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Research on the detection technologies of ship exhaust gas in emission control areas

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RESEARCH ON THE DETECTION TECHNOLOGIES OF SHIP EXHAUST GAS IN EMISSION CONTROL AREAS

By

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DECLARATION

I certify that all the material in this dissertation that is not my work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my personal views and are not necessarily endorsed by the University.

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ABSTRACT

Title of Dissertation: **Research on the Detection Technologies of Ship Exhaust Gas in Emission Control Areas**

Degree: **Master of Science**

The issue of ship emissions control has attracted significant attention from the world in recent years, and ship emission control areas (ECAs) have emerged. The International Maritime Organization (IMO) has designated four ECAs with stricter control. The European Union (EU) and the United States (US) have also established their own ECAs to set emission standards to regulate the emission from ships.

China has also introduced relevant laws to control the exhaust emissions from ships, and set Domestic Emission Control Areas (DECAs) for atmospheric pollution from vessels. Moreover, the construction of regional and national DECAs has taken initial shape. However, due to the late establishment of the control system, the lack of experience and other practical problems, China's DECAs on ship air pollutant emissions monitoring means cannot yet fully meet the regulatory needs.

This paper systematically introduces the regulatory initiatives of foreign ECAs, comprehensively analyzes the policy measures and implementation effects involved in DECAs, compares the advantages and disadvantages of various monitoring technologies, and takes the Shanghai port as the starting point, adopts a large amount of first-hand regulatory data from Shanghai Waigaoqiao port area, and focuses on monitoring of compliance with fuel sulfur content regulations through unmanned aerial vehicle (UAV) measurements of ship emissions. Using new technologies can strengthen China's adequate supervision of DECAs and provide technical support for China to become IMO- designated ECA.

KEYWORDS: Ship emissions; ECA； DECA; UAV

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LIST OF ABBREVIATIONS

AIS	Automatic Information System
DECA	Domestic Emission Control Area
ECA	Emission Control Area
EU	European Union
FSC	Fuel Sulfur Content
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LT	Local Time
MARPOL	International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978
MOT	Ministry of Transport
MSA	Maritime Safety Administration
PM	Particulate Matter
PPM	Parts Per Million
PRD	Pearl River Delta Region
TEU	Twenty-feet Equivalent Unit
THETIS	The Hybrid European Targeting and Inspection System
UAV	Unmanned Aerial Vehicle
US	United States
YRD	Yangtze River Delta Region

CHAPTER 1

INTRODUCTION

1.1 Background

Shipping is one of the significant modes of transportation, which transports about 90% of global trade. (ICS, 2021) Ships require massive energy and produce a lot of gas emissions (such as CO_2, SOx, NOx and PM2.5), which become an essential source of atmospheric pollutants and threaten human health and the environment.

According to the statistical data of the IMO in 2014, the emissions of SO_2 and NOx from ships in 2012 were 10.24 million tons and 19 million tons, respectively, accounting for 13% -15% of global emissions, of which nearly 70% were emitted into the sea within 400 kilometers from land, causing severe air pollution in coastal areas, especially around ports with heavy cargo traffic. (Shen, 2018)

As the ship travels over the vast ocean and stretches of rivers, it becomes impossible to regulate them all over the region around the clock. Facing this problem, the IMO has adopted the approach of establishing ECAs to gradually improve and solve the problem of ship emissions in the whole shipping industry.

The ECA is not set up aimlessly and arbitrarily but based on the spatial analysis of the emission data of a large number of shipping routes. It is finally found that the waters where ships enter and leave ports are the most densely emitted areas along the entire shipping routes. Due to the high density of ships in ports, waterways and anchorages and the proximity to densely populated areas, ship emissions will significantly impact these areas. (Zhang, 2014)

Therefore, setting up ECAs in core ports and major offshore routes can effectively limit the tailpipe emissions of ships throughout their operation. ECA, which is characterized by good technical feasibility and regulatory convenience, is a fundamental policy initiative to reduce air pollutant emissions from ships, which can help improve the air quality of ports and cities in the control area. (Li H. , 2022)

Therefore, this paper will focus on analyzing the regulatory approach and technical means of ship exhaust gas used in ECAs, pointing out current problems and the illustrating of the UAV for sulfur content detection of ship emissions, to provide technical support for strengthening China's effective supervision of DECAs.

1.2 Previous Research

1.2.1 Research of foreign scholars on the control of ship exhaust gas

1.The research on the necessity of control.

Ida-Maja (2013) argued that the pollution from ship exhaust gas cannot be ignored and directly caused about 60,000 deaths every year, with sulfur emissions from ships accounting for more than 80% of the total emissions. Keasling J.D. (2008) pointed out that the sulfur content of common marine fuel is 3500 times higher compared to that of automobile fuel.

Considering of the impacts on human health, DNV GL (2016) confirmed that SO_X and NO_X emitted from ships enter the lungs with breathing through chemical reactions, which may induce respiratory and cardiovascular diseases and even lead to cancer. Globally, about 64,000 people died each year due to diseases related to air pollution from shipping.

2. The research on regulation and enforcement.

In the field of conducting ship exhaust emission monitoring, CE Delft (2016) argued that the rapid fuel oil detection technology was relatively mature and able to take the actual ship inspection by the Dutch Port State Control Officers as an example to confirm that the detection equipment can meet the accuracy requirements.

In terms of penalties for excessive sulfur oxide emissions from ships, Bunker world (2016) argued that they were not strong enough and cites 315 (about 5% of the total number of ships) reports of non-compliant emissions received by the EU Maritime Agency in 2015 as an example, noting that a merge percentage of them imposed penalties and that the fines never exceeded the costs saved due to non-compliance.

Hartmut Ewald (2018) described a mobile gas sensing system for detecting combustion pollutants applicable to UAV-based systems. Villa Tommaso Francesco (2019) described the application of a simplified emission monitoring system using UAVs as a carrying tool, noting that UAVs can be used with sniffing equipment for monitoring specific gases such as CO_2, SO_2 and NO_2.

1.2.2 Domestic scholars' research on the control of ship exhaust gas

1. The research on the ECA system of ships.

Zhang Xianghui (2014) pointed out that China must always keep pace with the development of advanced regions in the world in terms of laws and regulations, formulation of implementation standards and research and development of new equipment and technologies in order to face the increasingly strict international ship emission standards in the future and to make the development of China's shipping industry greener and ensure environmental friendliness and people's health.

According to Peng Chuansheng (2018), the geographical scope and control requirements of China's DECAs were challenging to effectively reduce ship air pollutant emissions, and it was recommended to apply for the establishment of IMO-designated ECAs as early as possible. Xu Honglei (2018) summarized the experience and practice of European and American countries in ECAs with the actual port development in China, and proposed that China should apply for the establishment of IMO-designated ECA at an appropriate time to strengthen the control. However, scholars also had different opinions on whether to apply for the establishment of IMO-designated ECA. Yan Hecheng (2018) pointed out that compared with ECAs designated by the IMO, domestic policies are introduced with high efficiency and can be continuously improved according to the implementation effect, which is more in line with China's national conditions.

2. The research on regulatory enforcement.

The research on regulatory enforcement is mainly carried out by comparing with and learning from foreign advanced regulatory concepts and methods, such as Dong Xue (2017) proposed that the practice of joint enforcement between the U.S. Environmental Protection Agency and the Coast Guard can be followed and combined with the reality of China to strengthen the collaboration among functional management departments in charge of maritime, water transportation and environmental protection.

Yan Hecheng (2018) argued that China's control policies need to improve the science and feasibility by comparing with developed countries in the EU and the US and explore ways to establishing a joint management mechanism among China, Japan and Korea for preventing air pollution from ships.

Ni Xunpeng (2020) took Shanghai port as an example, analyzed the current situation and regulatory difficulties in regulating the exhaust emissions of underway vessels in the DECA, compared the domestic and foreign underway vessel exhaust emission monitoring technologies, and proposed a regulatory scheme for underway vessel exhaust emissions in Shanghai port, taking into account the characteristics of the waters and the navigation routes. Li Yajun (2021) discussed the feasibility and difficulties of monitoring ship exhaust gas by drones with sniffing equipment.

1.2.3 Summary

Foreign countries have carried out research on sulfur oxide emissions from ships earlier and has rich relevant experience in solving the relevant aspects. Compared with them, China had a late understanding of the hazards of ship exhaust pollution, and the research on the controlling air pollution emissions from ships in China started late. The supervision of exhaust emission was not carried out gradually in various places until the DECAs were establishment.

Domestic research scholars mainly adopt the UAVs with sniffers to implement the ship emission monitoring work of ship exhaust pollutants. It is mainly based on the rapid progress of drone technology in China in recent years, which has become a regular monitoring tool for the Maritime Safety Administrations (MSAs), as well as the low price of sniffers and the simplicity of the instrumentation and monitoring methods. By using such technology, the MSAs have also gradually established an effective and efficient ship emission monitoring system in the combination with the results of exhaust monitoring equipment to meet the actual needs of the maritime authorities for effective law enforcement in the DECAs.

1.3 Objectives of the research

China has paid attention to the shipping pollution issue as a rising and growing shipping power. And the problem of emission control for coastal and riverine ships in China needs to be solved.

Due to the constraints of international conventions and laws, it is difficult for China to effectively reduce the emission of air pollutants from ships under the DECAs defined by domestic laws, both in terms of geographic scope and control requirements, and the only way to solve these problems is to apply for the establishment of ECAs approved by the *International Convention for the Prevention of Pollution from Ships* (MARPOL) as soon as possible.

This paper summarizes and compares the detection technologies for ship air pollutant emissions in domestic and foreign ECAs, and analyzes the feasibility and promotion of new monitoring technologies by taking the current ship exhaust emission monitoring technology used in the Shanghai port as an example and taking the drone-mounted sniffer technology as an entry point.

The aim is to provide technical support for upgrading China's DECAs to an ECAs designated by IMO, to further solve the air pollution problem caused by ships, and to improve the ambient air quality in China's coastal and riverine regions.

1.4 Structure of the dissertation

This paper is divided into five parts.

In the first chapter, the article mainly introduces the background and significance of the selected topic. The current research results at home and abroad were gathered and demonstrated.

The second chapter mainly analyzes the ECAs revision of the designated under MARPOL Annex VI and the monitoring methods of ship air pollutant emissions in existing ECAs and focuses on the specific monitoring measures in the EU and the US.

The third chapter mainly describes the overview of China’s DECAs. The policy development and existing monitoring means, the current and problems of the control work in the DECAs are analyzed, and the practices of Shanghai port in policy formulation, regulatory scheme and monitoring technology are introduced.

The next chapter discusses the practical application of drone telemetry technology for the exhaust gas of ships underway in the Waigaoqiao Port area of Shanghai. Pudong MSA uses drones with sniffing equipment to collect ship exhaust gas and adopts the international mainstream ship exhaust telemetry technology - sniffing method. The preliminary detection of SO_2 and CO_2 in exhaust gas can screen out suspicious ships using sulfur content exceeding the standard that does not meet the relevant requirements of DECAs.

The fifth chapter first summarizes the main content of the paper; secondly, suggestions are provided to meet MSAs' needs to enhance their supervision efficiency in DECAs.

CHAPTER 2

OVERVIEW OF INTERNATIONAL CONVENTION REVISION AND FOREIGN ECAS REGULATION

To reduce the pollution of the environment and the threat to human health caused by the exhaust emissions from ships, an international consensus on the need to control the exhaust emissions from ships and several ECAs have been actively improved through the revision of conventions and the development of domestic regulations.

This chapter will elaborate on the process of IMO in revising conventions and developing emission standards and summarize the regulatory policies, measures and technical tools implemented by the EU and US in ECAs through the introduction of six internationally recognized ECAs.

2.1 Relevant IMO initiatives

2.1.1 Revision of the Convention and Establishment of ECAs

Because of the impact of ship emissions on the air environment, the Marine Environment Protection Committee (MEPC) of the IMO formally launched the discussion and consideration of the prevention of atmospheric pollution from ships as early as 1988, and revised the 1997 Protocol to the MARPOL 73/78 and adopted Annex VI "Prevention of Air Pollution from Ships". The *Code for the Prevention of Atmospheric Pollution from Ships* was revised and adopted as Annex VI on May 19, 2005, and entered into force for China on August 23, 2006.

The Code is the first for IMO to enter the air pollution prevention and control field, mainly for SO_X, NO_X, PM, ozone depleting substances and volatile organic compounds. As far as SO_X is concerned, the convention sets a general limit for SO_X emissions from ships and sets emission limits for global waters and ECAs, respectively, ranging from 4.5%m/m to 0.1m/m according to time points, as shown in Table 1.

Implementation area	Sulfur limits	Entered into force
Outside ECAs	≤4.5%	Before January 1, 2012
	≤3.5%	January 1, 2012, and after
	≤0.5%	January 1, 2020, and after
ECAs	≤1.5%	Before July 1, 2010
	≤1.0%	July 1, 2010, and after
	≤0.1%	January 1, 2015, and after

Table 1 –Sulphur limits in ECAs and outside ECAs

Meanwhile, IMO considers it necessary to control ship fuel pollution and designate ECAs on a global scale, divided into sulfur ECAs and nitrogen ECAs. Currently, IMO has designated four ECAs (see Figure 1), including sulfur oxide emission control areas in the Baltic Sea and the North Sea region and sulfur oxide, nitrogen oxide, and particulate matter emission control areas in North America and the Caribbean region. as shown in Table 2.

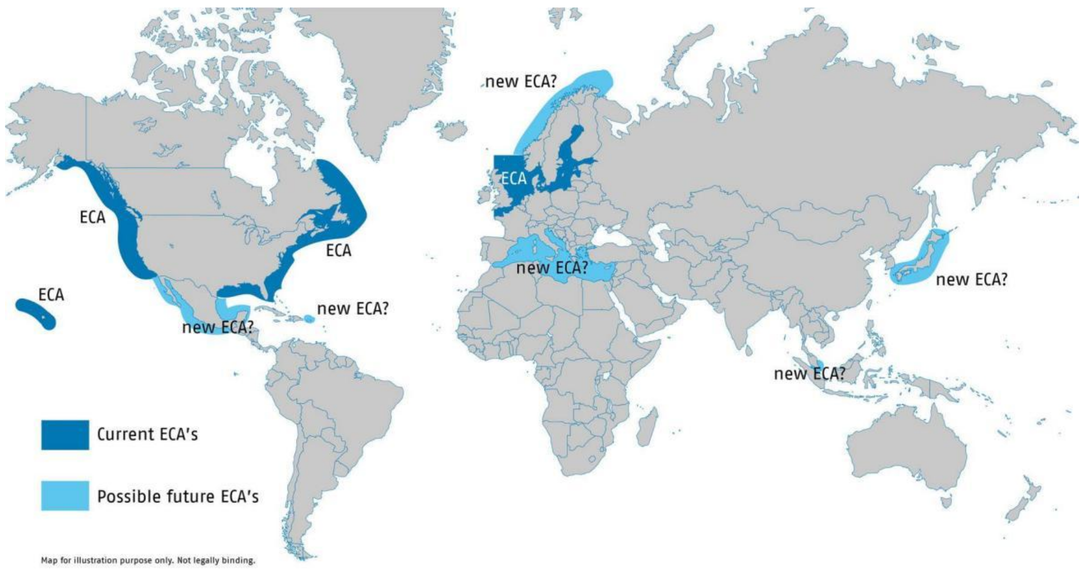

Figure 1- Current ECAs designated by the IMO

Adoption, entry into force & date of taking effect of Special Areas			
Special Areas	**Adopted #**	**Date of Entry into Force**	**In Effect From**
Annex VI: Prevention of air pollution by ships (Emission Control Areas)			
Baltic Sea (SO_x) (NO_x)	26 Sept 1997 7 July 2017	19 May 2005 1 Jan 2019	19 May 2006 1 Jan 2021
North Sea (SO_x) (NO_x)	22 Jul 2005 7 July 2017	22 Nov 2006 1 Jan 2019	22 Nov 2007 1 Jan 2021
North American ECA (SO_x and PM) (NO_x)	26 Mar 2010	1 Aug 2011	1 Aug 2012 1 Jan 2016
United States Caribbean Sea ECA (SO_x and PM) (NO_x)	26 Jul 2011	1 Jan 2013	1 Jan 2014 1 Jan 2016

Table 2- Four ECAs designated by the IMO

2.1.2 Establishment of ECAs in some areas and nations

There are two primary forms of international ECAs. One is designated by the IMO, and the other is for regional organizations, national and local governments to formulate and enforce regional ship emission control policies.

The establishment of an ECA needs to be assessed by the IMO, and the process is complicated and the evaluation is relatively stringent. Under the requirements of the MARPOL 73/78 and its Annex VI, it is confirmed that there is a need to prevent, reduce and control air pollution caused by three pollutants, namely sulfur oxides, particulate matter, and nitrogen oxides; IMO will consider the establishment of ECAs. (Tian, 2017)

At present, there are 6 ECAs recognized internationally, in addition to the IMO-designated ECAs, the EU and the US have also established their emission control area (See Figure 2). And the emission limit policies for ship SO_X are different (See Figure 3).

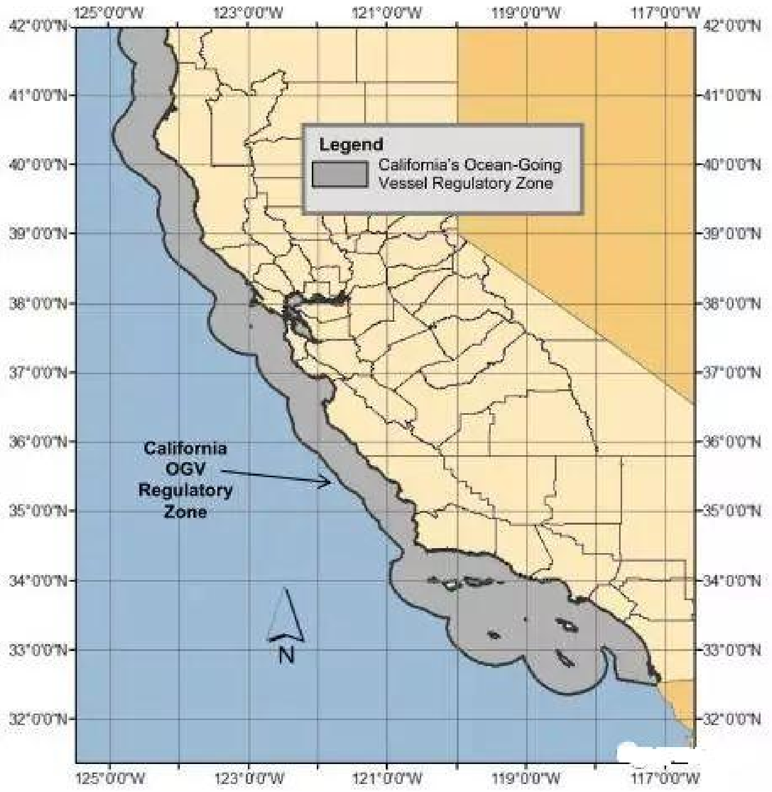

Figure 2- California's Ocean-Going Vessel Regulatory Zone

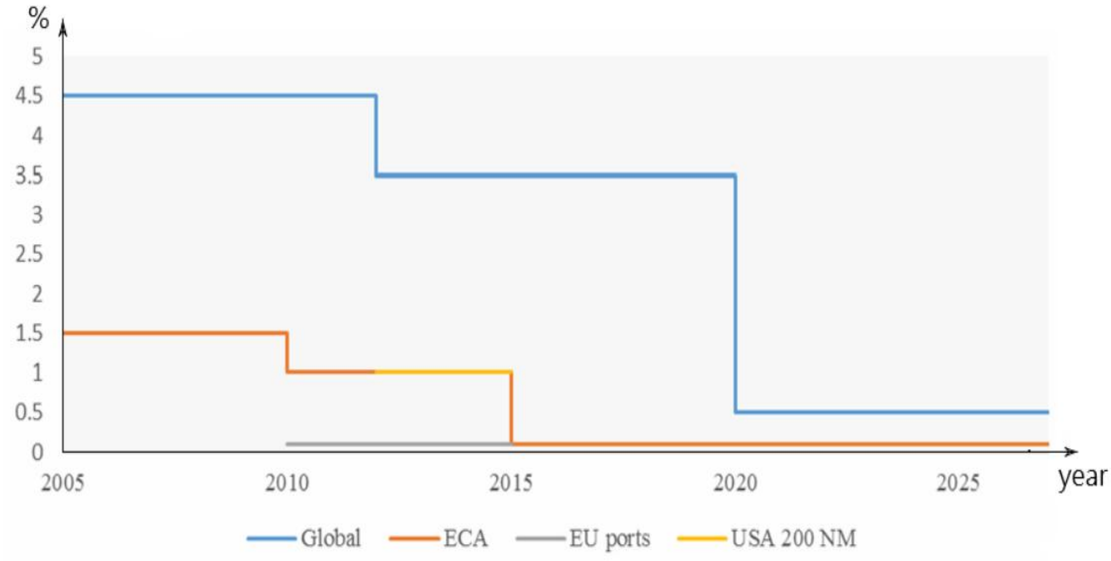

Figure 3- Evolution of the emission limit policy for Ship SO_X

In addition, China, South Korea, Norway, Iceland, Turkey, and other nations have introduced corresponding emission control zones and emission standards.

2.2 EU and US regulatory policies, measures, and technical means in ECAs

Atmospheric pollutant monitoring technology can be divided into traditional physical chemistry method, modern method, conventional optical method, and spectral measurement method. Currently, according to the classification of technical principles, the primary technical means of monitoring and supervision of ship exhaust emissions include sniffing technology, ultraviolet spectroscopy, infrared remote sensing technology, lidar technology, etc. Ni Xunpeng (2020) analyzed these four technologies from different dimensions (see Table 3).

	Sniffing	**Ultraviolet Spectroscopy**	**Infrared remote Sensing**	**Lidar**
Adaptability	Many installation methods, which can be fixed installation, UAV carrying, etc. SO_X, CO_X, NO_X, PM, etc. can be measured.	Installed on the bridge above the channel. SO_X, NO_X and PM can be measured but COX, cannot be measured.	Installed on the vehicle or boat. SO_X, CO_X, NO_X, PM, etc. can be measured.	Installed on the vehicle or boat. At present, only PM can be measured.
Accuracy	Contact test. The results are relatively accurate.	Non-contact detection The result error is relatively large.	Non-contact detection The result error is relatively large.	Non-contact detection The result error is relatively large.
Safety	With no obvious safety risks.	With no obvious safety risks.	With no obvious safety risks.	A potential safety risk in the application.
Economy	Relatively low.	Relatively low.	Relatively low.	Relatively high.

Table 3- Comparative analysis of four detection techniques

The comparison in Table 3 shows that sniffing technology is more cost-effective than the other three technologies. And it is widely used in the EU and US for regulating ships in the ECAs (fixed-wing aircraft carrying sniffing equipment, helicopters carrying sniffing equipment, installing fixed sniffing equipment on the shore or on the bridge, etc.).

With the research and development of regulatory technology, optical remote sensing technology has also been gradually introduced into the supervision of ship exhaust in the voyage.

2.2.1 EU Regulatory Policies, Measures, and Technical Technologies in ECAs

1. Establishment of THETIS data sharing system

To support the effective implementation of the new inspection system, the European Maritime Safety Agency has developed the Hybrid European Targeting and Inspection System (THETIS), which can receive and share information and data within the European Maritime Safety Agency. (EMSA, 2022)

The system uses each ship's unique IMO number to track and analyze the ship, which is an excellent response to the previous practice of changing the ship's name, flag state and shipping company to conceal the ship's bad history. On the other hand, it can reduce the number of inspections for those companies with good records while minimizing the number of low-standard ships in EU waters. Secondly, the THETIS data system records the inspection results, and all port state control authorities are able to share these inspection results through this system; it is also connected to other maritime safety-related databases, which makes the inspection objectives clear to each maritime authority quickly.

2. Set up a standardized inspection process

To carry out orderly and effective supervision of ships in the ECA, EU maritime enforcement officers strictly follow a standardized inspection process for their supervision and inspection. (EMSA, 2016) And the inspection process is divided into two steps.

The first step is the preparation of officers before boarding the ship. They search the related information about the ship, including the next port of call, arrival and departure time, duration of stay in port, the type of fuel oil stored on the ship, etc., through the THETIS data system, then choose the ship using any non-compliant bunker oil in other waters or ports as the targets for inspection.

The second is the boarding inspection. After obtaining the above information, officers access the ship to conduct a detailed inspection, first of all to carry out a clerical inspection if no obvious non-compliance is found and then check whether to take alternative measures that is, a mixture of bunker fuel and evaporative gases, exhaust gas cleaning systems, biofuels, alternative fuel oils such as Liquefied Natural Gas (LNG), methanol, etc... Suppose the vessel uses these alternative measures to meet emission standards. In that case, it should also be verified that the vessel is approved to use alternative measures (at trial or by commission) and that alternative measures are used for all combustion machinery on board. Suppose the paperwork is incorrect or the vessel has not taken alternative measures, in that case, the inspector should take samples of the fuel oil used to determine whether the sulfur content of the fuel oil meets the standards and take appropriate penalties.

3. Improve the sampling rate of marine fuel oil

In 2015, EU member states issued Decision 2015/253, which strictly regulates the frequency of sampling of bunker oil, checking the bunker logs of 10% of vessels arriving in the ECA and the oil records in the logbooks. The oil records in the bunkering logs and logbooks of 10% of the vessels inspected are checked. Fuel samples are taken and analyzed according to different shorelines, i.e., 40%, 30%, and 20% of the shorelines are within the ECA, some shorelines are within the ECA, and all shorelines are not within the ECA, respectively. (Official Journal of the European Union, 2015)

The increased rate of vessel inspections and oil sampling resulted in a significant decrease in the violation rate in 2015 compared to the previous rate. The EU has significantly reduced the room for ship operators or ship owners to cheat by introducing laws regulating the sampling rate of vessels and fuel oil, while enforcement officers conduct strict inspections.

4. Use the advanced remote sensing monitoring technology

The EU has designated the ECA early and continuously made innovations in the technical means of regulation.

The boarding inspection can only be carried out after the ship has docked, and whether the ship has complied with the regulations and switched to low sulfur fuel when it enters the emission control area cannot be confirmed by boarding inspection. To solve the various limitations of shipboard inspection, countries such as Denmark, Sweden and Belgium have tested and applied remote sensing monitoring technologies, including drone sniffing technology, fixed sniffers, differential absorption spectroscopy technology, etc.

Remote sensing monitoring technology can significantly enhance the efficiency of law enforcement. This advanced remote sensing monitoring technology can initially determine whether the ship violates the law to identify the ships to be inspected and narrow down the screening range. Then the maritime law enforcement officers can conduct detailed inspections of the screened-out ships.

The Danish and Swedish studies found that sniffing technology was more than four times more efficient at identifying non-compliant vessels than boarding and inspection: in 2015 and 2016, sniffing technology screened out 31% of non-compliant vessels; while law enforcement officers found only 7% of non-compliant vessels through fuel oil sampling during the same period. Using advanced remote monitoring technology, the EU has reduced the possibility of illegal operations by shipowners and reduced the workload of maritime enforcement officers. (Cao & Dong, 2017)

2.2.2 U.S. Regulatory Policies, Measures, and Technical Technologies in ECAs

In the technical means of enforcement in the ECAs, the US and other countries mainly use the boarding of ships to carry out inspections of ship documents, fuel oil sampling and the use of sniffing, telemetry and a combination of regulatory technology methods. Specifically:

1. Ship paperwork inspection.

It refers to the inspection of documents such as fuel log books and related records in the ship's computer system to analyze whether the ship complies with information such as fuel temperature and viscosity. It is understood that California Air Resources Board currently has 2 professional technicians working full-time to conduct boarding and inspection, and the inspection time is about half an hour for each vessel. (Li, Li, & Gao, 2017)

2. Rapid fuel testing.

By officers with portable equipment to check the ship fuel samples, sulfur content higher than the specified value will be transferred to the laboratory for testing to further confirm the sulfur content of fuel and determine whether to impose penalties. Currently, the rapid fuel testing method is more mature in the Netherlands, the US and Sweden and other countries have also begun to test the rapid testing method, the trial effect is better.

3. Laboratory fuel testing.

The test results can be used as a basis for penalties. Currently, there are more than ten large laboratories in the US with testing qualifications, mainly located on the northern East Coast and the northern West Coast of the US. The testing time is shorter, but the sample delivery time is longer. Take the 2015 port state supervision and inspection report issued by the US Coast Guard as an example, in which foreign vessels made

73,752 port calls and 17,920 inspections, compared with 79,091 port calls and 17,794 inspections in 2014, with the inspection ratio increasing from 22.5% to 24.3%, which is a slow-growth trend but still maintains a high level overall. The high frequency of sampling inspection makes the ship owner or ship operator take "non-compliance action" less and less, and gradually change to take "compliance action". The most direct effect of this shift is a significant improvement in air quality within the emission control area. (U.S. EPA, 1991)

4. Sniffing techniques.

Similar to the principle of air quality monitoring stations, the ratio of sulfur to carbon in the air is used to analyze the fuel sulfur content of passing ships for compliance. The sniffing equipment can be loaded at fixed locations such as land, bridges, or mobile platforms such as vehicles and aircraft. Sniffing technology is currently in use in the US, Germany, the Netherlands, and Sweden, etc. And the telemetry technology including differential absorption spectroscopy (DOAS) and other optical technology, can be loaded on land, bridges, vehicles, or aircraft and other locations. The application of this technology in various countries is mostly still in the exploration and trial stage.

5. Strengthen public supervision of the port environment.

The environmental protection department of the state where the port is located and the environmental information office in the regional office are responsible for the disclosure of environmental information. At the same time, the policies formulated by the port and their implementation will also be made public on the official website of the port and related websites. And the public can view environmental data and sample reports from all sites on the Clean Air Act Plan website and view the data in multiple formats. (EPA, 2021) In addition to air quality monitoring results, the public can also access environmental information such as water quality, soil quality, and wildlife on the Port's official website.

2.3 Chapter Summary

This chapter introduces the background of international conventions and emission requirements related to the establishment of ECAs. The six internationally recognized ECAs are mainly distributed in the EU and US, and this chapter collects their regulatory measures and technologies.

The EU and the US have established a standardized inspection process to confirm whether ships entering the ECAs are using fuel oil in compliance with regulations through inspection of ship instruments and testing of fuel oil sulfur content, and constantly update the use of monitoring technology. Currently, according to the classification of technical principles, domestic and foreign ship exhaust emission monitoring and supervision primary technical means include UV differential absorption, infrared remote sensing, sniffing, etc. These technologies, combined with drones, helicopters, boats and other equipment, can further enhance the monitoring of mobile pollution sources.

In addition, the EU and the US have adopted different monitoring technologies according to their respective realities. The THETIS allows the EU port state control authorities to share records of inspection results and relevant data to further strengthen the inspection of low-standard ships. On the other hand, the US has strengthened public monitoring through the disclosure of environmental information about ships and ports. These are all aimed at reducing air pollutant emissions from ships in ship emission control zones. It also provides a reference for other regions and port countries to build ECAs.

CHAPTER 3

OVERVIEW OF CHINA'S DECAS AND INTRODUCTION TO SHANGHAI PORT

3.1 Overview of China's DECAs

Currently, the IMO has not designated an ECA in East Asia, where China is located, but it cannot underestimate the scale of ship emissions in the region.

China is one of the busiest and fastest growing shipping regions in the world. While the prosperous development of the water transport industry has delivered huge economic benefits to China, it has also aggravated the air pollution problems along the waterways and in the surrounding port areas. And ship emissions have become the third-largest source of air pollution in China after industrial exhaust and motor vehicle exhaust, and an essential source of air pollutants in China's port cities. (Wan, He, & Huang, 2013) According to the China Mobile Source Environmental Management Annual Report 2019, the national emissions of SO_2, hydrocarbons, NOx, and PM from ships were 588,000 tons, 89,000 tons, 1,151,000 tons and 109,000 tons, respectively, in 2018, accounting for 98.33%, 11.68%, 26.88% and 24.49% of the national emissions from non-road mobile sources respectively. (Ministry of Ecology and Environment of the People's Republic of China, 2019)

As a major shipping country and a responsible power, China has actively dealt with international shipping emission reduction regulations and promoted the green development of the domestic shipping industry. The application for the designation of ECAs by the IMO, which takes a long period, aims to reduce emissions of air pollutants from ships as soon as possible, and China has drawn on the ECA policy of MARPOL 73/78 and established DECAs under *China's Atmospheric Pollution Prevention Law* and the implementation plans of ship emission control areas.

There is a large gap between the IMO-designated ECAs and China's DECAs. It is demonstrated by the fact that, on the one hand, the scope of the DECAs is limited to the territorial sea and internal waters over which China has jurisdiction; on the other hand, as a party to the *United Nations Convention on the Law of the Sea*, China needs to implement the "right of innocent passage" for international vessels within its territorial sea. Therefore, although the scope of the emission control area established by China is limited to the territorial sea and internal waters, China cannot impose further emission reduction requirements on the international shipping of other countries.

3.1.1 Relevant policies

1. *China's Atmospheric Pollution Prevention Law (hereinafter referred to as "Atmospheric Law")*

The Atmospheric Law has undergone four revisions since its promulgation in 1988, and the latest version was published and came into effect on October 26, 2018. The legislation of the new Atmospheric Law in terms of air pollution control is mainly reflected in the provisions on the quality of marine fuel, inspection of ship engines and related equipment, etc. At the same time, the Atmospheric Law gives the competent transportation department under the State Council the right to designate the DECAs in China's coastal waters. It clarifies the discretionary standards for administrative penalties imposed by MSAs on ships that do not meet the relevant requirements, which provides superior law support for the subsequent introduction of relevant regulatory documents by the Ministry of Transportation (MOT) and China MSA.

2. *Implementation Plan on Domestic Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and Bohai Rim (Beijing, Tianjin, Hebei) (JHF [2015] No. 177)*

The MOT issued this Implementation Plan at the end of 2015, establishing the three most developed regions of China's shipping economy as DECA (see Figure 4) and designating Eleven large ports, including the Port of Shanghai, are designated as "core ports". By setting a "five-year plan" starting January 1, 2017, ships will be mandated to use low sulfur fuel of no more than 0.5% m/m in the DECAs (compared to 3.5% m/m for ships outside the DECA at this time) (See Table 4), which aims to reduce SO_X emissions within DECAs by 65% by 2020.

Figure 4- DECAs in Waters of the Pearl River Delta Region (PRD), the Yangtze River Delta Region (YRD), and the Bo Sea Region (also known as the Jingjinji Region)

Stage	**Time**	**Emission control measures**
Stage 1	From January 1, 2016	Emission control area with the conditions of the port can be implemented during the berthing of ships using sulfur content ≤ 0.5% m / m fuel oil and other measures above the current emission control requirements.
Stage 2	From January 1, 2017	Vessels in the core port area of the emission control area during berthing (except for one hour after berthing and one hour before leaving port, the same below) should use fuel oil with sulfur content ≤ 0.5% m/m.
Stage 3	From January 1, 2018	Ships should use fuel oil with sulfur content ≤ 0.5% m/m during berthing at all ports in the emission control area.

Stage 4	January 1, 2019 onwards	Ships entering the emission control area should use fuel oil with sulfur content ≤ 0.5% m/m.
Stage 5	By December 31, 2019	Evaluate the effectiveness of the implementation of the aforementioned control measures and determine whether to take the following actions. 1. Ships enter the emission control area using fuel oil with sulfur content ≤ 0.1% m/m. 2. Expanding the geographic scope of emission control areas. 3. Other further initiatives

Table 4- The main implementation stages of the policy on DECAs in JHF [2015] No. 177

However, the problems such as low control requirements, insufficient control in coastal waters, and no further measures to control nitrogen oxide emissions from ships are not solved, so a new version of the Implementation Plan was mooted by the MOT at the end of 2018.

3. *Implementation Scheme of the Domestic Emission Control Areas for Atmospheric Pollution from Vessels (JHF [2018] No. 168)*

This Implementation Scheme was issued on November 30, 2018, and became effective on January 1, 2019. This further increased the control scope of the DECAs and raised the restriction standards.

The scope of control of the emission control area has been further expended. The coastal waters of the DECAs are extended to all waters and ports within 12 nautical miles of the baseline of the national territorial waters. Hainan waters and its ports are specially designated to implement more stringent control policies. In addition, it added two new inland river DECAs, namely the navigable waters of the Yangtze River Main Line and the Xijiang River Main Line. So far, the geographical scope of China's ship emission control areas has been expanded from the three regional waters to the country’s coastal and major inland waters. (See Figure 5)

Figure 5- China's national and regional emission control areas

At the same time, the restriction standard has been further improved. The use of marine fuel with a sulfur content of not more than 0.1% m/m is formally established as a requirement for emission restrictions. (See Table 5)

Stage	**Time**	**Emission control measures**
Stage 1	January 1, 2019 onwards	Marine vessels into the emission control area, should use sulfur content ≤ 0.5% m / m of marine fuel, large inland waterway vessels and direct river and sea vessels should use the newly revised national standards for marine fuel oil requirements of fuel; other inland waterway vessels should use diesel fuel in line with national standards.
Stage 2	From January 1, 2020	Marine vessels entering the inland control area should use marine fuel with sulfur content ≤ 0.1% m/m.
Stage 3	From March 1, 2020	Ships that do not use alternative measures such as sulfur oxide and particulate matter pollution control devices to enter the emission control area can only load and use the marine fuel they should use in accordance with the provisions of this program.

Stage 4	From January 1, 2022	Marine vessels entering the coastal control area Hainan waters, should use a sulfur content of not more than 0.1% m / m of marine fuel.
Stage 5	By January 1, 2025	In due course, assess the feasibility of ships using marine fuel with a sulfur content of not more than 0.1% m/m, and determine whether to require the use of marine fuel with a sulfur content of not more than 0.1% m/m for marine vessels entering the coastal control area from January 1, 2025.

Table 5- The main implementation stages of the policy on DECAs in JHF [2018] No. 168

NOx emissions are also restricted, requiring ships to meet the MARPOL 73/78 NOx emission limits for each stage according to the construction or major modification of marine diesel engine time, whether the output power of a single marine diesel engine exceeds 130 k W and other conditions.

3.1.2 Relevant measures

The implementation of the policy and effect of DECAs requires strong supervision means as a guarantee. At present, China MSAs mainly inspect the fuel quality, fuel supply and receipt documents, record documents and other related requirements of the control area during on-site enforcement, and conduct fuel sampling and testing as appropriate to achieve the supervision of sulfur content of ships' fuel in the DECAs, which has the shortcomings of random inspection targets, poor targeting, and relatively low efficiency.

How to make full use of the latest scientific and technological achievements to automatically identify suspect ships using fuel oil with excessive sulfur content and guide maritime site enforcement is urgently needed for relevant research. There are many ways of ship exhaust detection, such as UAV detection, boat-based detection, shore-based (including lightships, islands, etc.) detection, and different detection means have certain advantages and shortcomings.

1. UAV detection

With the development of UAV technology, the officers can fly the monitoring equipment over ships with UAVs carrying monitoring equipment for close monitoring. This method can not only achieve fast and effective monitoring coverage, but also its monitoring accuracy is higher than other methods due to the close monitoring distance.

In the current practice of UAV monitoring, the lack of an effective scheduling algorithm leads to many problems, such as high randomness of UAV monitoring target selection and low coverage targeting, wrong UAV flight direction and low flight efficiency, little UAV range planning, and the existence of lack of power forced to return and rich power after a return. At the same time, considering the appropriate monitoring equipment and the procurement cost of UAVs with the increasing number of monitoring vessels, how to effectively plan the flight route of UAVs is a problem that needs to be studied. In the current scenarios with more UAV applications, such as logistics scheduling, remote sensing mapping, and power grid inspection, the targets of UAVs in the scheduling process are generally fixed, so the difficulty of path planning is low. In ship exhaust monitoring UAV dispatch, on the other hand, the ships to be monitored are all mobile and have different monitoring importance, which further enhances the difficulty of dispatching planning. (Zhuo, Miao, & Xu, 2021)

Figure 6- An UAV carries a detection equipment

2. Boat-based detection

The marine patrol boat is a standard enforcement unit in maritime supervision, responsible for jurisdictional cruising. Therefore, the monitoring equipment loaded on the boat can achieve safe and convenient exhaust detection.

Figure 7- Onboard sniffing equipment and monitoring interface

Compared with UAVs, boats are relatively less affected by weather, but there are still some difficulties.

Lack of operational flexibility. Since the ship exhaust detection should be as close as possible to the ship, the operation of the patrol boat is relatively inflexible compared to the UAV. Too close to the target ship may affect the personal safety of officers, and too far from the target, the results may not be as accurate.

The scope of supervision is limited. Restricted by navigation conditions and work needs, the deployment of maritime patrol boats is often in dense waters in the port, and the number of patrol boats involved in daily cruises in distant waters prone to illegal acts is relatively small, so the scope of supervision is more limited compared with drones and shore-based detection. (Wang, Xu, & Hu, 2019)

3. Shore-based detection

Shore-based detection has a broader coverage compared to the drone and boat detection. Shore-based detection can use infrared, sniffing and other technologies to screen out target ships that are likely to use excessive fuel in a large number of transiting ships, which is a suitable means for large-scale supervision.

Figure 8- Quay drawbridge installation and deployment of shore-based fixed point reproduction monitoring equipment

The current difficulties are the following two points.

There is a time lag, and the crew may temporarily change the fuel. The deployment points are often on bridges, islands, etc. And it takes some time for the inspector to take samples after tracking the suspected use excessive use of fuel. There may also be cases where the crew changes the previously used fuel with excessive sulfur content to qualified fuel, making it difficult for the inspector to obtain evidence.

The ship identification tracking system needs to be further developed. The feedback information of ships traveling at sea is not real time, and the Automatic Identification System (AIS) has a time lag. It cannot transmit the ship information entirely in real-time. Therefore, in order to determine the suspicious ship information more accurately, the ship identification system needs to be further developed, which uses high-definition camera to scan and take pictures in real time at close range to make up for the problem of lagging monitoring data in AIS.

3.1.3 Achievements

Since the gradual implementation of the DECA regulations in China, stricter sulfur content requirements have been imposed on fuels used for inland, coastal and ocean-going vessels. Concentration levels of SO_2 in large port cities have declined significantly, but NOx emissions have not declined significantly in comparison.

At the same time, due to factors such as the ability to implement laws and regulations and the level of economic development of ports, the strength and status quo of ship exhaust emission regulation varies from port to port, so that this paper will select the port of Shanghai for specific analysis.

For the requirements of the ship emission control zone program, for the actual needs in the supervision of maritime authorities, research and analysis of the relevant regulatory technology of ship exhaust emissions, and the formation of replicable monitoring experience.

3.2 Introduction of Shanghai Port DECA

Since 2010, Shanghai Port has ranked first in the world in cargo and container throughput, and the total volume continues to soar. In 2021, Shanghai Port's container throughput exceeded 47.033 million Twenty-feet Equivalent Units (TEUs), an increase of about 8.1% year-on-year, ranking first in the world for 12 consecutive years and accounting for 60.7% of port cargo throughput. (See Table 6)

The importance of the Shanghai Port DECA is beyond doubt.

INTERNATIONAL CONTAINERS AND CARGO THROUGHPUT OF FOREIGN TRADE IN MAIN YEARS

Year	Weight of International Containers (10 000 tons)	International Containers (10 000 TEU)	of which	
			Input	Output
1990	446	45.6	22.4	23.2
1995	1 389	152.6	69.3	83.3
2000	5 170	561.2	266.1	295.1
2005	16 250	1 808.4	887.2	921.3
2006	19 595	2 171.9	1 064.4	1 107.5
2007	23 850	2 615.2	1 276.3	1 338.9
2008	25 992	2 800.6	1 397.8	1 402.8
2009	24 619	2 500.2	1 222.9	1 277.3
2010	27 992	2 906.9	1 436.1	1 470.8
2011	31 220	3 173.9	1 555.1	1 618.9
2012	32 480	3 252.9	1 605.1	1 647.9
2013	34 243	3 361.7	1 652.2	1 709.5
2014	35 335	3 528.5	1 732.3	1 796.2
2015	35 850	3 653.7	1 818.7	1 835.0
2016	36 736	3 713.3	1 825.2	1 888.1
2017	39 759	4 023.3	1 980.3	2 043.0
2018	41 126	4 201.0	2 064.6	2 136.4
2019	42 314	4 330.3	2 149.1	2 181.1
2020	43 473	4 350.3	2 146.7	2 203.7

Note: TEU is the abbreviation, which refers to 20-foot equivalent unit.

Table 6- Container Throughput of Shanghai Port 1990-2020

Considering the current implementation conditions of China's DECAs, China put forward the concept of "core port" when establishing the DECA. The core ports can assess the implementation conditions according to their situation and add more stringent emission control provisions independently outside the unified emission reduction requirements.

There are several core ports in three DECAs. The Shanghai port is one core port of the YRD DECA, attaching great importance to the implementation of the vessel emission control area policy. (MOT, 2015)

3.2.1 Relevant policies

To further improve the ambient air quality in Shanghai port and promote the green development of Shanghai International Shipping Center, the General Office of Shanghai Municipal People's Government issued the *Work Plan for the Implementation of DECA in Shanghai Port*, requiring the Shanghai port area (including sea and inland waters) to take the lead in implementing measures above the current emission control requirements from April 1, 2016.

Shanghai port also developed the Implementation guidelines, work programs, rules and other specifics to promote the effective implementation of the vessel emission control zone policy. (See Table 7)

Release Date	**Specific measures**	**Main content**	**Purpose**
2016/2/17	Notice on the Implementation of Ship Emission Control Zone in Shanghai Port	Since April 1, 2016, international vessels and domestic coastal navigation vessels during berthing (except for one hour after berthing and one hour before leaving port) should use marine fuel with sulfur content not greater than 0.5% (m/m), and inland vessels and direct river and sea vessels should use diesel fuel in accordance with GB252 standard.	Early implementation of national policy on ship emission control zone in Shanghai port.
2017/10/27	Notice on the forwarding of the "Notice on the work related to the full supply of ordinary diesel fuel with lithium content of not more than 10ppm nationwide" and other documents	The lithium content of ordinary diesel fuel added to inland vessels on or after November 1, 2017, is not greater than 10 ppm.	Improve the standard of sulfur content of fuel oil for inland waterway vessels.
2018/8/27	Notice on the Early Implementation of Emission Control Measures for Vessels Operating in Shanghai Port	Since October 1, 2018, international vessels and domestic coastal navigation vessels entering the port of Shanghai during navigation should use marine fuel with a sulfur content of not more than 0.5% (m/m).	Doing a good job of safeguarding the ambient air quality of the 2018 China International Import Expo and promoting ship emission reduction.

Table 7- Summary of Shanghai Port DECA Policy

3.2.2 Implementation Effect

Since the implementation of the DECA policy for ships, the maximum limit of sulfur content in fuel oil for marine vessels has dropped from 3.5% to 0.5%, a decrease of about 85%, and the maximum limit of sulfur content in fuel oil for inland river vessels has dropped from 350 ppm to 10 ppm, a decrease of about 97%, and the sulfur content of fuel oil used by ships has been significantly controlled at source, which in turn has reduced the sulfur oxides and particulate matter emissions from ship exhaust.

The average concentration of SO_2 in Shanghai was 16 μg/m3 before the implementation of the first phase control measures (in July 2015~June 2016) and 12 μg/m3 after the measures (July 2016~June 2018), a 25% decrease. (Shanghai Municipal Bureau of Ecology and Environment, 2018)

The air quality status report 2018 released by the Shanghai Ecological Environment Bureau shows that in 2018, the annual average concentrations of four major pollutants in Shanghai, including PM2.5, PM10, SO_2, and NO_2, were the lowest values since 2013.

Comparing the average concentration of SO_2 in the Waigaoqiao port area with the center of city, we can see that the concentration of SO_2 in the port station is 8μg/m^3 in 2021, and 15μg/m^3 in the same period of 2018, which is 47% lower than the same period of last year; the SO_2 in the city is 6μg/m3 in 2021, and 10μg/m^3 in the same period of 2018, which is 40% lower than the same period of last year, from the analysis of the above data, we can see that the decrease of SO rate is significantly higher than the city's average level of decline, indicating that the reduction of sulfur oxides from ships has made a greater contribution to the improvement of the city's air quality. In the second phase, measures on the low emission control area for ships continue to play an effective role. (Zhang K. , 2019)

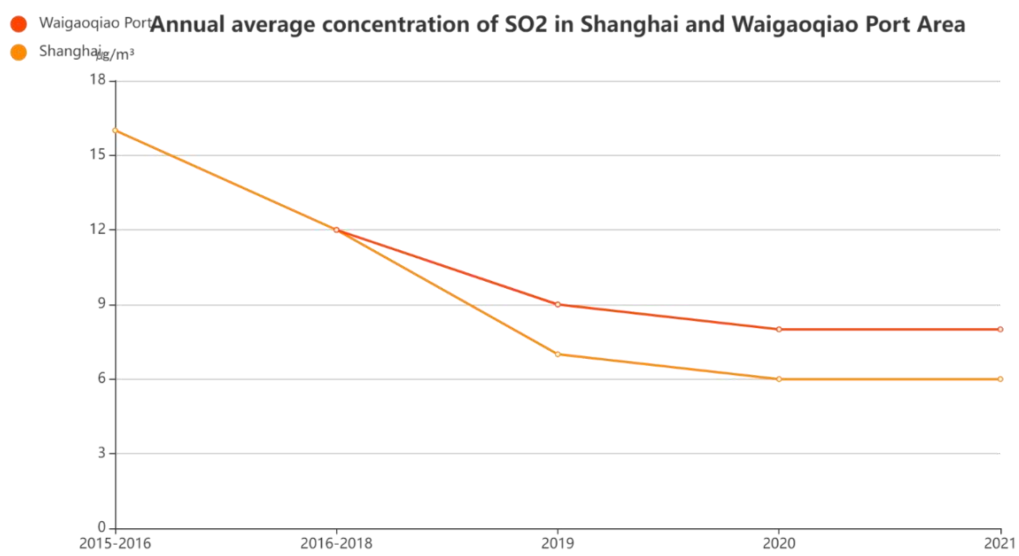

Figure 9- Annual average concentration of SO_2 in Shanghai and Waigaoqiao Port Area

3.2.3 Regulatory Difficulties

The MSAs have established a relatively sound procedure for the supervision and management of berthing ships in the Shanghai port DECA. From 2016 to the present, to fulfill the supervisory duties of the emission control area, the MSAs have selected a certain number of berthing ships to board and sample check the fuel oil sulfur content every year.

However, the supervision mode of boarding and sampling has also revealed the low sampling ratio, high enforcement costs, and the inability to target the ships underway. The supervision of the ships navigating in the DECAs is in urgent need of innovation in maritime supervision technology.

3.2.4 Response measures and use of technology

The implementation plan of the emission control area requires ships underway in the control area to use low sulfur oil of less than 0.5% after 2019. To meet the regulatory needs of ships underway, relevant domestic research institutes have started to research ship exhaust telemetry and detection technology.

Since 2019, the technical research results have been put into application in Jiangsu, Shanghai, Guangdong, Shenzhen and other maritime departments one after another, and several cases of illegal use of high-sulfur oil by ships underway have been investigated, which can provide services for efficient supervision of China's DECAs. (Chang, Zhu, & Chen, 2017)

3.3 Chapter Summary

This chapter introduces the relevant policies and initiatives of DECAs for regulating exhaust emissions from ships, analyzes the current status of regulation in DECAs, lists the practical experience, advantages and disadvantages of various regulation technologies, and takes the Shanghai port DECA as an example to analyze the initiatives in policy implementation, and elaborates on the implementation achievements, difficulties faced and countermeasures.

For the monitoring of the exhaust emission of berthing ships, the MSA has a more mature model and means to achieve the supervision of the sulfur content of the fuel oil of ships in the emission control area through the inspection of the fuel oil quality, supply and receipt of fuel documents, record documents and other relevant requirements of the control area in the process of on-site enforcement, and the fuel oil sampling and testing as appropriate, while the monitoring of ships underway is still in the exploration stage, tending to The use of telemetry technology, including fixed detection and mobile detection. Fixed detection such as shore-based detection, mobile detection includes boat-based detection and UAV detection. Exceptional, UAV detection can achieve fast and effective monitoring coverage, but its monitoring accuracy is also higher than other methods due to the close monitoring distance.

Therefore, the next section will take the Pudong MSA, which is in charge of the Shanghai Waigaoqiao port area, as an example, and focus on its exploration of using UAVs to detect ship exhaust and then calculate the sulfur content of ship fuel as a grip to solve the current regulatory challenges.

CHAPTER 4

TELEMETRY MONITORING TECHNOLOGY IN SHANGHAI PORT DECA - A CASE STUDY OF PUDONG MSA

4.1 Exploration and effectiveness

In 2019, the container throughput of Waigaoqiao port area reached about 20 million TEU, accounting for approximately half of the Shanghai port, including 568,000 TEU of dangerous goods container throughput, accounting for 51%, in addition, the bulk of dangerous goods cargo. In addition, the throughput of bulk dangerous goods cargo is 17.557 million tons, accounting for nearly 40% of Shanghai port, and the throughput of the ro-ro car is 1.5 million, accounting for 80% of Shanghai port, therefore, the demand for ship exhaust detection is enormous. (Pudong MSA, 2019)

However, Pudong MSA officers cannot board the ship to take samples for testing during the voyage, so it is also quite difficult to grasp whether the ship has used qualified fuel when it is within 12 nautical miles from the nearest land. In this case, telemetry supervision technology has become an excellent tool for maritime departments to strengthen the supervision of Shanghai DECA.

At the beginning of the year 2018, Pudong MSA analyzed the current situation of air pollutant emission supervision of ships underway in the DECA in the project research "Research on the Supervision of Vessels Underway in the Ship Emission Control Zone" and initially planned the implementation path of telemetry supervision technology such as infrared monitoring and sniffing technology detection in combination with the characteristics of Shanghai Port. From July 2016 to December 2019, Pudong MSA, jointly with Shanghai Combined Port Management Committee, Shanghai Maritime University and Shanghai Anxin Information Technology Co., Ltd., jointly carried out the research of the project "Research on Monitoring and Supervision of Vessel Exhaust Emissions in China (Shanghai) Pilot Free Trade Zone", and made a breakthrough in the efficient telemetry of vessel exhaust.

1. It verified the feasibility of sniffing technology in the exhaust gas detection of ships. The Sulphur content of marine fuel oil was calculated and tested against the actual Sulphur content data taken on board the ship. 96.7% of the data were within 1000ppm.

2. It established the standards for ship exhaust UAV testing based on the UAV flight test, the Data Recording Standard, Data Analysis and Processing Standard were established to make the UAV flight testing more standardized and data collection more accurate.

3. The ship exhaust gas testing pods have been independently developed, and the testing accuracy has reached the international leading level. Currently, the Shanghai Institute of Measurement and Testing Technology has certified the pod. The pod, weighing 0.9kg, is half the size and almost two-thirds the weight of the existing equipment on the market. The error of the exhaust gas telemetry data and the actual measurement data taken on board the ship is 100% controlled within 500ppm, which is generally within 1000PPM internationally, reaching the international leading level.

4. A new supervision mode of "UAV verification - Officers boarding ships for actual inspection" has been established. Changing the previous supervision method of blindly boarding vessels to take oil samples has improved the efficiency of maritime law enforcement.

5. The first domestic case of exceeding the sulfur content of fuel oil on board was seized. On July 15, 2019, the first case of exceeding the sulfur content of fuel oil used by ships on board was seized by using a UAV carrying an exhaust gas detection pod to monitor the exhaust the ship’s gas.

Compared with the previously used on-site enforcement process of fuel quality, fuel supply and receipt documents, record documents and other relevant requirements of the DECA inspection, and as appropriate, fuel sampling and testing, telemetry technology appears to be more rapid and efficient, and less interference with the order of navigation.

By arranging fixed monitoring systems in dense areas of ships, as well as using mobile detection equipment such as UAVs and patrol boats with sniffing equipment, the initial screening of suspicious sea vessels with fuel oil sulfur content over 0.5% m/m, thus locking the target for boarding and inspection. It can effectively change the existing supervision method of blindly boarding and sampling oil samples, save supervision resources and improve enforcement efficiency. According to the implementation of the project, it only takes 2 officers 10 to 15 minutes to monitor a ship with a drone, and it can monitor 10-20 ships every day. Compared with the previously tedious process of officers boarding ships, paperwork inspection, fuel sampling and testing, drone monitoring has dramatically improved the efficiency of supervision while achieving contactless supervision. (Pudong MSA, 2020)

4.2 Jurisdictional remote monitoring network deployment

4.2.1 Fixed monitoring system

In the ship dense area near the wharf or channel shore deployment and installation of ship exhaust emission pollutant detection instruments, so as to form a fixed detection point network, to achieve a full range of continuous monitoring of the surrounding ship pollutant emissions.

4.2.2 Mobile Monitoring System

For the detected "suspicious vessel", the inspector will send a drone to the vessel for further gas emission detection. In practice, it is proposed to use a UAV as a platform to mount gas monitoring pods. The pods will be transported by ground personnel to the vicinity of the ship's discharge port while using an onboard camera to record the images of the scene. For the detected "suspicious ships", the officers can also send the patrol boats to the ship for further gas emission detection. In practice, the patrol boat carries onboard monitoring equipment downwind of the detected vessel's exhaust, monitors the vessel's exhaust data through the monitoring equipment, and calculates the sulfur content of the vessel's fuel oil.

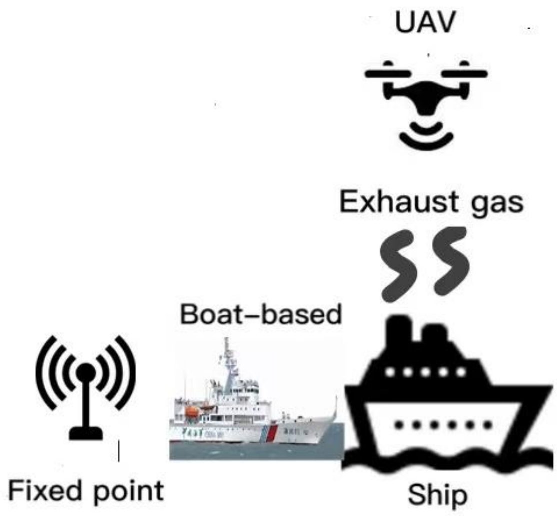

Figure 10- Monitoring Network in Waigaoqiao Port Area

4.3 Analysis of the use practice and effectiveness of drone sniffing technology

The ship's exhaust gas telemetry UAV system is shown in Figure 7, which consists of a UAV as a carrier, an exhaust gas detection pod and a ground data service terminal. During the regular operation of the system, the remote-controlled UAV with exhaust gas sniffing sensors flies to the exhaust plume of the ship, collects the concentration data of SO_2, CO_2 and other gases, records the time information and performs the calculation of the sulfur content of the ship's fuel oil, and completes the data integration and packaging process.

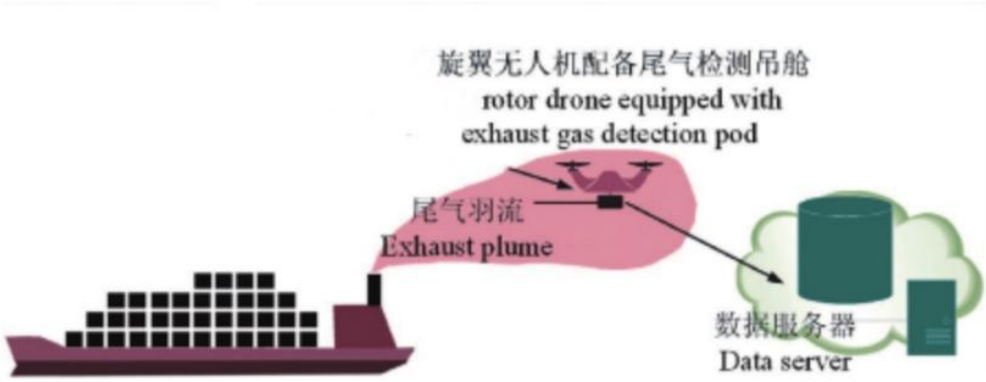

Figure 11- Overall design of ship exhaust telemetry UAV system

4.3.1 Technology principle and equipment

1. Technology Principle

Adopt the sniffing method, which is the global mainstream ship exhaust telemetry technology. It is accordant with that described in the MEPC guidelines 184(59) and previous studies. (Beecken, 2014)

The molar ratio of carbon and hydrogen in marine fuel oil is around 1:2, and the carbon content is calculated to be about 87%; according to the principle of material conservation, it can infer the sulfur content in fuel oil by monitoring the ratio of SO_2 and CO_2 (referred to as sulfur to carbon ratio) in the ship exhaust after diffusion dilution. (Kattner, Mathieu, Burrows, & Richter, 2015)

The current UAV system designed by Pudong MSA for ship exhaust telemetry mainly includes UAV, sniffing sensor and data monitoring ground station software.

2. Equipment

UAVs: The DJI M600pro UAV is an internationally popular consumer-grade micro drone that is low-cost, simple to operate, and can be equipped with sniffing sensors.

Ship exhaust gas monitoring pod (with sniffer sensor): It consists of an exhaust gas sensing module (currently equipped with SO_2, CO_2, NO_2 sensors, technical parameters see Table 5), power supply system, pod shell, exhaust gas data control, processing and transmission system and GPS module. The user can mount the vessel exhaust gas monitoring pod system under the UAV frame, control it by wireless transmission from the remote-control side of the UAV (e.g., monitoring sampling interval and air pump inlet speed), and transmit the exhaust gas monitoring data and Global Positioning System (GPS) data to the data server side by wireless transmission.

Data server side: Self-developed data monitoring software, it can monitor data and perform analysis and calculation, and then determine the sulfur content of fuel oil used by the ship by detecting the exhaust emission concentration of the ship.

Equipment name	Principle	Measurement Range	Precision
SO_2 Sensors	Electrochemical methods	0 - 10 PPM	±5% FS
CO_2 sensors	NDIR method	0 - 10000 PPM	±3%FS
NO_2 Sensors	Electrochemical methods	0 - 10 PPM	±5%FS

Table 8- SO_2, CO_2, NO_2 sensors' technical parameters

4.3.2 Detection methods

1. Flight procedures

The initial location measurements of the ship's smoke plume are shown in Figure 12. The UAV platform with sensors flies near the ship's funnel, hovers to collect the smoke, and then sends back the detection information. This process is not without risk, and a well-thought-out flight approach is recommended. We summarize the experimental steps as follows.

(1) Determine the location of the smoke plume based on wind speed, wind direction,

altimeter, infrared camera and other factors.

(2) Check the equipment to ensure that the power supply is adequate, the GPS signal is normal (more than 13 satellites are recommended), the electrochemical sensor is activated, and the residual gas in the pod gas circuit is de-charged.

(3) The UAV takes off vertically and rises to an altitude of 100 m (the first measurement point) for 3 minutes to determine the background values of SO_2 and CO_2. The takeoff is usually at the dock, more than 50 m away from the ship's smoke.

(4) The UAV was flown to the plume and hovered at about 10 m (second measurement point) and 5 m (third measurement point) from the funnel to collect the exhaust gases for 5 minutes each time.

(5) Lifting the UAV and then sending it back to the starting point. During this process, real-time observations of SO_2 and CO_2 are sent to the receiving end. The operator adjusts the position of the drone based on the observations to keep the sensor in the plume. Thus, in general, the UAV determines the approximate location of the plume at a distance of 10 m and then gradually approaches a position of about 5 m for acquisition.

Figure 12- Preliminary positioning measurements of ship plume by UAV

2. Calculation of fuel sulfur content (FSC)

As the UAV flies into the ship's plume, determine the peak areas for the SO_2 and CO_2

measurements and subtract the background for subsequent calculations. As the UAV hovers over the first measurement point, obtain the background for SO_2 and CO_2. When the UAV hovers at the second point or at the third measurement point (main observation point), the peak values of SO_2 and CO_2 are determined. In the calculations, the molecular weights of carbon and sulfur are 12 and 32 g mol-1, respectively, and the percentage of carbon mass in the fuel is 87 ± 1.5 %.

Assuming that 100% of the sulfur and carbon content of the fuel is emitted as SO_2 and CO_2, respectively, the mass percentage of FSC can be expressed as mass percentage of FSC can be expressed as follows.

$$\text{FSC}\ (\%) = \frac{S(kg)}{\text{fuel(kg)}} = \frac{\text{SO2 (ppm)}\cdot \text{A(S)}}{\text{CO2 (ppm)}\cdot \text{A(C)}} \cdot 87\ (\%) = 0.232 \frac{\int (SO2.peak - SO2.bkg)dt(ppt)}{\int (CO2.peak - CO2.bkg)dt(ppm)}\ (\%) \quad (1)$$

where A(S) is the atomic weight of sulfur and A(C) is the atomic weight of carbon. SO_2, peak, SO_2, bkg, CO_2, peak, CO_2, bkg are the peak and background of SO_2 and CO_2, respectively.

The response time of both sensors is less than 1 second. Even if the sampling rate of both sensors is set to the same, the two sensors are not perfectly synchronized, making it difficult to calculate the instantaneous ratios of SO_2 and CO_2. It should not set the interval time as too short or too long. Otherwise it will make the wave peaks too concentrated or too flat. After several experiments, 10s was chosen as the interval time.

3. Uncertainties

Since the measurements performed within the ship plume are analyzed relative to the background, the offset error values can be collected. However, there are certain uncertainties in the FSC estimation which can be summarized as sensor uncertainties, measurement uncertainties, calculation uncertainties, exhaust uncertainties, etc.

Concerning sensor uncertainty, it can be corrected by frequent calibration with standard gases and the progressive establishment of a quality management system that includes minimum requirements for sensor linearity, sensitivity, repeatability, hysteresis, resolution, stability, drift and other attributes.

Moreover, the measurement uncertainty is mainly attributed to improper sampling (the UAV did not fly into the plume). In addition, shipboard antennas, dock facilities and strong winds may interfere with finding the proper sampling point or even cause sampling failure. Such uncertainties can lead to incorrect estimates of the FSC. Therefore, we developed a flight procedure as described above.

The uncertainty of the calculation lies in the choice of background and peaks of SO_2 and CO_2. According to the law of error propagation (widely used in measurements, plots and statistics), it can obtain the relationship between the deviation of the measured values and the deviation of the FSC.

$$\begin{aligned}\Delta \mathrm{FSC} = {} & \frac{\partial f}{\partial \mathrm{SO}_{2,\mathrm{peak}}} \Delta \mathrm{SO}_{2,\mathrm{peak}} + \frac{\partial f}{\partial \mathrm{SO}_{2,\mathrm{bkg}}} \Delta \mathrm{SO}_{2,\mathrm{bkg}} \\ & + \frac{\partial f}{\partial \mathrm{CO}_{2,\mathrm{peak}}} \Delta \mathrm{CO}_{2,\mathrm{peak}} + \frac{\partial f}{\partial \mathrm{CO}_{2,\mathrm{bkg}}} \Delta \mathrm{CO}_{2,\mathrm{bkg}}\end{aligned}$$

This bias arises because not all of the sulfur in the fuel is emitted as SO_2, a systematic uncertainty. Preliminary studies have shown that between 1% and 19% of the sulfur in the fuel is emitted in other forms, possibly SO_3 or SO_4. Therefore, assuming that all of the sulfur is emitted as SO_2 underestimates the true sulfur content of the fuel. This factor needs to be considered when setting the alarm threshold for the FSC.

All these uncertainties appear during the measurement process, so there is some deviation between the estimated and true values of FSC.

Figure 13- Drone close to the ship exhaust funnel for exhaust gas collection and inspection

4. Results

(1) Data processing

UAVs carrying sniffing equipment hover over the ship plume to collect exhaust gases, detect information that is then sent back. In general, the changes observed for SO_2 and CO_2 can be divided into three phases.

1) The UAV took off and approached the vessel exhaust vent for about 3 minutes. The SO_2 and CO_2 observations were relatively low, and background was obtained at this stage.

2) The UAV gradually flew to the center of the plume and collected data. A rapid increase in SO_2 and CO_2 concentrations was observed, reaching a peak, which took about 10- 15 minutes. Peak data was obtained at this stage.

3) The UAV completed the gas collection and return, which took about 5 minutes. The SO_2 and CO_2 values were observed to return to background levels.

The air pump must remove residual gas in the airway before the following collection.

During the acceptance phase of the project, Pudong MSA conducted several experimental tests at the Waigaoqiao Port Area. After adjusting various technical parameters and accumulating UAV flight experience, the method can provide accurate results. In 2018, 10 smoke plumes emitted by ships have been detected, and the number of detections has been increased in the subsequent use. Fuel samples considered to be true FSC values were taken and sent for laboratory chemical examination. Finally, the results of the drone method were compared with the results of the laboratory tests.

According to Eq. (1), it is easier to select the background and peak values to calculate the FSC if the observations of SO_2 and CO_2 peak at the same time. However, the actual collected data is sometimes not ideal and there is a calculation uncertainty in selecting the background and peak values of SO_2 and CO_2.

For data consistency, uniform selection criteria are set for the selection of background values and peaks. The observations of SO_2 and CO_2 on the receiver side are synchronized during the detection process. Therefore, the background and peaks of SO_2 and CO_2 used to calculate the FSC were chosen to be observed simultaneously. According to the flight record, the minimum values of SO2 and CO2 collected at the first measurement point were selected as background. There is generally considerable uncertainty in the selection of peaks. Therefore, the simultaneous, stable, apparent, and largest values of SO_2 and CO_2 observations were selected as the peaks. The selection method is as follows.

1) The peaks of the observed values of SO_2 and CO_2 are determined at the second and third measurement points, respectively.

2) Excludes spikes in the full range of SO_2 or CO_2 sensors.

3) Spikes due to drastic changes in continuous observations (e.g., if the change in CO_2 exceeds 500 ppm or the change in SO_2 exceeds 500 ppb) are excluded because they may be related to sensor uncertainty, exhaust uncertainty, or unstable concentrations of SO_2 or CO_2 in the atmosphere.

4) Compare the peak occurrence times of SO2 and CO_2 values, and then the

simultaneous and most simultaneous peaks (with an interval of no more than 20 seconds) were re-retained. If there is a small deviation between the peak time points of SO_2 and CO_2, we choose the peak time point of SO_2. This will make the FSC value relatively larger than the value of CO_2. As in Eq. (1), a higher SO2 peak will result in a higher FSC estimate, while a higher CO_2 peak will result in a lower FSC estimate. As discussed in the "Calculation of sulfur content" section, not all of the sulfur in the fuel is emitted as SO_2, which would result in a lower estimate. Therefore, this choice will result in an estimate relatively close to the true value.

5) After the above filtering, about 1 to 4 points will be left as the peak selection points. The maximum value is selected as the peak value for calculating the FSC. It may measure the maximum value at the center of the ship plume. At this location, the measured values are very stable, and the probability of interference from other factors is low.

(2) FSC estimation

In most cases, using the method above provides the closest FSC value to the actual value. In a few cases, it may be sub-optimal rather than optimal.

The graph below shows the plume measurements for SO_2 and CO_2 from a trial.

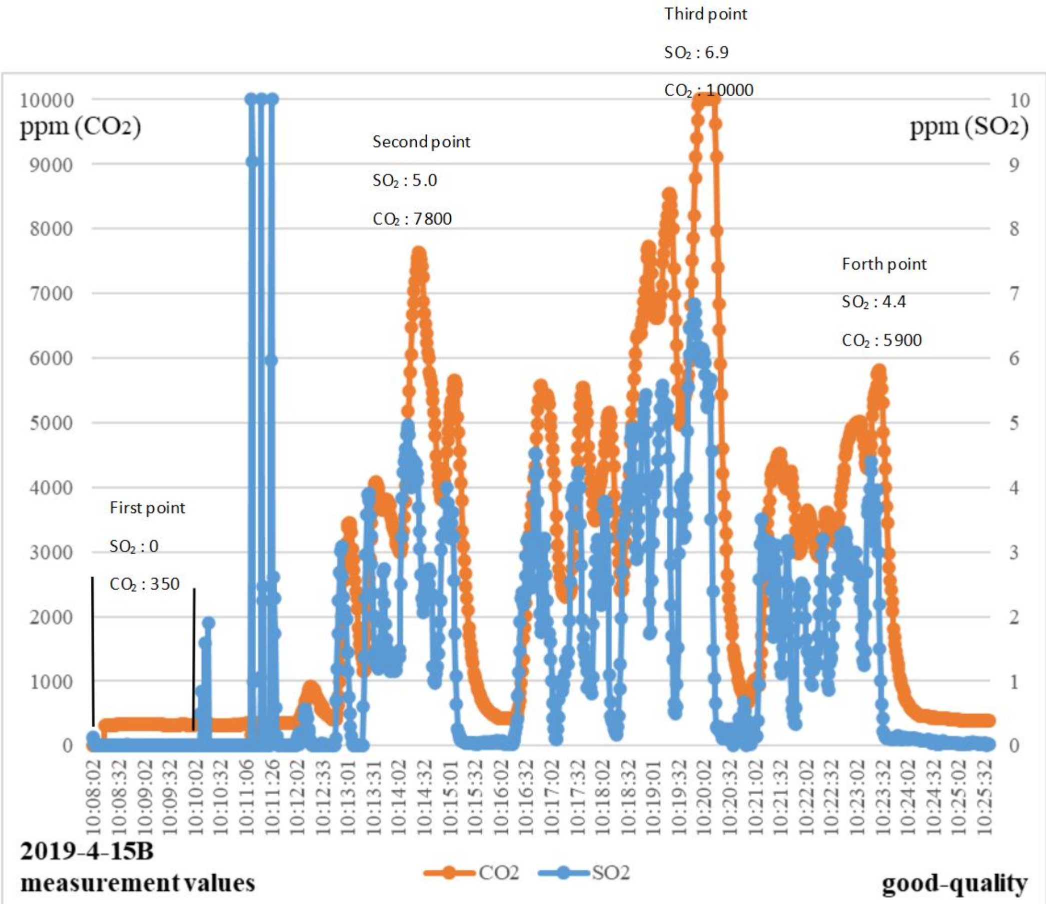

Figure 14- Plume measurement data for SO_2 and CO_2

When performing data analysis, good quality and poor-quality data need to be distinguished and excluded. So-called good quality plume data means that the peaks are obvious and easily distinguishable, while poor quality plume data means that the peaks are less obvious but still produce results. When results are not available, this part of the data is considered invalid.

There is a peak of SO_2 at 10:11 LT (local time), but no CO_2 at the same time. The data to be used for the experiment are the data for SO_2 and CO_2 which are both at their peak at the same time. Therefore, the data for this period were not used as the peak of the plume.

This time, measurement point 3 is selected as the peak data, "√" means selected, "×" means discarded.

Selected	**SO_2 (ppb)**		**CO_2 (ppm)**		**UAV measurement - Estimated FSC (ppm)**	**Sampling and testing - actual FSC (ppm)**	**Deviation(ppm)**	**Relative deviation (%)**
	Background	Peak	Background	Peak				
×	0	5000	350	7800	1557	1901	-344	-18.10%
√		6900		10000	1659		-242	-12.73%
×		4400		5900	1839		-62	-3.26%

Table 9- Comparison and verification of the estimated and true values of FSC

Based on this method, the FSC in the exhaust gas of other ships was measured and compared, and the results are shown below.

Serial number	Date	Ship Name	Exhaust Telemetry PPM	Sampling measurement PPM	Deviation (Telemetry - real measurement)	Relative deviation (Telemetry/actual measurement-1)
1	2018.8.6	KOTA LATIH	1261	1312	-51	-3.89%
2	2018.8.7	BOMAR SPRING	1886	1923	-37	-1.92%
3	2018.8.9	APL ENGLAND	489	396	93	23.48%
4	2018.11.23	YM UBERTY	1668	2387	-719	-30.12%
5	2018.11.26	APL SALALAH	652	1339	-687	-51.31%
6	2018.11.29	HYUNDAI FAITH	680	1030	-350	-33.98%
7	2018.12.18	SAN DIEGO BRIDGE	262	365	-103	-28.22%
8	2018.12.18	RHL CONSIENTIA	663	1302	-639	-49.08%
9	2018.12.19	SM VANCOUVER	256	429	-173	-40.33%
10	2019.1.22	LONGMEN	674.4	1036	-361.6	-34.90%

Table 10- Comparison table of fuel oil sulfur content test for some ships (ppm)

As shown in Figure 15, the deviation of FSC is different at different FSC levels. In many cases, the estimated FSC is generally smaller than the true value. This uncertainty factor leads to low FSC estimation results.

Despite some uncertainties, the FSC estimates calculated using this method, with the consideration of bias values, are considered as usable results.

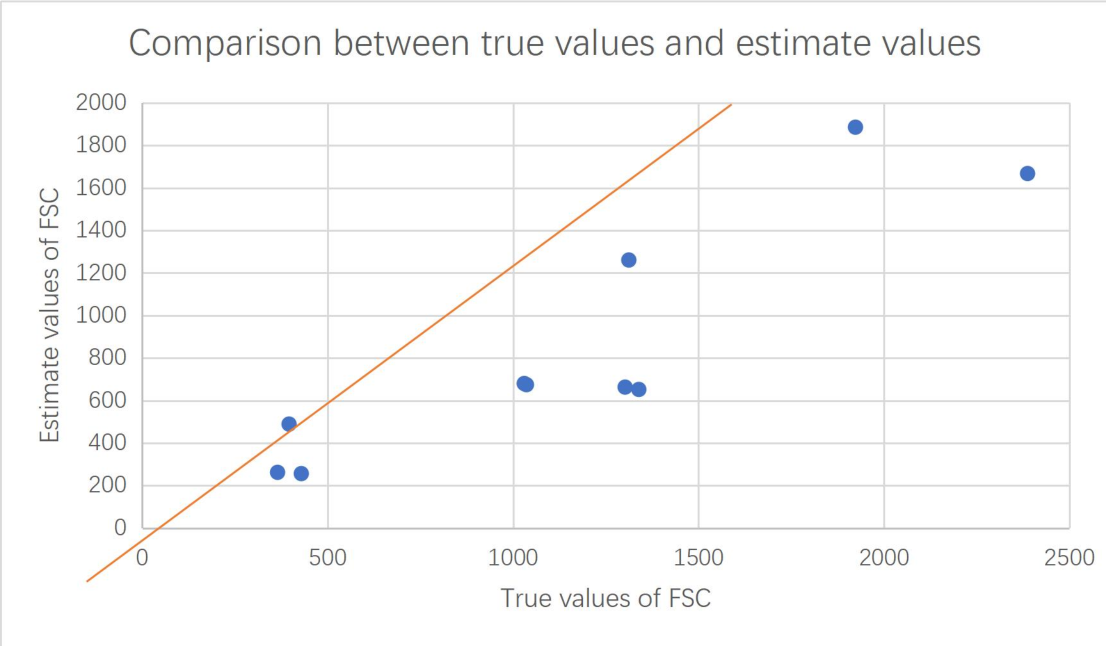

Figure 15- Comparison of measured and estimated FSC values

The experiment verified the reliability of the sniffing-based ship exhaust telemetry drone technology, and provided technical support for the establishment of a new supervision mode of "first exhaust telemetry, then boarding and inspection" in the maritime inspection system.

This system not only improves the efficiency of the maritime supervision, but also saves a lot of costs. According to incomplete statistics, the use of the system to screen high-sulfur oil tankers in the jurisdiction of Shanghai MSA saves at least 1 million yuan per year compared with traditional random boarding and inspection. Whether from the operability or from economic aspect, the “UAV + sniffing” detection technology is a successful experience and mature technology that can be replicated. (Shin Min Daily News, 2021)

4.4 Chapter Summary

This chapter introduces the research and application of the UAV telemetry technology of the on-board ship exhaust in the DECA of Waigaoqiao Port Area.

During the study, a remotely operated UAV with sniffing sensors was used to detect the ship's gas, and collect the background and peak values of SO_2 and CO_2. Then the sulfur content was calculated and this estimate values were compared to the laboratory determined FSC values.

Currently, the FSC limit in the Chinese emission control requirements is 0.5% (m/m), while the ECA limit is 0.1% (m/m). The officers can use the proposed method to monitor whether the ECA meets the FSC standard. However, after more than a year of testing and experiments, many problems still exist.

1. In about 10% of the cases, the UAV did not measure the effective background and peaks. This is mainly due to the UAV missing the plume during the flight. Therefore, effective methods for finding and navigating to the plume using real-time sensor feeds need to be explored.

2. In about 10% of cases, the absolute error exceeds 0.03% (m/m) , and in rare cases even 0.05% (m/m). Unstable atmospheric concentrations of SO_2 or CO_2 before the measurement may lead to such errors. In addition, uncertainties, such as sensor uncertainty, measurement uncertainty, calculation uncertainty, and exhaust uncertainty, can prevent accurate measurements.

3. Currently, the pod can only carry two sensors. In subsequent tests, it will be modified to carry more sensors. The use of different types of UAVs also needs to be evaluated.

CHAPTER 5

CONCLUSION AND SUGGESTIONS

5.1 conclusions

This paper systematically introduces the regulatory initiatives of ECAs in the EN and US, and fully analyzes the policy measures and implementation effects in China's DECAs, and takes the Shanghai port DECA as an example for specific research and analysis. In this dissertation, a large amount of first-hand regulatory data from the Waigaoqiao port area is applied to verify the feasibility of sniffing technology in the ship's exhaust gas detection. It studied the working procedure and sulfur content calculation method of close-range detection by UAV carrier with sniffing equipment and summarized the possible difficulties in the subsequent promotion of the use.

The mode of monitoring fuel sulfur content of ships through UAV technology provides the basic and technical support using the sniffing equipment in the future to monitor the ship's exhaust gas to determine the sulfur content of the fuel oil used by the ship, which will significantly improve the relevance and effectiveness of supervision and provide the MSAs with the non-contact supervision means under the normalized situation of epidemic prevention and control. Moreover, it can complement the existing shore-based and shipboard ship exhaust telemetry technology, further strengthen the maritime supervision force in the DECAs, then promote it.

5.2 suggestions

Based on international advanced control experience, combined with the practical experience of China's DECAs, especially the actual experience of maritime management. Additionally, countermeasures are proposed from three dimensions to improve the monitoring of DECAs in the next phase.

1. In terms of the construction of laws and regulations, improve the legal system, apply for IMO- designated ECA and moderately improve the penalty standard;

2. As for the strengthening of cooperative supervision, it is proposed to strengthen research and introduce new technologies.

3. With regard to the aspect of establishing and improving the supervision mechanism, it is proposed to build a complete government supervision system, guide industry self-regulation supervision and encourage public supervision.

The implementation of the "2020 Global Sulphur Limit" marks the beginning of a period of hard work in the control of air pollutant emissions from ships. These suggestions will provide policy and technical support to upgrade China's DECAs to an ECAs designated by the IMO, and further solve the air pollution problems caused by ships and improve the ambient air quality in China's coastal and riverine regions.

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