Research on the Emission Inventory and Pollution Characteristics of Air Pollutants from Ships in Beijing-Tianjin-Hebei Area

Fan Zhang1, 2, *

1CCCC Highway Consultants Co., Ltd., Beijing, China
2CCCC-AECOM Eco-Environmental Co., Ltd., Beijing, China

*Corresponding author e-mail: 18557780@qq.com

Abstract. As the key areas of China's air pollution control, Beijing-Tianjin-Hebei region are the busiest sailing area for ships. Therefore, the impact of air pollution caused by ships cannot be ignored. The bottom-up "dynamic method" was used in this study and the ships’ navigation process was divided into three processes: docking, entering and exiting port and cruising, and the emission of air pollutants from ships was calculated respectively, and the calculation method of air pollutants emission inventory for ships with high temporal and spatial resolution was established. Based on the ships’ basic information data from maritime database of China Classification Society and Lloyd’s Register, the Automatic Identification System data and the emission factor data for ships, the emission inventory for ships in 2014 in Beijing-Tianjin-Hebei area was calculated. In addition, the study also analyzed emission share rate of air pollutants from ships and the uncertainty of emission inventory.

1. Introduction

China is an important shipping country in the world, with nearly 170,000 water transport vessels. Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta regions, which are the key areas of air pollution control in China, are also the concentrated areas of ship navigation. Therefore, the impact of air pollution caused by ships and ports cannot be ignored. The Implementation Scheme for Special Action on the Prevention and Control of Pollution for Ships and Ports (2015-2020) [1], the Implementation Scheme for the Emission Control Areas of Ships in the Waters of the Pearl River Delta, Yangtze River Delta, and Bohai Rim (Beijing-Tianjin-Hebei) [2] and the Implementation Scheme for the Domestic Emissions Control Areas for Atmospheric Pollution from Vessels [3] were issued by the Ministry of Transport of the People’s Republic of China in 2015 and 2018, which put forward some control requirements, such as the establishment of emission control areas for atmospheric pollution from vessels in Beijing-Tianjin-Hebei and other waters, geographic scope of emission control areas, and the emission control requirements in stages for sulfur oxides, particulate matter and nitrogen oxides, so as to provide support for the fight against pollution and win the blue sky defense battle.

Therefore, the acquisition of scientific and reliable ship emission inventory [4-6] were the need of green shipping environmental management, which will provide an important basis for the improvement of air pollution control technology policy of ship mobile sources in the future, in order to ensure the smooth realization of the state's goal of ship air pollution control.
2. Acquisition of activity level data and emission factor data for ships

2.1. Activity level data for Ships

Activity level data for ships included the basic information data and the dynamic travel data of ships. The basic information data mainly included the classification quantity, rated power, host type, host speed, total ton, load ton, fuel type, maximum design speed of different ship types, etc. The different types of ships mentioned above included passenger ships, cargo ships, pushing tugs, non-transport vessels, maritime ships and other ships, adding up to 6 categories, 12 small types. The dynamic travel data of ships mainly included the load factor, the actual output power, the ship's travel speed, duration time, route information and so on, which were from the different types of ships under different driving conditions in the process of entering and leaving ports and docking.

According to the China Classification Society (CCS), Lloyd’s Register (LR) and International Maritime Organization (IMO) database, the basic information database was established in this research to meet the computing requirements for high-resolution emission inventory of air pollutants from ships in Beijing-Tianjin-Hebei waters. The database took the Maritime Mobile Service Identify (MMSI) as its sole identification code, which contained 278,656 non-repeating vessels, in which 128,475 were ocean-going vessels (with IMO number information). Their specific information included ship types, main engine rating power, secondary engine rating power, boiler power, host type, host speed, total ton, load ton, fuel type, maximum design ship speed, etc. Because the basic information database contained a wide range and had the relatively stable information for ships, the newly established database could be used for atmospheric pollutant inventory calculation in the corresponding area only need to match the Automatic Identification System (AIS) data in the study area, and there was no need to update and maintain data frequently. Therefore, the basic information database was considered to be static data from types.

The activity level data for ships was an important base for establishing the emission inventory of air pollutants from ships. This research used the 2014 AIS data to establish a database of activity level data for ships in the waters around Bohai Rim in China. It was shown in Figure 1 and Figure 2 about the AIS ships navigation trajectory and cross-sectional flow data in Bohai Rim waters and the Beijing-Tianjin-Hebei typical port region (Tianjin and Qinhuangdao), including MMSI numbers, IMO numbers, ship names, longitude, latitude, ground speed, ground direction, ship and cargo type, ship length, ship width and so on. Because the activity level data for ships varies dynamically in real time, the activity level data for ships (i.e. AIS data) was considered to be dynamic data from types.

![Figure 1. Diagram of AIS data in the region of Beijing, Tianjin and Hebei (Bohai Rim)](image)
2.2. Emission factor data for Ships

Through in-depth research on emission from ships at home and abroad, a database of multi-emission factors from ships were established to calculate emission inventory of air pollutants from ships. As a party to the International Convention on the Prevention of Pollution from Ships (MARPOL 73/78) by-laws VI, the emission factors of ocean-going vessels in China should be close to those in other countries. Therefore, the emission inventory of air pollutants from ships may be prepared partially with reference to emission factor data from foreign ships.

Emission factor data for ships was an important parameter to calculate emissions from ships, but due to the difficulty and high cost of ship testing, the domestic emission factor measurement for ships was very few. Based on domestic and foreign literature research results [7-11], and combined with the pioneering results obtained by the research team from Beijing Institute of Technology to carry out the survey of local ships [12, 13], this research compiled the multi-pollutant emission factor database for coastal and ocean-going vessels, as shown in Table 1, to prepare emission inventory calculation.

Table 1. Emission factor of different ships (units: g/kW·h)

| Emissions equipment | Fuel type | Sulphur content | Pollutant | Pollutant |
|---------------------|-----------|-----------------|-----------|-----------|
|                     | RO        | 2.70%           | SO₂       | 10.29     |
| ME (SSD)            | MDO       | 1.00%           | NOₓ       | 18.10     |
|                     | MGO       | 0.50%           | PM₁₀      | 1.42      |
|                     |           |                 | PM₂.₅    | 1.31      |
|                     |           |                 | HC        | 0.60      |
|                     |           |                 | CO        | 1.40      |
|                     | RO        | 2.70%           | SO₂       | 11.24     |
| ME (MSD)            | MDO       | 1.00%           | NOₓ       | 14.00     |
|                     | MGO       | 0.50%           | PM₁₀      | 1.43      |
|                     |           |                 | PM₂.₅    | 1.32      |
|                     |           |                 | HC        | 0.60      |
|                     |           |                 | CO        | 1.10      |
|                     | RO        | 2.70%           | SO₂       | 11.98     |
| AE                  | MDO       | 1.00%           | NOₓ       | 14.70     |
|                     | MGO       | 0.50%           | PM₁₀      | 1.44      |
|                     |           |                 | PM₂.₅    | 1.32      |
|                     |           |                 | HC        | 0.40      |
|                     |           |                 | CO        | 1.10      |
|                     | RO        | 2.70%           | SO₂       | 11.98     |
| Boilers             | MDO       | 1.00%           | NOₓ       | 14.70     |
|                     | MGO       | 0.50%           | PM₁₀      | 1.44      |
|                     |           |                 | PM₂.₅    | 1.32      |
|                     |           |                 | HC        | 0.40      |
|                     |           |                 | CO        | 1.10      |

Note: ME: Main Engine; AE: Auxiliary Engine; SSD: Slow Speed Engine; MSD: Medium Speed Engine; RO: Residual Oil; MDO: Marine diesel oil; MGO: Marine gas oil.
3. The method of calculating emission inventory of air pollutants from ships

Atmospheric pollutants were emitted by ships during their operation, berthing at ports. Considering that the fuel consumption statistics of ships were not precise and it was difficult to reflect the time-space changes of ship emissions for the fuel method, this research adopted the bottom-up "power method", which calculated emission inventory of air pollutants from ships based on working conditions of ship’s engines. To this end, it is necessary to first determine the power of the ship’s engines (including the main engine, auxiliary engine and boiler) under different operating conditions. According to the emission factor and the corresponding engine load correction factor, combined with the running time under the corresponding operating conditions, emission quantities of air pollutants from ships are calculated.

The calculation formula of the emission of air pollutants from ships based on the power method was as follows:

\[
E_{i,j,k,l} = P_j \times LF_{j,l} \times T_{j,l} \times EF_{i,j,k} / 10^6
\]

Where:
- \( E_{i,j,k,l} \) – the pollutants emission, unit is ton;
- \( P_j \) - the rated total power, unit is kW;
- \( LF_{j,l} \) - the load factor, dimensionless;
- \( T_{j,l} \) - the sailing time, unit is h;
- \( EF_{i,j,k} \) - the emission factor, unit is g/kW·h.

Due to irregularities or errors in the information from ports, ships and others, as well as complex marine environment, meteorological conditions and terrain factors, AIS information may be sent and received late or wrong, resulting in abnormal values in AIS data. As the carrier of emission inventory calculation, it is necessary to be preprocessed for AIS data before inventory calculation to remove the interference of outliers [14].

4. Calculation of high-resolution emission inventory of air pollutants from ships in Beijing-Tianjin-Hebei waters

4.1. Emissions inventory calculation range

Air pollution species about this inventory research included SO2, NOx, PM2.5, PM10, CO and HC.

The objects about this inventory research included all domestic and foreign ships entering the time and space range designated by the research, except fishing boats and ships for military purposes.

Time range: January, April, July, October 2014, and the whole 2014.

Space range: This research focused on the waters in the range of 38°N~40°N, 117.5°E~120.5°E, and the space was divided into the rectangular grid. The grid spacing was 0.0277 degrees (about 3 km), for a total of 72 × 108 = 7776 grids. Then, according to the scope of the waters under the jurisdiction of the maritime system, the waters was implemented in Tianjin, Cangzhou, Tangshan and Qinhuangdao division. It was shown in Figures 3 about the specific grid zoning.

![Figure 3. Grids of emissions inventory in the region of Tianjin and Hebei](image)
4.2. Emission inventory of air pollutants from ships in Beijing-Tianjin-Hebei waters

According to the calculation method of section 3, the emission inventory of air pollutants from ships in Beijing-Tianjin-Hebei waters was calculated. Based on the activity level data and emission factor data for ships, the total emissions from ships of SO₂, NOₓ, PM₁₀, PM₂.₅, HC and CO in the research area in 2014 were 59933 tons, 80294 tons, 7396 tons, 6822 tons, 2346 tons and 5833 tons respectively. It was shown in Table 2 about the specific data.

| Time (month) | SO₂    | NOₓ     | PM₁₀   | PM₂.₅  | HC     | CO     |
|--------------|--------|---------|--------|--------|--------|--------|
| 1            | 4101.94 | 5359.24 | 503.21 | 463.9  | 156.57 | 392.5  |
| 4            | 5233.94 | 6968.48 | 647.17 | 597.13 | 206.73 | 512.17 |
| 7            | 4830.02 | 6412.64 | 597.72 | 551.49 | 191.25 | 473.97 |
| 10           | 5811.73 | 8024.17 | 717.21 | 661.57 | 227.48 | 565.79 |
| All year     | 59932.89 | 80293.59 | 7395.93 | 6822.27 | 2346.09 | 5833.29 |

Using ARCGIS software, according to the scope of the waters under the jurisdiction of the maritime system, emissions of air pollutant from ships in Tianjin, Qinhuangdao, Cangzhou and Tangshan waters in the representative months of the year 2014 and the whole year 2014 were counted. It was shown in Table 3 about the results.

| Sea borders | Time | SO₂    | NOₓ     | PM₁₀   | PM₂.₅  | HC     | CO     |
|-------------|------|--------|---------|--------|--------|--------|--------|
| Tianjin     | 1    | 2410.47 | 3189.86 | 298.22 | 275.17 | 95.39  | 236.33 |
|             | 4    | 2956.43 | 3970.40 | 367.84 | 339.62 | 119.86 | 294.43 |
|             | 7    | 2907.77 | 3910.22 | 362.40 | 334.63 | 118.61 | 291.11 |
|             | 10   | 3098.43 | 4267.98 | 384.50 | 354.88 | 124.17 | 306.43 |
| All year    | 34119.30 | 46015.38 | 4238.88 | 3912.90 | 1374.09 | 3384.90 |
| Qinhuangdao | 1    | 583.60  | 760.55  | 71.21  | 65.62  | 21.79  | 59.44  |
|             | 4    | 655.04  | 847.43  | 80.49  | 74.22  | 25.19  | 62.95  |
|             | 7    | 727.05  | 951.20  | 89.56  | 82.59  | 28.24  | 70.39  |
|             | 10   | 824.48  | 1115.79 | 101.21 | 93.32  | 31.58  | 79.02  |
| All year    | 8370.51 | 11024.91 | 1027.41 | 947.25 | 320.40 | 801.90 |
| Cangzhou    | 1    | 341.74  | 459.68  | 41.66  | 38.38  | 12.69  | 32.12  |
|             | 4    | 733.50  | 993.08  | 90.07  | 83.04  | 28.10  | 70.40  |
|             | 7    | 421.48  | 560.90  | 51.59  | 47.54  | 15.91  | 40.08  |
|             | 10   | 812.94  | 1209.83 | 100.21 | 92.41  | 31.60  | 78.96  |
| All year    | 6928.98 | 9670.47  | 850.59  | 784.11 | 264.90 | 664.68 |
| Tangshan    | 1    | 766.13  | 949.15  | 92.12  | 84.73  | 26.70  | 69.11  |
|             | 4    | 888.97  | 1157.57 | 108.77 | 100.25 | 33.58  | 84.39  |
|             | 7    | 773.72  | 990.32  | 94.17  | 86.73  | 28.49  | 72.39  |
|             | 10   | 1075.88 | 1430.57 | 131.29 | 120.96 | 40.13  | 101.38 |
| All year    | 10514.10 | 13582.83 | 1279.05 | 1178.01 | 386.70 | 981.81 |

ArcGIS software was used to form the spatial distribution of the emission by the types of air pollutants from ships in the waters of Tianjin, Qinhuangdao, Cangzhou and Tangshan in 2014. It was shown in Figure 4 to Figure 6 about the specific space distribution.
Figure 4. Space distribution of SO$_2$ and NO$_x$ emissions inventory (units: tons)

Figure 5. Space distribution of PM$_{10}$ and PM$_{2.5}$ emissions inventory (units: tons)

Figure 6. Space distribution of HC and CO emissions inventory (units: tons)
4.3. Comparison of inventory calculation results and uncertainty analysis

At present, domestic research institutes in China had carried out research work on the emission of air pollutants from ships in some parts of China. Among them, within the Bohai Rim region, the marine emission inventory had been calculated by Xing and so on [15], and the results showed that the emissions of NOx, CO, HC, SO2 and PM from ships in the Bohai Bay region in 2014 were 173808t, 14436t, 6144t, 120748t and 15292t respectively. Compared with the results, the research area in this paper included only the waters in Tianjin and Hebei, which was part of the research scope of the Xing’s research, and there were statistical differences in the activity level and other data. In comparison, the emissions of air pollutants from all kinds of ships in this research were less than Xing’s results, and the magnitude is equivalent. In general, the calculation results of the inventory of air pollutants from ships in this research were reasonable.

In addition, in view of the difficulty of obtaining data on activities level for ships and the lack of localized emission factors, the preliminary analysis of the uncertainty about the emission inventory from ships in the Beijing-Tianjin-Hebei areas was as follows:

(1) The emission inventory from ships involved many parameters in the estimation process. In estimating SO2 emissions, the average sulphur content of fuel was used, which can lead to uncertainty due to difference in some degree in fuel used by different types of ships. For SO2, the estimate of emissions was mainly related to the sulphur content of fuels. Generally, other researches selected sulfur content of marine fuel oil about 3.5% m/m, and this research was based on the results of the national marine fuel quality survey, which showed that sulfur content of the fuel oil was mostly 0.5~2.7% m/m.

(2) Due to the lack of localized emission factors, most of the emission factors used in the calculation were based on research results from other countries. Although the consistency of ocean-going vessels in the research was good, there would be some differences in offshore vessels, which caused some uncertainty.

In general, due to the different pollutant emission factors and conversion ratio used by different researchers, the range of emission factor data obtained was relatively large, resulting in uncertainty. The emission inventory of air pollutants from ships established in this research had some uncertainty inevitably, but it was sufficient to reflect the basic spatial and temporal distribution of pollution sources for ships in Beijing-Tianjin-Hebei waters objectively. In the future, it is still necessary to improve the acquisition of specific parameters and the localization of emission factors of offshore ships further, which could help to reduce the uncertainty of inventory.

5. Conclusion

According to the characteristics of pollutants emission from ships, the bottom-up "power method" was used in this study and the ships’ navigation process was divided into three processes: docking, entering and exiting port and cruising, and the emission of air pollutants from ships was calculated respectively, and the calculation method of air pollutants emission inventory for ships with high temporal and spatial resolution was established. Based on the ships’ basic information data from maritime database of CCS and LR’s, the AIS data and the ship emission factor data, the emission inventory for ships in 2014 in Beijing-Tianjin-Hebei area was calculated. The inventory results showed that ships in Tianjin, Qinhuangdao, Cangzhou and Tangshan waters discharged SO2, NOx, PM10, PM2.5, HC, CO in a total of 59932.9t, 80293.6t, 7395.9t, 6822.3t, 2346.1t, 5833.3t in 2014.

This study compared the results of the inventory calculation with other research, which showed that the overall magnitude was equivalent. The calculation results of emission inventory were reasonable, and that was enough to reflect the basic situation of the space-time distribution of pollution source emissions from ships in Beijing-Tianjin-Hebei waters. At the same time, the emission inventory of air pollutants from ships obtained in this research had some uncertainty in fuel sulfur content and local emission factors of offshore ships, which needed to be improved in future research.

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