

Article

Performance Optimization and Knock Investigation of Marine Two-Stroke Pre-Mixed Dual-Fuel Engine Based on RSM and MOPSO

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Abstract: The two-stroke pre-mixed dual-fuel marine engine is prone to knocking at full load in gas mode, which affects the overall dynamic and economic performance of the engine. In this paper, the 7X82DF engine produced by Winterthur Gas & Diesel Ltd. (WinGD) was selected as the research object, aiming to investigate the effect of different parameters on engine power and knocking. Multi-objective optimizations were carried out. First, we used the one-dimensional simulation software AVL-BOOST to build the gas mode model of 7X82DF. Second, the pilot fuel start of combustion timing (SOC), the gas injection pressure, and the mass of diesel were taken as independent variables. The response surface methodology analysis of the independent variables was completed using the Design-Expert software and corresponding prediction model equations were generated. Finally, we took ringing intensity (RI) as the knock intensity evaluation index, combined with multi-objective particle swarm optimization (MOPSO) to optimize multiple-parameters to improve the overall performance and reduce combustion roughness of the engine. The optimization results showed that when the SOC was $-8.36^{\circ}\text{CA ATDC}$, the gas injection pressure was 20.00 bar, the mass of diesel was 14.96 g, the corresponding power was 22,668 kW, which increased by 0.68%, the brake-specific fuel consumption was 156.256 g/kWh, which was reduced by 3.58%, the RI was 4.4326 MW/m², and the knock intensity decreased by 6.49%.

Keywords: dual-fuel engine; ringing intensity; response surface methodology; MOPSO



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1. Introduction

Low-speed two-stroke diesel engines are widely used in marine engines due to their high thermal efficiency, high power performance, and strong reliability. Due to the engine being able to use heavy oil, it has better fuel economy [1]. With the shortage of petroleum energy and stricter emission regulations, natural gas has been widely applied and investigated due to its larger reserves and cleaner combustion, which can reduce emissions [2]. Dual-fuel (DF) engines that use natural gas as the main fuel and a small amount of diesel as the pilot fuel have been widely applied in marine engines in recent years [3]. For low-speed two-stroke DF engines, too fast of a heat release rate can easily cause the engine to knock under full load and high-temperature conditions, which affects the engine power performance and economy [4]. Currently, the research on two-stroke DF marine engines has mainly concentrated on the combustion and emission characteristics, lean burn and ignition limits, exhaust gas recirculation, the simulation optimization of structural parameters, etc. [5].

Theotokatos et al. used the GT-Power software to conduct simulation research on a large marine two-stroke low-pressure injection DF engine [6]. Through simulation, the combustion and emission characteristics of the engine in DF mode and diesel mode were revealed, and the effect of the parameter settings on knock was better understood. Zou et al. established a dual-zone quasi-dimensional model of a marine DF engine in the

Matlab/Simulink environment. The knock intensity index coefficient (KI) was used as the evaluation index of knock intensity. Based on this model, they studied the effects of the intake temperature and compression ratio on the engine's knock characteristics. The simulation results showed that the knock intensity would become greater with the increase of the intake temperature and compression ratio. The engine knock could be avoided by controlling the intake air temperature below 336 K and compression ratio under 15 [7]. Lounici et al. compared the knocking phenomenon of a spark-plug ignition engine and a DF engine fueled with diesel as the pilot, and studied the effects of knocking on the combustion temperature, heat release and peak firing pressure in the cylinder. Through research, it has been found that an appropriate increase in the amount of pilot fuel can delay the occurrence of knocking in the DF engine [8]. Wei et al. used methane instead of natural gas and n-heptane instead of diesel to numerically study the ignition characteristics and knock mechanism of gas/diesel DF engines [9]. Guo et al. used the computational fluid dynamics (CFD) software CONVERGE to study the performance effects of the pilot fuel injection conditions on the combustion and emissions of a marine LP-DF engine. The results showed that the average in-cylinder temperature, the average in-cylinder pressure, and the NO_x emissions gradually decreased with the delay of the pilot injection timing. Furthermore, the combustion situation gradually deteriorated as the pilot injection duration increased, which increased the knock tendency. Moreover, when the number of pilot injector orifices was 1, the engine performance and emission characteristics were very good [10]. Wang et al. conducted a comparative simulation study on the flame propagation process of the engine between normal combustion and knocking combustion. The simulation results showed that during knocking combustion, a small amount of vaporized fuel accumulates on the exhaust side under the action of in-cylinder turbulence and forms multiple hot spots that caused pressure fluctuations [11]. Li and Zheng conducted a numerical simulation on the effect of in-cylinder water injection technology on engine knocking combustion. The gasoline engine was induced to knock by advancing the spark timing, and then the influence of the water injection temperature on the knock and emissions was investigated. The results showed that the maximum pressure and pressure increase rate in the cylinder increased with the advance of sparking timing, which increased the tendency of the gasoline engine to knock. Water injection can effectively suppress knocking, and a lower water temperature can reduce the knock intensity and NO_x emission, but it will increase the soot emission [12]. Through three-dimensional (3D) numerical simulation, Wang et al. used the differential pressure method as the knock detection index to investigate the effect of the pilot fuel quantity and equivalence ratio on the combustion fluctuation of a large-bore marine natural gas engine. It was found that reducing the amount of pilot fuel can increase the engine power while suppressing knocking, and a high equivalence ratio can increase the flame jet but also increase the pressure oscillation amplitude [13].

In addition to the simulation of the engine operating parameters, researchers have also carried out many investigations on the optimization of the design structural parameters. Guo et al. used the CFD software CONVERGE to establish a 3D model of the engine and simulated and researched the influence of the structural parameters of the pre-combustion chamber on the performance and combustion of a low-pressure DF engine. The results showed that the diameter and the nozzle angle of the pre-combustion chamber can directly affect the flame propagation process, which affects the occurrence of knocking [14]. The researchers also conducted extensive research on the injectors number, the holes of the injectors, and the nozzle diameter in the pre-combustion chamber. The results showed that more injectors and nozzles and smaller nozzles diameter will improve the economic performance of the engine, but at the same time, the peak pressure rise rate (PPRR) and ringing intensity (RI) will increase, which increases the tendency to knock [15–17]. Rui investigated the effects of the central and left-right arrangement of the natural gas and diesel injectors on the combustion performance of the high-pressure direct injection engine [18]. Timzer and Cihan modeled and optimized the bowl-shaped combustion chamber in the

AVL-FIRE simulation environment. The optimized model showed that the fuel combustion and flame propagation process were more stable [19].

Investigations on alternative fuels, dual-fuel (CNG-diesel) and advanced combustion fuel systems have been carried out. Jatoth et al. conducted the study of compressed natural gas (CNG) and Schleicher oleosa oil methyl ester (SOME) with diesel as the pilot fuel and triacetin as an additive on the emission, combustion and performance characteristics of a four-stroke, single cylinder, common rail direct injection diesel engine working at a constant speed and varying operating scenarios. The experimental study revealed that, as compared to traditional dual-fuel (CNG-diesel), CNG-triacetin combination the amount of harmful pollutants such as smoke (5.38%), hydrocarbon (6.39%), carbon monoxide (10.24%) and oxides of nitrogen, was to a considerable extent. The combustion and performance of the engine were improved considerably when CNG and triacetin additives were blended together [20]. Paul et al. compared a CNG dual-fuel engine, which used a blend of 45% diesel, 15% ethanol and 40% Pongamia pinata methyl ester (PPME) as the pilot fuel with the same CNG injection strategies piloted by diesel. It was found that the pilot operation of the blend was instrumental in increasing the brake thermal efficiency of the engine at all the tested load conditions with higher pilot fuel consumption. The pilot operation of the blend also simultaneously reduced NO_x, hydrocarbon and CO emissions and improved the performance of the engines compared with pilot diesel operation [21]. Ismet Sezer researched diethyl ether as an alternative fuel in diesel engines. This study investigated the effects of diethyl ether on the fuel properties, injection, and combustion characteristics. It was found that adding diethyl ether to diesel can reduce the duration of combustion, which can improve engine performance and reduce exhaust emissions [22]. Michaela et al. focused on how the use of various alternative fuels affects combustion, especially in-cylinder combustion and investigated light fuel oil (LFO) and six alternative liquid fuels (LFO, marine gas oil, kerosene, rapeseed methyl ester, renewable diesel, renewable wood-based naphtha) in a high-speed, compression-ignition (CI) engine to understand their combustion properties. It was found that the HRR curve was slightly delayed with rapeseed methyl ester at the highest load and the combustion duration of neat naphtha decreased compared to LFO as the engine load was reduced [23].

The marine DF engine is a complex piece of equipment composed of multiple parameters operating together [24]. The development of intelligent algorithms brings more optimization space to the parameters of the engine. Chen et al. combined a genetic algorithm with an improved chicken swarm optimization (ICSO) algorithm to optimize the injection timing and intake valve closing timing, and the results showed that the combustion noise and pressure were well suppressed [25]. Wang et al. optimized the interval and quality of pre-injection for better combustion performance and lower knock behavior based on a design-of-experiments (DOE) response surface methodology [26]. Stratsianis et al. combined KIVA-3 with an evolutionary algorithm to investigate the effect of the post-injection strategy on the combustion characteristics of marine engines [27]. Ogren and Kong applied an artificial ant colony algorithm and cooperative particle swarm algorithm to optimize the number of injection strategies to find the best operating parameters [28]. Stochastic Bayesian optimization was adopted by Tang et al. to balance and optimize engine fuel economy and knock combustion performance [29]. Cong et al. established a 1-D model of a two-stroke DF engine in the AVL-BOOST environment, and the effects of natural gas mass fraction and intake temperature on engine performance and combustion were investigated, and while the MNLR-MOPSO algorithm was applied to optimize the parameters for obtaining the most optimal range settings [30].

The above references showed that for large marine engines, the combination of numerical simulation technology and optimization algorithm for research is an effective method due to its high accuracy and low cost [31]. Based on the briefly reviewed literature above, it can be found that the SOC, gas injection pressure and mass of diesel have a great influence on engine performance [32–34]. However, most of the research investigated and optimized the single operating parameter, structural parameter or variable strategy [35–37], and there

are few research works on engine performance and knocking optimization by combining the SOC, the mass of diesel and gas injection pressure especially in the field of large marine two-stroke pre-mixed dual-fuel engines. In addition, for large low-speed pre-mixed marine engines, the number of cylinders is mostly 5 cylinders, 6 cylinders or 8 cylinders. For example, the MAN 51/60DF engine has 8 cylinders, and the WinGD RT-flexDF engines have 5 cylinders or 6 cylinders. There are few investigations on 7-cylinder engines, and the 7X82DF engine selected as the research object in this article has 7 cylinders. In order to make up the previous research gaps, this paper applies the RSM prediction model and an optimization algorithm to the performance and combustion optimization of a large marine two-stroke dual-fuel engine and adopts a multi-parameter and multi-variable simultaneous optimization strategy to explore the trade-off relationship of the engine input parameters in order to obtain a higher power, lower brake specific fuel consumption (BSFC) and lower knock tendency. It is difficult to carry out corresponding experimental research on marine engines due to the large bore and size. Numerical simulation has been widely accepted as the best way and a partial alternative to study large marine engines because of its high efficiency and accuracy and low cost. This research provides an optimization method and train of thought for the 1D modeling and input parameter settings of a large two-stroke pre-mixed DF marine engine under full load in gas operation mode.

The response surface methodology is a statistical method for solving multivariate problems, which uses a quadratic regression equation to fit the functional relationship between factor and response values of the experimental data. Through the generated response surface plots, we can clearly and intuitively see the relationship between the variables and parameters. The RSM can optimize multi-objective problems and achieve a satisfactory result without constraints. However, the marine engine is a complex piece of equipment composed of multiple parameters and multiple constraints, so the RSM also needs to be combined with the multi-objective algorithm to complete a better optimization. The MOPSO algorithm has been widely used in the research of multi-objective problems due to its simple parameter setting and strong versatility. Therefore, in this study, the engine simulation software AVL-BOOST was used to establish a simulation model of a large low-speed two-stroke dual-fuel marine engine and conduct model calibration. Three input parameters, the SOC, the mass of diesel, and gas injection pressure were selected to conduct simulation research. Then, the response surface methodology analysis of the independent variables was completed by the Design-Expert software and the corresponding prediction model equations were generated. Finally, the MOPSO algorithm was used for multi-objective optimization, the main purpose of which was to obtain the best performance of the marine two-stroke dual-fuel premixed engine input parameter settings.

2. Modeling Methodology

The flow chart of this article is shown in Figure 1.

2.1. The Theory of Simulation Model

In this paper, we took the large low-speed two-stroke marine DF engine WinGD 7X82DF-1.0-LPSCR as the research object. DF refers to diesel and natural gas, and it can work in pure diesel or diesel/gas mixture mode. For this DF engine, two natural gas injectors are arranged symmetrically in the middle of the cylinder. The injected natural gas is mixed with air under the action of the scavenging vortex and is ignited by pilot fuel before reaching the top dead center. The 7X82DF engine's basic technical parameters are shown in Table 1.

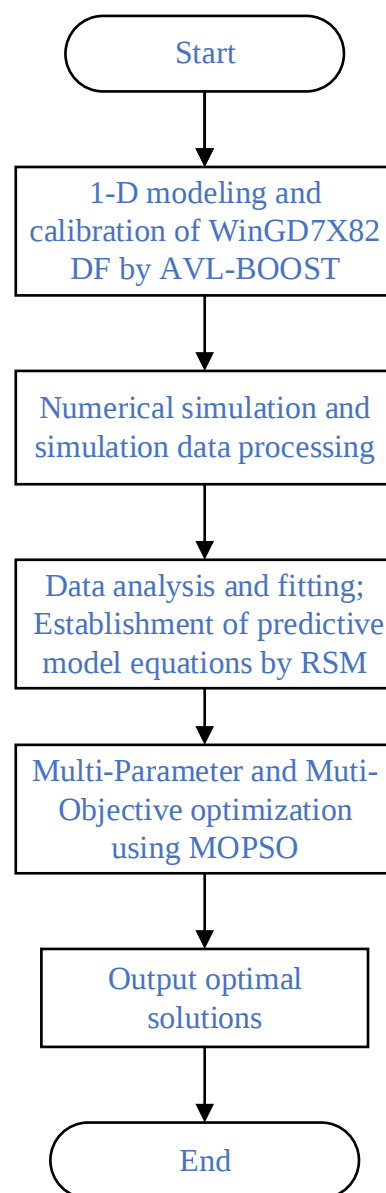


Figure 1. Flow chart of this article.

Table 1. Dual-fuel engine's main parameters.

Engine Parameters	Unit	Values
Cylinder	-	7
Bore	mm	820
Stroke	mm	3375
Compression ratio	-	12.4
Power	kW	22,531
Speed	rpm	62.5
BSGC	g/kWh	132.5
BMEP	bar	17.2
Firing order	-	1-6-3-4-5-2-7
Pilot injection pressure	bar	755
gas injection pressure	bar	14.8
Pilot timing	°CA ATDC	−8.5
Gas valve timing	°CA ATDC	224
Pilot injection duration	ms	1.1
gas injection duration	ms	26.9

We used the AVL-BOOST (2020) software which was manufactured by AVL List GmbH in Austria to establish the 1D model of the 7X82DF engine for studying the whole performance. The data of all input parameters came from the bench test report of the Dalian shipbuilding industry corporation.

In this paper, the Vibe 2-zone combustion model was taken to calculate the heat release, which is uncomplicated and widely used in simulation [38]. On the basis of the zero-dimensional model, the Vibe 2-zone model considers the cylinder temperature and the inhomogeneity of the distribution of various substances in the actual combustion process of the engine, and uses the flame front 2-zone model to divide the combustion chamber into two zero-dimensional zones, the burned and unburned zones. The combustion process occurs in the burned zone, which contains the injected fuel, air and natural gas mixture, and combustion products. Some of the generated combustion products will remain in the burned zone, and some will enter the unburned zone. The unburned zone contains the air, natural gas and combustion products of the burned zone, and the air will enter the burned zone to support and speed up the combustion reaction of the burned zone. In addition, the change in the total volume of the two zones is equal to the change in the cylinder volume, and the sum of the volumes of the two zones is equal to the total volume of the cylinder. This model can also predict the knocking characteristics of the engine, which is another important reason to use it. The model formulae can be described as follows:

$$\frac{dm_b u_b}{d\alpha} = -p_c \frac{dV_b}{d\alpha} + \frac{dQ_F}{d\alpha} - \sum \frac{dQ_{Wb}}{d\alpha} + h_u \frac{dm_b}{d\alpha} - h_{BB,b} \frac{dm_{BB,b}}{d\alpha} \quad (1)$$

$$\frac{dm_u u_u}{d\alpha} = -p_c \frac{dV_u}{d\alpha} - \sum \frac{dQ_{Wu}}{d\alpha} - h_u \frac{dm_B}{d\alpha} - h_{BB,u} \frac{dm_{BB,u}}{d\alpha} \quad (2)$$

$$\frac{dV_b}{d\alpha} + \frac{dV_u}{d\alpha} = \frac{dV}{d\alpha} \quad (3)$$

$$V_b + V_u = V \quad (4)$$

where α is the crank angle; Q_F is the total heat released by the combustion of the fuel; $h_u \frac{dm_B}{d\alpha}$ represents the enthalpy flow from the unburned zone to the burned zone; the subscript u represents the unburned zone; the subscript b represents the burned zone. Ignore the thermal radiation between the two zones

AVL-BOOST provides an extended zero-dimensional combustion model WOSHNI/ANISITS, which can predict the parameter m changes of the Vibe 2-zone according to the characteristic parameters and the Vibe 2-zone function under specified operating conditions, so as to correct the parameter m . The expressions of the WOSHNI/ANISITS model are as follows:

$$\Delta\alpha_c = \Delta\alpha_{c,ref} \cdot \left(\frac{AF_{ref}}{AF} \right)^{0.6} \cdot \left(\frac{n}{n_{ref}} \right)^{0.5} \quad (5)$$

$$m = m_{ref} \cdot \left(\frac{id_{ref}}{id} \right)^{0.6} \cdot \left(\frac{P_{SCAC}}{P_{SCA,ref}} \right) \cdot \left(\frac{T_{SCAC,ref}}{T_{SCAC}} \right) \cdot \left(\frac{n}{n_{ref}} \right)^{0.3} \quad (6)$$

where $\Delta\alpha_c$ is the duration of combustion; AF is the air/fuel ratio; n is the engine speed; P_{SCAC} is the pressure in the cylinder when the scavenging port is closed; T_{SCAC} is the temperature in the cylinder when the scavenging port is closed; ref indicates the standard reference condition.

Whether in combustion or the process of intake and exhaust, the engine is constantly exchanging heat. In AVL-BOOST, the heat transfer model converts the actual complex heat exchange process into the corresponding heat transfer coefficient to simulate and calculate the heat loss. The heat through the cylinder wall can be calculated from Formula (3), and using the Woschni 1978 model to calculate the convective heat transfer in the high-pressure

cycle of the engine under full load conditions [39]. The corresponding models are expressed as follows:

$$Q_{wt} = A_i \cdot \alpha_w \cdot (T_c - T_{wi}) \quad (7)$$

$$\alpha_w = 130 \cdot D^{-0.2} \cdot p_b^{0.8} \cdot T_b^{-0.53} \cdot \left[C_1 \cdot C_m + C_2 \cdot \frac{V_D T_1}{P_1 V_1} (P_b - P_0) \right]^{0.8} \quad (8)$$

In order to better investigate the combustion roughness in-cylinder, the ringing intensity (RI) is used as the evaluation index for knocking, which comprehensively consider the peak firing pressure (PFP), the peak firing pressure rise rate (PFPRR), and the peak temperature [40]. The evaluation index is as follows:

$$RI = \frac{1}{2\gamma} \cdot \frac{\left(\beta \frac{dP}{dt_{\max}} \right)^2}{P_{\max}} \cdot \sqrt{\gamma R T_{\max}} \quad (9)$$

where γ is the ratio of specific heat capacities (C_p/C_v); β is a scale factor; $\frac{dP}{dt_{\max}}$ is the in-cylinder peak firing pressure rise rate; R is the gas constant; $P_{\max}$ and $T_{\max}$ are the peak firing pressure and temperature in the cylinder, respectively.

2.2. Establishment and Calibration of DF Engine Simulation Model

The 1D simulation model of 7X82DF was established in combination with the bench report, as shown in Figure 2. The detailed descriptions of each component are shown in Table 2.

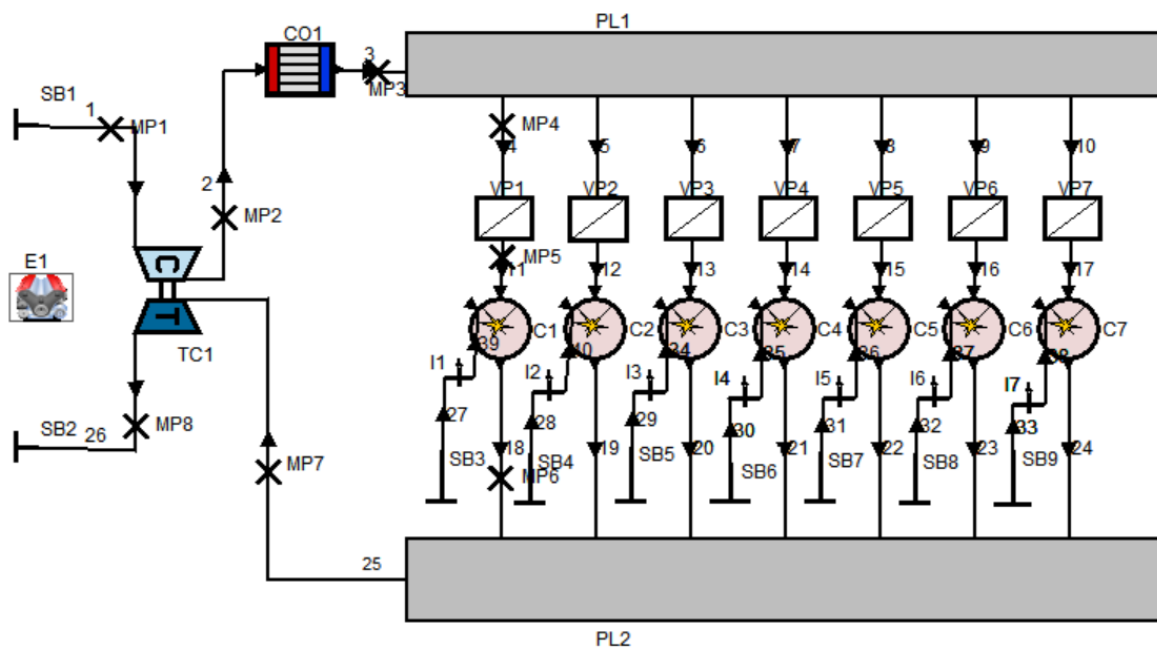


Figure 2. 7X82DF simulation model in AVL-BOOST.

It should be noted that the cylinder components of AVL-BOOST do not support setting two different fuels at the same time, and external gas injectors are required when establishing the simulation model. In order to simulate the actual injection combustion of diesel and gas, we took the general species transport to set the different fuel species, injection timing, and mass flow.

Since this paper aimed to investigate the gas injection pressure and other parameter settings, a detailed turbocharger (T/C) model was not established, but rather, we only used AVL-BOOST a model that is simple, practical, and widely accepted. The use of simplified model has been verified in [26,30,41], which proved that the simplified model can meet the requirement of simulation accuracy.

Table 2. The main definitions of the symbols.

No.	Symbols	Details
1	SB1	System intake boundary
2	SB2	System exhaust boundary
3	SB3-9	Natural gas intake boundary
4	E1	Engine
5	TC1	Turbocharger
6	CO1	Air cooler
7	PL1	Intake manifold
8	PL2	Exhaust manifold
9	VP1-7	Scavenge plenum
10	C1-7	Cylinder
11	I1-7	Gas injector
12	MP1-8	Measuring point
13	1–38	Pipe

Combined with the shipyard bench report, Figure 3 shows the comparison of the main simulation parameters and experimental parameters under different loads in diesel mode. Table 3 shows the errors of the simulation and experimental parameters in diesel mode.

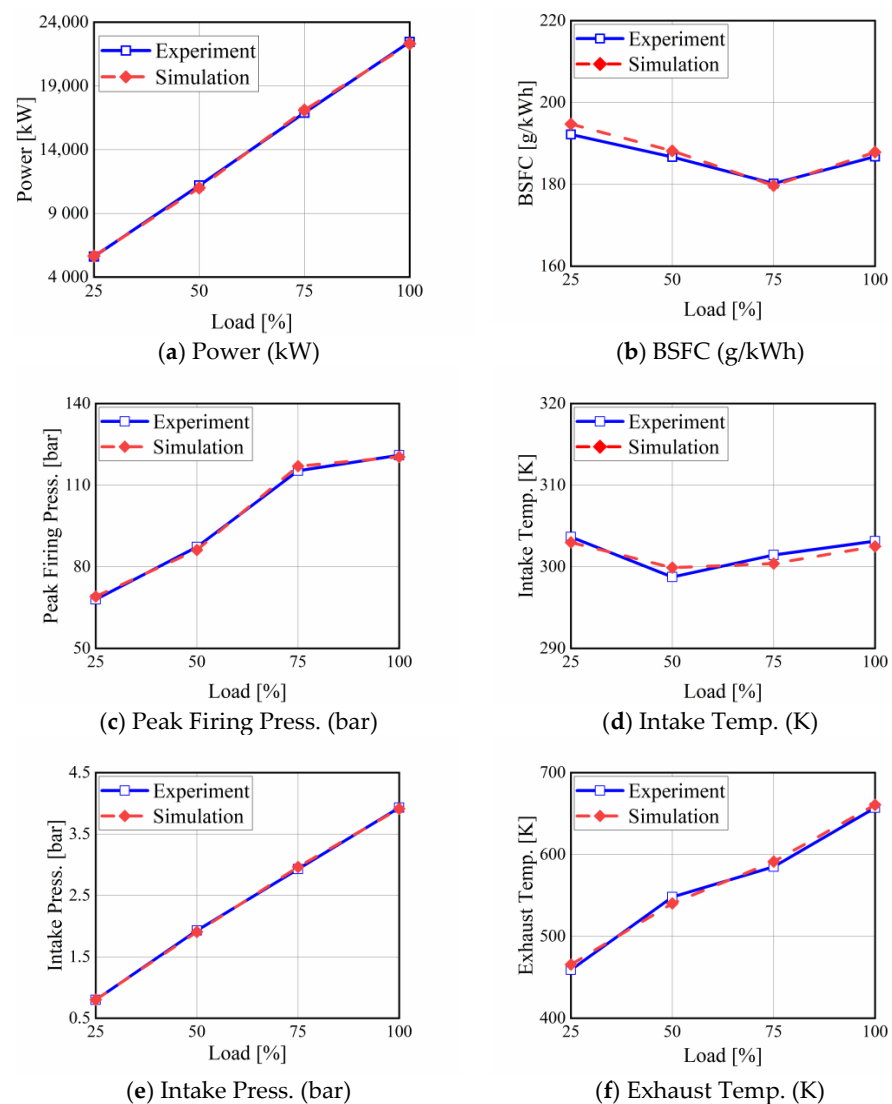
**Figure 3.** Comparison of the simulation and experiment in diesel mode.

Table 3. Calculation errors of the parameters in diesel mode.

Engine Load (%)	25	50	75	100
Mode	Diesel Mode Error (%)			
Power (kW)	0.33	−1.74	1.16	−0.63
BSFC (g/kWh)	1.32	0.79	−0.27	0.58
Peak Firing Press. (bar)	1.57	−1.14	1.46	−0.48
Intake Temp. (K)	0.22	−1.27	1.09	−0.43
Intake Press. (bar)	−0.21	0.38	−0.35	−0.21
Exhaust Temp. (K)	1.38	−1.45	1.05	0.53

Figure 4 shows the comparison of the simulation and experiment for different loads in gas mode, and Table 4 shows the errors of the main parameters of the 7X82DF engine in gas mode.

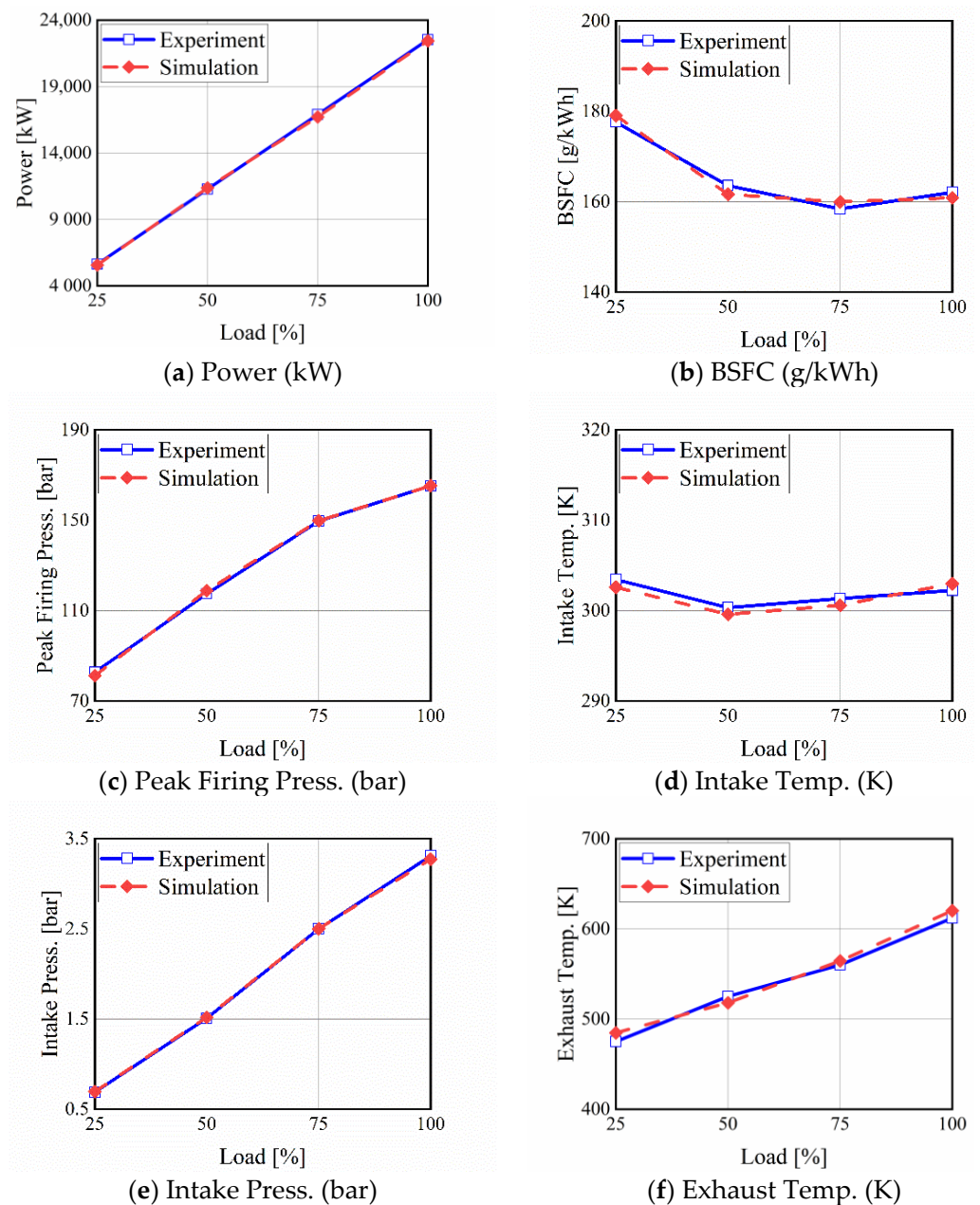
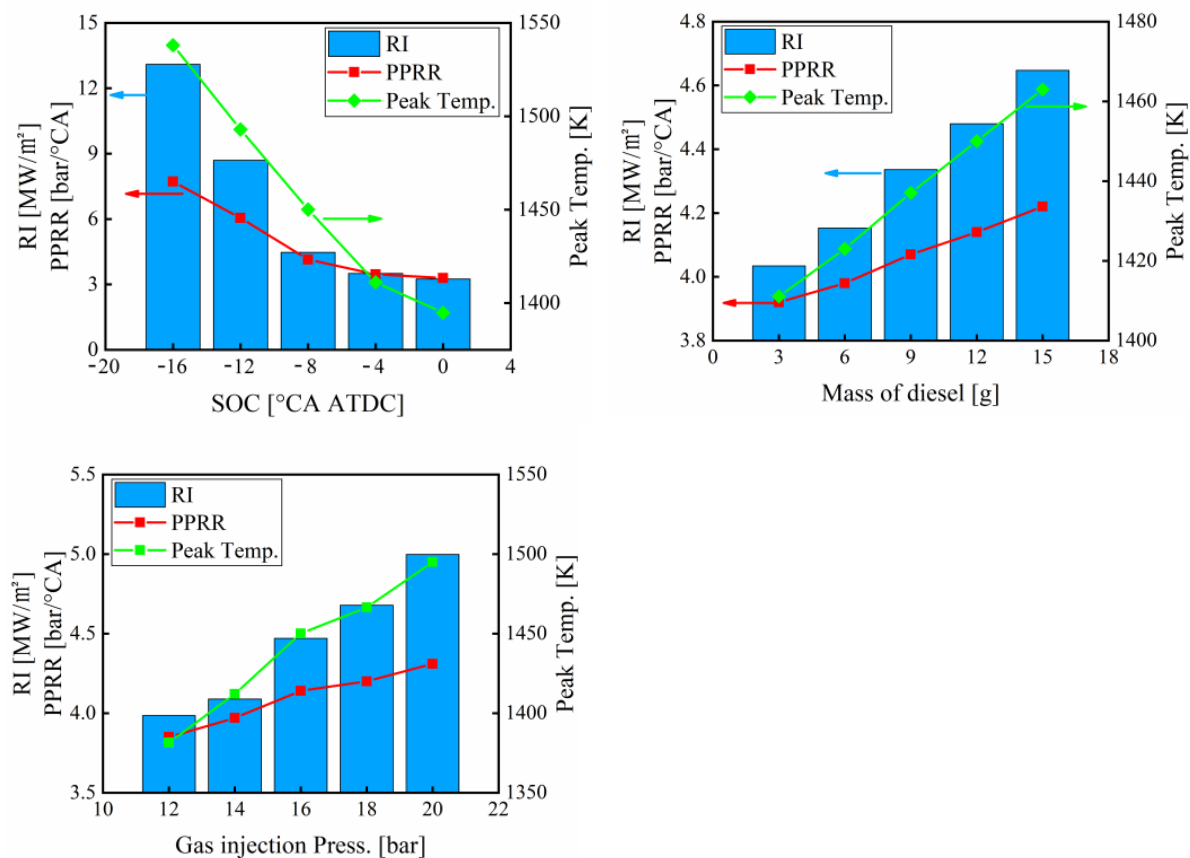
**Figure 4.** Comparison of the simulation and experiment in gas mode.

Table 4. Calculation errors of the parameters in gas mode.

Engine Load (%)	25	50	75	100
Mode	Gas Mode Error (%)			
Power (kW)	−1.20	0.82	−1.06	−0.41
BSFC (g/kWh)	0.83	−1.16	0.96	−0.73
Peak Firing Press. (bar)	−1.82	1.20	0.08	0.29
Intake Temp. (K)	1.04	0.61	−0.09	−1.07
Intake Press. (bar)	−0.28	−0.25	−0.25	0.24
Exhaust Temp. (K)	2.04	−1.35	0.78	1.32

From Tables 3 and 4, we can conclude that the simulation errors of the main parameters of the 7X82DF engine are within 3% both in diesel and gas modes, which indicates the better accuracy of the 1D simulation model in AVL-BOOST and that it can be used in the further research.

The calibrated 1D AVL-BOOST simulation model was run to investigate the effects of the pilot fuel start of combustion timing (SOC), the mass of diesel and the gas injection pressure on the DF engine peak firing pressure (PFR), peak pressure rise rate (PPRR) and peak temperature, and then the corresponding RI was calculated. The results of different simulation parameters are shown in Figure 5. As can be seen from Figure 5, the three independent variable parameters had a significant effect on the degree of combustion roughness in the cylinder. We took the power, BCFC, FPF, and RI as dependent variables to research the overall coupling effects of the three independent variables on several factors such as engine dynamics, economic performance, and combustion roughness.

**Figure 5.** Influence trend of different parameters on combustion.

2.3. RSM Parameters Prediction Model

The response surface methodology (RSM) is a statistical method for solving multivariate problems, which uses a quadratic regression equation to fit the functional relationship between factor and response values of the experimental data, through the analysis of the regression equation to obtain the optimal parameter settings [42].

In this paper, the RSM was used to analyze the influence trend of the independent variable parameters the SOC, gas injection pressure, and the mass of diesel on the engine power, BSFC, and RI. The dual-fuel engine based on RSM can be used to predict engine combustion and performance. The following quadratic model was used to fit the calculation [43].

$$P_i = a + b \cdot x + c \cdot y + d \cdot z + e \cdot x \cdot y + f \cdot x \cdot z + g \cdot y \cdot z + h \cdot x^2 + i \cdot y^2 + j \cdot z^2 \quad (10)$$

where P_i is the parameter response, including power, PFP, BSFC, and RI; x , y , and z are the SOC, mass of diesel, and gas injection pressure; a represents the constant term of response; b , c , and d are regression coefficients; e , f , and g are quadratic term coefficients; h , i , and j are cross-term coefficients.

The significance test was used to evaluate the predictive ability of the response surface model. The expression of the determination coefficient used for evaluating the accuracy of model is as follows:

$$R^2 = 1 - \left[\frac{SS_{residual}}{SS_{residual} + SS_{model}} \right] \quad (11)$$

where R^2 represents the degree to which the response surface matches the given data, and it should be greater than 0.9. The adjustment coefficient is calculated by the following Formula (8):

$$R^2_{Adj.} = 1 - \left[\left(\frac{SS_{residual}}{df_{residual}} \right) / \left(\frac{SS_{residual} + SS_{model}}{df_{residual} + df_{model}} \right) \right] \quad (12)$$

where $R^2_{Adj.}$ is the degree of regression which can affect the independent variables and dependent variables, and the degree of correlation is better when it is close to 1. The expression used for estimating the predictive ability of the response surface model is as follows:

$$R^2_{Pred.} = 1 - \left[\frac{SS_{predict}}{SS_{residual} + SS_{model}} \right] \quad (13)$$

where $R^2_{Pred.}$ represents the accuracy of the prediction, which must be greater than 0.80, and the difference with $R^2_{Adj.}$ must be less than 0.20.

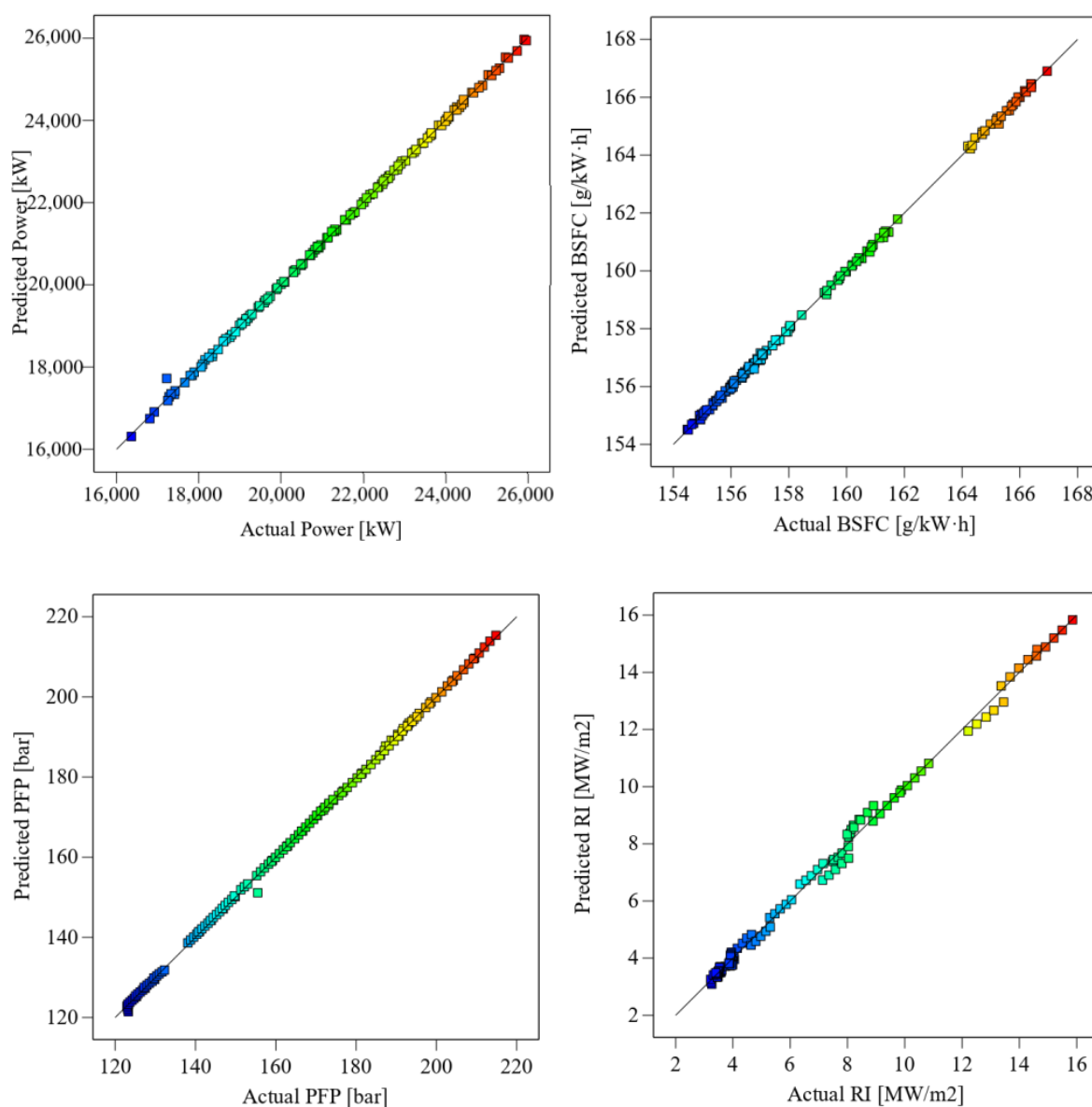
In the above evaluation parameters, SS represents the quadratic sum, $SS_{predict}$ represents the quadratic sum of prediction errors, and df is the degree of freedom.

We used the DOE module of the Design-Expert (2013) software which was manufactured by Stat-Ease in the United States to establish a response surface surrogate model for the DF engine power, BSFC, PFP and RI. The SOC varies from -16 to 0 °CA ATDC, and the interval is 4 °CA. The mass of diesel varies from 3 to 15 g, and the interval is 3 g. The gas injection pressure varies from 12 to 20 bar, the interval is 2 bar.

Table 5 is the analysis of the variance table for power, BSFC, PFP and RI, where x is the SOC, y is the mass of diesel, and z is the gas injection pressure. It can be concluded from the table that the R^2 , $R^2_{Adj.}$ and $R^2_{Pred.}$ of each parameter are all larger than 0.9, indicating the predictability and accuracy of the response surface model are better with the given data. All p-value are less than 0.0001, indicating that the significance of the regression model is better. Figure 6 is the predicted value and actual value of the power, BSFC, PFP, and RI. We can conclude from Figure 6 that the predicted values are almost proportional to the actual values, indicating that the fitness of the model is very good.

Table 5. Analysis of variance table.

Source	Power (kW)	BSFC (g/kWh)	PFP (bar)	RI (MW/m ²)
Type	Quadratic <i>p</i> -Value	Quadratic <i>p</i> -Value	Quadratic <i>p</i> -Value	Quadratic <i>p</i> -Value
Mode	<0.0001	<0.0001	<0.0001	<0.0001
<i>x</i>	<0.0001	<0.0001	0.0345	0.0483
<i>y</i>	<0.0001	<0.0001	<0.0001	<0.0001
<i>z</i>	<0.0001	<0.0001	<0.0001	<0.0001
<i>xy</i>	0.0107	0.6079	0.4787	0.0599
<i>xz</i>	0.1136	0.2268	0.2352	0.2262
<i>yz</i>	0.0326	0.0342	0.0033	0.0163
<i>x</i> ²	0.8172	0.1137	0.2885	0.6216
<i>y</i> ²	<0.0001	<0.0001	0.0915	<0.0001
<i>z</i> ²	0.0248	0.0008	0.0022	0.7016

**Figure 6.** Influence trend of different parameters on combustion.

The power model based on the RSM is as follows:

$$\begin{aligned} \text{Power} = & 19459.93594 + 125.22292 \cdot x - 174.38125 \cdot y - 47.59063 \cdot z \\ & - 0.868073 \cdot x \cdot y + 0.910625 \cdot x \cdot z - 1.00375 \cdot y \cdot z \\ & - 0.078576 \cdot x^2 - 7.46561 \cdot y^2 + 2.09773 \cdot z \end{aligned} \quad (14)$$

The BSFC model based on the RSM is as follows:

$$\begin{aligned} \text{BSFC} = & 160.37112 + 0.285458 \cdot x + 1.40326 \cdot y + 0.602831 \cdot z \\ & + 0.000579 \cdot x \cdot y - 0.003929 \cdot x \cdot z + 0.005836 \cdot y \cdot z \\ & - 0.003482 \cdot x^2 + 0.056456 \cdot y^2 - 0.024602 \cdot z^2 \end{aligned} \quad (15)$$

The PFP model based on the RSM is as follows:

$$\begin{aligned} \text{PFP} = & 157.66675 - 0.405833 \cdot x - 2.70937 \cdot y - 7.46187 \cdot z \\ & - 0.018385 \cdot x \cdot y - 0.003854 \cdot x \cdot z - 0.161250 \cdot y \cdot z \\ & + 0.036667 \cdot x^2 - 0.035117 \cdot y^2 + 0.337031 \cdot z^2 \end{aligned} \quad (16)$$

The RI model based on the RSM is as follows:

$$\begin{aligned} \text{RI} = & 2.61866 + 0.075896 \cdot x + 0.284984 \cdot y + 0.043531 \cdot z \\ & - 0.006557 \cdot x \cdot y - 0.007760 \cdot x \cdot z + 0.013789 \cdot y \cdot z \\ & + 0.001962 \cdot x^2 + 0.062424 \cdot y^2 + 0.003414 \cdot z^2 \end{aligned} \quad (17)$$

3. Results and Discussion

3.1. Response Surface Parameter Analysis

The response surface diagrams of the above parameters to the Power, BSFC, PFP, and RI are established in Figures 7–10.

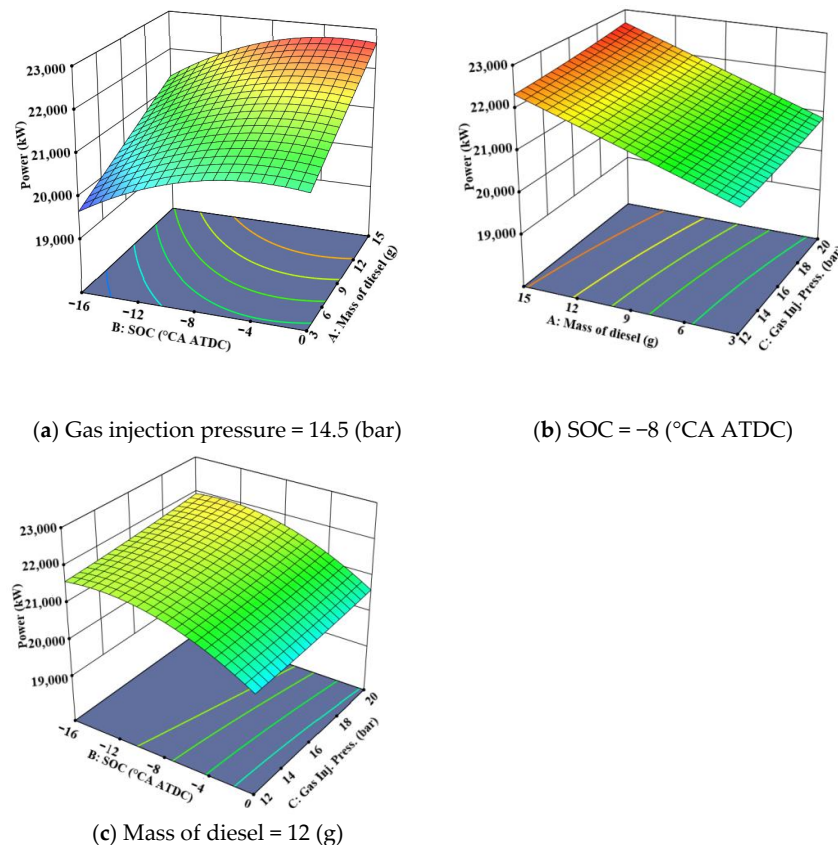


Figure 7. Response surface plot of the power.

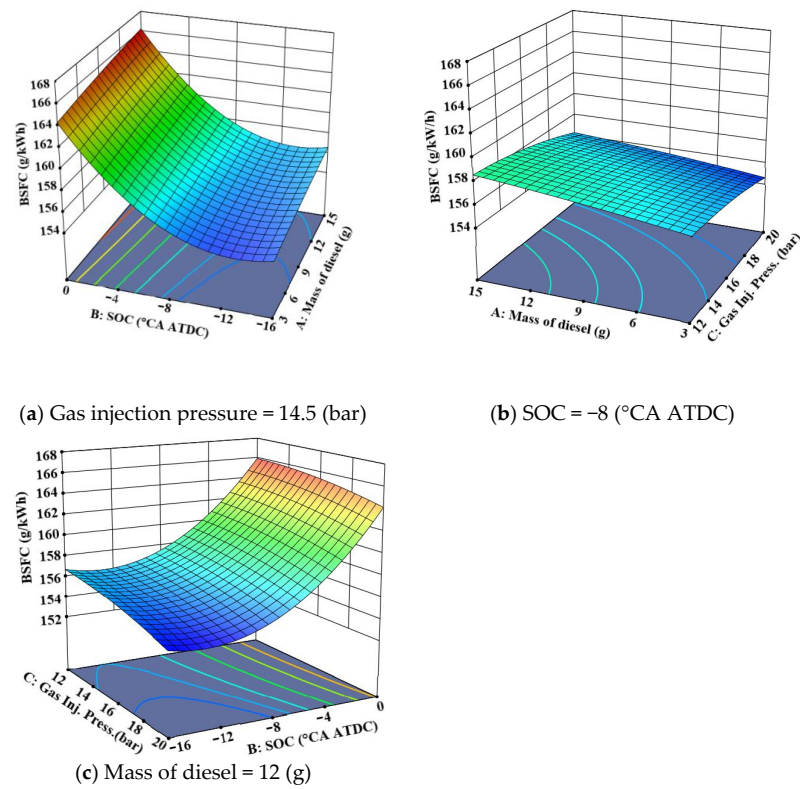


Figure 8. Response surface plot of the BSFC.

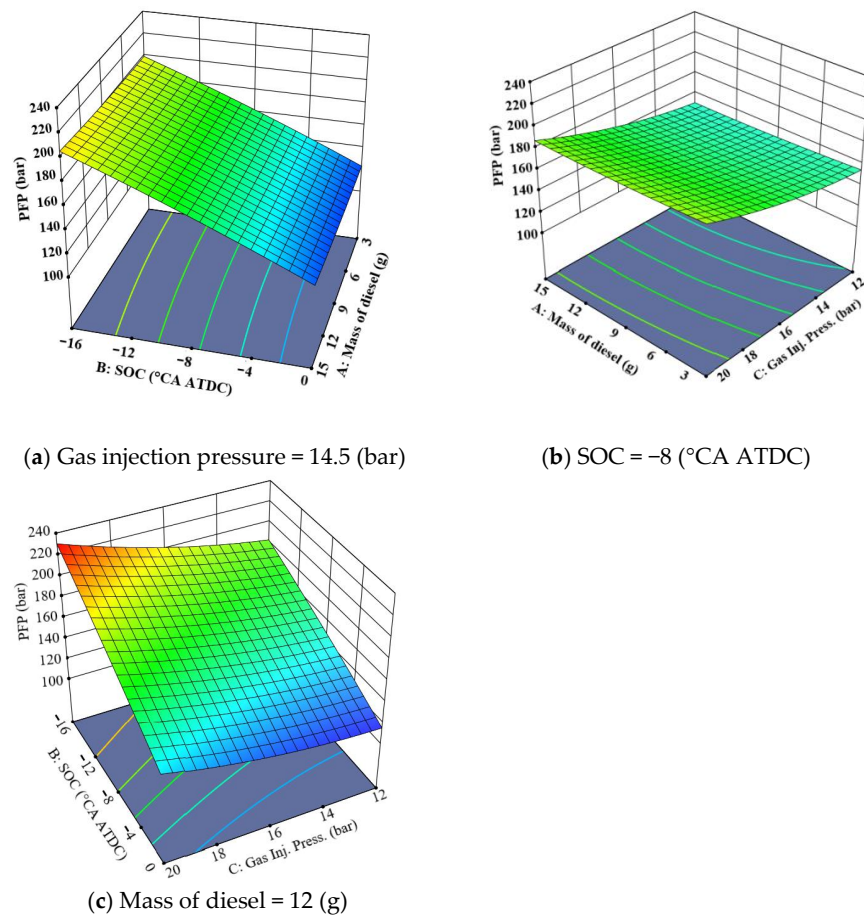


Figure 9. Response surface plot of the PFP.

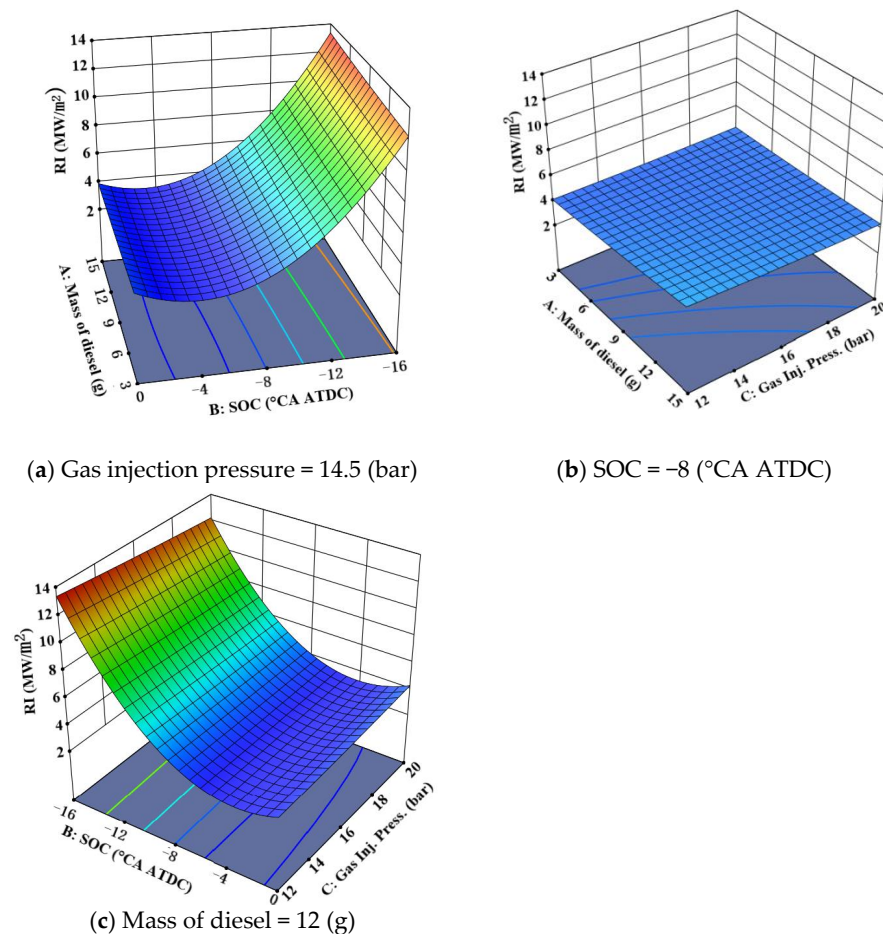


Figure 10. Response surface plot of the RI.

As we can see from Figures 7–10, with the advance of the SOC, the power of the DF engine first increased and then decreased, the BSFC first decreased and then increased; the PFP gradually increased; the RI had the same changing trend as the BSFC. The degree of the SOC directly affects the start time of the combustion of the in-cylinder mixture. With the advance of the SOC, the initial time of combustion will advance, and the combustion center of gravity will move forward, which shortens the afterburn period and enhances the constant volume of combustion. The working ability of the mixture can be improved, and the pressure will increase in the cylinder. However, too much advance in the SOC will burn more mixture before the top dead center and increase the compression resistance when the piston moves upward. This will lead to an increase in the negative work of the compression stroke and a decrease in the power of the DF engine. Moreover, the heat release of combustion will be more concentrated, and the heat load will increase, which lead to a higher peak firing pressure in the cylinder and an increase in the knocking trend.

As can be concluded from Figures 7–10, with the gas injection pressure increasing, the power, PFP, and RI will increase gradually, and BSFC will decrease. This was because the ignition delay period of natural gas became shorter with the increase in the gas injection pressure, and the mixture was ignited by the pilot fuel and burned rapidly. The combustion reaction was more violent in the early stage of combustion, which improved the combustion performance. The increase in the gas injection pressure led to an increase in the initial pressure in the cylinder, which raised the average combustion pressure, leading to a higher PFP.

As can be seen from Figures 7–10, with the mass of diesel increasing, the power, BSFC, PFP, and RI of the DF engine increased. The greater the mass of diesel, the more diesel was involved in atomization and combustion, and then the ignition energy would be stronger,

which causes the advance of the ignition phase. The mixture of diesel and natural gas was more uniform, and the diffusion combustion effect of the mixture was better.

In conclusion, the parameters of the SOC, mass of diesel, and gas injection pressure can directly affect the dynamic and economic performance of marine DF engines. Therefore, it is very important to obtain a reasonable SOC, mass of diesel, and gas injection pressure to improve the power, and reduce the BSFC and knock intensity under the premise of meeting the actual needs of the marine low-speed DF engines.

The results of the best optimization parameters obtained by the RSM are shown in Table 6. The SOC was -7.61°CA ATDC, the gas injection pressure was 20 bar; the mass of diesel was 14.03 g. The corresponding target values were a power of 22,484.8 kW, a BSFC of 156.443 g/kWh and an RI of 4.1779 MW/m². Compared with bench test experimental reports, the power was reduced by 0.43%, the fuel consumption rate was reduced by 3.47%, and the RI was reduced by 11.9%. The knocking tendency was effectively suppressed, but at the cost of reducing the power of the engine, which is not in line with the required optimization goal. Therefore, the following will continue the optimization in combination with the multi-objective algorithm.

Table 6. RSM optimization results.

SOC ($^{\circ}\text{CA}$ ATDC)	Gas Intake Pressure (bar)	Mass of Diesel (g)	Power (kW)	BSFC (g/kWh)	RI (MW/m ²)
-7.61	20	14.03	22,434.8	156.443	4.1779

3.2. Multi-Objective Parameter Optimization with MOPSO

Most engineering problems have a multi-objective formula, and trade-offs relationship often occur between the parameters. It is not possible to achieve a single solution that optimizes all objectives simultaneously. Therefore, the Pareto frontier alternative is the best choice in practice. Since the multi-objective particle swarm optimization (MOPSO) algorithm was proposed by Carlos [44] in 2002, it has been widely used in the research of multi-objective problems due to its simple parameter setting and strong versatility [45].

Morales et al. used MOPSO and neural networks to optimize the operating parameters of a 1.6L spark ignition gasoline engine to reduce exhaust emissions [46]. The results showed that after using the MOPSO algorithm optimization, CO, HC and NO_x were reduced by 13.68%, 83.80%, and 7.67%, respectively.

Taghavifar et al. conducted a numerical simulation of a diesel engine in the article [47]. The key parameters of the air/fuel ratio, compression ratio, swirl number, coolant temperature, and air temperature of the heat exchanger were taken as the input parameters for NO_x reduction and pressure increase by multi-objective particle swarm optimization. The simulation results showed that a 4.8% reduction in NO_x emissions while reducing the wall heat loss by 1.6%.

The above articles confirmed that the MOPSO algorithm has strong applicability to the multi-parameter and multi-objective optimization of an engine, and can achieve satisfactory optimization results. Therefore, this paper adopted for the MOPSO algorithm to optimize the response surface prediction equation.

The marine DF engine is a complex piece of equipment composed of multiple parameters operating together. Therefore, the use of the MOPSO algorithm it is suitable to find the Pareto frontier of the optimization parameters. Therefore, the MOPSO algorithm was taken to optimize the response surface prediction equation.

In this paper, we took the MOPSO algorithm to optimize the mass of diesel, SOC and gas injection pressure of the 7X82DF engine to obtain higher power, a lower RI and lower BSFC, as shown in Equation (14). The MOPSO algorithm is able to complete the

optimization of the engine operating parameters in the MATLAB (2021, MathWorks, U.S.) operating environment. The optimization flow chart is shown in Figure 11.

$$\begin{cases} \max y_1(\text{Power}) \\ \min y_2(\text{BSFC}) \\ \min y_3(\text{RI}) \end{cases} \quad (18)$$

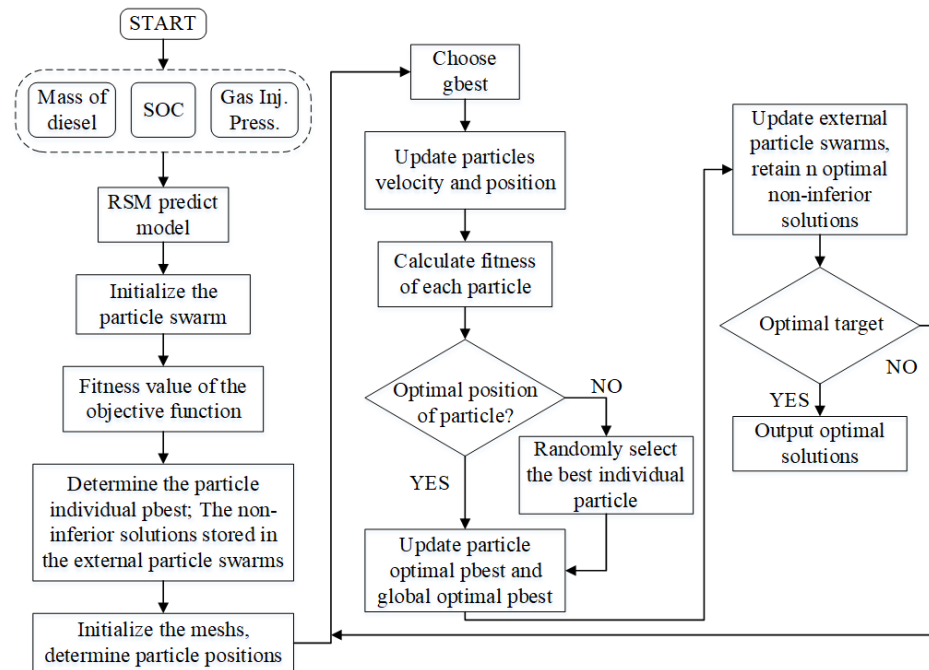


Figure 11. MOPSO optimization flow chart.

When trying to solve the maximum value of the objective function, the MOPSO algorithm will invert it and convert the maximum value into calculating the minimum value [48]. Therefore, the power is shown as a negative number in the optimization Figure 12. Combined with [49,50] and the experiments, the parameter settings of MOPSO were determined as shown in Table 7.

As shown in Figures 12 and 13, the multi-parameter optimization of the 7X82DF engine with the MOPSO algorithm achieved the expected results. It should be reiterated that the absolute value of the power in Figure 12 represents the actual value of the simulation.

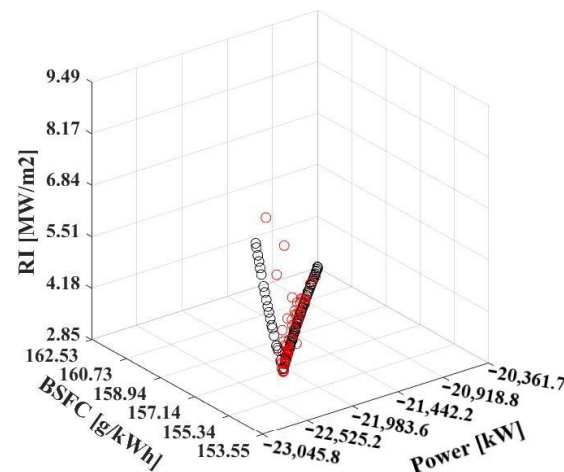
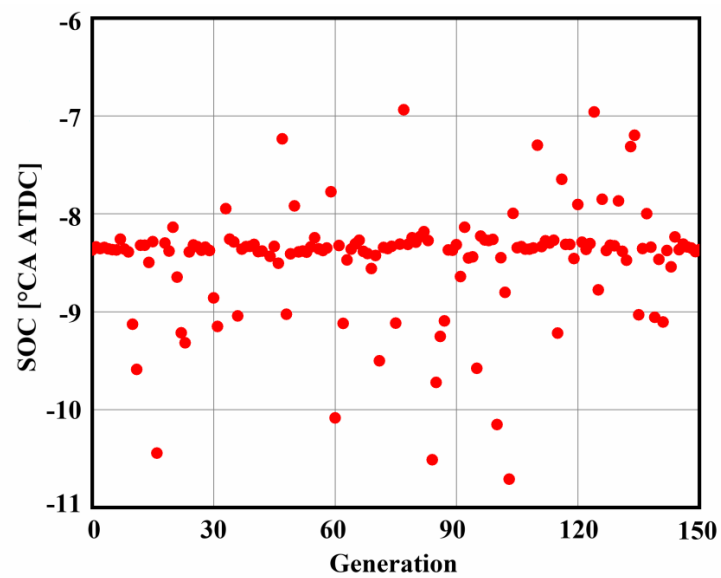


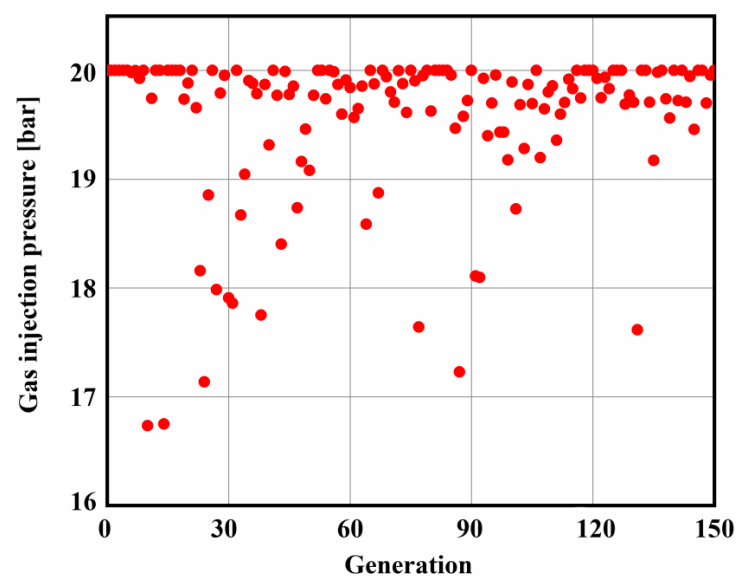
Figure 12. Optimized distribution of MOPSO.

Table 7. Parameters of MOPSO.

Parameters	Value
Population size	150
Repository size	150
Maximum number of generations	150
Inertia weight	0.7298
Individual confidence factor	1.5
Swarm confidence factor	1.5
Number of grids in each dimension	5
Maximum vel in percentage	5
Uniform mutation percentage	0.5

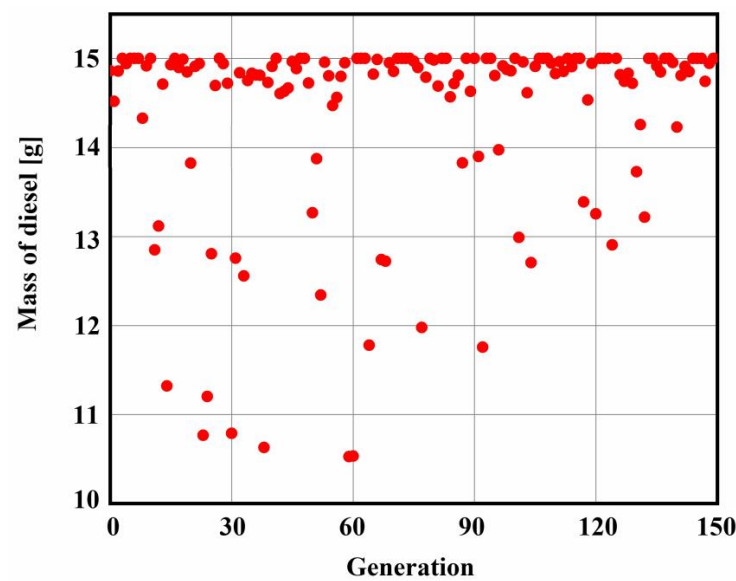


(a) Optimized distribution of the SOC



(b) Optimized distribution of the gas injection pressure

Figure 13. Cont.



(c) Optimized distribution of the mass of diesel

Figure 13. Optimized distribution of the target parameters.

As shown in Figure 13, the optimized SOC range was -9 to -8 °CA ATDC, the gas injection pressure was concentrated at 19 to 20 bar, and the optimized mass of the diesel range was 14 to 15 g.

Since the simulation optimization result was not only an optimal solution set, it needed to be screened. In this paper, the purpose was to improve the power and economy of the large low-speed marine pre-mixed DF engine and reduce the roughness of combustion at the same time. Therefore, the limitation was set as a power greater than 22,500 kW, and an RI is lower than 5 MW/m². The filtered solution sets are shown in Table 8.

Table 8. The filtered optimized solution sets.

SOC (°CA ATDC)	Gas Intake Pressure (bar)	Mass of Diesel (g)	Power (kW)	BSFC (g/kWh)	RI (MW/m ²)
−6.97	19.96	14.35	22,514.9	157.385	3.8464
−7.84	19.83	14.26	22,540.5	157.167	3.8267
−7.08	20.00	15.00	22,574.5	156.923	3.9567
−7.60	19.71	14.63	22,593.2	156.713	4.0793
−7.64	20.00	14.32	22,520.4	156.449	4.1967
−7.91	19.92	15.00	22,612.4	156.67	4.2093
−9.21	19.83	13.98	22,589.1	156.536	4.2362
−8.36	20.00	14.96	22,668.0	156.256	4.4326
−8.54	19.95	15.00	22,683.4	156.146	4.5325
−8.61	19.61	14.98	22,691.7	156.116	4.7761
−8.70	19.92	15.00	22,716.2	155.921	4.8125

The RI will become higher with the increase of the power, which increases the engine's tendency to knock during combustion. When knocking occurs, it not only affects the overall power performance but also destroys the mechanical parts of the engine and affects the safety of operation, which is not what we want to see. Under comprehensive consideration, we took the SOC as -8.36 °CA ATDC, the gas injection pressure as 20.00 bar, the mass of diesel as 14.96 g, the corresponding obtained power of 22,668 kW, the BSFC of 156.256 g/kWh, and the RI of 4.4326 MW/m². From Table 9 we can conclude that, compared with the experimental reports, after the optimization with the MOPSO algorithm, the power increased by 0.61%, the BSFC decreased by 3.58%, and the RI decreased by 6.49%,

which greatly improved the overall economy of the 7X82DF engine and greatly reduced the roughness of combustion.

Table 9. Comparison between bench test results and MOPSO optimization results.

Type	Power (kW)	BSFC (g/kWh)	RI (MW/m ²)
Bench test	22,531	162.066	4.74
MOPSO	22,668	156.256	4.4326
Optimization	+0.61%	−3.58%	−6.49%

4. Conclusions

In this paper, based on the RSM and MOPSO algorithms, the marine two-stroke pre-mixed DF engine WinGD7X82DF was investigated. The effects of the operating parameters the pilot fuel start of combustion timing, mass of diesel, and gas injection pressure on the engine power, brake specific fuel consumption and knock intensity were researched. The main conclusions are as follows:

- A 1D simulation model was established by using the AVL-BOOST software, including diesel mode and gas mode of the 7X82DF engine. Combined with the bench reports provided by the shipyard, the main parameters of diesel mode and gas mode were calibrated and verified respectively, and the errors are all within 3%, which confirmed the accuracy of the simulation model and can be used for future research. Taking the pilot fuel start of combustion timing, gas injection pressure, and mass of diesel in dual-fuel mode as the independent variable parameters, 125 sets of different simulation samples were designed and calculated by using the verified AVL-BOOST model.
- The 125 sets of simulation data were imported into the experimental design software Design-Expert for analysis, and the response surface models of the dependent variable parameters the power, BSFC, PFP, and RI were established, as well as the prediction model equation of each parameter was obtained. Through the response surface prediction model, we can conclude that with the advance of the SOC, the power of the DF engine first increased and then decreased, the BSFC first decreased and then increased, and the PFP gradually increased, and the RI had the same changing trend as the BSFC. With the increase in the gas injection pressure, the power, PFP, and RI increased gradually, and the BSFC decreased. With the increase in mass of diesel, the power, BSFC, PFP, and RI of the DF engine increased.
- Combined with the RSM prediction model and the MOPSO algorithm to perform multi-objective optimization of the above engine independent variable parameters. The optimization results showed that the optimal range of the SOC was -9 to -8 °CA ATDC, the range of the gas injection pressure was 19 to 20 bar, and the mass of diesel ranged from 14 to 15 g. With the limitation of suppressing the knocking tendency in the combustion process, the optimal solution sets were screened manually, and the parameter solution set was finally determined as -8.36 °CA ATDC (SOC), 20.00 bar (gas injection pressure), and 14.96 g (mass of diesel). Compared with the bench test data, the optimized power was increased by 0.61%, the BSFC was reduced by 3.58%, and the RI was reduced by 6.49%, which better suppressed the trend of knocking.

In conclusion, this research provides a method and train of thought for the 1D modeling and reducing of the combustion tendency of a large two-stroke pre-mixed DF marine engine under full load in gas operation mode. In this study, the RSM was applied to analyze and predict the performance and roughness of the combustion of a marine low-speed two stroke premixed dual-fuel engine, and the MOPSO optimization algorithm was combined to work out the engine parameter settings to obtain a higher power, lower BSFC and lower knock tendency. When the SOC was -8.36 °CA ATDC, the gas injection pressure was 20.00 bar, the mass of diesel was 14.96 g, the power obtained increased by 0.61%, while the BSFC and RI reduced by 3.58% and 6.49%, respectively. Optimization results can help to

better understand the influence of various parameters of this type of engine on the overall power performance, fuel economy performance and combustion roughness.

The 1D simulation carried out provides good numerical simulation research on engine operating parameters, but it cannot clearly obtain the development of the combustion flame in the cylinder, at the same time, the parameters that can affect the knocking characteristics such as vortex and turbulence in the cylinder cannot be studied. In future work, the 3D CFD software CONVERGE will be used to visualize the numerical simulation of in-cylinder combustion, which has been widely used in the investigations [51–53] and has achieved good results. At the same time, the multi-objective optimization software mode-FRONTIER can be used to directly couple with CONVERGE through the interface protocol to optimize the engine operating parameters.

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