Study on Characteristics of Emissions of Air Pollutants in Ships in the Yangtze River Delta and Countermeasures

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Abstract. In order to analyze the characteristics of air pollutant emission in ships in the Yangtze River Delta, this paper establishes the air pollutant discharge list of ships in the Yangtze River Delta in 2017 based on the dynamic method of AIS data, and analyzes the emission characteristics of air pollutants in ships under different working conditions. The effect of its emission reduction measures and the spatial distribution of annual emissions of air pollutants from ships in the study area. The results showed: Among the atmospheric pollutants emitted by ships in the Yangtze River Delta in 2017, the emissions of $SO_2$, $NO_x$, $PM_{10}$, $HC$ and $CO$ were 339,900 tons, 527,700 tons, 45,400 tons, 14,500 tons and 34,300 tons respectively. Low-speed navigation has the largest proportion of emissions. The use of shore power for ship berthing is an effective measure to reduce emissions from coastal areas in the region.

1. Introduction

Shipping is an important part of the global transportation industry and its importance is still increasing. Its negative impact on the atmospheric environment is also increasing. The ship engine releases a variety of atmospheric pollutants into the atmosphere during combustion [1]: $CO_2$, $NO_x$, $SO_2$, $PM$ and so on. China is the largest maritime countries, international shipping carrier China international trade import and export cargo transport up to 15 million or more trips. Research shows that Chinese 70% of the ship about emissions occur from the coast 100 km across [2], the contribution of Chinese coastal areas along the river and air pollution can not be ignored. Calculating the ship's air pollutant discharge list is an important basis for the prevention and control of ship air pollution.

The method system applied to ship emission inventory research is divided into fuel method [3], trade law [4], and dynamic method. Compared to the fuel law and trade law, the ship emission inventory based on the AIS dynamic method can obtain the spatial and temporal distribution characteristics of ship emissions.

In 2010, Entec researchers[5] used the AIS dynamics method to establish a 2007 UK waters ship air pollutant emissions inventory. In 2016, Liu H et al[6] estimated the emissions of air pollutants from ships in East Asian seas in 2013. In 2017, Zhu Qianru and others established a refined ship discharge list in the Pearl River Delta region based on AIS data[7]; in 2019, Xu Wenwen and others carried out research on inland ship discharge inventory[8].

In this paper, the AIS dynamic method is used to calculate the air pollutant emissions of ships in the Yangtze River Delta in 2017. Compared with the previous research, this paper obtains the discharge of air pollutants from ships in different operating conditions in the study area, and clarifies the space of...
marine air pollutants. Distribution, analysis of changes in pollutants after the implementation of emission reduction measures.

2. Research methods

2.1. Scope and objects
The time and spatial range, and types of atmospheric pollutants in the study are shown in Table 1.

| Year | Spatial range | Air pollutant types |
|------|---------------|---------------------|
| 2017 | north latitude: 28.00°–33°, East longitude: 119.00°–124.00° | SO₂, NOₓ, PM₁₀, HC, CO |

2.2. Calculation methods and parameter selection

2.2.1. Calculation method of ship emission inventory. In this study, it is assumed that the ship’s air pollution emissions only come from the main and auxiliary engines of the ship. Main and auxiliary discharge are main vessel, the auxiliary vessel to various output energy emission corresponding to the emission factor multiplication function formula based emission factor used in the calculation in g/kW·h for the unit of measurement.

The discharge of air pollutants from ships mainly includes main engine emissions, auxiliary machine emissions, and boiler emissions. The calculation formula 1 is as follows:

\[ E = E_{\text{main}} + E_{\text{auxiliary}} + E_{\text{boiler}} \]  
(1)

The calculation formula for calculating the air pollutant emissions of ships based on the real-time power of the ship is shown in Equation 2.

\[ E_i = MCR \times LF \times Act \times EFi \times EFlowload \]  
(2)

Among them:
\( E_i \) is the emissions of some type, unit: g; \( MCR \) to \( MCR \) ship maximum continuous rated power, the output power of the auxiliary vessel (unit: kW·h); \( Act \) as a ship sailing time, The unit is: h. \( EFi \) is the emission factor for this pollutant in g/kW·h. \( EFlowload \) is a low load correction factor.

The ship's main engine low load adjustment coefficient is shown in Equation 3.

\[ LF = \left( \frac{\text{Speed Actual}}{\text{Speed Maximum}} \right)^3 \]  
(3)

Among them:
\( LF \) is a low load, dimensionless unit for the ship's main engine. \( \text{Speed Actual} \) is the actual speed of the ship sailing, unit: knot; \( \text{Speed Maximum} \) is the maximum designed speed of the ship, unit: knot.

The ship emission inventory calculated by the institute includes the pollutant discharge of the main engine and the auxiliary machine. In the calculation process, the ship operating conditions are divided into five types: cruise, slow speed, maneuvering, berth and anchor. The determination method adopts IMO global. The method for judging the navigation status in the calculation of greenhouse gas emissions [9], the specific determination parameters are shown in Table 2.

| Ship speed                  | Status      |
|-----------------------------|-------------|
| Speed < 1 knot              | Berth       |
| 1 knot ≤ Speed ≤ 3 knots   | Anchor      |
| Speed greater than 3, and less than 20% of the MCR | maneuvering |
| MCR greater than 20%, while less than 65% of the MCR | Low speed |
| More than 65% of MCR       | cruise      |
2.2.2. Emission factors and other parameters. This paper selects the emission factor recommended by the US EPA [10], the pollutant emission factors of the main engine, auxiliary machinery and boiler were shown in the Table 3, Table 4 and Table 5. The boiler load power is derived from the boiler load power data provided by Entec Research [11].

**Table 3.** Ship main engine pollutants emission factor(g/kW·h)

| Main engine               | Year of built | SO₂  | NOₓ  | PM₁₀ | HC   | CO   |
|---------------------------|---------------|------|------|------|------|------|
| Low speed diesel engine   | Before 2000   | 10.29| 18.1 | 1.42 | 0.6  | 1.4  |
| Medium speed diesel engine| 2000-2010     | 10.29| 17.0 | 1.42 | 0.6  | 1.4  |
| Low speed diesel engine   | 2011-2015     | 10.29| 15.3 | 1.42 | 0.6  | 1.4  |
| Medium speed diesel engine| Before 2000   | 11.24| 14.0 | 1.43 | 0.5  | 1.1  |
| Low speed diesel engine   | 2000-2010     | 11.24| 13.0 | 1.42 | 0.5  | 1.1  |
| Medium speed diesel engine| 2011-2015     | 11.24| 11.2 | 1.41 | 0.5  | 1.1  |

Note: Low speed diesel engine, maximum speed < 130r/min; medium speed diesel engine, speed > 130r/min

**Table 4.** Ship auxiliary engine pollutants emission factor(g/kW·h)

| Year of built | SO₂ | NOₓ | PM₁₀ | HC | CO |
|---------------|-----|-----|------|----|----|
| ≤1999         | 12.3| 14.7| 1.5  | 0.4| 1.1|
| 2000-2010     | 12.3| 13.0| 1.5  | 0.4| 1.1|
| 2011-2015     | 12.3| 11.2| 1.5  | 0.4| 1.1|

**Table 5.** Boiler emission factor(g/kW·h)

| SO₂  | NOₓ  | PM₁₀ | HC | CO |
|------|------|------|----|----|
| 16.5 | 2.1  | 0.8  | 0.1| 0.2|

When the ship uses shore power, if the energy provided by the shore power can meet the needs of the ship and the staff, the ship auxiliary machine will be closed. In addition to this, the auxiliary machine is always on. Auxiliary power need to be adjusted according to the state of different vessels, vessels ship accessory load factor are shown in Table 6.

**Table 6.** Ship auxiliary machine load proportional coefficient

| Ship type          | Sailing state          |
|--------------------|------------------------|
|                    | Cruise | Low speed | Maneuvering | Berth |
| Car carrier        | 0.15   | 0.30      | 0.45        | 0.26  |
| Bulk carrier       | 0.17   | 0.27      | 0.45        | 0.22  |
| Container Ship     | 0.13   | 0.25      | 0.48        | 0.19  |
| Cruise ship        | 0.80   | 0.80      | 0.80        | 0.64  |
| General cargo ship | 0.17   | 0.27      | 0.45        | 0.10  |
| Ocean tug          | 0.17   | 0.27      | 0.45        | 0.22  |
| Refrigerated ship  | 0.20   | 0.34      | 0.67        | 0.32  |
| Roll-on ship       | 0.15   | 0.30      | 0.45        | 0.26  |
| Tanker             | 0.24   | 0.28      | 0.33        | 0.26  |
| Other types        | 0.17   | 0.27      | 0.45        | 0.22  |

For the missing auxiliary machine data, this study uses the main and auxiliary machine ratio method [13] to estimate the rated power of the auxiliary machine. The ratio of different types of main and auxiliary machines is shown in Table 7. When the host load is less than 20%, the need for the host
emission factors in Table 8 adjustment coefficient adjustment. In this study, a sulfur content of 2.27% m/m fuel oil was used during the operation of coastal vessels.

**Table 7.** Ship auxiliary engine to main engine power ratio

| Ship type         | Auxiliary machine power to host power ratio (%) |
|-------------------|-----------------------------------------------|
| Car carrier       | 0.266                                         |
| Bulk carrier      | 0.222                                         |
| Container Ship    | 0.220                                         |
| Cruise ship       | 0.278                                         |
| General cargo ship| 0.191                                         |
| Ocean tug         | 0.222                                         |
| Refrigerated ship | 0.406                                         |
| Roll-on ship      | 0.259                                         |
| Tanker            | 0.211                                         |
| Other types       | 0.222                                         |

**Table 8.** Ship main engine low load emission adjustment factor

| Load factor LF | SO\textsubscript{2} | NO\textsubscript{x} | PM\textsubscript{10} | HC     | CO     |
|---------------|----------------------|---------------------|----------------------|--------|--------|
| 1%            | 5.99                 | 11.47               | 19.17                | 59.28  | 19.32  |
| 2%            | 3.36                 | 6.43                | 7.29                 | 21.18  | 9.68   |
| 3%            | 2.49                 | 2.92                | 4.33                 | 11.68  | 6.46   |
| 4%            | 2.05                 | 2.21                | 3.09                 | 7.71   | 4.86   |
| 5%            | 1.79                 | 1.83                | 2.44                 | 5.61   | 3.89   |
| 6%            | 1.61                 | 1.60                | 2.04                 | 4.35   | 3.25   |
| 7%            | 1.49                 | 1.45                | 1.79                 | 3.52   | 2.79   |
| 8%            | 1.39                 | 1.35                | 1.61                 | 2.95   | 2.45   |
| 9%            | 1.32                 | 1.27                | 1.48                 | 2.52   | 2.18   |
| 10%           | 1.26                 | 1.22                | 1.38                 | 2.18   | 1.96   |
| 11%           | 1.21                 | 1.17                | 1.30                 | 1.96   | 1.79   |
| 12%           | 1.18                 | 1.14                | 1.24                 | 1.76   | 1.64   |
| 13%           | 1.14                 | 1.11                | 1.19                 | 1.60   | 1.52   |
| 14%           | 1.11                 | 1.08                | 1.15                 | 1.47   | 1.41   |
| 15%           | 1.09                 | 1.06                | 1.11                 | 1.36   | 1.32   |
| 16%           | 1.07                 | 1.05                | 1.08                 | 1.26   | 1.24   |
| 17%           | 1.05                 | 1.03                | 1.06                 | 1.18   | 1.17   |
| 18%           | 1.03                 | 1.02                | 1.04                 | 1.11   | 1.11   |
| 19%           | 1.01                 | 1.01                | 1.02                 | 1.05   | 1.05   |
| 20%           | 1.00                 | 1.00                | 1.00                 | 1.00   | 1.00   |

2.3. Emissions inventory

2.3.1. Emissions of air pollutants Yangtze waters ships characterization. In 2017, the total emissions of SO\textsubscript{2}, NO\textsubscript{x}, PM\textsubscript{10}, HC and CO in the Yangtze River Delta waters and the discharge status of different navigational conditions are shown in Table 9.

**Table 9.** Emissions from ships around the Yangtze River Delta to navigational status (10\textsuperscript{4} tons)

| Status                | SO\textsubscript{2} | NO\textsubscript{x} | PM\textsubscript{10} | HC     | CO     |
|-----------------------|----------------------|---------------------|----------------------|--------|--------|
| Anchored              | 0.33                 | 0.98%               | 0.55                 | 1.03%  | 0.06   | 1.33%  | 0.01   | 1.03%  | 0.04   | 1.09%  |
| Berth                 | 7.33                 | 21.64%              | 9.00                 | 17.06% | 0.88   | 19.42% | 0.24   | 16.88% | 0.67   | 19.61% |
| Manoeuvring           | 6.86                 | 20.23%              | 10.31                | 19.55% | 0.96   | 21.23% | 0.28   | 19.52% | 0.69   | 19.96% |
| Normal Cruising       | 6.88                 | 20.29%              | 11.96                | 22.67% | 0.94   | 20.80% | 0.33   | 22.76% | 0.73   | 21.29% |
| Slow Speed            | 12.50                | 36.87%              | 20.95                | 39.70% | 1.69   | 37.22% | 0.58   | 39.81% | 1.31   | 38.04% |
| Total Emission        | 33.90                | 100%                | 52.77                | 100%   | 4.54   | 100%   | 1.45   | 100%   | 3.43   | 100%   |
As apparent from Table 1, at anchor, berthing, the motor port, cruise, low-speed navigation that. At species navigation states slow speeds up discharge state, the average proportion of different pollutant emissions is 38.33% ; average emissions of different pollutants in the harbor maneuvering state accounted for 20.1% ; the average discharge of different pollutants in the berthing state is 18.92% ; the cruising state is 21.56% ; the mooring state accounts for the least proportion, accounting for only about 1% of the total emissions.

2.4. Ship spatial distribution of air pollutants
The ship emission inventory calculation, annual emissions plotted atmospheric pollutants spatial distribution of vessels, spatial accuracy of 1km×1km, SO$_2$, NO$_X$ emission spatial distribution shown in Figure 1(a), Figure 1(b). From the figure, the discharge vessel exhibits aggregation potential, which is the main route of the ship in a region of space with a high degree of consistency.

3. Effect analysis of emission reduction measures
3.1. Ship in port to use shore power
Ship shore power technology is in ship berthing closed auxiliary machine using the power provided by the shore to meet the electricity demand technique, this technique may reduce the ship in port during berthing emissions to the atmosphere. We hypothesized that all vessels in the study area during use by shore power port, is clear from the results of emission inventory, ship berthing during each pollutant reductions and the proportion of total emissions in Table 10.

Table 10. Emission reduction of ships using shore-to-ship power at port (10$^4$ tons)

|                     | SO$_2$ | NO$_X$ | PM$_{10}$ | HC   | CO   |
|---------------------|--------|--------|-----------|------|------|
| Ship pollutant emission reduction | 7.33   | 9.00   | 0.88      | 0.24 | 0.67 |
| Proportion of total emissions | 21.64% | 17.06% | 19.42%    | 16.88% | 19.61% |

3.2. Emission control area policy
The ship emission control area policy requires that ships entering the specified area should use fuel that meets the requirements. If all the region of the ship to complete oil change, using 0.50% m/m when the fuel oil, the total reductions of area 264.3 tons. If all ships in the area use 0.10% m/m fuel oil, the total emission reduction is 324,100 tons. For the use of fuels with different sulfur contents, the sulfur oxide emissions of ships in the Yangtze River Delta are shown in Figure 2.
4. Conclusion
Among the atmospheric pollutants emitted by ships in the Yangtze River Delta in 2017, the emissions of SO$_2$, NOx, PM10, HC and CO were 339,900 tons, 527,700 tons, 45,400 tons, 14,500 tons and 34,300 tons respectively. The main pollutants are NOx and SO$_2$, and their emissions account for 90.19% of the total emissions.

In the study area, the low-speed navigation state accounted for the largest proportion of emissions, and the low-speed navigation state NOx emissions accounted for 39.71%. The use of shore power for ship berthing is an effective measure for reducing emissions.

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