Effect of High Gradient Magnetic Separation (HGMS) Process on Ballast Water Treatment

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Abstract

Ultraviolet radiation is an effective process for ballast water treatment. In order to improve the performance of microorganisms inactivation by UV radiation, the High Gradient Magnetic Separation (HGMS) process was used as pretreatment process before UV irradiation. In this work, the influence factors of HGMS process were conducted and the removal rates of turbidity and microorganisms were selected as detection indexes. The effect of HGMS and UV composite technology for the ballast water treatment was also conducted through the continuous flow experiment. The results showed that the turbidity removal rate of HGMS process increased with magnetic field intensity, magnetic dosage and filled amount increasing, and decreased with flow rate increasing. Different diameters of the magnetic medium steel wire had different effects on the water turbidity, and mixed magnetic medium had better performance than the single diameter of the magnetic medium. HGMS process had a good performance for microorganism removal and the removal rates of all selected microorganisms were higher than 50%. Results also showed that the microbial removal rate of HGMS-UV composite process was higher than 99% and the discharge of the indicator microbes met the standards of Convention on the Control and Management of Ships' Ballast Water and Sediments. The above results showed both HGMS process and HGMS-UV composite technology have a good removing ability for particles matters and microorganisms.

Keywords: Ballast water, High Gradient Magnetic Separation (HGMS), Ultraviolet radiation, Turbidity
1. Introduction
With the quick development of the international marine transportation industry, the menace for public health and marine ecosystem caused by uncontrolled discharge of ballast water has been increasingly serious. Now discharge of ballast water has been listed as one of the four major threats to the oceans by the Global Environment Facility (GEF) [1].

For the characteristics of quick, convenience and no disinfection by-products, ultraviolet radiation was considered as one of green disinfection technologies for ballast water treatment [2]. A series of studies from some universities such as the Maryland of the United States [3] and the Helsinki of Finland [4] showed that the inactivation rate of microorganisms in ballast water by UV treatment was always higher than 95%. The OPTIMAR developed by Norway combines filter with UV irradiation and it had been equipped in actual ships. The effluent quality of OPTIMAR met the IMO standards with water flow established at 7000m³/h. Liu Fei [5] and Liu Wei [6] used different ultraviolet disinfection systems to treat ballast water and both of these studies showed that ultraviolet disinfection was a high-performance, simply equipped, low cost and convenient maintenance technology for ballast water treatment. Du Qinghua [7] concluded that the sterilization efficiency of UV technology for ballast water treatment was higher than 99%, which was better than O₃ inactivation.

However, as a photochemical disinfection method, the performance of ultraviolet disinfection is strongly affected by some environmental factors, such as turbidity, color and particulate matter. Suspended particles can protect organisms from UV irradiation by harboring bacteria and absorbing and scattering the UV light [8], [9], [10]. In order to overcome the shortages of individual UV technology, a patented technology (ZL200910073103.X), which combined HGMS equipment with UV irradiation process, was used for ballast water treatment. HGMS was a new magnetic separation method and could effectively remove suspended solids, viruses, bacteria, algae, color, turbidity, heavy metals, oils and radioactive contaminants in polluted water [11], [12], [13]. The HGMS equipment was placed at the output port of ballast pump and used for removing plankton and suspended particles which was larger than 50μm. After HGMS process, ultraviolet radiation was used to inactivate microorganisms.

This work was aimed to study the performance of HGMS process while it was used as a pretreatment technology before UV irradiation in ballast water treatment. In this work, the influence factors of HGMS process for turbidity and microorganism removal, such as the magnetic field intensity, residence time (flow rate), dosage of magnetic seeds, filling rate of magnetic medium, size of magnetic medium and mixed magnetic medium, were conducted. And the performance of combined process for microorganism removal from ballast water was also investigated.

2. Materials and methods
2.1 Experimental Device
The experimental device was shown in Fig.1. The treatment process of this system
Effect of High Gradient Magnetic Separation (HGMS) Process

was follow: (1) ballast water flow into the stirred tank in which it was well-mixed with Fe$_3$O$_4$; (2) peristaltic pump which was used for controlling the flow rate could pump this well-mixed water into a HGMS equipment, and the magnetic field intensity was varied by controlling current on a DC power; (3) after treated in HGMS equipment, the water flowed into the UV radiation equipment to inactive microorganisms; (4) the ballast water flowed into the examination tank after UV disinfection.

The main parameters of the experimental device were as follow: the flow rate was from 50 to 100L/h; the threshold of D.C. stabilized source (220V AC to DC) was 7A and 15V. Water current was up welled and paralleled to the direction of magnetic field. Fe$_3$O$_4$ and stainless steel wire were chosen as the magnetic seed and magnetic medium, respectively. The wire of the HGMS equipment was enamel wire which is pliable and convenient to twine. The diameter, length, turns and operating current of enamel wire were 1.50mm, 25cm, 1000 and 3A, respectively. There was no need for cooling equipment as the magnetic field intensity was just 0.0432T.

Fig. 1. High Gradient Magnetic Separation (HGMS) and UV irradiation composite system

2.2 Experimental water sample
The artificial seawater used in this experiment was prepared according to the International Ships' Ballast Water and Sediments Management and Control of the Convention. Chlorella was chosen to represent microorganisms which are 10μm to 50μm in size; S.aureus was used as reference bacteria. The physical and chemical indicators of water were based on the average quality of Chinese offshore. The pH was 7.5~8.0; temperature was 16~26°C; average salinity of artificial seawater was 35psu (the rate of sodium chloride, magnesium chloride and potassium chloride is 3:2:1); the turbidity, which formulated with diatomaceous earth and artificial seawater, was 70mg/L.

2.3 Experimental methods
Optical density method was used for algal concentrate measurement. To monitor the number of surviving S.aureus, colonies were counted in Nutrient Agar. All the
organism results were expressed in colony-forming units (cfu) per 100 ml of water samples. Turbidity was monitored by LP2000 turbidity meter.

3. Results and discussion
3.1 The performance of the HGMS process on turbidity removal
3.1.1 Effect of magnetic field intensity and flow rate

The effect of different magnetic field intensities on HGMS process for particles removal under different flow rates was conducted when the magnetic seeds dosage was 100mg/L and the initial turbidity was 70NTU, and results were shown in Fig.2.

It can be seen from Fig.2 that HGMS process had a good performance for particles removal and the removal rate was higher than 80%, even when the magnetic field intensity was as low as 2.5mT. Moreover, the results showed that the residual turbidity increased with increasing magnetic field intensity and decreased with increasing flow rate. When the magnetic field intensity was higher than 12.7mT or the flow rate was lower than 10L/h, the residual turbidity was lower than 5NTU which met the requirement of UV process [14]. According to the theory of HGMS [15], the separated particles are influenced by many forces, such as magnetic force, gravity, fluid viscous forces, buoyancy, fluid inertia force, centrifugal force and molecule gravity. Most of these forces adversely affect the separation except the magnetic force, so the greater the magnetic force is, the easier separation will be achieved. As the magnetic force is proportional to the magnetic field intensity, the particulate matters are easier to be removed from ballast water when magnetic field intensity increases.

Besides, flow rate was also an important factor for the performance of the HGMS process. On one hand, turbidity removal rate decreased with increasing flow rate, for the shear force and the resistance of fluid force increased with the increasing flow rate. On the other hand, increasing flow rate shortened the contact time between magnetic particles and magnetic medium, which also reduced the separation efficiency [16].

![Fig. 2. Effect of magnetic field intensity on HGMS process for turbidity removal under different flow rates](image-url)
3.1.2 Effect of magnetic seeds dosage
The effluent turbidity variation of HGMS process at different dosages of magnetic seeds was shown in Fig. 3, when the magnetic field intensity was 12.7 mT and the flow rate of ballast water was 10 L/h.

The results showed that the residual turbidity decreased as the dosage of magnetic seeds increased, and the removal rate of turbidity increased from 77.9% to 97.0% when the dosage of magnetic seeds increased from 50 mg/L to 1000 mg/L. It could also found that residual turbidity dropped sharply when the dosage of magnetic seeds was in a range from 200 mg/L to 400 mg/L. And the residual turbidity was bellow 5 NTU when the dosage of magnetic seeds was higher than 400 mg/L. According to the theory which had been proposed in some relevant investigation [17], [18], magnetic seeds could attach some soluble or insoluble material such as clay particle, bacterium, virus and phosphate due to the surface activity of magnetic seeds. In HGMS process, the increasing of magnetic seeds dosage increased the collision possibility between magnetic seeds and the turbidity particle, which caused more turbidity particles to be attached to magnetic seeds and be easily captured by HGMS process.

![Graph showing the effect of magnetic seeds dosage on turbidity removal](image)

**Fig. 3. Effect of magnetic seeds dosage on HGMS process for turbidity removal**

3.1.3 Effect of filling rate of stainless steel wire
In this experiment, stainless steel wire was chosen as the magnetization packing medium. The effect of different filling rates (0.5~6%) on HGMS process for turbidity removal was shown in Fig. 4, when the initial turbidity, magnetic field intensity, flow of water and magnetic seeds dosage were 70 NTU, 12.7 mT, 10 L/h and 400 mg/L, respectively.

In Fig. 4, it could be found that when the filling rate was less than 2%, turbidity removal efficiency was only 16.1%, and numerous Fe₃O₄ could be detected in the effluent water. The main reason was that relatively large spaces exist between magnetic medium when the filling rate was lower. Ballast water was flowing through these large spaces directly instead of flowing through the high gradient magnetic field on the surface of magnetic media. With the increasing of filling rate, the turbidity removal efficiency was also increasing. As the filling rate was 4%, the residual turbidity was only 2.0 NTU and the residual turbidity was maintained below 5 NTU.
3.1.4 Effect of magnetic medium size

Five different sizes of stainless steel wire (6μm, 10μm, 21μm, 28μm, 40μm) were chosen as the magnetization filling medium and the effect of magnetic medium size on HGMS process for particles removal was conducted when filling rate, initial turbidity, magnetic field intensity, flow of water and magnetic seeds dosage were 4%, 70NTU, 12.7mT, 10L/h and 400mg/L, respectively. The result was shown in Fig. 5.

It could be observed in Fig. 5 that the removal rate of turbidity was not always increasing with the reduction of steel wire diameter. When the diameter of steel wire changed from 6μm to 10μm, the residual turbidity reduced from 6.7NTU to 4.5NTU, and when diameter of steel wire increased from 10μm to 40μm, the residual turbidity increased from 4.5NTU to 11.3NTU, which meant stainless steel wire of 10μm in diameter was more suitable for the distribution of suspended matter in this test water.

3.1.5 Effect of mixed magnetic medium

The mixed magnetic medium was consisted of five different stainless steel wires (6μm, 10μm, 28μm, 21μm and 40μm in diameter) with the rate of 1:2:1:1:2. The
turbidity of water treated by different kinds of magnetic medium in different initial turbidities (50NTU, 70NTU, 168NTU, 215NTU) was shown in Fig.6, when the filling rate, magnetic field intensity, flow of water and magnetic seed dosage were 4%, 12.7mT, 10 L/h and 400mg/L, respectively.

It could be seen from Fig.6 that, for all initial turbidity, the treatment efficiency of HGMS process with 10μm stainless steel wire and mixed stainless steel wire was better than that with the 40μm stainless steel wire. For higher initial turbidity (≥168NTU) of ballast water, the performance of HGMS process with mixed stainless steel wire for turbidity removal was better than the other separation in removal efficiency of turbidity. For example, as the initial turbidity of ballast water were 50NTU, 70NTU, 168NTU, and 215NTU, the turbidity removal rate of HGMS equipment with 40μm stainless steel wire were 85.2%, 93.2%, 92.9%; the turbidity removal rate of HGMS equipment with 10μm stainless steel wire were 94.0%, 97.0%, 96.9%; the turbidity removal rate of HGMS equipment with mixed magnetic medium were 94.4%, 97.4%, 97.6%, respectively. From these results it can be concluded that HGMS process with the mixed magnetic medium has better performance for removal of turbidity and better adaptability to ballast water in various turbidities.

According to the “Matching Relationship” theory from some previous research [15], [19], the maximum relative magnetic force occurs when a wire diameter was about three times as much as the particle diameter, so the best wire diameters demanded to separate particles in different diameters from ballast water were not the same. Hence mixed magnetic medium would have better performance when applied to ballast water treatment with complex grain compositions of turbidity particles.

![Graph showing residual turbidity (NTU) vs. initial turbidity (NTU) for different magnetic media.](attachment:image)

**Fig. 6. Effect of the mixed magnetic medium on HGMS process for turbidity removal**

### 3.2 The removal effect of microorganisms by HGMS equipment

The relationship between the removal rate of microorganisms and magnetic field intensity was illustrated graphically by Fig.7, when the initial turbidity, flow of water and magnetic seeds dosage were 70~80NTU, 10L/h and 400mg/L, respectively.

From the Fig.7, it could be seen that the microorganisms’ population reduced with the increasing magnetic field intensity. For example, the maximum removal rate of *S.aureus*, *Chlorella* and total bacterial count were 55.8%, 79.9% and 69.7%, respectively. It was also found that the removal rate of *Chlorella* was higher than the removal rate of *S.aureus* at the condition of higher magnetic field intensity. The reason is *Chlorella* is easier to be attached by magnetic medium due to the larger size.
From the results above, it can be seen that HGMS process had a good removing ability not only for clay particles but also for microorganisms.

Fig. 7. Effect of magnetic field intensity on HGMS process for microorganism removal

3.3 The effect of HGMS-UV composite technology for microorganism removal
The treatment efficiency of HGMS-UV combination reactor was conducted when the flow rate, average UV dose, magnetic field intensity, initial turbidity and magnetic seeds dosage were 15L/h, 2201mJ/cm², 15mT, 70~80NTU and 400mg/L, respectively. The comparison of biological indexes before and after treatment was shown in Table 1.

It could be seen from Table 1 that HGMS-UV combination technology could effectively remove microorganisms from ballast water, and the water quality after treated could meet the standards of the International Convention for the Control and Management of Ship’s Ballast Water and Sediments on D-2. The removal rate of *S.aureus*, *Chlorella* and total bacterial were 99.75%, 99.89% and 99.66%, respectively.

Table 1. Comparison of biological indexes before and after HGMS-UV treatment

<table>
<thead>
<tr>
<th></th>
<th>D-2 standard (cfu/100mL)</th>
<th>Initial concentration (cfu/100mL)</th>
<th>Average concentration after treatment (cfu/100mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S.aureus</em></td>
<td>≤100</td>
<td>1.61×10⁴</td>
<td>39.9</td>
</tr>
<tr>
<td><em>Chlorella</em></td>
<td>≤1000</td>
<td>5.20×10⁴</td>
<td>54.9</td>
</tr>
<tr>
<td>Total bacterial</td>
<td>—</td>
<td>2.15×10⁴</td>
<td>73.4</td>
</tr>
</tbody>
</table>

8. Conclusions
Ultraviolet radiation is an effective process for ballast water treatment. In order to improve the effect of microorganism inactivation by UV radiation, the High Gradient Magnetic Separation (HGMS) was used as pretreatment process before UV irradiation. The aim of this paper was to study the performance of the HGMS process.
on turbidity removal and the microorganism removal rate of the individual HGMS process and the HGMS-UV composite technology. It had been demonstrated in this paper that HGMS process had a good removing ability both for particles matters and microorganisms. The turbidity removal rate by HGMS equipment increased with magnetic field intensity, filled amount and magnetic dosage increasing, and decreased with the increasing flow rate. It had also been proven that different diameters of the magnetic medium steel wire had different effects on the water turbidity and the mixed magnetic medium had better performance than the single diameter of the magnetic medium. The microbial removal rate of HGMS-UV composite technology was higher than 99% for all selected microorganisms, and the microorganisms’ populations in the effluent of this composite technology met the standards of Convention on the Control and Management of Ships' Ballast Water and Sediments.

Acknowledgements
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