Correlation Analysis of Thermal Parameters of Marine Low Speed Diesel Engine Based on Least Squares Method

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Abstract

Existing methods for processing abnormal data mainly include distance statistics combined with mathematical statistics, PCA for dimensionality reduction and data prediction classification based on SVM or BP. However, samples of these methods are not sufficient to support ideal test results because of the limited data. This paper uses the MAN B&W 6S35ME-B9 diesel engine as a model. The operating data of the actual host under load conditions of 25%, 50%, 75% and 90% are taken as training samples, and the diesel engine based on SVM regression analysis to obtain relationship between thermal parameters, the subsequent development trend of diesel engines, and the main factors affecting the changes in diesel engine performance.

Keywords

Diesel engine, support vector machine, performance prediction.

1. Introduction

As an internal combustion engine, diesel engines are widely used in transportation, such as mechanical engineering and other fields because of their mobility and economy, and they are increasingly becoming larger, more complex, faster, and more heavily loaded [1]. However, because diesel engines are more System, nonlinear complex reciprocating dynamic mechanical device, and has many characteristics such as many vibration sources and many moving parts [2], integrating mechanical, thermal, fluid and other disciplines. Therefore, how to accurately analyze the performance of diesel engines and make reasonable faults. Diagnosis is the embarrassment that restrict the further development of diesel engines.

At present, the performance judgment methods of diesel engines mainly include two aspects: extrapolation and internal disconnection. The traditional diesel engine fault treatment measures are mainly regular maintenance and after-sales maintenance. This method is relatively clumsy and has poor predictability. Large damage and high cost [3]. The existing diesel engine management and maintenance methods are mainly more scientific and reasonable maintenance, a targeted maintenance system based on the idea of preventive maintenance (RCM/RCMA) [4],this maintenance system is more in line with the future intelligent ship remote fault diagnosis .The trend has the advantages of small cost, small damage, and rapidity. The author mainly records the operating parameters of MAN B&W 6S35ME-B9 marine low-speed diesel engine under 25%, 50%, 75% and 90% load conditions, including speed, power, cabin temperature, supercharger speed, medium A total of 19 parameters, such as temperature and pressure before and after the water circuit and gas path, temperature and pressure before and after the turbine, analyze the relationship between the parameters, and judge the linear correlation between these parameters through the calculation of the correlation coefficient, and grasp the main Influencing the parameters, fitting the least squares method, extrapolating the performance of the diesel engine, analyzing the relationship of the diesel engine parameters, and analyzing the mechanism of the diesel engine.

Table 1 MAN B&W 6S35ME-B9 diesel engine parameters

Diesel engine model	MAN B&W 6S35ME-B9
Number of strokes	2

Compression ratio	21
Link length	1550 mm
Piston stroke	1550 mm
Bore diameter	350
rated power	3520 KW

2. Correlation coefficient

The correlation coefficient is based on statistical judgment of the degree of linearity between two or more variables, which is a criterion based on the uncertainty of big data. Due to the difference in the number of variables, there are three main definitions: simple correlation coefficient, complex correlation coefficient, and typical correlation coefficient.

In data processing, the correlation coefficient of the matrix is generally combined with the covariance matrix of the matrix, which is a means of dimensionality reduction, adopting the idea similar to PCA[5]. Let n-dimensional variable matrix $\{X_1, X_2, X_3, \ldots, X_n\}$, where Xi represents an N-dimensional column vector (N represents the number of samples), then the covariance matrix of X is:

$$COV(X,\ X) = \begin{pmatrix} COV(X_1, X_1) & \ldots & COV(X_1, X_n) \\ \ldots & \ldots & \ldots \\ COV(X_n, X_1) & \ldots & COV(X_n, X_n) \end{pmatrix} \tag{1}$$

If X is a decentered matrix, then Equation 1 can find that$X^T X = COV(X, X)$, ignoring the difference in sample size. The diagonal matrix of Equation 1 is the variance of each variable, representing the rate of change under different samples of the same variable. The remaining elements can reflect the relative performance between different variables, and Equation 1 can be transformed into:

$$COV(X, X) = \begin{pmatrix} \sum_{i=1}^{N}(X_{i1} - \overline{X_1})^2 & \ldots & \sum_{i=1}^{N}(X_{in} - \overline{X_n})(X_{i1} - \overline{X_1}) \\ \ldots & \ldots & \ldots \\ \sum_{i=1}^{N}(X_{i1} - \overline{X_1})(X_{in} - \overline{X_n}) & \ldots & \sum_{i=1}^{N}(X_{in} - \overline{X_1})^2 \end{pmatrix} \tag{2}$$

In the above formula, $\overline{X_i}$ and X_{ij}represent the mean of the i-th column vector and the j-th variable value of the i-th sample, respectively.

Let X_a and $X_b$be two different variable vectors, then the correlation coefficients of X_a and X_b can be expressed as:

$$\rho_{(X_a X_b)} = \frac{\sum_{i=1}^{n}(X_{ia} - \overline{X_a})(X_{ib} - \overline{X_b})}{\sqrt{\sum_{i=1}^{n}(X_{ia} - \overline{X})^2 \sum_{i=1}^{n}(X_{ib} - \overline{Y})^2}} = \frac{COV(X_a,\ X_b)}{\sqrt{D(X_a)}\sqrt{D(X_b)}} \tag{3}$$

Where$\overline{X_a}$ and$\overline{X_b}$are the mean values of the variables Xa and Xb, respectively. Equation 3 can be further calculated from Equation 2, where $\rho_{(X_a X_b)}$is between [-1, 1], and when $\rho_{(X_a X_b)}$is closer to 1, the degree of correlation between X_a and X_b is increased. High [6].

3. Least squares

For the overall trend prediction of known data, there are generally two methods of interpolation and fitting. Among them, there are too many constraints on interpolation, there will be over-fitting phenomenon, and the overall trend of the data cannot be judged well; the fitting refers to the whole of the data. Judging, a curve is selected to describe the data trend. The objective function is generally the smallest sum of squared errors (least squares meaning) of this curve to all data points.

Let n sets of data be samples:

$$(X_1, Y_2), (X_2, Y_2), (X_3, Y_3), \cdots, (X_n, Y_n) \tag{4}$$

Among them, X_i is an N-dimensional column vector, which is a characteristic parameter in each set of data, Y_i is its corresponding function value, and each sample data of Equation 4 is generally in the form of a linear function; however, a polynomial function fitting can also be used. If linear fitting is used, then $h(X_i) = \alpha_0 X_{i0} + \alpha_1 X_{i1} + \alpha_2 X_{i2} + \cdots + \alpha_N X_{iN}$, Let $X_{i0} = 1$, $h(X_i)$ can be expressed as Equation 5, and denoted as $h = \alpha X$.

$$(\alpha_0 \quad \cdots \quad \alpha_N)\begin{pmatrix} 1 & 1 & \cdots & 1 \\ X_{11} & X_{21} & \cdots & X_{n1} \\ \cdots & \cdots & \cdots & \cdots \\ X_{1N} & X_{2N} & \cdots & X_{nN} \end{pmatrix} = (Y_1 \quad \cdots \quad Y_n) \tag{5}$$

Where α is the row vector of N+1 dimension, and X is the N+1 dimension column vector whose first element is 1, and the objective function can be obtained:

$$\min \ ||\delta||_2^2 = \sum_{i=1}^{n} \omega(X_i)(h(X_i) - Y_i)^2 \tag{6}$$

In order to make the expression problem more general, the weight function $\omega(X_i)$is added in the above Equation 6, which indicates the proportion of each group of data. In this paper, the probability of occurrence of the data is the same, and the weight function value is taken as 1. For the convenience of subsequent derivation, Equation 6 can be transformed into:

$$\min \ ||\delta||_2^2 = \frac{1}{2}(\alpha X - Y)^T(\alpha X - Y) \tag{7}$$

Let equation 7 be biased to α and let it be 0. According to the matrix derivation chain formula, we can get:

$$\frac{\partial}{\partial \alpha}\left(||\delta||_2^2\right) = (\alpha X - Y)X^T = 0 \tag{8}$$

According to the above formula 8, the vector $\alpha = YX^T(XX^T)^{-1}$can be solved, and the final fitting curve can be obtained by substituting h(X). Since data fitting by least squares is a biased estimate, the overall effect of the fitted curve needs to be analyzed. Evaluate the excellent sum of the total deviation of the fitted curve, the sample determination coefficient and other methods. In this paper, the total deviation square sum decomposition is used to evaluate the performance. The total deviation squared sum (TSS) can be decomposed into the regression square sum (ESS). And the sum of the residual sum of squares (RSS)[7], the formula is as follows:

$$\sum_{i=1}^{n}(Y_i - \overline{Y})^2 = \sum_{i=1}^{n}(\hat{Y}_i - \overline{Y})^2 + \sum_{i=1}^{n}(Y_i - \hat{Y})^2 \tag{9}$$

In the above formula, $\hat{Y}_i$ represents the biased estimate of the regression, and $\overline{Y}$ represents the mean.

4. Parameter measurement

This type of marine low-speed diesel engine system mainly includes six parts of diesel engine body, turbine, compressor, intercooler, exhaust pipe and scavenging air tank. In order to judge the influence between these components parameters, according to the different energy formation and flow direction, the utilization The "volumetric method" modeling idea divides the entire diesel engine system into four units[8]: The combustion chamber unit mainly converts the fuel energy into the energy of the crankshaft work, including the diesel engine body, the exhaust pipe and the scavenging air box; the boosting unit mainly converts the heat energy and kinetic energy of the exhaust gas into mechanical energy compressed air, including the compressor and the turbine; The unit reduces the internal energy of the intake air by forced cooling, mainly the intercooler; and the external unit is the cabin temperature, and these parameters are respectively divided into the four units, and the parameters of each unit have a large influence on each other, and then analyzed. The effect between units and units. According to experience, the external unit is the cabin temperature, has a large influence on the parameters of the diesel engine system, especially the exhaust temperature (pre-turbine temperature)[9], but the correlation coefficient indicates that the connection between the cabin temperature and the remaining parameters is not large. When the reason for the analysis is known, the cabin temperature change is not obvious, and the reaction of the parameters of the diesel engine system to the remaining parameters is not obvious. Therefore, the influence of the cabin temperature is ignored in this paper. In order to further simplify the relationship between the parameters, it is obvious that the host load is proportional to the power, so the host load does not participate in the fitting of the remaining parameters. Table 1 shows some of the thermal parameters recorded.

Table 2 Partial diesel engine thermal parameters

Rotating speed	Turbine temperature	Scavenging pressure	Boost pressure	Scavenging temperature	Air cooler inlet temperature
90	330.3	0.02	0.03	32.9	24.7
89.1	328.3	0.05	0.05	35.2	27.7
114	362.9	0.11	0.11	36.1	29.4
114	361.5	0.11	0.11	30.4	31.8
130.1	375.5	0.17	0.17	31.3	33.2
137.3	398.7	0.22	0.21	32.1	28.4

However, it is not enough to determine the influence between the parameters through the unit selection. Therefore, by calculating the correlation coefficient of the recorded parameters, the host speed and the host power, the supercharger speed, the pre-turbine temperature, the pre-turbine temperature, and the increase are found. The correlation between the pressure and other parameters is high, $|\rho_{(XY)}|$ can reach above 0.9; the outlet temperature of the air cooler and the charge air temperature, the air inlet temperature of the air cooler, the scavenging temperature, the host power, etc. There is a high degree of correlation, $|\rho_{(XY)}|$ up to 0.7. Table 3 is the correlation coefficient between some parameters. It is found that the correlation between the temperature after the turbine, the inlet and outlet pressure of the air cooler and other parameters is not large, and it is difficult to judge its development trend.

Table 3 Partial correlation coefficient of thermal parameters of some diesel engines

	power	Supercharger-speed	Turbine-temperature	Turbine-temperature	Boost-pressure
Rotating speed	0.9867	0.9889	0.9426	-0.4276	0.9814
Scavenging-temperature	0.59	0.5895	0.6334	-0.136	0.5829
Turbine-temperature	-0.4716	-0.4601	-0.3159	1	-0.5342
Air cooler inlet- pressure	-0.1619	-0.1896	-0.0837	0.3051	-0.1839
Air cooler inlet-temperature	0.7063	0.7205	0.7626	-0.4133	0.713

5. Parameter fitting

The diesel engine ventilation system is mainly composed of turbocharger, intercooler, scavenging air box and air intake pipe. In order to predict the performance of the diesel engine ventilation system, the author selects the inlet temperature of the air cooler and the air cooler water channel through the evaluation of the correlation coefficient. The author selected the air cooler inlet temperature, the air cooler inlet and outlet temperature and the boosting temperature to carry out the curve fitting of the air cooler outlet temperature by Matlab software. Through the item-by-item regression analysis, the inlet temperature of the air cooler and the inlet temperature of the air cooler were selected as the parameters of the fitting curve, and the equation of the fitted curve was obtained $y = 0.4017 + 0.525x_1 + 0.3898x_2$, Where y is the air cooler outlet temperature (°), x1 is the air cooler inlet temperature (°), x2 is the air cooler inlet temperature (°), and Figure 4 is the air cooler inlet temperature selected after item-by-item regression. And some performance parameters of the air cooler inlet temperature fitting.

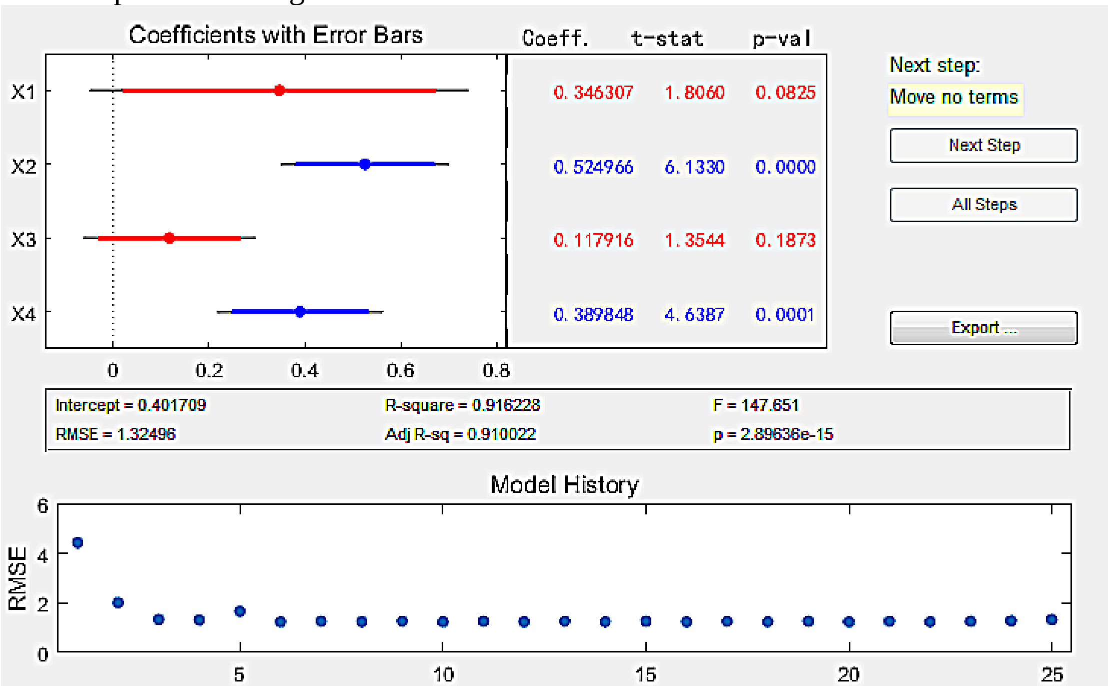

Figure 4 Partial performance parameters of the intake air temperature fitting

In order to cross-validate the multivariate one-time fitting curve as the optimal fitting curve, the multi-element fitting function is also used to fit the intake air temperature (air cooler inlet temperature), and the above trend can also be verified by trend analysis. The combined curve is the optimal curve.

The rest also selected the air inlet and outlet temperature of the air cooler, the air inlet and outlet temperature of the air cooler to fit the charge air temperature; the air inlet and outlet temperature of the air cooler, the air inlet and outlet temperature of the air cooler, and the charge air temperature to the scavenging temperature. For the fitting and the like, the main performance parameters of the calculation results are shown in Table 4.

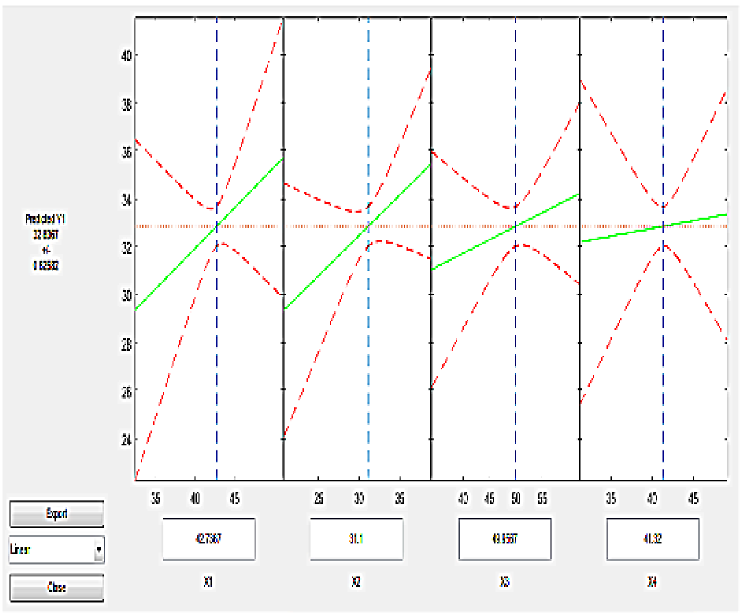

Figure5 Temperature fitting based on four elements

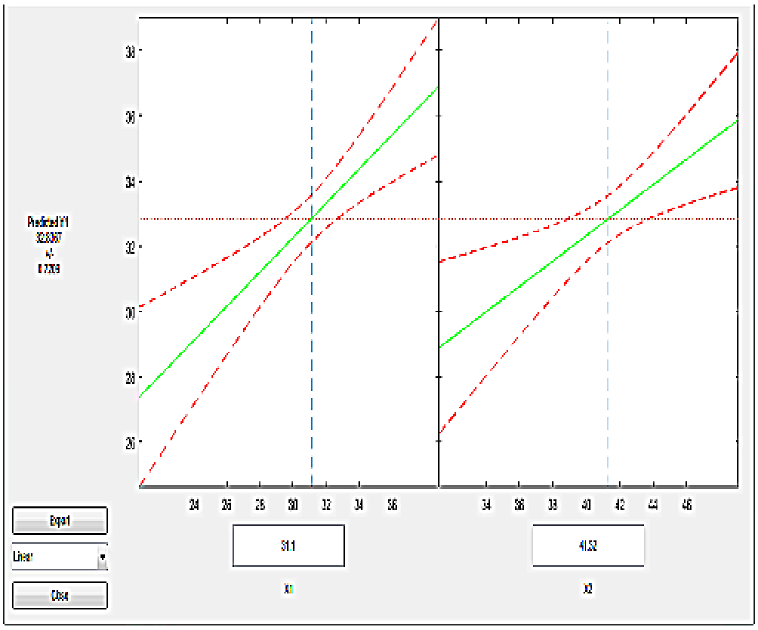

Figure6 Temperature fitting based on two elements

Table 4 Performance indicators of partial parameter fitting

	R-square	RMSE	F	Fitting formula
Rotating speed	0.997576	0.977326	5556.75	$y = 39 + 0.0052x_1 - 0.0048x_2$
Intake air temperature	0.916228	1.32496	147.651	$y = 0.4 + 0.525x_3 + 0.3898x_4$
Charge air temperature	0.932895	1.29432	389.255	$y = 2.8602 + 0.9651x_4$
Air cooler inlet-pressure	0.727101	2.09436	16.6522	$y = 17.5021 + 0.6520x_3$
Scavenging temperature	0.974936	142.358	1089.14	$y = -3228.4 + 45.5x_5$
power	0.99757	187.269	11497	$y = -7321.4 + 194.7x_5$
Supercharger speed	0.976543	5.25043	360.806	$y = 163 + 1.2x_5 - 2.4x_3 + 2.8x_6$
Turbine temperature	0.997576	0.977326	5556.75	$y = 39 + 0.0052x_1 - 0.0048x_2$

In the above table, x_1 and x_2 are the supercharger speed and the pre-turbine temperature; x_3 and x_4 are the air cooler inlet temperature and the air cooler inlet temperature; x_5 is the main engine speed; x_6 is the air cooler water outlet temperature.

From the fitting formula in the above table, it can be concluded that different performance parameter indicators are closely related to each process parameter, and the performance trend of the diesel engine in the future can be obtained by these formulas.

Table 5 Partial deviation of some fitting parameters

	fitted value	Measurements	Error amount
Rotating speed	73.5344	90	18.3%
Intake air temperature	127.4381	129.1	1.3%
Charge air temperature	26.7783	26.7	0.3%
Air cooler inlet-pressure	31.6069	30.7	3.0%

Scavenging temperature	42.8153	42.7	0.3%
power	33.6065	36.7	8.4%
Supercharger speed	866.6	903.9	4.1%
Turbine temperature	10202	9979.8	2.2%

The above table compares the value obtained by substituting part of the actual parameters into the fitted curve and compares the actual measured parameters. It can be found that the error amount of most data except for the individual data is within 5%, which mainly considers that the overall parameters are not abnormal data. Filter.

6. Fitting curve analysis

Since the diesel engine system itself is a complex and interrelated system, each parameter affects each other, and the curve fitting equation is based on the mechanism analysis and correlation coefficient selection, grasping the main parameters and ignoring the secondary factors, and calculating the relationship between the main parameters can better analyze the working process of the diesel engine system.

The speed of the diesel engine is related to many factors. The load, the torque of the diesel engine body and the moment of inertia all have an effect on the speed of the diesel engine [10]. However, under steady-state conditions, the moment of inertia and load are fixed, so the speed of the diesel engine Most of it depends on the torque of the body, According to the mathematical model of torque (Equation 10), since η_e is determined by factors such as diesel engine speed and excess air ratio, it can be seen that the factors affecting the torque of the diesel engine are fuel and air, which cause the fluctuation of the maximum burst pressure in the cylinder. , which in turn causes changes in torque and speed. In the ventilation system, the turbocharger is directly affected by the intake of the diesel engine, and the exhaust temperature (pre-turbine temperature) directly reflects the combustion state in the cylinder. Therefore, the fitted curve of the host speed takes into account two of the most important factors affecting the speed of the diesel engine: the turbocharger speed and the exhaust temperature.

$$M_D = k \cdot g_c \cdot \eta_e \tag{10}$$

In the above formula.k $= 1000H_u i/\pi\tau$. H_uIs the low heating value of the fuel; i is the number of cylinders; τ is the number of strokes; η_e is the effective efficiency of the diesel engine.

When the air cooler is considered separately, it is simplified to the throttling and cooling components for parameter calculation. Generally, when considering the cooling efficiency, factors such as air flow, temperature, structure and material need to be considered from the perspective of energy transfer, but further Simplification, by introducing the cooling coefficient of the air cooler, the mathematical model of the main engine intake air temperature (air cooler air outlet temperature) can be obtained, which can generally be expressed by Equation 11. From this, it can be clearly seen that the decisive factor affecting the intake air temperature of the main engine is The inlet temperature of the air cooler and the inlet temperature of the air cooler are the same, and the fitting curve of the inlet air temperature is also consistent. Therefore, the above curve fitting equation has certain physical meaning.

$$T_S = T_K - \eta_c(T_K - T_{cwi}) \tag{11}$$

In the above formula, T_S is the intake air temperature; T_K is the inlet temperature of the air cooler; η_c is the cooling coefficient of the air cooler; and T_{cwi} is the inlet temperature of the air cooler.

In the diesel engine system, the exhaust gas temperature is an important indicator for judging the performance of the diesel engine. Most of the current calculations of exhaust gas temperature are mainly three ways: average temperature over time, average temperature at flow rate, average temperature at thermal energy [11], but these three calculation methods are complicated, and the cost of many parameters is too large. Therefore, the existing model generally uses the empirical formula to solve (Equation 12). It can be seen that the exhaust gas temperature is related to the diesel engine speed, fuel injection amount, and air-fuel ratio[10], and the fitting curve of the exhaust temperature is the diesel engine. The speed is related to the inlet and outlet temperature of the air cooler. Except for the speed, there is no necessary connection between them. Therefore, the above curve fitting equation does not have complete physical meaning.

$$T_4 = \Delta T + T_{in}$$
$$\Delta T = \frac{\chi}{1+A_F} \cdot \frac{H_u \eta_{cy}}{C_{pex}} + f(n_D) \quad (12)$$

In the formula, χ is the ratio of the energy that the exhaust gas is introduced into the exhaust pipe to the amount of fuel injected into the cylinder; A_F is the air-fuel ratio; andη_{cy} is the combustion efficiency.

7. Conclusion

The existing methods for detecting abnormal test data are mainly based on the distance method combined with statistical theory, based on the assumption that sample data has a probability distribution model, combined with distance, deviation density and other methods, using statistical theory to analyze the abnormal data by inconsistency test. Point or PCA principal component analysis for dimensionality reduction to achieve high-dimensional data mapping in low-dimensional space and predictive classification from SVM or BP etc. These methods which to diagnose machine faults all are based on a number of data, so predicting the change trend of diesel engine thermal parameters is the key technology for intelligent ship fault diagnosis, which has great practical significance [12]. This paper passes the MAN B&W 6S35ME-B9 marine low-speed diesel engine with 30 sets of records at 25%, 50%, 75 load. The thermal parameters under % and 90% conditions were analyzed by regression analysis based on the least squares method, and the following conclusions were drawn:

The fitted thermal parameter curve equation is obtained, and the error analysis of the fitted curve is tested by using another four sets of data, and it is found that the error amount is mostly within 5%.

Analyze the element of the fitted curve from the mathematical model of the diesel engine system, and try to explain the rationality of the fitting curve from the mechanism.

The fitting curve obtained in this paper can effectively extend the range of data and provide effective samples for the detection of subsequent abnormal data.

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