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Optimizing Methanol Blending Performance of Electronically Controlled Diesel Engines through Fuzzy Analysis

Zheng Cai[1], Chenxi Yang[1], Jinyu Fan[1,2*], Pinfang Li[1,2], Zhaoxia Huang[3], Jialiang Huang[1,2]

[1] Marine Engineering Institute, Jimei University, Xiamen 361021, China.
[2] Key Laboratory of Ship and Marine engineering, Fujian Province, China.
[3] School of Science, Jimei University, Xiamen 361021, China.

Abstract: This paper presents a comprehensive optimization approach for enhancing the performance of a methanol/diesel Exhaust Gas Recirculation (EGR) engine. Initially, a hybrid fuel engine combustion chamber model was developed using AVL-FIRE software, and the simulated results were compared with the values obtained from bench tests. An orthogonal experimental design was employed to optimize five key factors, namely methanol blending ratio, EGR rate, injection advance angle, intake pressure, and intake temperature. Evaluation indexes were established, with indicated power and NO emissions assigned weights of 0.35 and 0.65, respectively. The optimal parameter combinations were determined as follows: methanol blending ratio (a1=20%), EGR rate (a2=12.5%), injection advance angle (a3=16.6°CA), intake temperature (a4 = 315.15 K), and intake pressure (a5=0.173 MPa). The indicated power of the optimized configuration reached 47.8 kW, slightly lower than the original 55 kW, while the NO emission mass fraction decreased to 1.9×10^{-4}%, representing a significant reduction of 77.6% compared to the original value of 8.5×10^{-4}%. This optimization methodology demonstrates the effective reduction of NO emissions without compromising power performance in methanol/diesel EGR engines.

1.Introduction

To meet emission regulations while ensuring sufficient power output of diesel engines, researchers have been seeking new methods and technologies. Parameters related to marine diesel engines, such as blend ratio, exhaust gas recirculation (EGR), and intake pressure, often exhibit numerous parameters, complex interactions, and nonlinear correlations. Xuan Rong[1] et al. investigated the influence of EGR and intake pressure on combustion and emissions of dual-fuel engines in a four-cylinder marine diesel engine. The introduction of EGR with blended fuels significantly reduced NOx emissions, meeting the International Maritime Organization Tier III emission standards. Cenk Sayin et[2] al. studied the effects of methanol blend ratio, injection pressure, and injection timing for alcohol-blended fuels, with methanol ratios of 5%, 10%, and 15%. The experiments showed that increasing the methanol blend ratio improved thermal efficiency and economic performance while reducing emissions of soot, carbon monoxide (CO), and hydrocarbons (HC). However, higher injection pressure and advanced injection timing resulted in reduced soot and HC emissions but increased NOx emissions.

This paper is based on the experimental platform of the 4190-type electronically controlled marine diesel engine. Using AVL-FIRE, a combustion chamber model for methanol/diesel blended fuels was established. Initially, a simulation calculation was conducted by employing an orthogonal experimental design to investigate five key operating parameters. Fuzzy mathematics analysis was then applied to the simulation results to determine the optimal parameter combination, achieving simultaneous optimization of the power performance and NOx emissions for the blended-fuel engine.

2.Electronically controlled diesel engine model building and validation

2.1.Model establishment

The 4190-diesel engine modified with electric control diesel engine as the object of study, its technical parameters are shown in Table 1

Using AutoCAD software to draw the combustion chamber center cross-sectional area 1/2 model Figure 1, it will be imported into the fire ese diesel generated three-dimensional graphics, complete dynamic mesh division and check. As there are 8 nozzles in the 4190-diesel engine, the combustion chamber is divided into 8 equal parts to simplify the calculation,A simulation study was conducted by selecting 1/8 of the combustion chamber for investigation, as shown in Figure 2. By changing the size of each small grid within this 1/8 portion, the number of grids was reduced to achieve a balance between maintaining the accuracy of the simulation model and

* Corresponding author: jyfan2002@163.com

simplifying the computational process[3].

Tab.1 4190 diesel engine basic parameters

Diesel engine type	Four-stroke medium-speed
Cylinder bore(mm)×stroke(mm)	190×210
Combustion chamber shapes	Straight mouth ω type
Compression ratio ε	14:1
Calibration speed r/min	1000
Calibrated power kW	220
Rated fuel consumption rate g/(kW.h)	206
Spray hole diameter mm	0.30

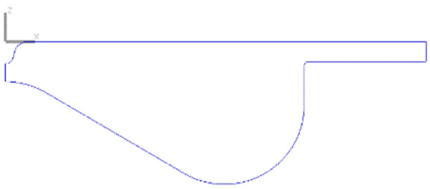

Fig.1 Schematic diagram of center section 1/2 of the combustion chamber

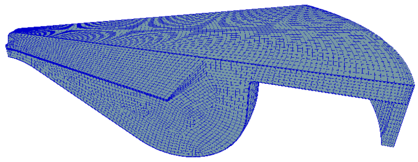

Fig.2 Diesel engine combustion chamber 1/8 calculation model

2.2.Computational Model

The research conducted in this paper investigates the influence of methanol-diesel blend ratio and exhaust gas recirculation (EGR) rate on the engine's performance, particularly focusing on in-cylinder combustion, including diffusion and convective combustion. For the computational model, a standard two-equation model was selected, known for its accurate simulation of flow phenomena and high convergence precision. The spray model was chosen as follows: the KH-RT model in AVL_FIRE was selected as the spray breakup model, while the Multi-component model was chosen for the evaporation model in simulating the combustion process of methanol-diesel blends. The Walljet1 model was utilized for liquid droplet impingement on walls, and the Enable model was employed for the turbulent diffusion model [4].

2.3.Experimental and Simulation Model Parameter Settings

Firstly, for the diesel engine operating parameter settings, the methanol blend ratio is specified as a volume percentage mixed with diesel fuel injected into the cylinder through the fuel injector. The experimental setup employs a high-pressure common rail fuel injection system, controlled by an electronic control system that regulates key parameters such as injection timing. The injection characteristics of the fuel injector are controlled accordingly[5]. The HORIBA MEXA-1600DSEGR exhaust gas analyzer and AVL smoke meter are used to measure and analyze components such as NOx, CO, THC, and Soot in the exhaust gas. The KISTLER combustion analyzer measures parameters such as cylinder pressure, temperature, and heat release rate. The FC2010 intelligent fuel consumption meter is used to measure the consumed fuel amount, and the EGR rate is controlled by adjusting the opening of the EGR valve.

In the simulation experiments, the AVL-FIRE software is utilized to establish an in-cylinder combustion model for the blended-fuel engine. Within the software, the four parameters of interest in this study, namely intake pressure, methanol blend ratio, EGR rate, and injection timing, are configured. However, the in-cylinder reactions involving methanol are extremely complex, demanding high requirements for simulation calculations and involving a large computational workload. This study adopts the chemical reaction mechanism of methanol-diesel dual fuel as described by CHANG [6]. Regarding the setting of the EGR rate, it is defined as the percentage of recirculated gas in the total mixture (including fresh air and intake fuel), as shown in Equation 1[7].

$$EGR(\%)=\left(\frac{m_{EGR}}{m_{air}+m_{fuel}+m_{EGR}}\right)\times 100\% \quad (1)$$

2.4.AVL-FIRE Simulation Verification

The average cylinder pressure and heat release rate are two key parameters in the simulation verification process. This is because many engine parameters, including indicated power, brake-specific fuel consumption, and NOx emission mass fraction, primarily depend on the average cylinder pressure and thermal efficiency. Figure 3 shows the comparison curve between the simulated results (with pure diesel fuel and EGR rate set to 0) and the experimental results obtained from the actual engine.

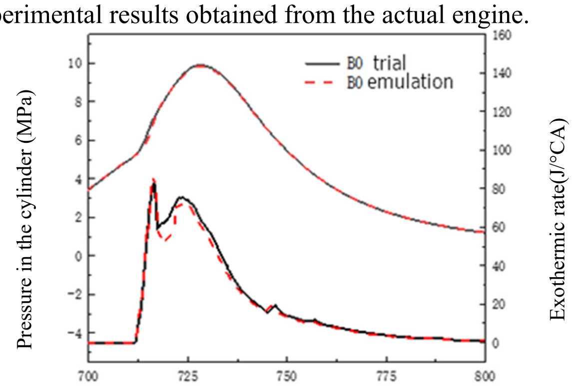

Fig.3 Comparison of simulated and measured pressure curves and heat release rate curves

In Figure3, both the pressure curve and the heat release rate curve show slightly higher values in the experimental results compared to the simulated results. This can be attributed to factors such as poor sealing of the intake and exhaust valves and carbon deposits in the intake manifold, resulting in a reduction in the actual intake air volume and a slightly higher compression ratio in the actual engine compared to the simulation model. The discrepancy is within 3%, suggesting that the simulation model is capable of accurately replicating the experimental conditions of the actual engine.

3.Orthogonal experimental design

Orthogonal experimental design allows for a scientifically reasonable arrangement of experiments, reducing the number of trials required. In this study, an orthogonal experimental design is applied to investigate the effects of five factors: methanol blend ratio (a1), EGR rate (a2), injection timing (a3), intake temperature (a4), and intake pressure (a5) through simulation. The evaluation criteria are indicated power of the blended-fuel engine (y1) and NO emission mass fraction (y2).The orthogonal array L16 (45)[8] is chosen to arrange the parameters for simulation. The analysis of the simulation results is presented in Table 2.

Tab.2 Orthogonal test table and extreme difference analysis table

Test Group	*a*1/%	*a*2/%	*a*3/°CA	*a*4/K	*a*5/MPa	*y*1/kW	*y*2/10^{-4}%	*b*1	*b*2	*b*'
1	0	0	16.6	315.15	0.173	61.23	6.88	1.00	0.09	0.41
2	0	7.5	18.6	325.15	0.193	59.34	5.89	0.89	0.28	0.50
3	0	10	20.6	335.15	0.213	59.12	5.17	0.88	0.42	0.58
4	0	12.5	22.6	345.15	0.233	58.66	4.39	0.85	0.57	0.67
5	10	0	18.6	345.15	0.213	58.16	7.35	0.83	0.00	0.29
6	10	7.5	16.6	335.15	0.233	57.11	5.99	0.77	0.26	0.44
7	10	10	22.6	325.15	0.173	56.49	4.36	0.73	0.58	0.63
8	10	12.5	20.6	315.15	0.193	54.41	3.41	0.61	0.76	0.71
9	20	0	20.6	325.15	0.233	53.95	6.52	0.59	0.16	0.31
10	20	7.5	22.6	315.15	0.213	52.83	5.44	0.52	0.37	0.42
11	20	10	16.6	345.15	0.193	50.35	3.07	0.38	0.82	0.67
12	20	12.5	18.6	335.15	0.173	49.13	2.16	0.31	1.00	0.76
13	30	0	22.6	335.15	0.193	48.16	6.57	0.26	0.15	0.19
14	30	7.5	20.6	345.15	0.173	46.35	4.41	0.16	0.57	0.42
15	30	10	18.6	315.15	0.233	45.48	3.17	0.11	0.81	0.56
16	30	12.5	16.6	325.15	0.213	43.62	2.36	0.00	0.96	0.62

4.Fuzzy Analysis

4.1.Membership Degree of Indicators

Based on the orthogonal experimental results presented in Table 2, fuzzy mathematical analysis is conducted. In fuzzy mathematics, the five factors investigated in this study constitute the universe of discourse *Z*. The values of the factors obtained from the i-th experiment (i = 1, 2, 3, ..., 16) are elements of *Z*, denoted as (Z_{ij})∈[0, 1]. Z_{ij} → [0, 1], where any element $Z_{ij} \in Z$ is referred to as a fuzzy subset of Z, denoted as = { (Z_{ij} | f_{aj} (Z_{ij})) }. Here, f_{aj} (Z_{ij}) represents the membership degree function of Z_{ij} with respect to. For a specific, the membership degree f_{aj} (Z_{ij}) represents the degree to which belongs to the fuzzy set. f_{aj} (Z_{ij})=1 indicates full membership, which is considered satisfactory, while f_{aj} (Z_{ij})=0 indicates no membership, which is considered unsatisfactory[9].

4.2.Establishment of Membership Functions Taking

Indicated power (*y*1) and NO emission mass fraction (*y*2) as evaluation indicators, P={*y*1, *y*2}, the experiments are conducted 16 times, resulting in the evaluation set *Q* = {*Q*1, *Q*2, ..., *Q*16}. Membership functions reflect the degree to which the evaluation indicator values reach the concept of "satisfactory." When establishing membership functions, the influence of the evaluation indicator values on the evaluation indicators themselves should be considered. Evaluation indicators can be categorized into three types: the larger the indicator value, the better (larger-is-better type), the smaller the indicator value, the better (smaller-is-better type), and the closer the indicator value to the ideal value, the better (intermediate type) [10]. In this case, indicated power (*y*1) is a larger-is-better type indicator, and NO emission mass fraction (*y*2) is a smaller-is-better type indicator. The membership functions are defined as follows:

$$s_{1i} = \frac{y_{1i} - \min\left\{y_{1j}\right\}}{\max\left\{y_{1j}\right\} - \min\left\{y_{1j}\right\}} \tag{2}$$

$$s_{2i} = \frac{\max\left\{y_{2j}\right\} - y_{2i}}{\max\left\{y_{2j}\right\} - \min\left\{y_{2j}\right\}} \tag{3}$$

In the equation: i = 1, 2, ..., 16. The membership functions of the two evaluation indicators form a fuzzy relation matrix *S* = {*s*1, *s*2}. The membership calculation results for y1 and *y*2 are shown in Table 2.

4.3.Comprehensive Evaluation Membership Calculation

The allocation of weights to fuzzy subsets is based on different optimization objectives. In response to the increasing emphasis on emissions from marine diesel engines worldwide, the weight of NOx emissions should be greater than the weight of power output. Taking values of 0.65 and 0.35, respectively, for the weights of NOx emissions and power output, the fuzzy subset is defined as W=(0.65, 0.35). In fuzzy mathematics, the formula for calculating the comprehensive evaluation membership fuzzy relation is given by: $B = W \cdot S$, as shown in column bi of Table 2 for the calculation results. To visually compare the degree of proximity between different levels of each factor and the comprehensive evaluation membership, the calculation results are shown in Table 2.

4.4.Comprehensive Evaluation

Membership Range Analysis Based on Table 2, the sum of the comprehensive membership degrees for different levels of each factor is calculated and shown in Table 3. By applying range analysis to the comprehensive evaluation membership, the values in descending order are: 1.567 ($a2$), 0.365 ($a1$), 0.304 ($a5$), 0.232($a3$), 0.133 ($a4$). The maximum sum of fuzzy comprehensive evaluation membership is obtained when a1 is at level 3, $a2$ is at level 4, $a3$ is at level 1, $a4$ is at level 1, and $a5$ is at level 2. This indicates the order of the factors' impact on the overall performance of the engine as: $a2$, $a1$, $a4$, $a3$, $a5$. The optimized parameter matching is as follows: a1 = 20%, a2 = 12.5%, a3 = 16.6°CA, a4 = 315.15K, a5 =0.173MP. This set of optimized parameter combinations is not included in the 16 experimental designs of the orthogonal test design in Table 2, which indicates that fuzzy analysis can meet the need for multi-objective optimization.

Tab.3 Analysis of extreme differences in affiliation of different levels of comprehensive evaluation of each factor

	$a1$	$a2$	$a3$	$a4$	$a5$
$\Sigma_i b_{ij1}$	2.155	1.195	2.142	2.099	2.061
$\Sigma_i b_{ij2}$	2.066	1.778	2.104	2.060	2.221
$\Sigma_i b_{ij3}$	2.161	2.442	2.021	1.967	1.917
$\Sigma_i b_{ij4}$	1.796	2.762	1.910	2.051	1.978
$\Delta\Sigma_i b_{ij4}$	0.365	1.567	0.232	0.133	0.304

4.5.Verification of Fuzzy Analysis Parameter Optimization

Under the calibration conditions, the parameter combination optimized through fuzzy mathematical analysis was applied to the established combustion model of the hybrid fuel engine (with other parameters kept the same as the original engine). The obtained indicated power was 47.8kW, slightly lower than the original engine's 55kW under the same conditions. At the same time, the NO emission mass fraction was found to be 1.9×10^{-4}%, which reduced by 77.6% compared to the original engine's NO emission of 8.5×10^{-4}%. This demonstrates the improvement in combustion characteristics achieved by using electronic control for diesel-methanol co-combustion and the significant reduction in NO emissions using EGR, while maintaining a higher indicated power.

5.Conclusion

(1) The combustion chamber model of the hybrid fuel engine was established using AVL-FIRE software with the ESE module. The simulated cylinder pressure curve was compared with the measured curve from the test bench, and the error was within 3%. This indicates that the established model is accurate and can be used for simulation studies.

(2) To address the limitation of optimizing only a single evaluation criterion, indicated power, and NO emissions in orthogonal experiments, fuzzy mathematical analysis was combined with orthogonal experimental design. Important operational parameters (methanol blending ratio $a1$, EGR rate $a2$, intake temperature $a3$, intake temperature $a4$, intake pressure $a5$) were optimized through multi-parameter matching under the condition of weighting indicated power and NO emissions with weights of 0.35 and 0.65, respectively. The order of the factors' influence on the engine's comprehensive performance was determined as follows: $a2$, $a1$, $a5$, $a3$, $a4$. The optimal parameter combination for the comprehensive performance was found to be: $a1$=20%, $a2$=12.5%, $a3$=16.6°CA, $a4$=315.15K, a5=0.173MPa. Under the same conditions, the optimized parameter combination resulted in a slightly lower simulated indicated power of 47.8kW compared to the original engine's 55kW, and the NO emission mass fraction was reduced by 77.6% to 1.9×10^{-4}% from the original engine's 8.5×10^{-4}%. This demonstrates that using fuzzy mathematical analysis to optimize parameter matching for multiple evaluation criteria can improve the combustion characteristics of electronic control diesel-methanol co-combustion, significantly reduce NO emissions through EGR, and achieve a higher indicated power.

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