Simulation and experiment of NO\textsubscript{X} concentration detection in diesel engine exhaust gas

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Abstract. As people pay more attention to environmental problem, the issue of how to measure and reduce pollutant of the exhaust of ships were put on the agenda. To realize the detection of NO\textsubscript{X}(nitrogen oxides) content in the marine diesel exhaust emissions, the SIMULINK of MATLAB software with superior data processing capabilities was selected in this paper to enable the detection of NO\textsubscript{X} content by direct absorption measurement based on laser absorption spectroscopy (TDLAS). The absolute error of the simulation model was less than 0.15\%, and the maximum relative error didn’t exceed 1.25\%. At the same time, the simulation error of the model was less than 5.0\% compared with the test results of the AVL emission meter. The results had shown that the model can accurately simulate the detection process of nitrogen oxides of diesel exhaust emissions. It not only provides reference data onto people to detect harmful gases in ships but also provides valuable experience in optimizing diesel engines control strategies.

1. Introduction

Diesel engines have become the first choice in the field of ship transportation because of its high combustion performance, strong power, economy and reliability\textsuperscript{1}. With the continuous development of the shipbuilding industry, the total volume and tonnage of ships were increasing, resulting in the proportion of ship pollutant emissions in the air pollution problems increasing year by year. Environmental problems have become one of the important issues that restrict social development and affect the national economy and people's livelihood. The SO\textsubscript{2}, NO\textsubscript{X} and other exhaust gases generated during the operation of the ship was absorbed by substances existing in the environment to further generate harmful substances, which will cause serious harm to human society\textsuperscript{2}. For example, the major harmful product NO\textsubscript{X} contains NO\textsubscript{2} that can enter the human respiratory system, leading to lung and bronchial diseases\textsuperscript{3}. Therefore, it is imperative to accurately detect the concentration of emissions to achieve the task of emission reduction.

Most of the traditional marine diesel engines emission testing methods have the characteristics of long sampling periods, complex system structure and huge volume, which lead to the poor dynamic response characteristics and mobility of the existing testing equipment, and can’t achieve real-time monitoring of marine diesel engines in operation\textsuperscript{4}. Given the problems existing in the field of pollutant emission measurement of marine diesel engines, it is urgent to develop a new testing method, which has high dynamic response characteristics, high testing accuracy, and strong environmental adaptability. At the same time, the system should have structural simplicity and good operability\textsuperscript{5}. In order to meet the real-time online monitoring requirements of marine diesel engines emissions and
meet the new requirements of emission testing methods in the future marine diesel engines emission regulations.

In this paper, a lot of preliminary research work had be done and the actual characteristics of marine diesel engines emissions were considered, a new model was proposed to solve the problem of traditional test methods of the detection of NOX in the exhaust gas of marine diesel engines, which based on tunable laser absorption spectroscopy technology as the main research method.

2. Principle of direct measurement

Since the results were obtained by the direct measurement method, which can visually observe the interference and noise between the spectral lines in the signals. The measured spectral absorption rate signal directly indicates the intensity of the gas absorption Simultaneously, it does not need to be calibrated with standard gas, and the measurement process is very convenient, so it was called direct measurement method[6]. Based on the Beer-Lambert law, the concentration expression of direct absorption measurements can be described as follows[7]:

\[
X = \frac{-\ln\left(\frac{I}{I_0}\right)}{P(S(T)\phi(\nu)L)}
\]

\(I_0\) is the original light intensity that has not been absorbed by the gas medium, it is the absorbed light intensity after gas absorption, \(T\) is the ambient temperature [K], \(P\) is the total pressure of the gas to be measured [atm], and \(X\) is the volume concentration of the gas\([\text{mol}\cdot\text{cm}^{-3}\cdot\text{atm}^{-1}]\), and \(L\) is the effective propagation distance [cm], \(\phi(\nu)\) is the absorption coefficient of the gas molecule[cm].

The direct measurement method utilizes the tunable characteristics of the laser. Changing the magnitude of the current injected into the laser can change the wavelength of laser light emitted by the laser, which enables the laser to produce a small range of laser output near the absorption peak [8]. The absorption rate of the gaseous medium can be obtained by measuring the change in laser intensity. Then, other parameters such as \(P\), \(T\), and \(L\) are substituted into the expression to obtain the gas concentration value.

The direct detection method is a method of obtaining a gas concentration value to be measured by mathematically calculating the spectral absorption rate. Therefore, the direct detection method is not affected by the overall attenuation of the optical signal. It can effectively reduce the measurement error caused by the attenuation of the optical signal caused by the particulate matter in the diesel exhaust pollutants[9]. At the same time, the direct calibration method can be used to obtain the absolute concentration information about the components in the pollutant discharge, which can eliminate the complicated calibration process. Therefore, the method is beneficial to the real-time monitoring of the marine diesel engine during the operation of the ship.

3. Establishment of concentration simulation model

The SIMULINK library of MATLAB2014b software with powerful data processing functions was selected to establish a simulation model for diesel engine emission concentration detection based on TDLAS[10]. The simulation model of concentration measurement mainly includes three parts: laser source model, gas chamber absorption model and data processing model.

In the light source module, the periodic sawtooth wave scanning signal was superimposed on the fixed value output to form the simulated light in a certain wavenumber range. The air chamber module adopted the Lorentz linear function model and used the different summation, constant and multiplication modules in SIMULINK to form the air chamber absorption simulation modules. The data processing model could realize the integral area calculation and the concentration calculation[11], which need to be embedded in the corresponding calculation program. Finally, run the model and analyze the resulting data results.
Figure 1. TDLAS system concentration test simulation diagram.

Combined with the concentration formula (1), the concentration tests simulation model shown in Figure 1 above can be constructed. NOX was selected as the experimental object because it’s one of the main components of the exhaust gas of the diesel engines. Because the concentration of NO in diesel exhaust is greater than that of NO2 and the ratio is close to 9:1, this condition should be satisfied when the concentration of NO and NO2 are set separately. According to the principle of spectral line selection, it was sufficient to select the emission laser center wave number of 1900cm⁻¹ and 1628.66cm⁻¹ for concentration detection. In the model, the effective optical path was set to 30 cm, the initial light intensity was $I_0$, and the gas temperature was 600K. Each part and overall simulation analysis was performed with the initial conditions given.

Table 1. System simulation error analysis.

| Set Value/% | Simulation Concentration/% | Absolute Error/% | Relative Error/% |
|-------------|----------------------------|------------------|------------------|
| NO          |                            |                  |                  |
| 7.20        | 7.1226                     | 0.0774           | 1.075            |
| 8.10        | 8.0091                     | 0.0909           | 1.122            |
| 9.00        | 8.8956                     | 0.1044           | 1.160            |
| 9.90        | 9.7812                     | 0.1188           | 1.200            |
| NO₂         |                            |                  |                  |
| 0.80        | 0.7914                     | 0.0086           | 1.025            |
| 0.90        | 0.8899                     | 0.0101           | 1.100            |
| 1.00        | 0.9884                     | 0.0116           | 1.110            |
| 1.10        | 1.0868                     | 0.0132           | 1.145            |

The results obtained by simulation analysis of a given concentration in the well-established simulation system were shown in Table 1. The absolute and relative errors of the high concentration simulation concentration are larger than the low concentration. The maximum absolute error was 0.1188% and the maximum relative error was 1.16%. The measurement system could achieve ppm or even lower detection limit, but it was not suitable for high concentration measurement.
4. Simulation models of concentration tested

To realize real-time synchronous detection of NO and NO₂ of diesel engines emissions, the signal detection system was required to simultaneously generate two kinds of optical signals. In this experiment, an optical co-channel technique was used, in which a 5.26 μm laser was used to measure the NO concentration, and a 6.14 μm laser was used to measure the NO₂ concentration.[12]. After the combined beam passed through the emission test area, the two lasers were separated by a spectroscopic grating and the two laser signals were simultaneously measured by two detectors. Finally, the concentration information of the NO and NO₂ components of the diesel exhaust could be obtained. A schematic diagram of the experimental system was shown in Figure 2(a) below.

During the experiment, a signal generator was used to generate a 200 Hz trigger signal with a frequency of 200Hz. The sawtooth wave scanning input signal was set according to the laser wavelength required by gas. The laser controller used an external modulation mode, which is to modulate the laser by set the sawtooth signal generated by the signal generator and set the appropriate laser operating temperature values through the internal TEC system. Two symmetrical through holes were drilled into the exhaust pipe of the diesel engine for mounting a transparent window to enable the light path to penetrate. A CaF₂ glass of infrared transmittance of 90% or more was used as a transmission window and the size of the window was larger than the spot diameter to avoid the influence of the vibration of the exhaust pipe on the laser light path of the operation of the diesel engine. After the laser signal was absorbed by the exhaust gas, the optical signal was converted into an electrical signal by the photodetector and the electrical was transmitted to the oscilloscope. The data collected by the oscilloscope can be further processed by the calculator, or directly using the complete processing unit to directly derive the concentration value. The test site is shown in Figure 2(b).

![Figure 2](image1)
![Figure 2](image2)

**Figure 2.** Schematic diagram of the online measurement scheme for direct detection.

**Figure 3.** Comparison of signal detection before and after the direct detection of diesel engine.
An on-line test experimental study on the concentration of NO\textsubscript{X} emission components was carried out on the YC6K420LN-C31 dual-fuel marine engine. The figure shows the test signals obtained by the spectral absorption tested the system before and after the engine is running.

It is not difficult to see from the above figure that the engine exhaust component has a certain attenuation effect on the optical signal intensity, but it does not affect the signal waveform obtained by the detector. However, the slowly varying light intensity attenuation will not affect the test results, because the direct detection method is to invert the gas component concentration information by the spectral absorption rate. It is worth noting that the temperature and pressure of the exhaust gas under different working conditions will change the line strength and line type of the absorption line, which will have a certain influence on the process of inversion of the direct detection method. Therefore, temperature and the pressure correction algorithms need to be introduced as necessary. The obtained data needs to use the environmental parameter correction algorithm, and the obtained test results need to consider the fluctuation of exhaust temperature and pressure under different working conditions.

In this paper, the content of the NO\textsubscript{X} concentration of different working conditions of diesel engines was studied. The NO\textsubscript{X} component concentration test of different operating conditions was carried out by changing the operating state of the diesel engine, and the NO\textsubscript{X} component concentration can be obtained according to Lambert Beer's law.

The initial value of the optical signal was obtained by cubic polynomial fitting, and then fitted by a reasonable linear function to obtain the spectral absorption rate of a single cycle. Finally, the average value of the spectral absorption rate of the multi-period signal was combined with the molecular absorption line parameters under the condition to obtain the concentration values of the NO\textsubscript{X} components of the discharged pollutants. The baseline fit and line set results in the data processing are shown in Figure 4.

![Figure 4. A fitting graph in the data processing.](image-url)

According to the above calculation process, the spectral absorbance values obtained in the experiment were processed to calculate the concentration value information about the NO\textsubscript{X} content of the discharged pollutants under different working conditions of the engine. The concentration values of NO and NO\textsubscript{2} under different conditions were obtained by the tunable laser absorption spectroscopy test system. In order to verify the accuracy of the test results, the above test results were compared with the experimental data obtained by AVL’s AMA i60 emission analyzer. The specific comparison is shown in Table 2 below.

It is not difficult to see from the comparison data that the NO\textsubscript{X} component content of the diesel engine obtained by the tunable laser absorption spectroscopy test system was ±5% deviation from the value obtained by the sampling method. At the same time, the tunable absorption spectroscopy
technique can be used to obtain the concentration information on NO and NO$_2$ components in the pollutants discharged at the same time. The gas component concentration value obtained by the spectral absorption measurement method was the average concentration value of the trajectory of the beam, whereas the sampling method measurement reaction more reflects the concentration information about the local field. In view of the large discharge of marine diesel engine and the non-uniform distribution of concentration field, the selection of the average concentration value of the discharge field can better reflect the component content of the gas molecules measured in the pollutant.

### Table 2. Emission analyzer and direct test online test data.

| NO$_X$ Concentration | Simulated NO/NO$_2$ Concentration Value | Relative Error |
|-----------------------|-----------------------------------------|----------------|
| 534.7ppm              | 502.4ppm/55.8ppm                        | 4.4%           |
| 639.8ppm              | 534.9ppm/72.9ppm                        | 5.0%           |
| 743.1ppm              | 716.5ppm/62.3ppm                        | 4.8%           |

5. Conclusions
In this paper, the direct measurement method in tunable absorption spectroscopy technology was combined with SIMULINK simulation software of MATLAB for building a simulation model of NO$_X$ concentration detection in diesel exhaust to realize the detection of NO and NO$_2$ gas concentrations. According to the experimental results, the absolute error of the model was less than 0.15%, and the relative error was less than 1.25%. At the same time, the error increases as the concentration increases. Therefore, the measurement system is suitable for measuring ppm concentration or even lower detection limit, but not for high concentration testing.

Besides, the actual operating data onto the dual fuel marine engine was collected into the model to verify the accuracy of the model measurement. It can be seen from the results that the test results were in good agreement with the actual ones. Compared with the results of the AVL company's emission analyzer, the error of the simulation results was slightly increased, but the range still satisfies within 5.0%. The model referred to herein be suitable for simulating the measurement of diesel engine low emission concentration NO$_X$. Simulating different concentrations of gas detection can be achieved by changing the parameters of the gas chamber in the model and adjusting the corresponding parameters of the light source module. The research in this paper not only verifies the achievability of TDLAS technology in the measurement of NO$_X$ gas in diesel exhaust but also prepares for the study of reducing NO$_X$ gas emissions from diesel engines. This research will play an important reference role in energy saving and emission reduction of marine diesel engines.

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