35}, r_{36}]$ = [0.5290, 0.7323, 0.7383, 0.7613, 0.4869, 0.4794], where $r_{34} > r_{33} > r_{32} > r_{31} > r_{35} > r_{36}$ (r_{3j}, $j = 1 \ldots 6$, stand for the correlation degree of each fuel properties to NO_x emissions), which showed that the influence of the oxygen content of blended fuels on NO_x emissions was the highest.

The correlation degree of each fuel properties to test result $\{Y_4\}$ was $[r_{41}, r_{42}, r_{43}, r_{44}, r_{45}, r_{46}]$ = [0.5276, 0.6564, 0.6563, 0.6749, 0.5266, 0.5151], where $r_{44} > r_{42} > r_{43} > r_{41} > r_{45} > r_{46}$ (r_{4j}, j = 1 … 6, stand for the correlation degree of each fuel properties to CO emission), which indicated that the influence of the oxygen content of blended fuels on CO emission was the highest. Oxygen content affected the complete combustion of fuel in the fuel-rich zone inside the diesel engine cylinder. Increasing the oxygen content improved fuel combustion and reduced CO emission.

The correlation degree of each fuel properties to test result $\{Y_5\}$ was $[r_{51}, r_{52}, r_{53}, r_{54}, r_{55}, r_{56}]$ = [0.5115, 0.6918, 0.6915, 0.6999, 0.5008, 0.4924], where $r_{54} > r_{52} > r_{53} > r_{51} > r_{55} > r_{56}$($r_{5j}$, j = 1 … 6, stand for the correlation degree of each fuel properties to CO_2 emission), which described that the influence of the oxygen content of blended fuels on CO_2 emission was the highest. The higher the total oxygen content of the blended fuels, the lower the amount of residual combustion emission, in particular HC emissions. If the fuel injected into the cylinder was burnt completely, then the amount of CO_2 in the emissions decreased.

The correlation degree of each fuel properties to test result $\{Y_6\}$ was $[r_{61}, r_6, r_{63}, r_{64}, r_{65}, r_{66}]$ = [0.9207, 0.4951, 0.4963, 0.4900, 0.8806, 0.9131], where $r_{61} > r_{66} > r_{65} > r_{63} > r_{62} > r_{64}$ (r_{6j}, j = 1 … 6, stand for the correlation degree of each fuel properties to opacity), which illustrated that the influence of the KV of blended fuels on opacity was the highest. The KV of the blended fuels affected combustion completeness by affecting atomization of the fuel.

The completed correlation degree matrix, R, is given below:

$$R = \left(r_{ij}\right) = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} & r_{26} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} & r_{36} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} & r_{46} \\ r_{51} & r_{52} & r_{53} & r_{54} & r_{55} & r_{56} \\ r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & r_{66} \end{bmatrix} = \begin{bmatrix} 0.5445 & 0.7377 & 0.7338 & 0.7195 & 0.5200 & 0.5493 \\ 0.7446 & 0.6231 & 0.6255 & 0.6164 & 0.7248 & 0.7334 \\ 0.5290 & 0.7323 & 0.7383 & 0.7613 & 0.4869 & 0.4794 \\ 0.5276 & 0.6564 & 0.6563 & 0.6749 & 0.5266 & 0.5151 \\ 0.5115 & 0.6918 & 0.6915 & 0.6999 & 0.5008 & 0.4924 \\ 0.9207 & 0.4951 & 0.4963 & 0.4900 & 0.8806 & 0.9131 \end{bmatrix}$$

From the above analysis and the correlation matrix R, we determined the following:

(1) The mean values of the correlation degrees of sub-sequences X_1, X_2, X_3, X_4, X_5, X_6 in the correction matrix R were [0.6296 0.6561 0.6570 0.6600 0.6066 0.6138], respectively. The mean value of the correlation degree of X_4 was the highest; thus, the sub-parameter in this line was the superior sub-parameter, *i.e.*, the influence of the oxygen content of blended fuels on the test results was the most significant.

(2) The mean values of the sums of the correlation degrees of sequences Y_1, Y_2, Y_3, Y_4, Y_5, Y_6 in the correction matrix R were $[0.6341\ 0.6777\ 0.6212\ 0.5928\ 0.5980\ 0.6993]^T$, respectively, in which the mean value of the correlation degree of Y_6 was the highest. Thus, the parameter in this line was the superior parameter, *i.e.*, the influence of the fuel properties on opacity was the most significant.

CONCLUSIONS

1. From the correlation degree of the fuel properties to the combustion–emission characteristics, provided by GRA, it was determined that the density of blended fuels has greater influence on the BSFC, the oxygen content of blended fuels has greater influence on the emissions of NO_x, CO, and CO_2, and the KV of blended fuels has greater influence on the HC emissions and opacity.
2. The results showed that the oxygen content of the blended fuels is the main parameter affecting combustion and emissions.
3. The analysis of the fuel properties and the combustion–emission parameters of the EL–diesel fuel mixture by the GRA method was different from a direct combustion–emission analysis. Correlation degrees between fuel properties and the combustion–emission parameters were calculated. A method for reducing BSFC and emissions could be found according to the analysis result, and this result can be tested in future studies.
4. The possible measures for reducing emission include (1) reducing KV of blended fuels to achieve reductions in the emission of HC and smoke opacity; (2) finding appropriate oxygen content of blended fuels to control emissions of CO, CO_2, and NO_x; (3) finding an appropriate density of blended fuels to bring down BSFC.

ACKNOWLEDGEMENTS

The present investigations have been funded by the Hi-tech Research and Development Program of China (2012AA051802).

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Article submitted: Jan. 31, 2013; Peer review completed: March 10, 2013; Revised version received: April 1, 2013; Second revision received and accepted: April 13, 2013; Published: April 17, 2013.