Study on the performance and mechanism of high gradient magnetic separation in treating ship ballast water

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Abstract. The discharge of ship ballast water serves as a primary pathway for marine biological invasion, which has caused severe ecological and economic harm worldwide. Consequently, this study assessed the efficacy and underlying mechanism of high gradient magnetic separation (HGMS) as a pretreatment technology for ship ballast water treatment. Initially, operational parameters were optimized through orthogonal experiments, yielding optimal process conditions: a magnetic seed concentration of 0.5 g/L, a PAC concentration of 0.007 g/L, a flow rate of 200 mL/min, a rotational speed of 700 r/min, and a current intensity of 4 A. Under these optimal operational conditions, HGMS consistently achieved a turbidity removal rate exceeding 98%, the removal rate of marine *Chlorella* > 99%, and the removal rate of *Escherichia coli* is 63%. Mechanistic analysis revealed that HGMS removes microorganisms through throttling and physical disruption. In summary, HGMS represents an effective pretreatment technology that significantly reduces turbidity and microbial load, thereby creating favorable conditions for subsequent advanced disinfection and offering an alternative solution for shipborne ballast water treatment systems compliant with international regulations.

1 Introduction

Ship ballast water is essential for vessel stability during unloaded voyages. However, its discharge and uptake between ports have become a major vector for marine biological invasions[1]. Such non-indigenous species that are brought through the ballast water are a severe threat to the local ecological equilibrium, economic development and even the health of the people in the ports [2,3]. Reacting to this, the International Maritime Organization (IMO) has introduced strict standards of ballast water discharge (D-2 standard) which requires that the onboard treatment systems should effectively inactivate or eliminate different harmful organisms in the water[4].

Currently, single technologies like ultraviolet (UV) disinfection are prone to light-shielding effects in high turbidity, leading to unstable treatment efficiency[5]. Therefore, an improved pretreatment process is needed to reduce turbidity and create favorable conditions for subsequent deep disinfection. High-Gradient Magnetic Separation (HGMS) technology is an effective physical separation technology, which has the following benefits: high processing capacity, high efficiency and low sensitivity to variations in water quality. It has enormous potential in the treatment of high-turbidity water and the removal of particulates and microorganisms and thus it is very appropriate as a pretreatment unit to treat ballast water[6].

HGMS technology applies an external magnetic field within a reaction zone packed with magnetic media (such as stainless steel wool), creating a high-gradient magnetic field. This exerts a strong magnetic force to capture magnetic particles or magnetic flocs formed via magnetic flocculation[7]. This technology has been studied for application in the water treatment field. Current improvement directions primarily focus on optimizing operational parameters (such as magnetic seed and coagulant dosages) and modifying the magnetic collection media to enhance its performance[8].

This paper addresses the needs of ship ballast water treatment and aims to evaluate the effectiveness of High Gradient Magnetic Separation (HGMS) as a pretreatment process. The study first optimizes the operational parameters of the HGMS unit through systematic experimentation to achieve efficient turbidity removal. It then analyzes the operational mechanism of HGMS through zeta potential and particle size analysis. Subsequently, the study evaluates the individual treatment efficacy of the optimized HGMS on typical microorganisms (marine *Chlorella* and *Escherichia coli*) and conducts an in-depth investigation of its inactivation mechanism through microscopic characterization. This study provides experimental evidence and theoretical support for developing efficient, synergistic onboard ballast water treatment technologies.

2 Experimental Setup Design and Optimization of Operating Conditions

Kaolin, polyaluminum chloride (PAC, Al_2O_3: 32%, basicity: 80%-85%), and Fe_3O_4 (20 nm average particle size) were obtained from Tianjin Kaimate Chemical Co., Ltd. All reagents were of analytical grade. The prepared

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water had a turbidity of 70-100 NTU and a pH of 7.5.

This study employed a self-designed HGMS experimental setup, shown in Figure 1. Its core consists of an excitation coil and a reaction zone packed with SUS430 stainless steel wool (a type of high-permeability magnetic collection medium[9]). The designed flow rate was 120-450 mL/min. The magnetic field strength was adjusted via a DC regulated power supply (0-10A). Measured data showed a good linear relationship between magnetic field strength and current: $y = 3.18816 + 0.97248x$ (y: magnetic field strength (mT); x = current intensity (A)). The magnetic seed was Fe_3O_4, and the coagulant was Poly-Aluminum Chloride (PAC).

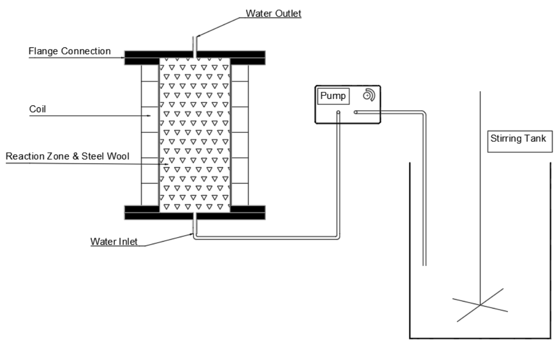

Figure 1. HGMS Separator.

To achieve optimal pretreatment results, the study first optimized the operating conditions of the HGMS unit with turbidity removal rate as the target. A five-factor, four-level ($L_{16}(4^5)$) orthogonal experiment was conducted to investigate the effects of magnetic seed concentration, PAC concentration, magnetic field strength (represented by current value), flow velocity, and stirring intensity. The factor levels were set as: magnetic seed concentration (0.1, 0.3, 0.5, and 0.7 g/L), PAC concentration (0.001, 0.003, 0.005, and 0.007 g/L), rotation speed of the stirrer (300, 500, 700, and 900 r/min), current (2, 4, 6, and 8 A), and flow velocity (120, 200, 280, and 360 mL/min).

Table 1. Orthogonal array.

Factor	K1avg %	K2avg %	K3avg %	K4avg %	F	P
Fe_3O_4	84.05	86.24	93.21	93.36	2.09	0.28
PAC	71.27	94.38	94.52	96.69	13.14	0.03
R	85.88	86.88	92.41	91.69	-	-
I	84.74	92.14	86.81	93.17	1.52	0.37
V	85.81	92.90	91.28	86.87	1.06	0.48

Through orthogonal experiments, the optimal operating conditions for the HGMS unit were determined as follows: magnetic seed (Fe_3O_4) concentration of 0.5 g/L, PAC concentration of 0.007 g/L, magnetic field current of 4 A, flow rate of 200 mL/min, and stirring intensity of 700 r/min. As shown in Table 1, PAC concentration was the only statistically significant factor affecting turbidity removal ($P = 0.03$), while magnetic seed concentration showed no significant effect ($P = 0.28$). Although the highest average turbidity removal (93.36%) was obtained at 0.7 g/L Fe_3O_4, the removal efficiency at 0.5 g/L was almost identical (93.21%). Considering comparable performance and the objective of reducing chemical consumption, the lower magnetic seed concentration of 0.5 g/L was selected. The selection of current intensity followed the same principle. The stirring intensity column was used as an error term (blank column) in the ANOVA, and its F/P values are therefore omitted in Table 1.

Under optimal operating conditions, HGMS treated water with an influent turbidity of 96.87 NTU. Experimental results showed (Figure 2) that the turbidity removal rate rapidly increased and stabilized at >98% after just 2 minutes of operation.

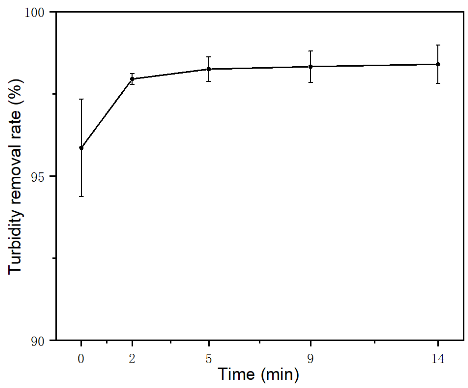

Figure 2. Variation of turbidity removal rate over time.

3. Treatment Efficacy and Mechanism Analysis of HGMS on Microorganisms

3.1 Mechanism Analysis of HGMS

To investigate the operational mechanism of high-gradient magnetic separation (HGMS), this study analyzed the Zeta potential of the system during the treatment process and the particle size distribution of the influent and effluent.

Zeta potential is a crucial indicator for characterizing the stability of colloidal particle dispersion systems, and its absolute value reflects the energy barrier for mutual repulsion between particles. In this section, the Zeta potential was measured under four different water sample conditions: raw water, raw water with Fe_3O_4, raw water with PAC and raw water with Fe_3O_4 and PAC. The results are shown in Figure 3.

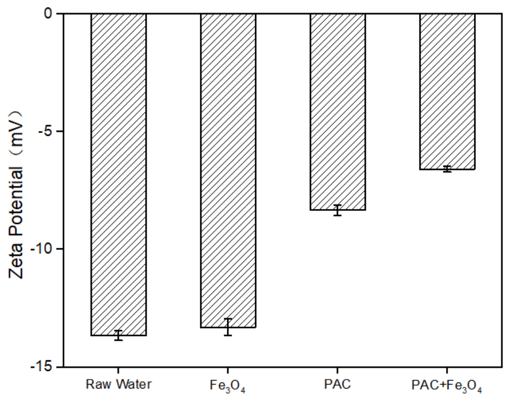

Figure 3. Zeta Potential.

Figure 3 shows that the surface of raw water particles is negatively charged. Adding PAC alone will significantly reduce the zeta potential, which is due to the neutralization of PAC hydrolysates (such as Al^{3+} and its hydroxyl polymer). Adding Fe_3O_4 alone has little effect on zeta potential. However, when PAC and Fe_3O_4 were added at the same time, the zeta potential of the system was further reduced, which was lower than that when PAC was added alone. This shows that although the neutralization ability of Fe_3O_4 itself is limited, its existence can significantly enhance the neutralization efficiency of PAC. The magnetite particles likely act as nucleation sites, adsorbing positively charged PAC hydrolysis products and promoting aggregation with negatively charged pollutants. This facilitates destabilization and aggregation, creating essential conditions for the formation of large magnetic flocs that are easily trapped by the magnetic field. Particle size distribution changes effectively reflect the flocculation performance and particle removal characteristics of the HGMS device. The results are shown in Figure 4.

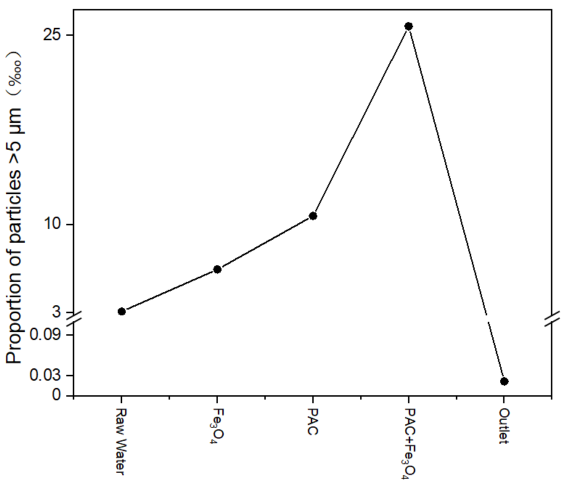

Figure 4. Particle Size Analysis.

Figure 4 shows the particle size distribution in the raw water, the flocs formed after dosing PAC and magnetite seeds, and the effluent after HGMS treatment. As shown in Figure 4, after dosing PAC and magnetite seeds followed by stirring, the proportion of particles larger than 5 micrometers increased significantly. This directly proves that the coagulation action of PAC and the adsorption/bridging effects of the magnetite seeds promote the aggregation of fine particles, forming larger flocs. These large-sized magnetic flocs are readily captured by the subsequent magnetic field. After treatment by the HGMS device, the proportion of particles larger than 5 micrometers in the effluent decreased sharply, indicating that the device can effectively intercept and remove these magnetic flocs, while also demonstrating a certain removal capability for residual fine particles in the water.

Overall, the results of the Zeta potential study indicate that magnetite seeds used in combination with PAC is the best method to enhance the processes of charge neutralization and flocculation. Particle size analysis presents the visual evidence that the large magnetic flocs are formed in this process, and that the HGMS device is able to remove those. Collectively, they clarify the essence of the working principle of magnetic flocculation-enhanced coagulation and high-gradient magnetic separation.

3.2 Treatment Efficacy of HGMS on Microorganisms

Under the optimal operating conditions, the treatment efficacy of HGMS on indicator microorganisms in simulated ballast water was evaluated. The indicator microorganisms selected were marine *Chlorella* (10-50 μm microorganisms, GY-H6 *Chlorella sp.*) and *Escherichia coli* (<10 μm microorganisms, ATCC 25922).

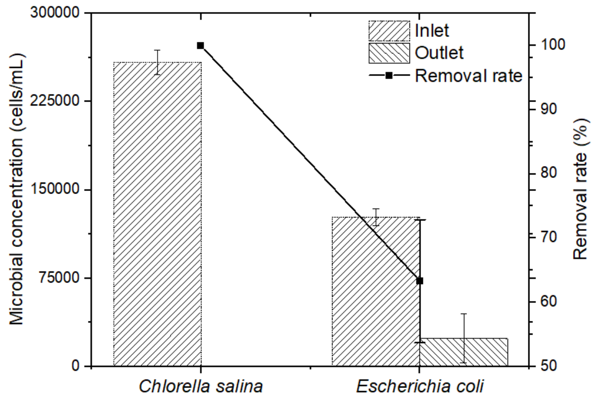

Figure 5. Treatment Efficacy of HGMS on Microorganisms.

For marine *Chlorella* with a size of 10-50 μm, the optimized HGMS unit demonstrated excellent removal capability, the removal rate of treated effluent > 99%, shown in Figure 5. This indicates that HGMS pretreatment not only efficiently removes turbidity but also has a direct physical interception and removal effect on larger-sized microorganisms. For *Escherichia coli* smaller than 10 μm, HGMS also achieved a removal rate of 63%. This result is consistent with the conclusions of references[10,11], indicating that HGMS, as a pretreatment technology, can effectively reduce the load on subsequent treatment units.

3.3 Inactivation Mechanism of HGMS on Microorganisms

To investigate the inactivation mechanism of HGMS, scanning electron microscopy (SEM) observations and K^+ leakage analyses were conducted on the microorganisms. The resulting SEM images and K^+ leakage data are illustrated in Figure 6 and Figure 7, respectively.

Figure 6(b) illustrates that following HGMS treatment, the morphology of *Chlorella* cells exhibited notable alterations, encompassing severe rupture, localized collapse, and flocculent aggregation, thereby indicating that intense physical forces directly compromised the cellular structure. Figure 6(d) reveals that post-HGMS treatment, surface shrinkage of *E. coli* was observed, suggesting minor physical damage inflicted by HGMS on *E. coli*.

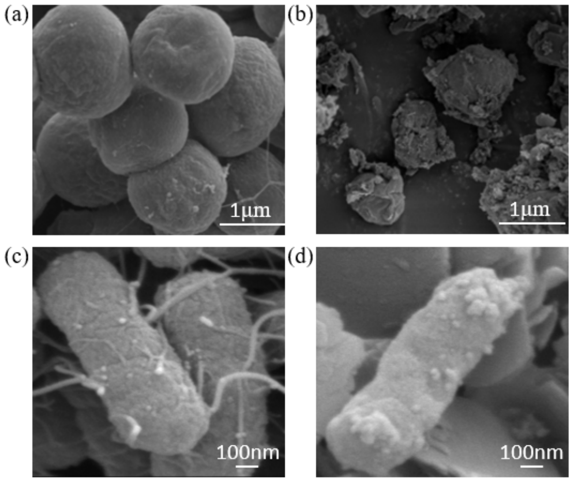

Figure 6. (a) *Chlorella* influent; (b) *Chlorella* effluent; (c) *E. coli* influent and (d) *E. coli* effluent.

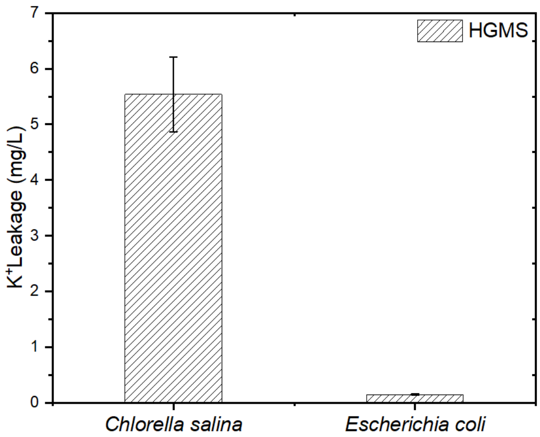

Figure 7. K^+ Leakage.

Figure 7 shows that after HGMS treatment, the K^+ concentration in the *Chlorella* water sample increased by 5.75 mg/L compared to the influent. This proves that HGMS treatment damaged the integrity of the microbial cell membrane, leading to the leakage of intracellular electrolytes. The K^+ concentration in the *E. coli* water sample increased by 0.13 mg/L compared to the influent, indicating that HGMS treatment altered the morphology of *E. coli* and caused slight leakage of intracellular contents, primarily through physical interception. These characterization results collectively reveal that the synergistic effect of physical interception and damage to the macromolecular cell membrane is the key mechanism by which HGMS achieves microbial inactivation. This means that the pretreatment caused by HGMS can effectively reduce the microbial pressure on subsequent treatment processes.

4 Conclusion

This study optimized HGMS operational parameters for ballast water pretreatment via orthogonal experiments. Optimal conditions (0.5 g/L Fe_3O_4, 0.007 g/L PAC, 4 A current, 200 mL/min flow rate, 700 r/min stirring) achieved >98% turbidity removal. The removal rate of *Marine Chlorella* > 99%, and the removal rate of *Escherichia coli* is 63%. The mechanistic experiments indicated that a combination of magnetic seeds and PAC was able to optimize the charge neutralization and flocculation process to create large magnetic flocs that could be easily trapped by the magnetic field. HGMS inactivates microorganisms through synergistic physical interception and cell membrane damage, evidenced by cell shrinkage and potassium ion leakage. This paper proves that, as an effective pretreatment technology, HGMS can considerably decrease the turbidity of ballast water and inactivate microorganisms, to provide a conducive environment to other deep disinfection methods such as UV. Future work will investigate HGMS-UV synergy and magnetic matrix modifications to improve sterilization and long-term stability.

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