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Establishment of Inland Ship Air Pollution Emission Inventory Based on Power Method Correction Model

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Abstract: The atmospheric pollutants and greenhouse gases emitted by ships have a significant impact on the air quality of the cities around the port and the physical and mental health of the residents. In order to promote the low-carbon, green, and sustainable development of the region, it is urgent to conduct comprehensive research and control the air pollution emissions from ships in the region. In this paper, the traditional power-based emission inventory calculation model is improved through field tests, and the engine propeller matching coefficient is proposed. Combined with the actual situation of local ships, the parameters suitable for the air pollution emission inventory of ships in the region are comprehensively selected. In the case of statistical comparison of the air pollutant emissions of the main and auxiliary engines under different navigation conditions, the uncertainty analysis was carried out, and the AIS (Automatic Identification System) combined with the power method was used to obtain the air pollution emission inventory of ships in the main urban area of Chongqing. The research in this paper can improve the calculation model of the power method emission inventory according to the situation of ships in the inland river area, which provides a reference for the development and improvement of the emission inventory in the inland river area, and also provides suggestions and thinking for the government to formulate energy saving and emission reduction measures in the inland river area.

Keywords: ship emission inventory; AIS data; engine propeller matching coefficient; air quality; emission factor

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1. Introduction

In recent years, with the gradual strengthening of motor vehicle pollution control, the emission sharing rate of ship exhaust pollutants has gradually increased, so the government and researchers have begun to pay attention to the issue of ship pollution control [1]. China is rich in inland shipping resources. In 2018, the freight volume of the Yangtze River trunk line reached 2.69 billion tons, a year-on-year increase of 7.6%, ranking first in the world's inland rivers. At the same time, the annual container throughput of the Yangtze River trunk line reached 17.5 million TEU (20 feet in length), 6.1% [2]. In the last few years, with the gradual strengthening of motor vehicle pollution control, the emission sharing rate of ship exhaust pollutants has gradually increased, so the government and researchers have begun to pay attention to the issue of ship air pollution control. Ships generally use diesel engines as power sources. The diesel engines have poor operating conditions, harsh working environments and high power, and the quality of the marine fuel or diesel used is difficult to guarantee. In addition, the emission standards of ships in my country are seriously behind the emission standards of motor vehicles, and most ships are neglected in maintenance. Therefore, the impact of air pollutants emitted by a single ship on the environment is generally far more serious than that of motor vehicles. Marine diesel engines produce a large number of air pollutants during operation, mainly including CO, CO_2, NO_X, SO_X, HC, particulate matter $PM_{2.5}$, VOC_S (volatile organic compounds), and BC (black carbon) [3]. The SO_2 and NO_X produced by ship emissions undergo chemical reactions again in the atmosphere to generate pollutants such as sulfate and nitrate [4]. The growing inland shipping has seriously affected the environment near ports and waterways and the air quality of cities and has brought enormous pressure to the prevention and control of atmospheric pollution.

With the gradual expansion of the shipping trade and the control of sulfur content in fuel oil, the characteristics of air pollution emissions from ships have changed significantly. Air pollution emissions from ships have attracted more and more attention from the public sector and scientific researchers [5]. In the past ten years, the government and relevant environmental protection departments have formulated and implemented a series of regulatory control measures for the emission of air pollutants from motor vehicles in the region. In contrast, the research on air pollution emissions from ships in inland waters is still relatively weak. The atmospheric pollutants and greenhouse gases emitted by ships will have a great impact on the air quality of the cities around the port and the physical and mental health of the residents. With the promulgation of the country's new air quality standards and the pressure to reduce air pollution from the regional environment, in order to promote the low-carbon, green and sustainable development of the region, it is urgent to conduct comprehensive research and control on regional ship air pollution emissions.

In view of this, the GB3552-2018 "Ship Water Pollution Discharge Control Standard" issued by the Ministry of Environmental Protection and the General Administration of Quality Supervision and Quarantine of the People's Republic of China has been implemented since 1 July 2018 [6]. The main purpose is to prevent and control water pollution and promote the green development of the manufacturing industry of ships and related devices. The Outline of the Construction Planning of the Chengdu–Chongqing Economic Circle clearly pointed out that the concept of ecological civilization should be fully implemented, the ecological protection of the upper reaches of the Yangtze River should be strengthened, and the red line of ecological protection should be strictly observed [7]. The "14th Five-Year Plan" for the maritime system clearly states that by 2025, the NO_X and SO_X emissions from operating ships will drop by 7% and 6%, respectively, compared with 2020 [8]. At the two sessions in 2021, "carbon peaking" and "carbon neutrality" were written into the government report for the first time. China solemnly pledged to achieve "carbon peaking" by 2030 and strive to achieve "carbon neutrality" by 2060. "Carbon peaking" and "carbon neutrality" are not only related to the responsibility relationship between countries to reduce emissions but they are also closely related to China's sustainable development goals [9]. It can be seen that the country and the government have paid more and more attention to the influence of the atmospheric environment on the health of the people, and it is imperative to strengthen the control of air pollution and improve the atmospheric environment.

At present, the research on ship pollution discharge in China is in the stage of rapid development. The research on ship pollution discharge mainly focuses on ocean shipping and coastal cities [10–13], and there are not many studies on inland shipping. Therefore, it is urgent to establish a high-precision ship air pollution emission inventory for a more refined emission calculation model in the inland river area [14]. The traditional power method model does not consider the matching of the propeller of the ship and is not applicable to the actual navigation of the ship in the inland river area. Engine propeller matching greatly affects the efficiency of diesel engine energy conversion. When the engine–propeller matching is unreasonable or even poor, the diesel engine will be damaged during the ship's sailing process, and the fuel consumption rate will increase. It is directly related to the air pollution emissions of ships. After conducting the tail shaft power test of representative ships in the region, it was found that the matching coefficient of the propellers affects the accuracy of the ship's pollution emission inventory. Therefore, this paper corrects the traditional power method emission inventory calculation model by introducing the engine propeller matching coefficient, which can optimize the pollution emission inventory of inland ships, and also provide suggestions and thinking for the Chinese government to formulate energy saving and emission reduction measures in inland river areas.

2. Research Methods and Technical Routes

2.1. Literature Review

In order to formulate effective measures for the prevention and control of the air pollution from ships, it is necessary to establish a complete emission inventory and find out the emission status of various pollutants in the study region [15]. At present, there are many calculation models [16,17]. According to the database and method based on, the calculation model can be mainly divided into fuel consumption method (top-down) and power method (bottom-up).

2.1.1. Fuel Consumption Method

The fuel consumption method is a method of obtaining the fuel consumption of various types of ships according to statistics, obtaining the pollution emission factor of a certain type of ship, and then multiplying the fuel consumption by the emission factor to obtain the total pollution emission [18]. This method is also known as the "top-down" method. The operation is relatively simple, but it lacks the reflection of the actual sailing state of the ship. Therefore, the calculation results of this method have great uncertainty. It is often used to compile emission inventories at the national and global levels. Li et al. [14], based on the actual local situation, referring to the reports of ship energy consumption in the jurisdiction, and using the fuel consumption method, established the 2018 coastal and oceangoing ship air pollutant emission inventory of Zhuhai Gaolan Port.

2.1.2. Power Method

In order to effectively improve the accuracy of a ship emission inventory, AIS is gradually applied to the compilation of ship pollutant emission inventory. Detailed information such as the speed, time, and position of AIS is used to reflect real-time dynamic activity information such as the ship's navigation trajectory and navigation conditions. This method is also known as the "bottom-up" method. This method records the activities of ships in detail and selects targeted emission factors according to the actual navigation status, which can reflect the spatial and temporal distribution characteristics of pollution emissions [19]. However, this method has high requirements on the model and requires a large amount of basic ship information and activity data. These data sources are different and difficult to obtain, so improper selection may easily lead to uncertainty.

In 2009, Jalkanen et al. [20] used AIS data for the first time in the compilation of the Baltic Ship Pollution Emission Inventory. Li et al. [21] developed a highly resolved inventory of ship emissions in China's Pearl River Delta region using precise data from AIS. Bie et al. [10] conducted field measurements around Qingdao Port and used various methods to evaluate and analyze the data to determine the pollution emission inventory of ships. Combined with regional emission factors, Yang et al. [12] used the "bottom-up" method based on AIS data to establish a Tianjin high-space-time ship emission inventory. Yin et al. [13] used the emission factor method of ship activities, combined with AIS data and ship characteristic information of Lloyd's Register of Shipping, and established the Ningbo-Zhoushan Port Ship Emission Inventory. Wang et al. [11] adopted the "bottom-up" dynamic method, based on AIS data combined with a large number of field survey information of Xiamen ports, and established the 2018 Xiamen air pollution emission inventory. Shen [22] combined the basic ship information database of the Maritime Safety Administration and the dynamic information of AIS to establish a high-precision ship air pollutant emission inventory in Shanghai Port. Yuan et al. [23] combined AIS data and Lloyd's Register database and used the STEAM model to establish a ship emission inventory for 10 control sections in the Jiangsu section of the Yangtze River.

2.2. Research Methods

With the continuous development and improvement of AIS technology, all ships are restricted to requiring to install AIS, and the static database and dynamic database of ships have been gradually improved. The power method based on AIS data has gradually become the mainstream method for calculating the air pollutant emission inventory of ships in small-scale sea areas and inland river areas. At present, domestic research on ship pollution emissions is in a stage of rapid development. The research on ship pollution emissions mainly focuses on ocean shipping and coastal cities, and there are not many studies on inland shipping. Therefore, it is urgent to establish a high-precision ship air pollution emission inventory for a more refined emission calculation model in the inland river.

2.2.1. Data Acquisition

Before the calculation of regional ship air pollution emissions, it is necessary to analyze and process the obtained AIS data while obtaining the AIS data published on the Internet through the python computer programming language. Firstly, the AIS information is translated and decoded into data that can be read and used intuitively by using Python computer programming language, and the basic information data including ship name, ship type, Captain, ship width, MMSI (Maritime Mobile Communication Service Identification Code), timestamp, longitude and latitude, speed, course, and destination are obtained. The above data are stored in the ship navigation information database. In order to perform the subsequent emission calculation process more intuitively, AIS data were acquired every 3 min in this study. In the acquired AIS data under the same MMSI, if there are duplicate data with the last acquisition, they will not be written into the database. If the subsequently acquired data of the ship is different, they will be written into the database. The time between the two data is acquired by the ship. The interval represents the time in the moored state. The acquired AIS data may contain bit error rate, abnormality, and missing data, and subsequent data elimination and sorting are required. For example, the MMSI and ship position information obviously do not conform to the actual situation, and different ships use the same MMSI and data that the speed obviously does not conform to the actual situation. Therefore, it is necessary to clean the AIS data, automatically identify abnormal data, and supplement the missing data before the subsequent calculation of pollution emissions.

2.2.2. Technical Routes

This article uses the above methods to obtain and process data. Based on the AIS data combined with the power method, the regional ship air pollution emission inventory is obtained by making full use of the ship data information. Considering the regional hydrological environment and ship characteristics, the traditional power method is improved, and a local inland ship emission calculation model is proposed so as to optimize the accuracy of the discharge inventory. The technical route of this research is shown in Figure 1.

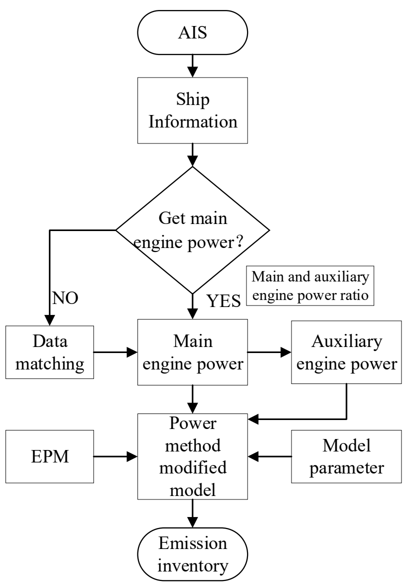

Figure 1. Technical route.

3. Establishment of Ship Emission Calculation Model

The Ship Traffic Emission Estimation Model (STEAM) based on AIS was proposed by Jalknean et al. [20]. On the basis of simplifying STEAM to meet the localization requirements, Gu et al. [24] proposed a basic equation suitable for inland ships, as shown in Equation (1).

The matching of the propeller of the ship affects the energy conversion efficiency of the diesel engine, which in turn affects the fuel consumption, and which will lead to a large deviation in the calculation of the pollutant emission inventory. Therefore, Equation (1) is improved in this paper, and the engine propeller matching coefficient (*EPM*) is introduced to further modify the model. The "bottom-up" power method was used to calculate the air pollution emissions from ships in the main urban area of Chongqing, and the model was revised by introducing the ship's engine propeller matching condition coefficient. The specific revision process of the model is shown in Section 3.4 below.

Equation (1) represents the original STEAM model, Equation (2) represents the revised main engine emission model, and Equation (3) represents the auxiliary engine emission model.

$$E = MCR \times LF \times EF \times FCF \times T \tag{1}$$

$$E_{Mj} = MCR \times LF_i \times EF_{ij} \times FCF \times EPM \times T_i \times 10^{-6} \tag{2}$$

$$E_{Aj} = ELD \times LF_i \times EF_{ij} \times FCF \times T_i \times 10^{-6} \tag{3}$$

where E is pollutant emission (t), M is main engine emission model, A is auxiliary engine emission model, MCR is the main engine power (kW), and ELD is auxiliary engine power (kW). Moreover, i is the driving mode, which is divided into four modes: cruise, low-speed cruise, maneuvering, and mooring. Furthermore, j is the pollutant type, and it is divided into CO, HC, NO_X, PM_{10}, $PM_{2.5}$, SO_X, and the greenhouse gas CO_2.

LF is the load factor, and the load factor is determined by the engine type and sailing conditions. EF is the emission factor, and it is determined by the engine type, operating conditions, and fuel type. FCF is the fuel correction factor. EPM is the engine propeller matching correction coefficient. T is time (h).

The parameters in the model will be studied and determined below.

3.1. Determination of Ship Main and Auxiliary Engine Power

The engines on ships are divided into the main diesel engine that provides power and the auxiliary diesel engine that is used to generate electricity. Because the rated power information of the main and auxiliary engines is missing from the AIS ship data published on the Internet, in recent years, some researchers have obtained the main engine power of the ships from the Lloyd's Register database. The Lloyd's Register database counts global ship information. Considering that there are some differences in the main engine power of ships on the Yangtze River trunk line in my country compared with other countries, this study uses the ship MMSI provided in the AIS information as a key factor to find and obtain the main engine of the ship in the National Maritime Traffic Safety Management Information Service Platform (AIS Information Service Platform). It records the power, the ship design speed, shipload, and other information. However, a small number of ships have not recorded the main engine power in the AIS information service platform. Some researchers have fitted the main engine power of the ship by combining the basic dimensions of the ship, the maximum design speed or the deadweight, and other data. For example, Xing et al. [3] proposed a fitting function between the main engine calibration power, the ship's design speed, and the ship's deadweight in the calculation of marine exhaust emissions in the vicinity of ports in Liaoning Province. The main urban area of Chongqing City in this study area belongs to the Three Gorges Reservoir area. For this reason, this paper refers to the captain classification in the "Main Scale Series of Standard Ship Types for Transport Ships in the Chuanjiang and Three Gorges Reservoir Areas"

(2016 Revised Edition) and selects the recommended power value of the main engine according to the ship type and captain.

Ship auxiliary engine power is seriously missing in the ship static database. At present, most researchers calculate the rated power of the auxiliary engine through the ratio of the rated power of the main and auxiliary engines according to the ship type. The California Air Quality Commission obtained the power ratio of main and auxiliary engines of different types of ships by investigating the power of main and auxiliary engines of a large number of ships [25]. After comprehensive analysis and comparison, the ratio of the rated power of the auxiliary engine to the rated power of the main engine is comprehensively determined according to the characteristics of the power ratio of the main and auxiliary engines of the ship in the field research area and the actual ship measurement experiment process of the ship's shaft power. The power ratio of the main and auxiliary engines of various types of ships is shown in Table 1 below.

Table 1. Ship main and auxiliary engine power ratio.

Ship Type	Ratio of Auxiliary Engine Power to Main Engine Power
Cargo ship	0.222
Passenger Ship	0.278
Oil tanker	0.225
Special ship	0.186
Container ship	0.220
Other type	0.191

3.2. Determination of Load Factor of Main and Auxiliary Engines of Ships

The load factor is mainly affected by the type of engine and the operating state of the ship. According to the product of the rated power and the load factor of the main and auxiliary machines under different working conditions, the actual operating load power of the main and auxiliary machines under different working conditions can be obtained. Most of the output power of the marine diesel engine is used to drive the propeller to rotate, and the load factor of the diesel engine changes according to the principle of the propeller. The calculation of the load factor of the marine diesel engine is shown in Equation (4) below.

$$LF = (Speed_{Actual}/Speed_{Maximum})^3 \tag{4}$$

in which

LF is the ship main engine load factor (dimensionless)

$Speed_{Actual}$ is the actual speed of the ship sailing(kn)

$Speed_{Maximum}$ is the maximun design speed of the ship(kn)

The auxiliary engine load factor of ships cannot be obtained directly through the formula. In this study, the recommended value of the auxiliary engine load factor for different ship types under different sailing conditions was from the IMO meeting report by Smith TWP et al. [26]. For the auxiliary engine load factor, see Table 2 for details.

Table 2. Load factor of main and auxiliary engines.

Operating Conditions	Main Engine	Auxiliary Engine
Cruise	0.8	0.13
Low speed cruise	0.6	0.20
Maneuvering	0.2	0.25
mooring	0	0.17

3.3. Main and Auxiliary Engine Pollution Emission Factor with Correction Factor

The emission factor is mainly determined by the engine type, sailing conditions, fuel type, etc. The main engine of the regional inland ships is generally a medium-speed engine, and the auxiliary engine is a high-speed engine. Theoretically, the fuel used is light diesel with a sulfur content not exceeding 0.1%. This paper refers to the relevant research results at home and abroad and carries out the correction method to comprehensively determine the basic emission coefficient of the main and auxiliary engines of ships in the main urban area of Chongqing [13]. For inland ships in the Yangtze River Basin, the relevant researchers used diesel fuel with a sulfur content of 2.7% for the ship's air pollutant emission factor. The emission factors are shown in Table 3.

Table 3. Fuel emission factor (2.7% sulfur content).

Type	CO g/kWh	HC g/kWh	NO_X g/kWh	PM_{10} g/kWh	$PM_{2.5}$ g/kWh	SO_X g/kWh	CO_2 g/kWh
Main engine	1.1	0.5	11.2	1.5	1.2	11.5	646.1
Auxiliary engine	0.9	0.4	8.2	1.5	1.2	12.3	690.7

In December 2018, the Ministry of Transport adjusted the scope and control standards of emission control for the navigable waters of the Liuhe Estuary in Jiangsu. The plan requires that from 1 January 2019, ships entering the Yangtze River Basin shall not use fuel oil with a sulfur content exceeding 0.1%. The scope of this study is the main urban area of Chongqing, from September to December 2021. Therefore, based on the basic emission factor (*FCF*), the corrected value of 0.1% of the sulfur content of marine fuel oil is used as the actual emission factor. The correction factor of light diesel with 0.1% sulfur content in ships is shown in Table 4.

Table 4. Fuel correction factor (sulfur content 0.1%).

Fuel Type	CO	HC	NO_X	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Light diesel	1	1	0.94	0.17	0.17	0.04	1

It can be seen from the above table that the emission factors of CO, HC, and CO_2 did not change after the marine fuel oil used light diesel with a sulfur content of 0.1%, while the effect of SO_X was more significant, followed by PM_{10}, and $PM_{2.5}$ has little effect on NO_X. The use of light fuel oil with a sulfur content of 0.1% has a greater impact on the calculation of sulfur-containing pollutant emissions and also has a certain degree of impact on PM_{10} and $PM_{2.5}$.

3.4. Engine Machine Propeller Matching Coefficient

3.4.1. Measurement of Shaft Power of Marine Diesel Engine

Diesel engine load refers to the ratio of the actual output effective power to the maximum power that can be output at a certain speed. The diesel engine load characteristics are the main basis for discussing the fuel economy of ships. When the engine–propeller matching is poor, the diesel engine load is heavy, and the fuel consumption is high. When the diesel engine is in a low-load incomplete combustion state, continuing to increase the fuel supply will cause a lot of black smoke. On the one hand, the above two situations make the diesel engine prone to wear and consumption, causing failures and affecting the life of the diesel engine. Therefore, it is of great significance to understand the load status of the diesel engine shaft power test of regional inland river ships, to make the calculation inventory of air pollutants more accurate and to have more obvious spatial and temporal distribution characteristics.

3.4.2. On-Board Measurement of Marine Diesel Engine Shaft Power

Due to the large number of ship types and the high testing cost of actual ships, this study selected five representative inland river ships that sail in the region all year round.

Regional ships are mainly cargo ships, so the test objects selected in this paper are mainly cargo ships. The parameter information of the ship is shown in Table 5. The test site was selected as the Three Gorges Reservoir area with gentle water flow and a wide section of the river to ensure that the test results are affected as little as possible by the external hydrological environment. In this study, the resistance strain gauge torque measurement method was used to track and measure the tail shaft power of the diesel engines in real time on five representative ships in the region. The arrangement of the shaft power measuring points is shown in Figure 2.

Table 5. This Regional Ship Loading Conditions.

Hull Number	Main Engine Type	Rated Power (kW)	Rated Speed (r/min)	Main Engine	Load Ratio
1	ZC817ZLC-20	575	1350	Left Right	123% 141%
2	ZC6210ZLC-1	735	830	Left Right	127% 122%
3	ZC6200ZLC-2	882	1000	Left Right	125% 124%
4	ZC6200ZLC-4	1103	1000	Left Right	119% 121%
5	ZC6220ZLC-1	992	1000	Left Right	126% 125%

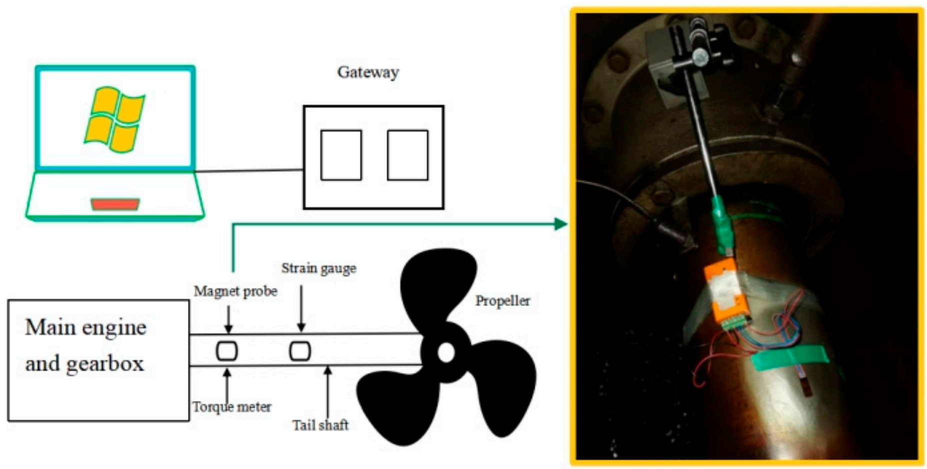

Figure 2. Layout of axis power measuring points.

3.4.3. Engine–Propeller Matching Status of Regional Ships

Engine–propeller matching greatly affects the efficiency of diesel engine energy conversion. When the engine–propeller matching is unreasonable or even poor, the diesel engine will be damaged during the ship's voyage, and the fuel consumption rate will be increased, which is directly related to the ship's air pollution emission. For this reason, according to the test data of the tail shaft power of five representative ships in the region, this paper shows that the engine–propeller matching of ships in the region is generally poor due to factors such as the hydrological environment of the inland waterway and the old diesel engine and untimely maintenance. The propeller load is generally heavy, and the detailed data are shown in Table 5.

From Table 5, it can be concluded that the average matching of the right main engine propeller of the No. 1 is 141%, and the average matching of the left main engine propeller is 123%. The propellers of both main engines are heavy, resulting in higher fuel consumption than other ships at the equivalent speed. Considering that the engine–propeller matching has an important impact on the ship's air pollution emissions, this paper introduces the engine–propeller matching coefficient into the calculation model, and the coefficient is taken as the average value of the five ships' load ratio of 1.25. The above-mentioned shaft power test experiments provide a scientific basis and guarantee for the subsequent development of high-precision ship air pollution emission inventories and accurate analysis of spatial and temporal distribution characteristics.

4. Calculation of Air Pollutant Emissions from Ships

The study area was set as 106°25.233 E, 29°40.117 N—107°06.017 E, 29°19.650 N, covering three major ports in the main urban area of Chongqing, namely Guoyuan Port, Cuntan Port, and Luoqi Port. The specific location of the port is shown in Figure 3. Based on the obtained AIS data published on the Internet and the above-mentioned emission calculation models and parameters, this section mainly calculates the regional emissions of air pollutants from ships. The data calculation time range was from September to December 2021, Beijing time, for a total of 4 months. Considering the large amount of acquired AIS data and the multi-source heterogeneity, which causes the number of calculations to be large and complicated, this paper obtained 5-day regional ship AIS data over one month, took the average value, and multiplied the average value by the monthly average value. The number of days, in which the time of each acquisition was from 00:00 to 24:00 of the day, and the AIS data collection frequency was collected every 3 min. In order to make the emission calculation result closer to the real value, the 5th, 10th, 15th, 20th, and 25th of each month were considered to be the AIS data collection time after comprehensive analysis.

Figure 3. Port location map.

4.1. Air Pollutant Emissions under Different Navigation Conditions

From September to December 2021, the air pollutants CO, HC, NO_X, PM_{10}, $PM_{2.5}$, SO_X, and greenhouse gas CO_2 emitted by ships in the study area were 95.03 t, 42.96 t, 873.87 t, 25.04 t, 18.80 t, and 43.44 t, respectively, 61,002.97 t, totaling 62,102.12 t. The largest emission was CO_2, followed by NO_X, the third and fourth were CO and SO_X, and the smallest emission was $PM_{2.5}$. Among them, the total emission of main engine cruising was 16,491.52 t, the total emission of main engine low-speed cruise was 21,381.66 t, the total emission of maneuvering in the main engine port was 533.05 t, the total emission of auxiliary engine cruising was 528.13 t, the total emission of auxiliary engine low-speed cruise was 1388.40 t, and the total emission of maneuvering in the auxiliary engine port was 100.95 t. The total mooring emission of the auxiliary engines was 21,678.42 t. The atmospheric pollutant emissions of the main and auxiliary engines under different navigation conditions are shown in Tables 6 and 7.

Table 6. Air pollutant emissions of main and auxiliary engines under different navigation conditions (unit: t).

Condition	CO	HC	NO_X	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Main engine cruise	27.52	12.51	263.41	6.38	5.10	11.51	16,165.09
Main engine low sailing	35.68	16.22	341.49	9.81	6.62	14.92	20,956.93
Main engine motorization	1.39	0.70	8.30	0.23	0.18	0.37	521.86
Auxiliary engine cruise	0.68	0.30	5.81	0.19	0.15	0.37	520.62
Auxiliary engine low sailing	1.78	0.79	15.27	0.51	0.40	0.97	1368.67
Auxiliary engine motorization	0.13	0.06	1.11	0.04	0.03	0.07	99.52
Auxiliary engine mooring	27.85	12.38	238.49	7.89	6.31	15.22	21,370.28

Table 7. Contribution ratio of each pollutant under different navigation conditions (unit: %).

Condition	CO	HC	NO_X	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Main engine cruise	28.96	29.12	30.14	25.47	27.15	26.49	26.50
Main engine low sailing	37.54	37.75	39.08	39.17	35.18	34.35	34.35
Main engine motorization	1.47	1.64	0.95	0.91	0.97	0.86	0.86
Auxiliary engine cruise	0.71	0.70	0.66	0.77	0.82	0.85	0.85
Auxiliary engine low sailing	1.88	1.85	1.75	2.02	2.15	2.24	2.25
Auxiliary engine motorization	0.14	0.13	0.13	0.15	0.16	0.17	0.16
Auxiliary engine mooring	29.30	28.81	27.29	31.51	33.57	35.04	35.03

Among the various air pollutants emitted by ships, the first three items with the largest proportion of the navigation state are the auxiliary engine mooring, the main engine low sailing, and the main engine cruising. The total discharge of each pollutant in these three states accounts for about 95% of the total discharge of this pollutant, which is related to the data on the activity level of ships in the region. The power of the auxiliary engine is much smaller than that of the main engine, and the air pollution emission of the main engine per unit of time is much larger than that of the auxiliary engine. The mooring state takes the longest time during the ship sailing process, followed by the main engine low sailing and the main engine cruising. During the voyage of a single ship in inland rivers, two main engines and one auxiliary engine are generally operated.

4.2. Uncertainty Analysis of Emissions Calculation

In the process of calculating air pollution emissions from ships, due to the influence of data collection and sorting, uncertainty inevitably exists, but the uncertainty can be analyzed and studied to make the calculation results as close to the real value as possible. Based on AIS data, this paper uses the power method to calculate and analyze the air pollution emissions from ships in the main urban area of Chongqing from September to

December 2021. When calculating AIS ship activity data, there may be some ships in the area without AIS equipment installed, and there may be data collection errors and human errors in the process of collecting AIS data using python code. The uncertainty of this study mainly includes the following four aspects:

- Ship database. Since there is no ship main and auxiliary engine power in the obtained AIS data, this study used the ship MMSI provided in the AIS information as a key factor to finding the ship's main engine power in the National Maritime Traffic Safety Management Information Service Platform (AIS Information Service Platform). The greater the power of the main engine, the more environmental protection fees need to be paid. For this reason, some shipping companies have transformed the main engine of the ship to make the "inconsistency", causing the real main engine power of the ship to be greater than the main engine power in the AIS information service platform. In addition, some ships without main engine power in the AIS information service platform use the recommended main engine power value, which is far from the actual value of the main engine power of the ship. On the other hand, the database of auxiliary engine power is seriously lacking. This study uses the ratio of main and auxiliary engine power to determine the auxiliary engine power based on domestic and foreign research experience.
- Emission factor. Emission factors are particularly important in the calculation of emissions inventories. The experimental cost of emission factor measurement is high, and the operation is difficult. At present, there are few experimental measurement results of the emission factor of inland river ships in China, and the authenticity is difficult to guarantee. Therefore, this study refers to the emission factors commonly used at home and abroad to try to select the appropriate emission factors for ship pollution in this area. However, there are certain differences in the performance of diesel engines, fuel consumption, crew operating habits, and the hydrological environment characteristics of inland ships in the study area, which makes the calculation results still differ from the real values of ship emissions in this region.
- Fuel. The Ministry of Transport has promulgated the implementation standard of sulfur content in fuel oil, but some shipping companies have not reached this standard in order to save shipping costs but still use high-sulfur fuel oil. The emission coefficients of high-sulfur fuels are several times higher than those of low-sulfur fuels, which makes the calculated results of emissions differ greatly from the actual values.
- The condition of the ship connecting to the port shore power is not considered. If the ship is connected to the port shore power during the port of call, the air pollution emission will be reduced accordingly.

5. Discussion

In this paper, the methods for calculating the air pollution emission inventory of ships are investigated, and the advantages and disadvantages of the methods are analyzed and compared with reference to the literature. Finally, the power method with higher calculation accuracy is selected to calculate the regional air pollution emission inventory of ships. Considering the complex and changeable hydrological environment of inland rivers in the region, the generally high age of ships, old diesel engines, untimely maintenance, etc., the representative ship load conditions were measured, and a calculation model of ship air pollutant emissions with regional characteristics was established. The research of this paper mainly focuses on the following three aspects:

Firstly, using the power method to calculate the air pollution emission inventory of ships. Among them, AIS real-time navigation data help to identify various basic information about the ships, and the ship navigation information database provides us with a convenient data storage platform, which makes the subsequent emission inventory calculation more intuitive. In previous studies, AIS data did not play to the advantage it should have.

Secondly, with reference to the latest regulations of the Ministry of Transport on the sulfur content of fuel oil for ships entering the Yangtze River, the pollution emission factors of the ship's main and auxiliary engines in the ship's emission inventory model have been updated. For inland ships in the Yangtze River, previous researchers used diesel with a sulfur content of 2.7%. According to the regulations, light diesel oil with a sulfur content of 0.1% was introduced as the fuel correction factor for the emission factor. In this way, the emission inventory calculation model of inland ships can be updated in time.

Thirdly, real-time tracking and measurement of the tail shaft power of diesel engines were carried out on five representative inland river ships, and the matching of the propellers of the marine diesel engines was studied. The propeller load of ships in the region is generally heavy, and the unreasonable matching of propellers leads to an increase in the load of diesel engines during the sailing process of ships, resulting in an increase in fuel consumption rate, which directly affects the air pollution emissions of ships. In previous studies, the pollution discharge inventory of inland river ships did not take into account the matching of the ship's engine and propeller, resulting in increased uncertainty in the emission inventory. Therefore, after the field test, the load ratio of the marine diesel engine was selected as 1.25. The above shaft power measurement experiment verified the heavy load of the ship according to the actual situation of the inland ship and introduced the engine propeller matching coefficient. This provides a strong basis for the calculation of emission inventory of old ships in inland rivers and improves the universality of the calculation model of ship emission inventory.

Compared with the research in China in recent years, the advantages of real-time navigation status data carried by AIS in the process of ship emission inventory development have been fully utilized. In this paper, many parameters involved in the compilation of ship emission inventory based on AIS data, including main and auxiliary engine power, main and auxiliary engine load factor, emission factor, fuel correction factor, engine propeller matching coefficient, etc., are analyzed and determined one by one. On the basis of referring to foreign ship emission inventories, it is necessary to combine the actual situation of local ships, and comprehensively select parameters suitable for the ship air pollution emission inventory in the region, so that the established ship air pollution emission inventory can better reflect the actual local ship air pollution emissions.

6. Conclusions

This paper introduces two common methods for calculating a ship pollution emission inventory, proposes the engine propeller matching coefficient to modify the traditional power method, and refers to the research of domestic and foreign scholars and combines the characteristics of the ship activity level in the region to comprehensively determine the parameters of the calculation model. In the case of statistical comparison of the air pollutant emissions of the main and auxiliary engines under different navigation conditions, the uncertainty analysis was carried out, and the AIS combined with the power method was used to obtain the air pollution emission inventory of ships in the main urban area of Chongqing.

For the traditional STEAM model, combined with the relevant regulations of the region, this paper introduces the fuel correction factor and the engine propeller matching coefficient to correct the traditional ship emission inventory calculation model. Establishing a reliable ship emission inventory is in line with the development trend of ship air pollution prevention and control strategies. Under the complex navigation environment of inland ships, it solves the problem that the calculation of pollutants caused by the hardware conditions of old ships does not match the actual situation. This provides industry researchers with new ideas to improve the accuracy of emission inventories and provides important methods and data support for the further improvement of ship emission inventories. In addition, the emission of air pollutants from ships will cause various harm to the health of residents, such as the impact of pollutants on respiratory diseases and immune function, inducing tumors and even death. The establishment of the ship's air pollutant emission inventory and the implementation of government prevention and control measures have improved the atmospheric environment of coastal people's lives and will further enhance their physical health. The establishment of a more accurate emission inventory is convenient for the environmental protection department to monitor and manage the seriously polluted ports, such as: promoting the access of ships to shore power and installing diesel engine purification equipment. With access to real-time AIS data, new energy replacement and other emission reduction measures will play a greater role in forecasting the effect.

However, although the research in this paper can provide a reference for the prevention and control of air pollution from ships in the main urban area of Chongqing in the Yangtze River to a certain extent, the research still has certain limitations.

At present, there are few domestic research results on the experimental measurement of inland waterway ship emission factors, and the authenticity is difficult to guarantee. Since emission factors are an important part of emission inventories, further emission testing is required to determine emission factors for ship engines that meet national conditions. For the old ships in inland rivers in the region, after testing the load power of the diesel engine, the engine propeller matching coefficient is determined to be 1.25, which is not universal. For newly built ships and ships with a higher degree of automation, further experiments are needed to determine the engine propeller matching coefficient. In addition, when calculating the monthly ship pollution discharge in the study area, this paper collects 5 days of ship activity data per month, calculates the daily emissions separately, and then multiplies the average value by the number of days per month to obtain the monthly ship pollution emissions. In order to make the calculated regional ship emissions more accurate, in the future, the ship activity data can be collected continuously and completely through Internet servers and other equipment to calculate a more reliable regional ship air pollution emission list.

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