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An Overview on Oily Wastewater Treatment Technology for Ships

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Abstract

With the rapid development of the global economy and the increasingly close connections among countries, maritime transport has become one of the major modes of international trade. Meanwhile, the rapid expansion of the shipping industry has drawn growing attention to pollution from ships. Among various pollutants, oily wastewater from ships has become an important issue in marine environmental protection due to its wide range of sources, complex composition, and difficulty in treatment. Based on a review of relevant domestic and international studies, this paper summarizes the sources, occurrence forms, hazards, and discharge requirements of oily wastewater from ships, and focuses on the characteristics and application scope of major treatment technologies, including physical, chemical, and biological methods. On this basis, it is proposed that future treatment technologies for oily wastewater from ships should develop toward multi-process integration, high efficiency, low energy consumption, equipment miniaturization, and intelligent operation. This study provides a reference for the selection of treatment processes and further research on oily wastewater from ships.

Keywords

Ships; Oily Wastewater; Treatment Technology; Marine Environment.

1. Introduction

Since the beginning of the 21st century, global economic ties have continued to strengthen, and the scale of international trade has expanded steadily. Owing to its large transport capacity, low transportation cost, and suitability for long-distance cargo movement, maritime transport has become a vital mode of international freight transportation. However, with the rapid development of the shipping industry, pollutant emissions generated during ship operations have attracted increasing attention. Among these pollutants, oily wastewater from ships is one of the major sources affecting marine water quality [1].

Oily wastewater from ships is mainly produced during navigation, berthing, loading and unloading, maintenance, and cleaning operations. Common types include engine room bilge water, oily tank wash water, and contaminated ballast water. This wastewater usually contains fuel oil, lubricating oil, cleaning agents, suspended solids, and certain persistent organic pollutants. It is characterized by diverse sources, complex composition, and significant fluctuations in oil concentration [2]. If discharged directly into the ocean without effective treatment, oily wastewater can spread over the sea surface and form an oil film, reducing light penetration and affecting the photosynthesis of phytoplankton and marine plants, thereby disrupting the stability of marine ecosystems.

In recent years, with the growing emphasis on green shipping and marine environmental protection, the compliant discharge and efficient treatment of oily wastewater from ships have received increasing attention. Due to the various forms of oil pollutants in oily wastewater from ships, especially emulsified oil and dissolved oil, which are difficult to remove, traditional single treatment methods often fail to meet long-term and stable treatment requirements. Therefore, selecting appropriate treatment processes according to the water quality characteristics of oily wastewater from ships is essential for improving operational stability and treatment efficiency. This has become an important research topic in the field of ship pollution prevention and control.

2. Sources, Occurrence Forms, Hazards, and Discharge Standards of Oily Wastewater from Ships

2.1. Sources of Oily Wastewater from Ships

According to its generation location and formation process, oily wastewater from ships can be divided into three main categories: tank washing wastewater from oil tankers, oily ballast water, and machinery space bilge water.

2.1.1. Tank Washing Wastewater from Oil Tankers

Tank washing wastewater from oil tankers is mainly generated during the cleaning of cargo tanks, oil tanks, and related oil transfer pipelines. After transporting crude oil, fuel oil, or other oil cargoes, a certain amount of oil residue usually remains on tank walls, tank bottoms, and inside oil transfer pipelines. To meet the requirements of subsequent loading, maintenance, and safe operation, these tanks need to be cleaned. During this process, residual oil, sediment, rust, cleaning agents, and other substances are discharged together with the washing water, thereby forming tank washing wastewater.

Tank washing wastewater from oil tankers is generally characterized by high oil concentration, high suspended solids content, and a high degree of emulsification. Since surfactants or other cleaning chemicals may be used during the cleaning process, some oil pollutants tend to form relatively stable emulsions, which increases the difficulty of subsequent oil–water separation.

2.1.2. Oily Ballast Water

Ballast water is taken in or discharged by ships to maintain stability, adjust draft, and ensure navigational safety. When ballast water enters tanks that have previously carried oil cargoes, or comes into contact with residual oil on tank walls and tank bottoms, oily ballast water is formed. The formation of oily ballast water is closely related to the loading condition of the ship, ballast operation mode, tank cleanliness, and the amount of cargo residue.

Compared with tank washing wastewater from oil tankers, oily ballast water usually has a larger volume and more obvious fluctuations in oil concentration. Its water quality is affected not only by residual oil, but also by suspended solids, salinity, and other pollutants. Therefore, when treating oily ballast water, it is necessary to fully consider the influence of water quality fluctuations on the stability of the treatment system.

2.1.3. Machinery Space Bilge Water

Machinery space bilge water is a common type of oily wastewater generated during the daily operation of ships. The machinery space of a ship contains main engines, auxiliary engines, pumps, valves, pipelines, lubrication systems, and other equipment. During equipment operation, maintenance, pipeline aging, and valve leakage, fuel oil, lubricating oil, hydraulic oil, cooling water, and cleaning wastewater may enter the bilge and gradually mix to form machinery space bilge water.

The composition of machinery space bilge water is relatively complex. In addition to oil pollutants, it may also contain cleaning agents, metal particles, suspended solids, and some refractory organic compounds. The rolling, vibration, and mechanical agitation of ships during navigation further enhance the mixing of oil and water, causing some oil substances to exist as

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dispersed oil or emulsified oil, thereby reducing the treatment efficiency of traditional gravity separation methods.

2.2. Occurrence Forms of Oil Pollutants in Oily Wastewater from Ships

Oil pollutants in oily wastewater from ships do not exist in a single form. Instead, they are affected by factors such as oil properties, water salinity, mechanical agitation, cleaning agents, and retention time, and therefore occur in different forms. In general, oil pollutants in oily wastewater from ships mainly include floating oil, dispersed oil, emulsified oil, and dissolved oil.

Floating oil mainly exists on the water surface. It has relatively large oil droplets and weak stability, and can usually be removed by gravity separation, oil skimming, or static settling. Dispersed oil refers to oil substances suspended in water in the form of smaller droplets. Its droplet size is smaller than that of floating oil, and its stability is relatively stronger; therefore, treatment methods such as air flotation, filtration, or centrifugal separation are usually required. Emulsified oil is a stable oil–water system formed under the action of mechanical agitation, cleaning agents, or surfactants. Its oil droplets are relatively small and do not easily float naturally, making it one of the most difficult components to remove in the treatment of oily wastewater from ships. Dissolved oil exists in water in molecular or extremely fine states. Although its concentration is usually low, it is difficult to remove and often requires advanced treatment methods such as adsorption, membrane separation, advanced oxidation, or biological treatment [3].

The different occurrence forms of oil pollutants determine the selection of treatment processes. For oily wastewater mainly containing floating oil and dispersed oil, physical methods such as gravity separation, air flotation, and filtration can be preferentially adopted. For oily wastewater with high contents of emulsified oil and dissolved oil, methods such as coagulation–demulsification, membrane separation, adsorption, electrochemical oxidation, and biological treatment should be combined to improve the overall treatment efficiency.

2.3. Hazards of Oily Wastewater from Ships

2.3.1. Hazards to the Marine Ecological Environment

If oily wastewater from ships is discharged directly into the sea without effective treatment, oil substances will spread over the seawater surface and form an oil film. This oil film reduces the light transmittance of seawater and blocks sunlight from entering the water body, thereby affecting the photosynthesis of marine plants such as phytoplankton and algae and reducing marine primary productivity. At the same time, the oil film weakens oxygen exchange between the air and seawater, causing a decrease in dissolved oxygen in local water bodies, which is unfavorable for the normal growth of fish, shellfish, and other aquatic organisms [4].

In addition, oily wastewater from ships may contain petroleum hydrocarbons, aromatic hydrocarbons, and other refractory organic pollutants. These pollutants are toxic to a certain extent and may adversely affect the growth, reproduction, and metabolism of marine organisms. Some pollutants may also be absorbed by marine organisms and accumulate in their bodies, thereby affecting the stability and biodiversity of marine ecosystems.

2.3.2. Hazards to Socio-economic Activities

Pollution caused by oily wastewater from ships can also affect fisheries, aquaculture, tourism, and port operations in coastal areas. After oil pollutants enter nearshore waters, they may adhere to fishing gear, aquaculture facilities, docks, and coastlines, increasing cleaning and maintenance costs. For fisheries and aquaculture, oily pollution may reduce the quality of aquatic products and, in severe cases, lead to reduced production, thereby affecting the economic benefits of related industries.

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At the same time, oil pollution on the sea surface and beaches can damage coastal landscapes, reduce the value of coastal tourism resources, and affect the development of tourism in coastal areas. For ports and ship operators, substandard discharge of oily wastewater may also lead to regulatory penalties, ship detention, and damage to corporate image. Therefore, pollution caused by oily wastewater from ships is not only an environmental issue, but also a source of economic and management risks.

2.3.3. Potential Hazards to Human Health

Some toxic organic compounds in oily wastewater from ships may be enriched by marine organisms and transferred along the food chain. When contaminated fish, shellfish, and other aquatic products enter the human body, they may pose food safety risks. In particular, long-term exposure to certain petroleum hydrocarbons and refractory organic pollutants may have potential adverse effects on human health.

In addition, volatile components in oily wastewater may affect the air quality of port areas, docks, and nearshore areas, posing health risks to workers engaged in ship maintenance, wastewater treatment, and port operations. Therefore, strengthening the treatment and discharge control of oily wastewater from ships is not only beneficial to marine ecological protection, but also important for safeguarding the health and safety of coastal residents and related workers.

2.4. Discharge Standards for Oily Wastewater from Ships

To reduce the impact of oily wastewater from ships on the marine environment, both international and domestic regulations have established clear requirements for its discharge. Internationally, MARPOL Annex I provides regulations for the prevention of oil pollution from ships. For oily wastewater from machinery spaces, the oil content after treatment by oily water separation equipment is generally controlled at 15 ppm. Ships are also required to control discharge through qualified oily water separation equipment or oil content monitoring devices [5].

The current Chinese standard, Discharge Standard for Water Pollutants from Ships (GB 3552—2018), provides specific requirements for the discharge of oily wastewater from ships. This standard defines oily wastewater from ships as wastewater produced during ship operations that contains crude oil, fuel oil, lubricating oil, other petroleum products, and residues, including oily wastewater from machinery spaces and oily wastewater containing cargo oil residues. For oily wastewater from machinery spaces, the discharge limit for petroleum pollutants is 15 mg/L, with the monitoring location set at the outlet of the oily wastewater treatment device, and the discharge should be carried out while the ship is underway. For oily wastewater containing cargo oil residues, the standard also specifies corresponding requirements according to ship type, navigation waters, and discharge conditions [6].

It can be seen that discharge standards for oily wastewater from ships focus not only on the oil concentration in the effluent, but also on discharge waters, ship types, discharge methods, and monitoring conditions. Therefore, when selecting a treatment process for oily wastewater from ships, it is necessary to comprehensively consider pollutant removal efficiency, equipment operational stability, and discharge standard requirements.

3. Treatment Methods for Oily Wastewater from Ships

3.1. Physical Methods

Physical methods achieve oil–water separation through density difference, flotation, filtration, membrane screening, and adsorption. They are mainly suitable for removing floating oil, dispersed oil, and suspended solids.

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Table 1. Comparison of Physical Treatment Methods for Ship Oily Wastewater

Treatment method	Main treatment object	Basic principle	Characteristics
Gravity / air flotation separation [7]	Floating oil, dispersed oil, suspended solids	Density difference and microbubble flotation	Simple process, low cost, and suitable for pretreatment; limited removal of emulsified and dissolved oil.
Filtration / coalescence separation [8]	Dispersed oil, fine oil droplets, suspended particles	Interception by filter media and coalescence of fine droplets	Effective for fine oil droplets and common in oil–water separators; prone to clogging and requires regular maintenance.
Membrane separation[9]	Emulsified oil, suspended solids, some dissolved oil	Membrane pore screening and surface selectivity	Good effluent quality and compact equipment; membrane fouling and maintenance costs are relatively high.
Adsorption[10]	Emulsified oil, dissolved oil, organic pollutants	Adsorption by activated carbon, biochar, and modified materials	Effective for low-concentration oily wastewater; adsorbents require regeneration or replacement.

3.2. Chemical Methods

Chemical methods remove pollutants by adding chemical agents or using electrochemical reactions to change the stability of oil pollutants in oily wastewater, causing oil droplets to undergo demulsification, flocculation, sedimentation, or oxidative degradation. These methods have good treatment effects on emulsified oil, colloidal particles, and some refractory organic compounds, and are commonly used for the enhanced or advanced treatment of oily wastewater from ships.

Table 2. Comparison of Chemical Treatment Methods for Ship Oily Wastewater

Treatment method	Main treatment object	Basic principle	Characteristics
Coagulation / demulsification[11]	Emulsified oil, colloidal particles, suspended solids	Destabilization, flocculation, and aggregation of oil droplets	Mature process and good effect on emulsified oil; chemical dosage and sludge generation need control.
Electrocoagulation[12]	Emulsified oil, suspended solids, some organic pollutants	Electrode reactions generate metal ions and flocs	Low chemical dosage and high efficiency; electrode consumption and energy demand should be considered.
Electrochemical oxidation[13]	Dissolved oil, refractory organic compounds	Electrode reactions generate oxidizing species	Suitable for degrading refractory organics; equipment requirements and operating costs are relatively high.
Advanced oxidation [14]	Refractory organic compounds, dissolved pollutants	Oxidation by hydroxyl radicals and other active species	Strong oxidation capacity and good treatment effect; reaction conditions and energy costs are relatively high.

3.3. Biological Methods

Biological methods use the metabolic activity of microorganisms to degrade petroleum hydrocarbons and other organic pollutants in oily wastewater from ships. Compared with physical and chemical methods, biological methods have the advantages of lower operating cost, environmental friendliness, and less secondary pollution. However, their treatment efficiency is easily affected by temperature, pH, salinity, dissolved oxygen, and nutrient ratio.

Common biological treatment methods include microbial degradation[15], biofilm processes [16], immobilized microorganism processes[17], and membrane bioreactor processes [18]. Among them, microbial degradation mainly relies on oil-degrading bacteria or other functional microorganisms to decompose petroleum hydrocarbon pollutants. Biofilm processes use microbial films attached to packing materials to adsorb and degrade pollutants. Immobilized microorganism processes fix functional bacteria onto carriers, thereby increasing microbial concentration and system stability. Membrane bioreactor processes combine biodegradation with membrane separation and can achieve relatively good effluent quality.

For aerobic biological treatment, the degradation of petroleum hydrocarbon pollutants can be simplified as follows:

$$C_nH_m + \left(n + \frac{m}{4}\right)O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O \tag{1}$$

where C_nH_m represents hydrocarbon pollutants in oily wastewater, O_2 is the oxygen required during microbial degradation, and CO_2 and H_2O are the final oxidation products.

In practical treatment processes, pollutant concentration gradually decreases as reaction time increases. The degradation process can be approximately described using first-order reaction kinetics:

$$\ln\left(\frac{C_0}{C_t}\right) = kt \tag{2}$$

4. Conclusion

Oily wastewater from ships mainly originates from machinery space bilge water, oily ballast water, and tank washing wastewater from oil tankers. It is characterized by complex sources, large fluctuations in oil concentration, and various types of pollutants. Oil pollutants mainly exist as floating oil, dispersed oil, emulsified oil, and dissolved oil. Different forms of oil pollutants have different degrees of stability and removal difficulty. In particular, emulsified oil and dissolved oil are the key and difficult components in the treatment of oily wastewater from ships.

At present, the main treatment methods for oily wastewater from ships include physical, chemical, and biological methods. Physical methods have simple processes and stable operation, and are suitable for removing floating oil, dispersed oil, and suspended solids. Chemical methods can enhance the removal of emulsified oil and refractory organic pollutants through coagulation, demulsification, electrocoagulation, oxidation, and other processes. Biological methods use the metabolic activity of microorganisms to degrade organic pollutants and have the advantages of environmental friendliness and relatively low operating cost. However, due to the complex composition of oily wastewater from ships, a single treatment method is often difficult to meet discharge requirements stably over a long period of time.

Therefore, future treatment technologies for oily wastewater from ships should develop toward multi-process integration, high efficiency, low energy consumption, equipment miniaturization, and intelligent operation. By reasonably combining physical separation, chemical enhancement, and biological degradation, the adaptability of treatment systems to complex water quality and their ability to achieve stable standard discharge can be improved. This is of great significance for reducing pollution discharge from ships, protecting the marine ecological environment, and promoting the development of green shipping.

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