DESIGN OF NEW CLEAN AND EFFICIENT COMBUSTION MODE AND THERMODYNAMICS RESEARCH USING NSGA-II ALGORITHM

by

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Original scientific paper
https://doi.org/10.2298/TSCI191016004S

In order to study a new clean and efficient combustion mode, which can relieve the pressure of traditional energy and ensure low emissions, in this study, a diesel/natural gas dual fuel engine is designed by non-dominant sorting genetic algorithm (NSGA-Ⅱ), and its thermodynamic characteristics are studied. The WP10.290 Diesel engine is modified into a diesel/natural gas dual fuel engine. The emissions of harmful substances and thermal efficiency of the modified engine under different working conditions are compared. The combustion chamber structure and adaptability between combustion chamber and injection parameters are optimized by using NSGA-II algorithm and CFD software. The results show that the emission of NO_x and CH_4 and the fuel consumption rate can be reduced simultaneously by using the composite combustion model compared with the original engine. When the CH_4 emission is close to zero, the fuel consumption rate decreases obviously, and NO_x slightly increases. When the angle between the injection holes is 141.57°, the amount of NO_x in the cylinder is large. When the injection advance angle is 21.91 ℃A, the pressure in the cylinder is the highest, the CH_4 production is the lowest, the NO_x production is higher, and the oxygen content in the combustion mixture is less. The NO_x production is the lowest. diesel/natural gas dual fuel engine can ensure efficient combustion while reducing emissions. In this study, the performance of the dual fuel engine at various speeds can be further studied, which can provide theoretical support for the design of diesel/natural gas dual fuel engine.

Key words: *diesel/natural gas dual fuel engine, NSGA-II algorithm, CFD, pollutant emissions*

Introduction

In recent years, the use of natural gas has become more and more popular. Because of its large reserves and relative cleanness, natural gas has become one of the target alternative energy sources. Moreover, natural gas has become the most potential alternative energy. Due to the high ignition point of natural gas, the temperature of the gas in the cylinder cannot reach the self-ignition temperature required by natural gas during the compression process of the engine, so it is necessary to rely on electric spark ignition or diesel to ignite natural gas

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[1]. Because of the flexible use of fuel, low emissions of carbon and smoke, and no need to make too much changes to the engine, dual fuel engine has become the object of scholars' research [2]. At first, some scholars found that diesel/natural gas dual fuel engine consumes less fuel and has higher efficiency. Therefore, on this basis, some scholars analysed the influence of different natural gas injection pressures on the pressure, heat release rate, ignition delay time and emissions of diesel/natural gas dual fuel engine [3]. It is found that under low load condition, delayed injection of natural gas can realize stratified mixing of air fuel in different cylinders [4]. In addition, some scholars have found that increasing the intake air temperature can improve the combustion efficiency of diesel/natural gas dual fuel engine and meet the demand of low emissions under the condition of low load [5]. Domestic scholars in the field of dual fuel engine are also in continuous exploration. Scholars in China have found that the characteristics of the ignition and ignition of the ignited diesel fuel largely determine the performance of the dual fuel engine [6]. On the basis of the existing research, some scholars have studied the most appropriate diesel intake and the impact of air causes on combustion and emission performance [7]. Therefore, the research on diesel/natural gas dual fuel engine has always been a hot issue in the industry. In this study, the problem will also be studied.

In this study, the diesel/natural gas dual fuel engine is designed by optimizing NSGA-Ⅱ algorithm, and its thermodynamic characteristics are studied. The research process of this study is: WP10.290 Diesel engine is converted into diesel/natural gas dual fuel engine [8], the emission of harmful substances and thermal efficiency of the modified engine under different working conditions are compared, and the CFD software simulation method is relatively easy. The requirements for time, place and other conditions are low, and the cost performance is relatively high. Therefore, the application of numerical simulation in engine research is relatively high.

Method

The application of natural gas in compression ignition engine can be divided into the following three modes: pilot type of gas injection diesel, pilot type of in cylinder direct injection diesel and compression ignition type [9]. In this study, the engine with pilot type of gas injection diesel is mainly discussed. The pure Diesel engine is converted into diesel/natural gas dual fuel engine, and the modified engine and pure Diesel engine are compared and analysed. According to the analysis results, the coupling method of NSGA-II algorithm and CFD is used to improve, and the improved results are analyzed.

The NSGA -II algorithm

Genetic algorithm mainly includes six elements: coding mechanism, initial population generation, control parameter setting, fitness function, genetic operator and algorithm termination [10]. Compared with other algorithms, genetic algorithm has become the priority of scholars because of its good applicability and strong robustness. Multi-objective optimization algorithm is an evolutionary algorithm of genetic algorithm. Generally, multi-objective genetic algorithm is divided into target weighted genetic algorithm, order and density selection method and non-dominant sorting genetic algorithm method (NSGA-II), *etc.* [11]. The NSGA-II is proposed by Srinivas and Deb. Because NSGA-II algorithm is easier to realize than other traditional multi-objective optimization methods, and has fast convergence, in this study, NSGA-II algorithm is used to study.

The NSGA-II algorithm is an improvement on the basis of conventional genetic algorithm. Its key steps are:

– Design of fast non dominated sorting operators.

Finding the optimal solution set of Pareto is the key to multi-objective optimization. In NSGA-II algorithm, the fast non dominated sorting is to stratify the population according to the level of non-inferior solution. Its function is to guide the search to the direction of Pareto optimal solution set [12]. It is a cyclic fitness grading process. First of all, it is necessary to find out the set of non-dominated solutions in the group, which is recorded as the first non-dominated layer *F*. All of its individuals are assigned the non-dominated rank $i_{\rm rank} = 1$ (where $i_{\rm rank}$ is the non-dominated rank value of individual *i*) and removed from the whole population. It is necessary to continue to search for the non-dominated solution set in the remaining population until the population is completely stratified. Individuals in the same hierarchy have the same non-dominant order $i_{\rm rank}$.

– Design of individual crowding distance operator.

In order to be able to perform selective sorting within individuals with the same non-dominated order $i_{\rm rank}$, NSGA-II algorithm proposes the concept of individual crowding. The crowding distance of individual *i* is the calculated distance between two adjacent individuals $i + 1$ and $i - 1$ in the target space. The distance between the individuals in the same layer are initialized [13], so that $L[i]_d = 0$ (where $L[i]_d$ represents the crowding distance of any individual). The individuals in the same layer are arranged in ascending order according to the $m^{\rm th}$ objective function value, so that the individuals on the edge of the order have the selective advantage. The crowding distance of the individuals in the middle of the sorting is solved:

$$\frac{L[i]_d = L[i]_d + (L[i+1]_m - L[i-1]_m)}{f_m^{\max} - f_m^{\min}} \tag{1}$$

By giving priority to individuals with large crowding distance, the results can be evenly distributed in the target space to maintain the diversity of the population.

– The design of elite strategy selection operator.

The elite strategy is to keep the excellent individuals in the parent generation to enter the child generation directly, so as to prevent the loss of Pareto optimal solution [14]. The elite strategy selection operator optimizes the population R_i composed of the parent C_i, the child D_i and the composite R_i according to three indexes to form the new parent $C_i + 1$. First, it is necessary to eliminate the infeasible scheme in the parent generation. Secondly, according to the order of $i_{\rm rank}$ from high to low, the whole population is put into $C_i + 1$ according to this order, until the size of $C_i + 1$ exceeds the population size limit N when it is put into F_j. Finally, according to the order of individual crowding distance from large to small in F_j, continue to fill $C_i + 1$ until the population number reaches *N*.

The CFD (KIVA-3V) software simulation

Kiva is the combustion process simulation program set of internal combustion engine launched by Los Alamos National Laboratory in 1985, which is at the leading level [15]. According to the basic control equation, mass conservation equation, momentum conservation equation, and energy conservation equation of KIVA-3V, the model equation is calculated.

Using the standard κ-ε turbulence model, the kinetic energy κ equation of turbulence is:

$$\frac{\partial \rho\kappa}{\partial t} + \nabla(\rho)\frac{\partial \rho\kappa}{\partial t} + \nabla(\rho u\kappa) = -\frac{2}{3}\rho\kappa\nabla u + \sigma : \nabla u + \nabla\left[\left(\frac{\mu}{\Pr_\kappa}\right)\nabla\kappa\right] - \rho\varepsilon + \dot{W}^s \tag{2}$$

The equation of turbulent kinetic energy dissipation rate ε is:

$$\frac{\partial\rho\varepsilon}{\partial t}+\nabla\left(\rho u\varepsilon\right)=-\left(\frac{2}{3}c_1-c_3\right)\rho\varepsilon\nabla u+\nabla\left[\left(\frac{\mu}{\mathrm{Pr}_\varepsilon}\right)\nabla\varepsilon\right]+\frac{\varepsilon}{\kappa}(c_1\sigma:\nabla u-c_2\rho\varepsilon+c_s\dot{W}^s) \tag{3}$$

Among them, the constant c_1 = 1.43, c_2 = 1.91, c_3 = –1, and c_s = 1.51, all of these values are based on real experiments.

The spray equation is:

$$\frac{\partial f}{\partial t}+\nabla_x\left(fv\right)+\nabla_v\left(fF\right)+\frac{\partial}{\partial r}\left(fR\right)+\frac{\partial}{\partial T_d}\left(f\dot{T}_d\right)+\frac{\partial}{\partial y}(fy)+\frac{\partial}{\partial\dot{y}}(f\dot{y})=\dot{f}_{coll}+\dot{f}_{bu} \tag{4}$$

where t is the time, v – the droplet velocity, r – the droplet size, F = dv/dt – the droplet acceleration, and y – the droplet sphericity. Because there are many variables in the droplet probability distribution function, f, the discrete particle method of Monte-Carlo method is used to solve the jet dynamics. The f is replaced by f' in the discrete state:

$$f'=\sum_{p=1}^{\mathrm{NIP}}N_p\delta\left(x-x_p\right)\delta\left(r-r_p\right)\delta\left(T_d-T_{d_r}\right)\delta\left(y-y_p\right)\delta\left(\dot{y}-\dot{y}_p\right) \tag{5}$$

The droplets with the same position, same velocity, same diameter and same temperature constitute particle, p, so the moving orbits of these droplets are the same.

Results

Research results of engine emission characteristics

The main parameters of the modified engine are shown in tab. 1.

Table 1. Main engine parameters

Engine model	WP10.290
Engine form	Water-cooled, Four-stroke, Charge inter-cooling
Bore [mm]	126
Stroke [mm]	130
Displacement	9.726
Compression ratio	17.0:1
Rated power/rated speed [rpm]	2.15/2200
Maximum torque/maximum speed [rpm]	1160/1200~1600
Maximum burst pressure [MPa]	15.6

The emission characteristics of CO are shown in fig. 1. When the diesel/natural gas dual fuel engine is working at low load, the temperature of fuel combustion is relatively low, so the combustion of natural gas is not complete, and the CO emission is significantly higher than that of pure diesel. In the high load state, the wall quenching effect increases. These results in a significant increase in CO emissions compared to pure diesel fuel, and a shorter combustion time, which is very detrimental to CO oxidation.

The CO is the product of incomplete combustion of hydrocarbon fuel, and its formation is mainly affected by equivalence ratio. In addition, CO will have a great impact on human body, resulting in necrosis of body tissue due to hypoxia, serious damage to heart, softening and necrosis of brain tissue. Therefore, the research of all engines must ensure the CO emission within the safe range and reduce as much as possible.

The comparison of NO_x emission between pure diesel engine and dual fuel engine is shown in fig. 2.

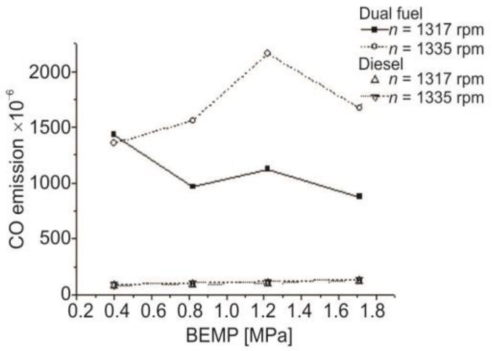

Figure 1. The CO emission characteristics

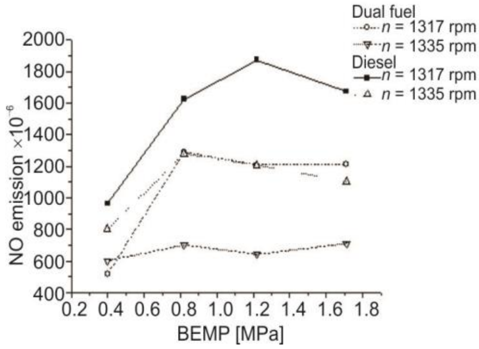

Figure 2. The NO_x emission characteristics

It can be seen from the fig. 2 that the combustion temperature of diesel oil in the low load state of dual fuel engine is relatively low. Under the condition of high load, the amount of diesel fuel to be ignited increases. Therefore, with the increase of high temperature area, the combustion of diesel oil and NO_x emission also increase. As the main cause of NO_x is diesel ignition, the NO_x emission of pure Diesel engine is generally higher, about 30% more than that of dual fuel engine.

The comparison of CH_4 emissions between pure Diesel engine and dual fuel engine is shown in fig. 3.

It can be seen from the fig. 3 that due to inadequate combustion, the CH_4 emission of dual fuel engine is very high under low load. With the increase of load, CH_4 emission is obviously reduced, but it is still higher than pure diesel engine.

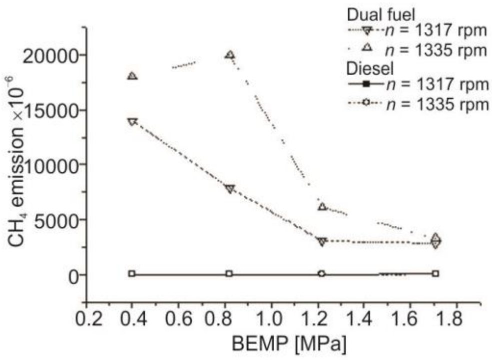

Figure 3. The CH_4 emission characteristics

Thermodynamic analysis results

According to the First law of thermodynamics, the thermal efficiency of the dual fuel engine is analysed. Due to the high CH_4 emission and high CO emission of dual fuel engine under low load, the thermal efficiency of dual fuel engine is low. Therefore, in order to improve the thermal efficiency of the dual fuel engine, it is necessary to simulate the movement and combustion mode of the mixture in the cylinder. In this study, only the combustion in the cylinder is considered, and the influence of intake and exhaust is not further analysed. The turbulent flame speed closure method of composite combustion model is used. Moreover, the combustion process is characterized by combustion process variables.

Results of improved emission characteristics

The optimal combustion model is obtained by optimizing the injection quantity, injection time and injection angle. The optimized variables and their value ranges are shown in tab. 2.

When the angle between the injection holes is 141.57°, the natural gas mixture is mainly ignited by diesel under the combustion chamber, and the air-flow below is stronger.

Table 2. Optimized variables and their value ranges

Main parameter	Abbreviate	Unit	The original machine	Value range
Convex platform height	*h*	cm	0.675	0.5000-1.5000
The distance from the centre of the combustor to the centre line	R1	cm	3.765	3.6000-5.0000
The distance from the centre of the bottom circle of the combustion chamber to the centre line	R2	cm	2.890	2.6000-3.8000
Fuel injection angle	α	°	146.0	100.00-170.00
Injection timing	β	°CA bTDC	7.61	0.00-20.00

When the angle between the injection holes is 109.43°, the natural gas mixture is mainly ignited by diesel above the combustion chamber. When the angle between the injection holes is 136.21° and 141.57°, respectively, the peak pressure in the cylinder is the largest. The higher the peak temperature in the cylinder, the higher the NO_x generation rate. When the angle between the injection holes is 141.57°, the amount of NO_x generated in the cylinder is large, mainly because the combustion temperature is high and the NO_x generated quickly. When the injection advance angle is 21.91 °CA, the pressure in the cylinder is the highest, the CH_4 production is the lowest, the NO_x production is higher, the oxygen content in the combustion mixture is less, and the temperature is higher. Therefore, NO_x production is the lowest, as shown in figs. 4-6.

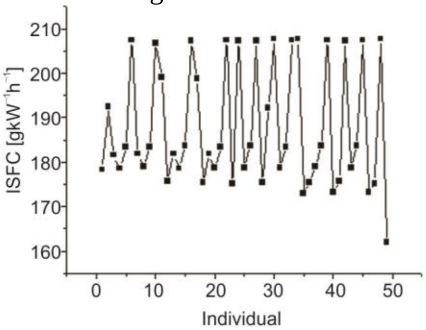

Figure 4. The ISFC change corresponding to Pareto optimal calculation example

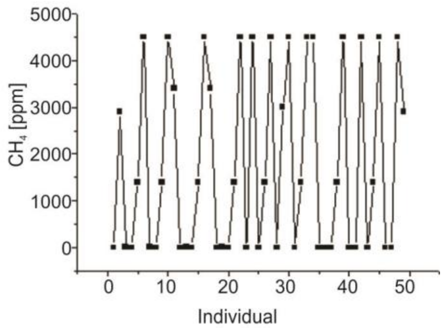

Figure 5. The CH_4 change corresponding to Pareto optimal calculation example

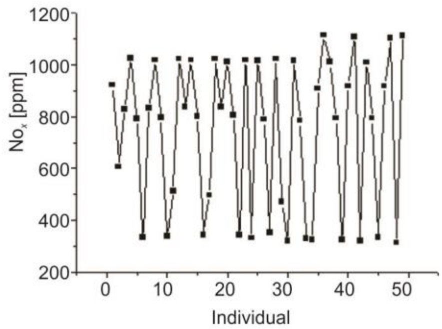

Figure 6. The NO_x change corresponding to Pareto optimal calculation example

The figs. 4-6 show the changes of NO_x, CH_4, and ISFC (indicated specific fuel consumption) corresponding to Pareto optimal example. It can be seen that the CH_4 emissions of some Pareto optimal cases are close to zero. When the β angle is earlier than the original engine, CH_4 emission will be reduced. At the same time, the ISFC will be lower. When α decreases, CH_4 emissions will increase.

Discussion

According to the analysis results, the method of coupling NSGA-Ⅱ algorithm and CFD is used to improve, and the improved results are analysed.

– Based on the CFD software, the κ-ε turbulence model, KH-RT spray model and PaSR combustion model are determined. Based on the i_{prep} module of KIVA, the geometric and grid models are established, the conditions of calculation are determined, and the simulation calculation is carried out.
– Aiming at the current situation that the Diesel engine combustion model has poor prediction ability for the composite combustion process of the diesel micro natural gas dual fuel engine, a composite combustion model of dual fuel engine based on PaSR coupled turbulent flame propagation model is proposed. The combustion process of dual fuel engine is simulated.
– An artificial intelligence combustion chamber structure parameters automatic optimization method based on the non-dominated genetic algorithm coupled with the combustion chamber grid automatic generation algorithm is proposed, and the matching of combustion chamber structure parameters and fuel injection parameters is optimized according to this method.

Conclusions

In order to improve the combustion and emission characteristics of diesel/natural gas dual fuel engine, the combustion chamber parameters and injection parameters are studied. WP10.290 Diesel engine is converted into diesel/natural gas dual fuel engine. The emission of harmful substances and thermal efficiency of the modified engine under different working conditions are compared. The adaptability between NSGA-Ⅱ algorithm and CFD software is used to optimize combustion chamber structure and combustion chamber and fuel injection parameters.

The emission of NO_x and CH_4 and the fuel consumption rate can be reduced simultaneously by using the composite combustion model compared with the original engine. When the CH_4 emission is close to zero, the fuel consumption rate decreases obviously and NO_x slightly increases. When the angle between the injection holes is 141.57°, the amount of NO_x in the cylinder is large. When the injection advance angle is 21.91 °CA, the pressure in the cylinder is the highest, the CH_4 production is the lowest, the NO_x production is higher, and the oxygen content in the combustion mixture is less. The NO_x production is the lowest. Diesel/natural gas dual fuel engine can ensure efficient combustion while reducing emissions.

Acknowledgment

Fund Project: Scientific Research of Department of Education of Zhejiang Province in 2019: Optimization of Engine Combustion and Emission Based on Flash Boiling Spray (Grant No. Y201942849).

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Paper submitted: October 16, 2019
Paper revised: November 29, 2019
Paper accepted: December 11, 2019