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Full length research paper

A study on relationship between the compositions and properties of fuel and emissions from diesel engine with fuzzy – gray theory

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A significant work is presented in this paper on studying the relationships between the compositions and properties of fuel and exhaust emissions from engine; for the compositions and properties of fuel have a great effect on exhaust emissions from engine. A fuzzy model which evaluates the relationships between the compositions and properties of fuel and exhaust emissions from engine has been built up with the criteria of HC, CO, PM, NO_x and CO_2; the evaluation objectives of the fuels. The weight showing the importance of each criterion was calculated with the model. A fuzzy multicriteria evaluation has been done for the emissions performance of light-duty diesel engine with eleven fuels having different compositions and properties, getting their correlative grades and correlative sequence that represents the emissions performance of light-duty diesel engine. A detailed analysis has been achieved for the relationships between the compositions and properties of fuel and exhaust emissions from light-duty diesel engine. The results demonstrate that it is beneficial to decrease exhaust emissions and improve the emissions performance of light-duty diesel engine with the fuel having bigger cetane number, lower distillation, lower aromatics contents and smaller density.

Key words: light-type diesel engine, compositions and properties of diesel fuel, exhaust emission, fuzzy multicriteria evaluation, gray correlative degree

INTRODUCTION

There is a great effect from the compositions and properties of diesel fuel on the exhaust emissions from the light-duty diesel engine. There is an important way in which the exhaust emissions can be decreased by improving the compositions and properties of the diesel fuel. It is significant that the relationships between the compositions and properties of the diesel fuel and the exhaust emissions are analyzed. A variety of analyzing methods were used widely in the engine research (Kevin et al ; Haury and Graham). In this paper, the relationships which exist between the compositions and properties of the diesel fuel and the exhaust emissions from the light-duty diesel engine have been analyzed with the fuzzy theory.

A FUZZY MODEL

Evaluating the effect of the compositions and properties of the diesel fuel on the exhaust emissions from light-duty diesel engine with fuzzy theory, the basic method is as follows:

FUZZY MULTICRITERIA EVALUATION

The exhaust emissions of NO_x, PM, HC, CO and CO_2 from light-duty diesel engine are selected as the evaluation criteria, showed with u_i (i=1,2,…,5). The fuzzy relations usually exist among them. The fuzzy set $\underset{\sim}{U}$ consists of u_i, that is: $\underset{\sim}{U} = \{u_1, u_2, \ldots, u_5\}$ (1)

Because each criterion has a different important degree in the course of evaluation, a weight coefficient w_i (i=1, 2,…,5) should be given. The fuzzy set $\underset{\sim}{W}$ consists of w_i, that is:

$$\underset{\sim}{W} = \{w_1, w_2, \ldots, w_5\} \quad \left(\sum_{i=1}^{5} w_i = 1, w_i > 0\right) \qquad (2)$$

The weight coefficient can also be defined by the following methods as elucidated by Yaomin (1999):

- The fuzzy precedence relations are constructed with $\underset{\sim}{U}$, i.e., $\underset{\sim}{B}$: $\mu_1(u_i,u_j)$. In $\underset{\sim}{B}$, $\mu_1(u_i,u_j)$ =1.0 (If u_i is more important than u_j), $\mu_1(u_i,u_j)$ =0.5（If ui is of the same importance as u_j）, $\mu_1(u_i,u_j)$ =0.0 (If u_i is less important than u_j).
- The fuzzy precedence relations $\underset{\sim}{B}$ will be modified to be the fuzzy consistent relation $\underset{\sim}{C}$, it can be shown with: $\underset{\sim}{C}$: $\mu_2(u_i,u_j)$. In $\underset{\sim}{C}$, $\mu_2(u_i,u_j)=\frac{c_i-c_j}{2*m}+0.5$, $c_i=\sum_{k=1}^{5}\mu_1(u_i,u_k)$.
- The weight coefficient w_i of each criterion can be calculated with the following formula, i.e. $w_i=\left[\prod_{j=1}^{5}\mu_2(u_i,u_j)\right]^{(1/5)}$.
- The fuzzy precedence relations of each criterion have been given in table 1, according to it: $\underset{\sim}{W}$ = {0.2876 0.2446 0.1791 0.1791 0.1097}.

A set of diesel fuels having different compositions and properties will be selected as the evaluation objectives, so the sets of evaluation Fi(ui) can be gotten, that is:

$F_i(u_i)=\{f_{i1}(u_i),f_{i2}(u_i),\ldots,f_{im}(u_i)\}$ (i=1,2,…,5) (3)

The membership degree of each evaluation objective to the criterion can be got with the optimization principle, Gao Faliang (1989). For the exhaust emissions of light-duty diesel engine, the formula of membership degree is: $r_{ij}=\underline{f_{ij}(u_i)}\big/f_{ij}(u_i)$, in the formula, $\underline{f_{ij}(u_i)}$ =min{$f_{i1}(u_i),f_{i2}(u_i),\ldots,f_{im}(u_i)$} (i=1,2,…,5; j=1,2,…,m).

A set of membership degree for all evaluation objectives to the criterion can be got. It is a fuzzy set, that is:

$$\underset{\sim}{R_i}=\{r_{i1},r_{i2},\cdots,r_{im}\} \quad (4)$$

Considering all the criteria, the evaluation matrix is as follows:

$$\underset{\sim}{R}=\begin{bmatrix}\underset{\sim}{R_1}\\ \underset{\sim}{R_2}\\ \vdots\\ \underset{\sim}{R_5}\end{bmatrix}=\begin{bmatrix}r_{11} & r_{12} & \cdots & r_{1m}\\ r_{21} & r_{22} & \cdots & r_{2m}\\ \vdots & \vdots & \ddots & \vdots\\ r_{51} & r_{52} & \cdots & r_{5m}\end{bmatrix} \quad (5)$$

Considering the important degree of each criterion, it follows that:

$$\underset{\sim}{A}=\underset{\sim}{W}\circ\underset{\sim}{R}=(a_1,a_2,\cdots,a_m) \quad (6)$$

In the formula:

$$a_j=(w_1\overset{\bullet}{*}r_{1j})\overset{+}{*}(w_2\overset{\bullet}{*}r_{2j})\overset{+}{*}\cdots\overset{+}{*}(w_5\overset{\bullet}{*}r_{5j})$$

(j=1,2,…,m)，it can be shown simply with the model M($\overset{\bullet}{*},\overset{+}{*}$), in the model, $\overset{\bullet}{*}$ indicates generalized fuzzy "and", $\overset{+}{*}$ indicates generalized fuzzy "or", they both indicate the composition operation of the matrix.

In engineering application, according to different generalized fuzzy operations, the model M ($\overset{\bullet}{*},\overset{+}{*}$) has a different format, three operations have been used in this paper from Zhang Yue's Fuzzy Mathematics Method and its Application (1999):

(1) M (•, +): The matrix may be compounded with the common "product" and "add" operation, the formula is given as follows:

$$a_{j1}=\sum_{i=1}^{5}w_ir_{ij} \quad \text{(j=1, 2, …, m)} \quad (7)$$

(2) M (·,∨): The matrix may be compounded with the common "product" and "maximum "operation (∨), the formula is given as follows:

$$a_{j2}=\max(w_1r_{1j},w_2r_{2j},\cdots,w_5r_{5j})=\bigvee_{i=1}^{5}w_ir_{ij} \quad \text{(j=1, 2 ,…, m)} \quad (8)$$

(3) M(power, ∧): The matrix may be compounded with the "power" and "minimum" operation (∧), the formula is given as follows:

$$a_{j3}=\min(r_{1j}^{\ w_1},r_{2j}^{\ w_2},\cdots,r_{5j}^{\ w_5})=\bigwedge_{i=1}^{5}r_{ij}^{\ w_i} \quad (9)$$

Therefore, the fuzzy multicriteria evaluation result for the emissions performance of each diesel fuel can be shown as follows:

$$A_j=(a_{j1},a_{j2},a_{j3}) \quad \text{(j=1,2,…,m)} \quad (10)$$

THE GRAY CORRELATIVE DEGREE

Three composition operations have been used for the fuzzy multicriteria evaluation in this paper, the emissions performance of the diesel fuels have been evaluated with them in different aspects, there are some deficiency in them. In order to rationally evaluate the emissions performance of the diesel fuels, the correlative degree

Table 1: The fuzzy precedence relations of the evaluation criteria along with weight coefficients

Evaluation criteria	NO_x	PM	HC	CO	CO_2	w_i
NO_x	0.5	1	1	1	1	0.2876
PM	0	0.5	1	1	1	0.2446
HC	0	0	0.5	0.5	1	0.1791
CO	0	0	0.5	0.5	1	0.1791
CO_2	0	0	0	0	0.5	0.1097

Table 2: Main compositions and properties of the diesel fuel

Diesel fuel code	1	2	3	4	5	6	7	8	9	10	11
Density (kg/m^3)	829.2	828.8	857.0	855.1	828.8	855.5	826.9	855.1	855.4	826.6	827
Polyaromatics (CVS%)	1.0	7.7	1.1	7.4	7.1	7.6	1	7.3	8	1.1	0.9
Cetane number	51.0	50.2	50.0	50.3	50.6	50.2	49.5	54.8	59.1	58	57.1
Distillation T_{95}(℃)	344	349	348	344	346	371	326	345	344	347	329

Table 3: Exhaust emissions from light-duty diesel engine (g/km)

fuel code	1	2	3	4	5	6	7	8	9	10	11
HC	0.085	0.085	0.111	0.103	0.085	0.099	0.089	0.083	0.073	0.063	0.066
CO	0.432	0.431	0.551	0.517	0.446	0.513	0.454	0.434	0.378	0.331	0.327
NO_x	0.556	0.564	0.532	0.546	0.556	0.539	0.554	0.552	0.559	0.534	0.551
PM	0.048	0.052	0.061	0.063	0.051	0.066	0.045	0.065	0.066	0.051	0.049
CO_2	179	180	180	182	180	180	179	181	181	177	178

Table 4 Fuzzy evaluation results

Diesel fuel code:	1	2	3	4	5	6	7	8	9	10	11
Evaluation results:	3	7	6	9	5	8	4	10	11	1	2

theory of the gray system is used on the base of the fuzzy multicriteria evaluation, its idea is given as follows: first, a clear multicriteria evaluation A_k is used, then the correlative degree of A_j to A_k is calculated for each diesel fuel, finally comparing with the correlative degree, the correlative sequence showing the emissions performance of the diesel fuel is got. The steps are as follows:

(1) Defining the clear multicriteria evaluation A_k

According to the kind diesel fuel, the clear multicriteria evaluation A_k is selected as follows:

$$A_k = (a_{k1}, a_{k2}, a_{k3}) \quad \text{(k=1,2,…,m)} \tag{11}$$

In the formula, $a_{kl} = \begin{cases} 1 & k = j \\ 0 & k \neq j \end{cases} (l = 1,2,3)$

(2) Calculating the correlative degree $\gamma_j(k)$ for A_j to A_k, as explained by Deng Julong (1990):

$$\gamma_j(k) = \frac{1}{3}\sum_{l=1}^{3}\xi_{jl}(k) \quad (12)$$

In the formula,

$$\xi_{jl}(k) = \frac{MMIN(j) + \zeta * MMAX(j)}{\Delta_{jl}(k) + \zeta * MMAX(j)} (0 < \zeta < 1),$$

$$\Delta_{jl}(k) = |a_{jl} - a_{kl}|$$

$$MMIN(j) = \min_l \min_j \Delta_{jl}(k),$$

$$MMAX(j) = \max_l \max_j \Delta_{jl}(k)$$

(3) Defining the emissions performance of the diesel fuel

Making $\gamma_j = \max(\gamma_j(1), \gamma_j(2), \cdots \gamma_j(m))$, the emissions performance index of the jth diesel fuel will be got, comparing the values of γ_j with each other, the emissions performance grade of the diesel fuels will be got.

CASE

The test data from the paper "(EPEFE)-Light Duty Diesel Study" by Hublin et al, will be used to evaluate the effect of the compositions and properties of the diesel fuel on the exhaust emissions from the light-duty diesel engine. The main compositions and properties of the diesel fuel is given in table 2, the emissions test result for the light-duty diesel engine is given in table 3 (ECE+EUDC). The correlative degree gotten by the model is given as follows:

γ=(0.6498 0.6107 0.6282 0.5720 0.6303 0.5973 0.6448 0.5676 0.5641 0.9564 0.8890)

The evaluation result of 11 diesel fuels got from the correlative degree is given in table 4; number 1 shows the best emissions performance and the number 11 shows the worst emissions performance.

Hence, it can be concluded that the 10th diesel fuel has the best emissions performance and the 9th diesel fuel has the worst emissions performance. The following relationships between the compositions and properties of the diesel fuel and the exhaust emissions from light-duty diesel engine may be found from table 4:

- From 11 diesel fuels, the 10th diesel fuel has bigger cetane number, its distillation (T_{95}) is located in the middle level, having nearly the same distillation (T_{95}) as the 3rd diesel fuel, its aromatics content is lower and its density is small. In the evaluation results, it has the best emissions performance. Comparing with the 10th diesel fuel, the cetane number, aromatics content and density of the 11th diesel fuel is almost equivalent to those of the 10th, but its distillation is very low, so the latter has a bad emissions performance than the former. It can be seen that if the distillation is too low the fuel will have a bad emissions performance.
- The 9th diesel fuel has the biggest cetane number, its distillation (T_{95}) is located in the middle level, having nearly the same distillation (T_{95}) as the 3rd diesel fuel, its aromatics content is the highest and density is bigger, it has the worst emissions performance. Comparing with the 9th diesel fuel, the density and distillation of the 8th diesel fuel is almost equivalent to those of the 9th, its aromatics content is a little lower, cetane number is smaller than that of the 9th, the latter has a better emissions performance than the former. It may be seen that if the cetane number is too big the fuel will have a bad emissions performance.
- The first and 7th diesel fuel both have smaller cetane number, smaller aromatics content, also smaller density, the distillation T_{95} of the first diesel fuel is located in the middle level, having nearly the same distillation T_{95} as the 3rd diesel fuel, the distillation T_{95} of the 7th diesel fuel is very low, thus the former has a better emissions performance than the latter. The reason why the light-duty diesel engine has a better emissions performance with them is possibly because their aromatics content and density are both smaller.
- The 5th diesel fuel has smaller cetane number, its distillation T_{95} is located in the middle level, having nearly the same distillation T_{95} as the 3rd diesel fuel, its aromatics content is higher and density is smaller, it has a bad emissions performance. Comparing with the 5th diesel fuel, the 3rd diesel fuel has smaller aromatics content and bigger density, the latter has a worse emissions performance than the former. It may be seen that the density has greater effect on the emissions performance than the aromatics content.

CONCLUSIONS

The relationships between the compositions and properties of the diesel fuel and the exhaust emissions from the light-duty diesel engine have been analyzed with the fuzzy theory. It is simple and explicit. The result gotten by the method corresponds with the actual result.

It is important that in other to decrease the exhaust emissions from the light-duty diesel engine, the diesel fuel has bigger cetane number, lower aromatics content, smaller density, its distillation T_{95} is located in the middle level and having nearly the same distillation T_{95} as the 3rd diesel fuel.

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