Research on Ship Exhaust Gas Accounting in Yangtze River

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Abstract. Based on the comparison and analysis of existing ship exhaust emission accounting methods, and combined with the characteristics of ship exhaust emissions in the Yangtze River channel, this paper selects the appropriate calculation idea, and revises the basic accounting method of ship exhaust emissions according to the calculation accuracy requirements in this paper. Finally, a calculation model for the emissions of ships in the Yangtze River channel is established, and its reliability and accuracy have been confirmed by model tests of the model data. In this paper, the Yangtze River ships are divided into sea-going ships and inland river ships, and their corresponding parameters are calculated respectively, in order to make sure that the accounting results have higher accuracy. The model has strong applicability to the exhaust emission of ships in the Yangtze River, and its calculation results are relatively accurate, and the calculation process is simple and efficient. This paper has a very high social significance and practical value for the analysis and model optimization study of the Yangtze River's exhaust emission accounting.

1. Introduction

In recent years, with favorable policy support and the good trade environment at home and abroad, inland river shipping industry has also made remarkable achievements along with the tide of development, among which the Yangtze river waterway transportation, as an important part of inland river shipping in China, has become the busiest inland river transportation channel, causing the rapid growth of various kinds of waste gas emissions [1].

At present, the current situation of energy consumption and exhaust emission in China's waterway transportation industry is not optimistic. However, studies on calculation of ship energy consumption and exhaust emission accounting are not very sufficient, and there is a lack of accurate prediction of future growth or change trend. Therefore, there are still great difficulties in macro and local supervision of exhaust emission. The accounting of ship exhaust emission is an important means to regulate ship exhaust emission and evaluate the total amount of abandoned emission in the region. Therefore, the research on improving the accounting accuracy of exhaust emission, optimizing calculation model and simplifying accounting method has extremely high social and economic value [8].
2. Research content and research route

2.1. Research object and content analysis
The accounting study of ship exhaust emission in China's Yangtze River waterway has certain particularity. The Yangtze River waterway is not only an important part of China's inland waterway, but also an important entrance and exit of China's inland waterway and ocean. Therefore, this paper will focus on the research on the accounting of ship exhaust emissions in the Yangtze River. At present, the research direction of the academic circle in this field is relatively fixed, which usually takes a single port or voyage section as the research object to study and calculate the air pollution situation, so as to get the emission list of ship exhaust emissions. This paper will start from the whole Yangtze River waterway, eliminate some waterways with insufficient navigable capacity, and calculate the types and emissions of ship exhaust in different time and space in the whole waterway. On the other hand, the Yangtze River ships studied in this study are mainly for cargo and passenger ships with a certain tonnage, while fishing boats, engineering ships and other ships that are difficult to be standardized are not included in this study.

The research contents of this paper can be divided into three parts according to the order of research development. The research contents of each part will be discussed one by one in the following chapters. The specific research contents are as follows:

(1) Based on the research of the existing calculation methods, combined with the characteristics of the research object and scope of this paper, the appropriate calculation methods are selected, according to the difficulty of obtaining the relevant data, the appropriate indexes are selected, and the accounting methods are optimized, and the research ideas and models of the Yangtze River ship exhaust gas accounting method are preliminarily obtained in this paper.

(2) The second part is the analysis and calculation of the selected research indicators. AIS data is an important data source to determine the research indicators in this paper. In this part, the static and dynamic information provided by AIS is analyzed to obtain the calculation models of many research indicators in this paper, so as to calculate and determine the core index in the model – main engine load factor, which lays an important research foundation for later optimization and enrichment of the Yangtze river ship exhaust emission accounting model proposed in this paper.

(3) Based on the above exploration of research objects, research methods, data indexes and preliminary research models, this part mainly proposes the optimized accounting model of ship exhaust emissions in the Yangtze river, and proposes the calculation method of the list of ship exhaust emissions in the Yangtze river after the study of the main waterway of the Yangtze river by using this model, so as to preliminarily verify the reliability and applicability of the model of ship exhaust emissions in the Yangtze river.
2.2. Research route analysis

Figure 1. Research roadmap

The accounting model of ship exhaust emission in the Yangtze River is the focus of this paper, and also the core of the whole paper. Aiming at putting forward and optimizing the model and application method of ship exhaust emission in the Yangtze River, we design a preliminary research route. The research roadmap is shown in the figure above. Its basic structure consists of three levels, namely, the original data layer, the data processing layer and the research model layer. Ship AIS data is the data source of many indicators in this paper. Therefore, for the study of the model, this paper will start from the analysis of AIS data and mainly study the information of ship type, ship real-time speed, ship operating condition and ship voyage track. The research of ship type and ship real-time speed is to work out the calculation model of ship main engine load factor, which is the core data index of ship exhaust emission. The ship operating condition data, together with the main engine load factor obtained and the auxiliary engine load factor and emission factor obtained from literature search, can be used to calculate the exhaust emission of ships in the Yangtze River under certain operating conditions. Finally, the comprehensive analysis of AIS data of ship voyage, navigation and track data, Combined with the above mentioned emissions of ships, the total emissions of ships with the characteristics of time and space distribution were obtained. On this basis, the basic data were brought into the study, and the emission list of ships in the main waterway of the Yangtze River was obtained, finally achieving the research objective of this paper.

3. Waste gas accounting method for ships in the Yangtze river

3.1. Vessel activity level data collection

The research object of this paper is the ships in the Yangtze River channel, and the navigation situation of the ships in the Yangtze River channel is quite special. There are not only a large number of inland ships, but also many sea ships coming into the river from the Yangtze River estuary. Since there are certain differences between the two kinds of ships in ship size, power of equipment power, fuel type and
data richness, it is necessary to analyze and collect the activity level data respectively, so as to calculate the corresponding parameter indexes accurately and efficiently.

According to the literature, there are two accounting methods of ship exhaust emission. The top-down calculation method is used to calculate the total exhaust emission of the whole industry or a large water area. Due to the high difficulty in accurately collecting fuel data in a certain area, it is not applicable to the research object of this paper. On the other hand, this paper will study the temporal and spatial distribution characteristics of ship exhaust emissions from the whole Yangtze River channel. The study on the temporal and spatial distribution is inseparable from the detection and calculation of ship movement, so the collection of ship activity level data is an important link in this paper's accounting research.

The data source of ship activity level mainly comes from the AIS system. Static information transmitted by the AIS on board includes ship name, call sign, captain, ship width, imo number and ship type. Dynamic information includes ship position (latitude and longitude), course, speed, sailing status, etc. Through the analysis of AIS data, we can further query the rated power of main and secondary machines.

For inland river ships, the rated power of the main engine of the ship without AIS system can be obtained through the report information of the ship entering and leaving port and the information of the ship passing the lock; Rated power of auxiliary engine can be carried out by means of questionnaire survey. If there is no actual survey data, reference value of rated power of auxiliary engine of inland ships in technical guide for compilation of air pollutant discharge list of inland ships, a local standard of jiangsu province, can be adopted, as shown in table 1 [2].

| Table 1. Reference value of rated power of auxiliary engine for inland ship |
|---------------------------------------------------------------|
| **Ship type** | **Vice machine power rating (kw)** |
| Dry cargo ship |  
| First ship | 16.0 |
| Second ship |  
| Third ship | 13.7 |
| Fourth ship | 12.7 |
| Fifth ship |  
| Chemical tanker | 11.2 |
| Container ship | 16.0 |
| Tugboat/pusher tanker | 29.3 |
| Other ships | 12.7 |

According to the calculation accuracy requirements in this study, the navigation process is classified into three stages: cruise, berthing and anchoring. In the cruise stage, the main engine and auxiliary engine of the ship are kept in normal working state. In the berthing operation, the power of the main engine decreases and the power of the auxiliary engine increases. In the anchorage state of a ship, when the main engine is closed and the auxiliary engine and boiler are only kept at a low level, it can be considered that only the auxiliary engine is in use [3].

### 3.2. Emission factor

The emission factor of ship's exhaust gas represents the exhaust emission of ship at unit power, which is influenced by the main engine (or auxiliary engine) type, fuel type, ship's working condition and load of main engine and auxiliary engine. At present, the methods to get the emission factor of ship's exhaust...
gas are mainly the measurement method and the literature survey method. Based on 0 # diesel oil as the research sample, at the same time, with 0.2% of the sulfur content as emission factor correction range, according to the compilation requirements of the main engine emission factors of inland ships in the technical guide of compiling the list of atmospheric pollutants from inland ships in Jiangsu province, the recommended values of the emission factors corresponding to the following six types of exhaust emissions from inland ships are obtained, as shown in table 2:

| Project       | Emission factor | Nox  | PM10 | PM2.5 | SO2  | CO   | HC   |
|---------------|-----------------|------|------|-------|------|------|------|
| The host      | Medium speed    | 17.23| 1.59 | 1.40  | 12.30| 1.10 | 0.40 |
| Vice machine  | Medium speed    | 12.22| 0.29 | 0.26  | 0.86 | 1.10 | 0.40 |

There are some differences between the oil used by inland river ships and sea ships. According to the monitoring data of some oil products of Nanjing maritime administration, the sulfur content of oil products of sea ships ranges from 1.0% to 3.5%, while the sulfur content of oil products of sea ships is concentrated around 2.7%. The sulfur content of oil products in inland rivers ranges from 0.19% to 2%, and the sulfur content of oil products in inland rivers is concentrated around 1.5% [4]. According to the statistical results, the auxiliary engines are generally high-speed machines. Through literature search, the recommended values of various waste gas emission factors of sea-going ships are shown in table 3 [5]:

| Project       | Emission factor | Nox  | PM10 | PM2.5 | SO2  | CO   | HC   |
|---------------|-----------------|------|------|-------|------|------|------|
| The host      | High speed      | 18.10| 1.50 | 1.22  | 10.30| 0.50 | 0.60 |
|               | Medium speed    | 14.00| 1.50 | 1.22  | 11.31| 1.10 | 0.50 |
| Vice machine  | Medium speed    | 12.00| 0.32 | 0.26  | 0.86 | 1.10 | 0.40 |

| Project       | Emission factor | Nox  | PM10 | PM2.5 | SO2  | CO   | HC   |
|---------------|-----------------|------|------|-------|------|------|------|
| The host      | Host low load correction factor |
| load/%        | PM   | Nox  | Sox  | CO   | HC   |
| 2             | 7.29 | 4.63 | 1    | 9.68 | 21.18|
| 3             | 4.33 | 2.92 | 1    | 6.64 | 22.68|
| 4             | 3.09 | 2.21 | 1    | 4.86 | 7.71 |
| 5             | 2.44 | 1.83 | 1    | 3.89 | 5.61 |
| 6             | 2.04 | 1.6  | 1    | 3.25 | 4.35 |
| 7             | 1.79 | 1.45 | 1    | 2.79 | 3.52 |
| 8             | 1.61 | 1.35 | 1    | 2.45 | 2.95 |
| 9             | 1.48 | 1.27 | 1    | 2.18 | 2.52 |
| 10            | 1.38 | 1.22 | 1    | 1.96 | 2.18 |
| 11            | 1.3  | 1.17 | 1    | 1.79 | 1.96 |
| 12            | 1.24 | 1.14 | 1    | 1.64 | 1.76 |
| 13            | 1.19 | 1.11 | 1    | 1.52 | 1.6  |
| 14            | 1.15 | 1.08 | 1    | 1.41 | 1.47 |
| 15            | 1.11 | 1.06 | 1    | 1.32 | 1.36 |
| 16            | 1.08 | 1.05 | 1    | 1.24 | 1.26 |
| 17            | 1.06 | 1.03 | 1    | 1.17 | 1.18 |
| 18            | 1.04 | 1.02 | 1    | 1.11 | 1.11 |
| 19            | 1.02 | 1.01 | 1    | 1.05 | 1.05 |
| 20            | 1    | 1    | 1    | 1    | 1    |
The recommended value of the above main engine emission factor is determined when the host load is more than 20%. When the host load is less than 20% and continues to decline, the energy efficiency of the host will continue to decline, and the emission factor has a tendency to increase. When this happens, it is necessary to modify the main engine emission factor of the ship to some extent. The following is the reference value of partial main engine emission factor correction when the main engine load is less than 20%:

3.3. The load factor

Ship load factor refers to the proportion between the output power of real-time ship power equipment and its rated power under different sailing conditions, i.e., P/P amount. In normal sailing, in order to maintain the best performance of the power equipment of the ship, and due to the influence of the actual sailing environment on the ship's propulsion, the actual sailing power is generally less than its rated power, so there is a load factor. The load factor of the ship includes the load factor of the main engine and the load factor of the auxiliary engine. For the load factor of the main engine of the ship, it can be solved by the ratio of the propeller speed of the main engine of the ship to the rated maximum speed. At the same time, the load factor of the ship is also constant when the working condition of the ship is constant (the loading condition and sea condition and other information remain unchanged). Therefore, the calculation formula is as follows:

$$L_m = \left(\frac{n}{n_0}\right)^3$$

In the above formula: $L_m$ is the load factor of the ship's main engine; $n$ is the speed of the main engine under a certain working condition; $n_0$ is the maximum rotation speed of ship main engine.

However, in actual calculation, it is difficult to make statistics of the speed data of the main engine under specific working conditions by means of investigation or experiment. Meanwhile, due to the widespread application of AIS in ships in the Yangtze River channel, it is convenient to obtain the real-time speed data of ships, and the load factor of the main engine is closely related to the speed of ships. Therefore, the calculation method of the ratio between the real-time speed of ships and the maximum speed of ships can be used in the calculation.

$$L_m = \left(\frac{V}{V_{MAX}}\right)^3$$

In the actual calculation, real-time ship speed can be obtained through the analysis of AIS data, and the IMO number and name of the ship can be used to query the ship speed data in Lowe’s maritime database. On the basis of the obtained ship speed, the maximum speed of the target ship can be estimated by multiplying by 1.046.

The sub-engine load factor of ships mainly depends on the type of ships and the navigation state of ships. The types of ships in the Yangtze River channel mainly include bulk carriers, container ships, cruise ships, general cargo ships, tugs and oil tankers. Generally speaking, the sub-engine load factors of the above types of ships can be referred to the following data under the cruising, berthing and mooring conditions [6, 7]

| Ship type         | cruise | berthing | anchoring |
|-------------------|--------|----------|-----------|
| Bulk carrier      | 0.17   | 0.22     | 0.22      |
| Container ship    | 0.13   | 0.17     | 0.17      |
| Cruise ship       | 0.80   | 0.64     | 0.64      |
| General cargo ship| 0.17   | 0.22     | 0.22      |
| Tug               | 0.17   | 0.22     | 0.22      |
| Ro-ro             | 0.15   | 0.30     | 0.30      |
| Tanker            | 0.13   | 0.67     | 0.67      |
3.4. Construction of exhaust gas accounting model

This paper mainly studies the issue of ship emission accounting in the Yangtze River waterway. Its main feature is the accounting of the emission elements of a single ship in the waterway, such as the type of ship emissions, the emission characteristics of ships under specific working conditions, and the emission distribution of ships in different channel sections, etc. Therefore, the accounting method selected should have a considerable accuracy and reliability for the calculation of ship activities and the emission capacity of a single ship. In the current accounting method, the ship exhaust gas accounting method based on ship fuel consumption can only make a macroscopic estimation of global shipping emissions, which is not applicable to the research scenario in this paper. Meanwhile, because the popular AIS ship data source is reliable and relatively easy to obtain, the ship exhaust gas accounting method based on ship movement will be adopted in the following paper to further study the problem of ship exhaust gas accounting in the Yangtze River.

Based on the literature, we know that the way to calculate the exhaust emission based on the ship movement is to calculate the exhaust emission of the main engine and the auxiliary engine respectively. The basic formula is:

\[ E = E_m + E_a \]  \hspace{1cm} (3)

In the above formula: \( E \) is the ship's exhaust emission; \( E_m \) is the exhaust emission from the main engine of the ship; \( E_a \) is the exhaust emission of ship auxiliary engine.

Calculation of ship power plant emissions need to obtain the power of the equipment, operation time, emission factor and the load factor of the device in order to get the following formula:

\[ E_i = \sum_i P_j L_j T_j F_{i,j} = P_m L_m T_m F_{i,m} + P_a L_a T_a F_{i,a} \]  \hspace{1cm} (4)

In the above formula: \( i \) is the type of ship exhaust gas, \( E \) is ship exhaust emission, \( P \) is the power of ship power equipment, \( J \) is the power equipment type, \( m, a \) stands for main engine and auxiliary engine respectively; \( L \) is ship load factor; \( T \) is the running time, \( F_{i,j} \) is emission factor. The calculation formula of load factor of ship main engine is:

\[ L_m = (V/V_{MAX})^3 \]  \hspace{1cm} (5)

Substitute equation (5) into equation (4) to get:

\[ E_i = P_m (V/V_{MAX})^3 T_m F_{i,m} + P_a L_a T_a F_{i,a} \]  \hspace{1cm} (6)

Based on the above formula, we can know all the calculation parameters we need to determine. Through the analysis of 1, 2 and 3, we can carry out the calculation by referring to the above reference data when the basic information of the ship is known.

On the other hand, the operating conditions of the ship also determine the selection of some measured data when calculating the exhaust emissions, such as the speed of the ship, the number of power equipment and the load factor of the auxiliary machine. The time data of the ship's berthing conditions and the ship's mooring conditions are easier to obtain, and the running time of the ship under normal navigation conditions needs to be further converted. The conversion formula is:

\[ T = L/V \]  \hspace{1cm} (7)

In the above formula: \( T \) is the running time of the normal navigation conditions of the ship; \( L \) is the length of the channel; \( V \) is the speed of the ship. Among them, the ship's speed is relatively stable under normal operating conditions, and it is easy to estimate its average speed during navigation.
4. Single ship exhaust emission level calculation example

4.1. Verification object
In order to verify the accounting method of this model, we selected the voyage data of a seagoing ship to measure its emission characteristics during the voyage. In the process of calculation, only the exhaust emissions of the ship's main engine and the ship's auxiliary machine are considered. The navigation trajectory, speed change and working condition changes of the ship are recorded in the voyage. The sea boat mentioned above is used. With reference to the data, the emission of the six types of exhaust gas is finally obtained, and the emission list of the voyage is initially drawn up. The basic data of the four measured ships are shown in the following table [9]:

| MIMSI       | Ship type    | Date of construction | Weight (t) | The host power | The host type                      |
|-------------|--------------|----------------------|------------|----------------|-----------------------------------|
| 413774189   | Dry cargo ship | 2010/10/8            | 359        | 220            | internal combustion engine        |

We analyze the activity data of the ship and number it. The data is shown in the following figure:

| The ship number | MIMSI | voyage | Time of departure | End of voyage time |
|-----------------|-------|--------|-------------------|-------------------|
| Cargo ship A    | 413774189 | 4411   | 1517414434        | 1527601325        |

**Figure 2.** Dry cargo ship a track scatter diagram

**Figure 3.** Trajectory of cargo ship a voyage 4-411
4.2. Conclusion analysis

Through the above data analysis, we selected six kinds of exhaust gases, such as NOx, PM, SO2, CO and HC, to calculate the calculation method of the Yangtze River's exhaust emission accounting based on AIS data constructed above. The following calculation results do not consider the impact of factors such as waves and currents on ship activity data. The calculation results are shown in the following table:

| Serial number | SO2   | CO    | CO2   | PM    | NOX   |
|---------------|-------|-------|-------|-------|-------|
| Cargo ship A  | 31192.36 | 3805.03 | 1867516 | 2856.66 | 49639.35 |

The accuracy of the calculation of the Yangtze River's ship's exhaust gas can vary with the accuracy of the flight segment. We can calculate the ship's exhaust emissions for a specific flight time period by locking the measurement time and can calculate the ship's exhaust emissions for a specific flight segment by locking a measured flight segment, and finally realize customized accounting of ship exhaust emissions under different working conditions at different time and space latitudes in the Yangtze River channel [10].

5. Conclusion

The regulation of exhaust emissions in the shipping industry is difficult, and its scope and base are large. As far as the current level of supervision capability is concerned, the control of ship emission in both inland and sea areas is still very difficult, especially for the Yangtze River Channel. Increasing the level of ship exhaust gas regulation has become a problem we have to face. This paper studies how to efficiently and accurately calculate the emissions of Yangtze River's ships. The research includes analyzing the characteristics of research objects, exploring reliable data sources, comparing calculation methods, accounting model construction and accounting method instance verification. The main research objective is to optimize the ship exhaust gas calculation model and analyze the emission characteristics of ships (including inland vessels and sea vessels) in the Yangtze River channel. Finally, the model calculates the emission data of the main components of the ship's exhaust gas, and finally draws out the ship exhaust emission list for the Yangtze River basin.

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