

DESIGN OF CONTROL SYSTEM FOR MARINE DIESEL/LNG DUAL-FUEL ENGINE BASED ON MATLAB

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Abstract: According to the operating characteristics of the T8138ZLCz marine diesel engine and the advantages of liquefied natural gas (LNG) as an alternative fuel, a set of diesel/natural gas dual-fuel engine control system was designed using MATLAB/Simulink software. Without changing the original engine structure, an LNG supply system and an electronic control system were added. Engine performance bench tests were carried out to analyze the economic and emission performance of the dual-fuel engine, and comparisons were made with the original engine. The test results show that the control system can ensure the reliable operation of the engine in dual-fuel mode; under the same operating conditions, the modified dual-fuel engine has a significant improvement in economic performance and a certain degree of improvement in emission performance compared with the original engine.

Keywords: Dual-fuel engine; Control system; Liquefied natural gas (LNG); Emission characteristics

1 INTRODUCTION

Liquefied natural gas (LNG), whose main component is methane (CH_4), has the characteristics of abundant resources, high purity, high calorific value, and convenient storage and transportation [1-2]. In recent years, natural gas engines have attracted increasing attention due to their advantages of low emissions, low energy consumption, and low cost. Using natural gas as an alternative fuel for engines can effectively reduce the emissions of harmful substances such as NO_x and particulate matter from engines [3-6]. However, the ignition point of natural gas is relatively higher than that of diesel, making it difficult to ignite by compression ignition. It requires spark plug ignition or ignition by a portion of diesel [7]. For diesel engines, the diesel pilot ignition method can realize the alternative combustion of natural gas without changing the basic structure of the original engine. Therefore, the diesel/LNG dual-fuel engine modified from a diesel engine has become a major research trend due to its practicality, good emission performance, and economic benefits [7-9], especially in the application of medium and large-sized engines, it has become an important development direction.

When burning LNG with diesel pilot ignition, it is necessary to accurately control the natural gas substitution rate under various operating conditions to ensure the stable operation of the engine. For this reason, this paper uses MATLAB/Simulink software to build a diesel/LNG dual-fuel engine control model and conduct system design, which can realize the optimal control of natural gas injection volume under various operating conditions. Through bench tests of propulsion characteristics, the power performance, economic performance, and emission performance of the engine at each operating point on the propulsion characteristic curve under pure diesel and dual-fuel modes were compared and analyzed, providing theoretical and experimental references for the optimal design of diesel/LNG dual-fuel engines.

2 DESIGN OF CONTROL SYSTEM

2.1 Composition of the Control System

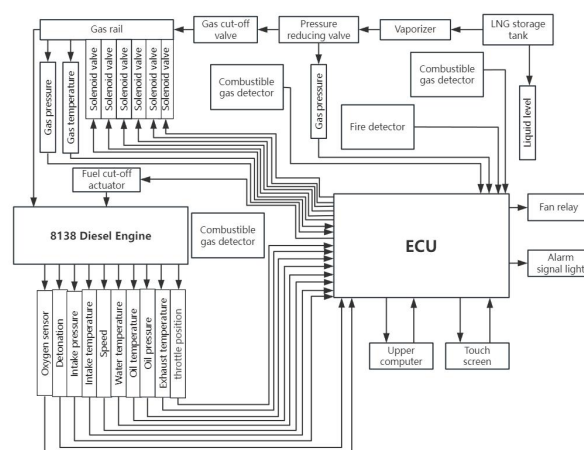


Figure 1 Diesel/LNG Dual Fuel Engine System

In order to realize the automatic switching between pure diesel mode and dual-fuel mode according to different working states of the diesel engine; operate the control strategy in dual-fuel mode and automatically parse the ideal natural gas/diesel ratio to maximize the balance of the engine's power performance, economic performance, and emission performance. For this reason, taking the marine Tongchai 8138 diesel engine as the research object, MATLAB/Simulink software was used to build a controllable diesel/LNG dual-fuel engine control system. The system is mainly composed of three parts: gas supply system, safety protection system, and communication/control system. Figure 1 shows the schematic diagram of the designed diesel/LNG dual-fuel engine control system.

2.1.1 Gas supply system

The mixed combustion system consists of two parts: a diesel supply system and a natural gas supply system. The supply and injection volume control of diesel is completed by the original diesel engine system. The natural gas supply system is composed of ECU, gas injection valve, sensor and other components. The liquefied natural gas in the gas storage tank becomes gaseous natural gas through the vaporizer. The pressure reducing device maintains the pressure at the inlet end of the gas injection valve at 0.3MPa. Then, the ECU in the system calculates the optimal gas injection volume under the current operating condition based on various engine operating parameters and converts it into the opening time of the gas injection valve. The gas injection valve injects natural gas into the engine intake port according to the gas injection pulse width. At the same time, to prevent the valve body from overheating due to continuous work, the gas injection valves work alternately in groups.

2.1.2 Safety protection system

The safety protection system is composed of an alarm, an indicator light, a ventilation fan, and multiple combustible gas sensors installed at different positions. When the combustible gas sensor detects that the concentration of combustible gas at its location reaches a certain limit, the system will issue an alarm, turn on the ventilation fan, and even forcibly cut off the natural gas supply.

2.1.3 Communication/control system

The communication/control system is composed of CAN communication equipment and an industrial touch screen, whose main function is to display the operating status of the engine in real time and control the switching of its working modes. The electronic control unit sends the engine operating information to the touch screen through CAN communication. At the same time, the switching between dual-fuel or pure diesel mode can be realized by operating the touch screen, and the emergency stop of the engine as well as the opening and closing of the fan can also be controlled.

2.2 Control Strategy of Natural Gas Supply System

The natural gas supply volume is mainly determined by the electronic control unit based on the engine operating conditions and operating parameters collected by various sensors. Figure 2 is a flow chart of single gas supply control, where Flag is the gas supply enable flag bit.

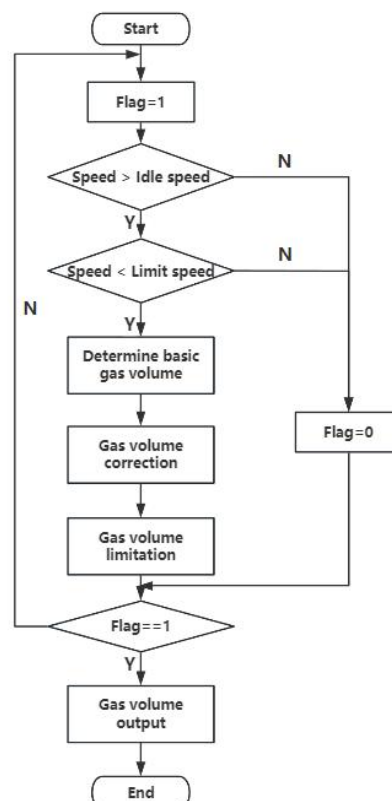


Figure 2 Gas Control Flow Chart

When the engine is in dual-fuel mode, if its speed is higher than the idle speed and lower than the limit speed, the system obtains the final gas volume output after three processes: table lookup, correction, and gas volume limitation. The table lookup process determines the basic gas volume by linear interpolation of the two-dimensional MAP based on the current speed and handle position. The main basis for gas volume correction is the collected data of various sensors. Equation (1) is the correction formula for gas volume:

$$Gas_m = Gas_b \times M_n \times (1 + M_{et} \times M_{wt} \times M_l) \quad (1)$$

Where:

Gas_m is the corrected final gas volume;

Gas_b is the basic gas volume obtained by looking up the speed and handle position;

M_n is the gas volume correction coefficient caused by sudden speed changes;

M_{et} is the exhaust temperature correction coefficient;

M_{wt} is the engine block temperature correction coefficient;

M_l is the engine load change correction coefficient, whose value is mainly related to the current handle position and exhaust temperature change rate.

To ensure the stable operation of the engine and extend its service life, it is necessary to limit the gas volume under some special conditions. These conditions mainly include: excessively high exhaust temperature, excessively high engine block temperature, excessively large engine speed fluctuation rate, excessively large handle position change rate, etc.

3 EXPERIMENTAL EQUIPMENT AND SCHEME

3.1 Experimental Equipment

Table 1 shows the main parameters of the diesel engine used in the test.

Table 1 Main Parameters of the Engine

Type	T8138ZLCz
Cylinder Diameter	138mm
Piston Stroke	163mm
Compression Ratio	15.5
Displacement	19.5L
Idle Speed	500r/min
Exhaust Gas Temperature	< 470°C
Overload Power/Speed	323.4kW/(1545r/min)
Continuous Power/Speed	294kW/(1500r/min)

Figure 3 is a schematic diagram of the test bench layout of the diesel/LNG dual-fuel engine. The control unit sends engine operating parameters to the touch screen and PC 2 through CAN at the same time. Another main function of PC 2 is data calibration. The controller controls the engine load by changing the excitation current of the dynamometer, and PC 1 displays the speed and torque of the dynamometer in real time. The fuel consumption meter and flow meter realize the measurement of diesel and natural gas consumption.

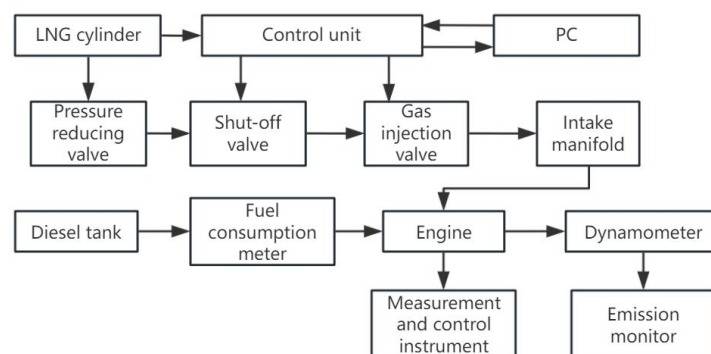


Figure 3 Arrangement of Dual Fuel Engine Test

3.2 Propulsion Characteristic Experimental Scheme

The engine used in the test is mainly used for ships and generally works according to propulsion characteristics. The research focus of marine diesel engines is generally their economic and emission characteristics. Therefore, this paper focuses on studying the fuel consumption, natural gas consumption, and exhaust gas concentration of the engine under propulsion characteristic conditions, and compares and analyzes the economic and emission characteristics of the engine under diesel/LNG dual-fuel mode and pure diesel mode.

Figure 4 is the propulsion characteristic curve of the original engine, and Equation (2) is the relationship between torque and speed under propulsion characteristics.

$$T = c \times n^2 \quad (2)$$

Where:

c is a constant determined by the propeller diameter and advance ratio;

n is the engine speed.

During the test, 10 operating points were selected at intervals of 100r/min between 600r/min and 1500r/min. The torque value corresponding to each speed was calculated according to Equation (2). Under the conditions of constant speed and constant torque, the fuel consumption, natural gas consumption, exhaust gas composition and other data of each operating condition were recorded respectively.

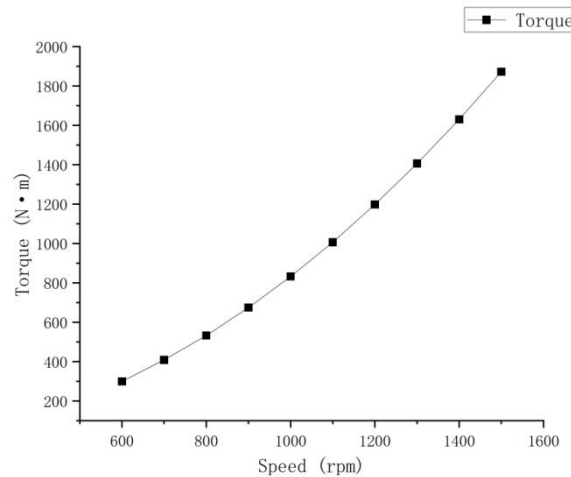


Figure 4 The Propulsion Characteristic of Original Machine

3.3 Economic and Emission Comparison Scheme

For economic calculation, diesel was calculated at the current market price of 7.70 yuan/kg and natural gas at 4.33 yuan/kg. The operating cost calculation formulas are shown in Equations (3), (4), and (5):

$$P_D = D1 \times 7.70 \quad (3)$$

$$P_M = D2 \times 7.70 + G \times 4.33 \quad (4)$$

$$S = \frac{P_D - P_M}{P_D} \times 100\% \quad (5)$$

Where:

P_D is the cost consumption rate in pure diesel mode;

P_M is the cost consumption rate in dual-fuel mode;

S is the cost saving rate;

$D1$ is the diesel consumption rate in pure diesel mode;

$D2$ is the diesel consumption rate in dual-fuel mode;

G is the natural gas consumption rate in dual-fuel mode.

Under the same operating conditions, the emissions of CO, HC, NO_x, and particulate matter in pure diesel mode and dual-fuel mode were compared respectively.

4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Economic Performance

Figure 5 shows the variation law of fuel consumption rate of the engine with engine speed when operating in dual-fuel mode and pure diesel mode under propulsion characteristics. To facilitate the analysis of LNG substitution rate, the curves of diesel and LNG fuel consumption rates in dual-fuel mode are given respectively. It can be seen that as the speed increases, the total fuel required by the engine in both modes increases. Before 1200r/min, with the increase of speed, the diesel consumption only increases slightly. At this time, diesel only plays a role of igniting natural gas in the dual-fuel mode, and most of the fuel is provided by natural gas. When the speed is higher than 1200r/min, the increase in diesel consumption becomes larger, while the increase in natural gas consumption gradually slows down, and even the natural gas consumption does not increase but decreases after 1400r/min. This is because the further increase of natural gas will make the mixture too rich, resulting in incomplete fuel combustion, which will reduce the engine power and make the operation unstable. Therefore, the natural gas substitution rate should be appropriately reduced at this time to ensure the power performance and operation stability of the engine.

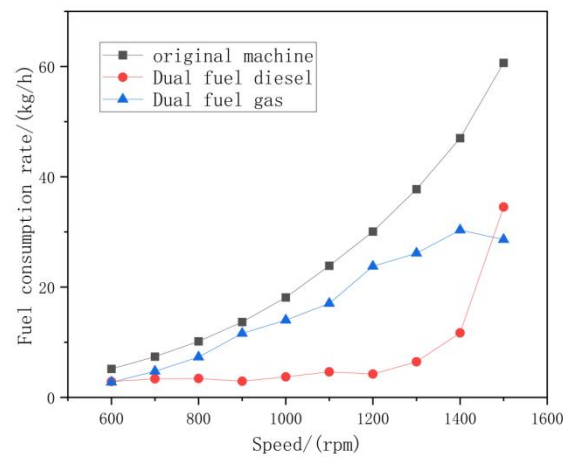


Figure 5 Comparison of Fuel Consumption Rate

Figure 6 is the natural gas substitution rate curve in dual-fuel mode. It can be seen that as the speed increases, the substitution rate first rises and then falls, with the highest value of 85.9% at 1200r/min. When the speed is 600r/min, the substitution rate of natural gas for diesel is 44.24%, at which time the total fuel required by the engine is the least and the diesel consumption is at the minimum value that can ignite natural gas. When the speed is 1500r/min, the substitution rate is the lowest at 43.09%. At this time, the mixture is in an over-rich state, and the substitution rate must be reduced to ensure the stable operation of the engine.

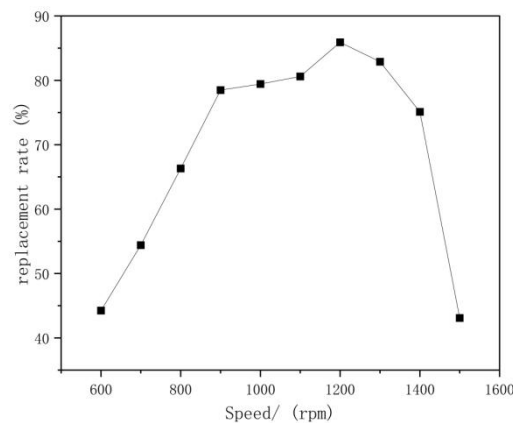


Figure 6 Replacement Rate

Figure 7 is a comparison diagram of the costs of the engine in the two modes. It can be seen that the operating cost in dual-fuel mode is generally lower than that in pure diesel mode. As the speed increases, the cost saving rate gradually increases, reaching the highest of 28.7% at 1300r/min. After 1300r/min, the significant increase in diesel consumption leads to a decrease in the cost saving rate.

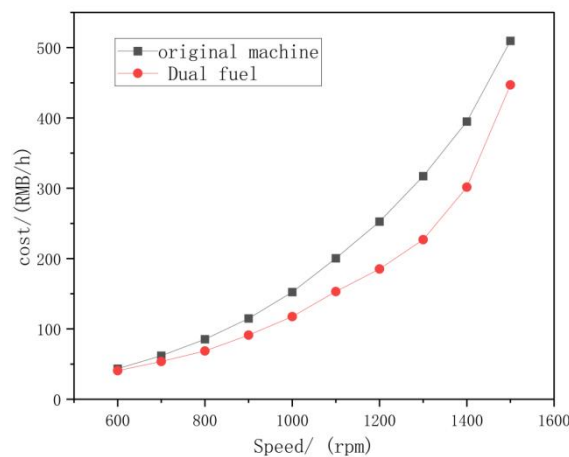


Figure 7 Cost Comparison

4.2 Emission Performance

Figure 8 is a comparison diagram of CO emissions when operating in pure diesel and dual-fuel modes under propulsion characteristics. It can be seen that the CO emission in dual-fuel mode first increases and then decreases to its minimum value of 0.12% at 1000r/min, and rises again as the speed increases further, while the CO emission in pure diesel mode varies only within the narrow range of 0.04% to 0.06%, with its minimum value of 0.04% appearing at 600r/min, 700r/min and 900r/min. This is because the temperature in the cylinder is low under low-speed operating conditions, and the mixture is too rich at high speeds, both of which will cause incomplete fuel combustion, resulting in more CO generation. It can also be seen that under the same speed, the CO emission in dual-fuel mode is higher than that in pure diesel mode. On the one hand, the ignition temperature of natural gas is lower than that of diesel, leading to a lower temperature in the cylinder, which promotes the generation of CO; on the other hand, natural gas adopts the intake port injection method, which occupies a part of the air volume, resulting in a decrease in the actual air-fuel ratio and more serious incomplete combustion.

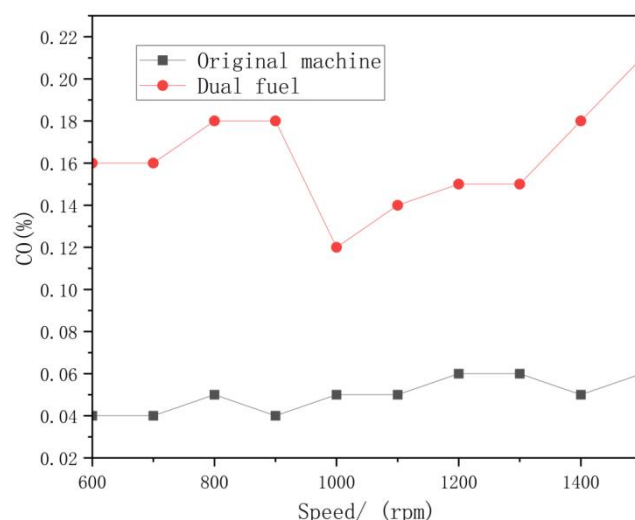


Figure 8 Comparison of CO Emissions

Figure 9 is a comparison diagram of HC emissions in the two modes under propulsion characteristics. It can be seen that the HC emission in pure diesel mode is always low, and only increases slightly with the increase of speed, with the maximum volume fraction of only 22×10^{-6} . However, the HC emission in dual-fuel mode is generally higher, and first increases and then decreases with the increase of speed. The maximum value appears at 1000r/min, which is 485×10^{-6} ; the minimum value appears at 1500r/min, which is 186×10^{-6} . This is because, on the one hand, the combustion temperature in dual-fuel mode is low, and the incomplete combustion of fuel leads to an increase in HC emissions; on the other hand, natural gas adopts the intake port injection method, and the overlap of intake and exhaust valves will inevitably cause a part of natural gas to be directly discharged from the exhaust pipe without participating in combustion. Before 1000r/min, with the increase of injected natural gas volume, HC emissions continue to increase; after 1000r/min, the increase in load increases the combustion temperature, and the incomplete combustion is alleviated, so HC emissions gradually decrease.

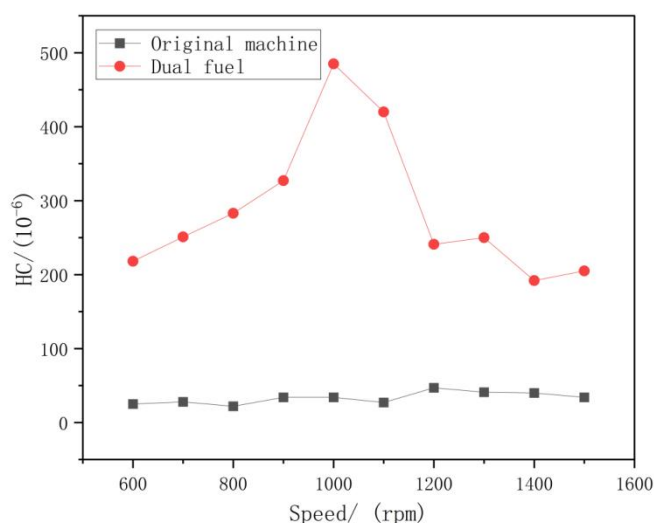


Figure 9 Comparison of HC Emissions

Figure 10 is a comparison of NO_x emissions between the original diesel engine and the dual-fuel diesel engine under propulsion characteristics. The NO_x emission in pure diesel mode first increases and then decreases with the increase of speed, with the maximum value of 1038×10^{-6} at 1200r/min. This is because as the speed increases, the temperature of the fuel in the cylinder rises, forming a high-temperature environment that promotes the generation of NO_x . The decrease in NO_x emission at high speeds is because the mixture is too rich at this time, and the oxygen concentration in the cylinder is low, which is not conducive to the formation of NO_x . Under the same speed, the NO_x emission in dual-fuel mode is significantly lower than that in pure diesel mode. The most obvious reduction occurs at 600r/min, from 662×10^{-6} to 210×10^{-6} , with a reduction rate of 68.3%. This is because the stoichiometric air-fuel ratios of natural gas and diesel are 17.2 and 14.3 respectively. The air required for fuel combustion in dual-fuel mode is higher than that in pure diesel mode, resulting in less air reacting with N_2 . On the other hand, the combustion temperature in the cylinder is lower in dual-fuel mode, which inhibits the generation of NO_x .

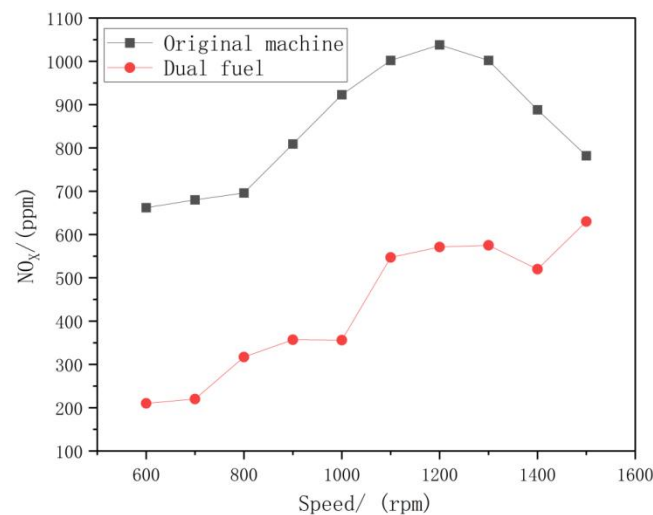


Figure 10 Comparison of NO_x Emissions

Figure 11 is a comparison diagram of light absorption coefficients in the two modes. It can be seen that as the speed increases, the smoke values in both modes increase, and the maximum values both appear at 1500r/min. The light absorption coefficient in pure diesel mode is 0.46 m^{-1} , and that in dual-fuel mode is 0.1 m^{-1} . Moreover, the smoke value corresponding to the dual-fuel mode is lower than that of the pure diesel mode at each speed, and the reduction effect becomes more obvious with the increase of speed. This is because the mixture of the original engine is too rich at high speeds, and the incomplete combustion of diesel will lead to a significant increase in soot emissions. However, the main component of natural gas is CH_4 , whose HC structure is smaller than that of diesel, and almost no particulate matter is produced after combustion. Therefore, the particulate matter emission in dual-fuel mode is significantly reduced.

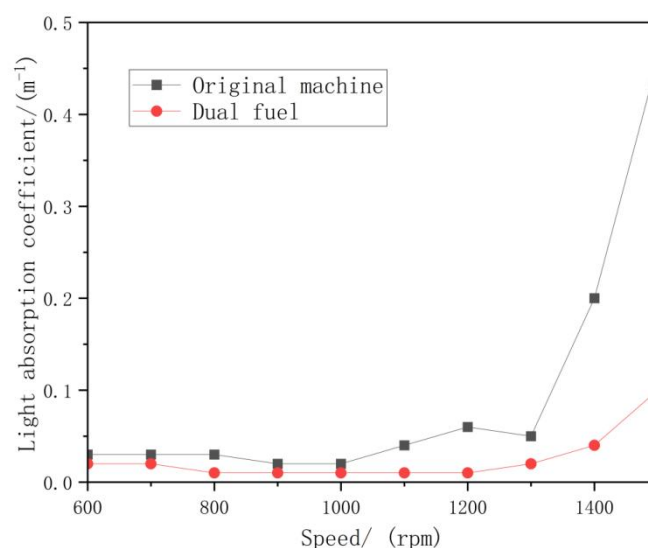


Figure 11 Comparison of Light Absorption Coefficient

5 CONCLUSIONS

The designed diesel/LNG dual-fuel engine control system adds an independently developed LNG injection system without changing the basic structure of the original engine, realizing the stable operation of the engine in diesel/LNG

dual-fuel mode and the intelligent switching between single/dual fuel modes. On the premise of ensuring unchanged power performance, the economic performance of the modified dual-fuel engine is comprehensively improved. The natural gas substitution rate is relatively high at medium speeds, reaching a maximum of 85.9% (1200r/min); the overall operating cost is reduced, and the cost saving rate reaches a maximum of 28.7% (1300r/min). When operating in diesel/LNG dual-fuel mode, NO_x and particulate matter emissions are significantly reduced. The NO_x emission reduction is relatively large at medium and low speeds, with a maximum reduction rate of 68.3% (600r/min); the particulate matter emission reduction effect is more obvious at high speeds, with a maximum reduction rate of 78.3% (1500r/min). However, HC and CO emissions have increased. Therefore, it is necessary to add after-treatment devices such as DOC to improve the overall emission performance of the engine.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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