The investigation and simulation of the UVOM ballast water treatment device

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Abstract. The marine environments are threatened by discharged wastewater from ships, especially ballast water. In this study, a novel ballast water treatment device (UVOM) was designed and operated for ballast water treatment. The main process of UVOM consists of membrane filter, venture tubes, the UV catalytic TiO2 unit and an ozone generator. Salinity, flow rate and UV intensity was investigated for their efforts on process efficiency. Results indicated that salinity cause less effects on the removal efficiency of UVOM, and flow rate and UV intensity played more important roles. For UV intensity of 50 W and the flow rate no more than 200 L/h, and UV intensity of 75 W and the flow rate no more than 400 L/h, the discharged ballast water can meet the D-2 standard. Back propagation neural network (BPNN) was constructed for simulating the process performance, and it can better describe the process with less deviation between predictive values and real values. The deviation of the total bacteria was from 4.14% to 6.16%, and the deviation of E. coli was from 3.6% to 7.2%. In addition, the results showed that the relative importance of flow rate (65.96%) was significantly larger than UV intensity (34.04%).

1. Introduction
With the development of world industry, marine environments is becoming more and more serious [1,2]. In allusion to environment sustainability, some researchers focus on marine environmental pollution [3], energy saving methods for refrigeration rooms [4], power consumption [5,6], energy conversion [7,8], et al. However, marine environments are also susceptible to wastewater of ships, especially from ballast water. Nowadays, more than 10 billion tons of ballast water is carrying by the ship each year [2,3]. Ballast water is usually used to maintain the balance and the stability of ship structure during the voyage. As ballast water is directly pumped from the sea water, the plankton, as well as planktonic bacteria from the sea water are inevitably brought into the ballast tank. The marine environmental pollution and biological invasion might occur due to the emissions of ballast water. In order to reduce the global spread of invasive aquatic species, international regulations have already required the reductions of the number...
of organisms in ballast water discharged by ships. To achieve this purpose, various treatment methods and regulations are designed to prevent the transfer of invaders in ballast water.

In this study, a novel ballast water treatment device (UVOM) is operated for the efficient treatment of ballast water. By the combination of a membrane filter, venturi tubes, a UV catalytic TiO\textsubscript{2} unit and an ozone generator, the UVOM can achieve the cascade disinfection of planktonic bacteria in different sizes to make sure the preferable treatment efficiency. The influenced factors of UVOM, such as flow rate and UV intensity, are investigated for their effects on the performance of the process. In order to better understand the importance factors of the process, the back propagation neural network (BPNN) is constructed to reveal the correlations among influencing factors and the results.

2. Materials and methods

2.1. Experimental device

The UVOM ballast water treatment device consists of a membrane filter, the UV catalytic TiO\textsubscript{2} unit, venturi tube and an ozone generator, and the construction of the process is shown in figure 1. The membrane filter is used to physically remove more than 50 \( \mu \)m microorganisms primarily. The venturi tube (length: 100mm; diameter: 10mm; aperture ratio: 0.5) can activate the cavitation effect, and then cause the turbulent flow pattern to improve the mixture, reduced the residence time, as well as produce instantaneous pressure. For the ozone and UV catalytic TiO\textsubscript{2} unit, the UV lamp is inserted into the quartz tube with a length of 105 mm and a diameter of 24 mm, and the tubes that coated with TiO\textsubscript{2} are sealed at the end of the sleeves with a length of 700 mm and a diameter of 80 mm. The wall of the tubes is also coated with TiO\textsubscript{2}. After the treatment, the discharged ballast water at last goes into the ballast tank. Ozone is also added in the front of the unit, which is generated by an ozone generator.

![Figure 1. The flowchart of UVOM](image)

2.2. Operation of the process

Artificial ballast water was firstly injected into the tank, and then goes through the membrane filter, venturi tube and the ozone and UV catalytic TiO\textsubscript{2} unit. During the operation, the designed flow rate is 600 L/h, and the experimental flow rates are 200 L/h, 400 L/h, 600 L/h and 800 L/h, corresponding to the hydraulic residence time of 212 s, 106 s, 70 s and 53 s. The UV lamp intensity is set to 32 W, 50 W and 75 W with the corresponding UV radiation intensity of 7808 \( \mu \)J/cm\(^2\), 12200 \( \mu \)J/cm\(^2\) and 18300 \( \mu \)J/cm\(^2\). The concentration of ozone is 400mg/h. After the treatment, the effluent at the outlet is sampled for detecting the numbers of planktonic bacteria.
2.3. Analysis methods
The quality standards of effluent follow the criterions of International Convention for the Control and Management of Ships Ballast Water & Sediments (Table 1). The analytical methods and instruments used in the experiment are listed in Table 2. The simulation of BPNN is carried out by using Matlab software.

Table 1. The D-2 standards of the International Convention for the Control and Management of Ships Ballast Water & Sediments

| Organism category                                             | Requirements            |
|---------------------------------------------------------------|--------------------------|
| Plankton, >50 μm in minimum dimension                        | < 10 cells / m³          |
| Plankton, 10-50 μm                                           | < 10 cells / ml          |
| Toxicogenic Vibrio cholera (O₁ and O₁₃₉)                     | < 1 cfu / 100 ml         |
| Escherichia coli                                              | < 250 cfu / 100 ml       |
| Intestinal Enterococci                                        | < 100 cfu / 100 ml       |

Table 2. Detection methods in the experiments

| No. | Items       | Units     | Methods                          | Instruments                      |
|-----|-------------|-----------|----------------------------------|----------------------------------|
| 1   | algae       | entries / mL | blood count plate and microscope directly counting method | QIUJING XB-K-25 CIC XSZ-7G |
| 2   | bacteria    | entries / mL | test card                         | Beijing Land Bridge Technology Co., Ltd. |
| 3   | plankton    | entries / m³ | concentrated counting method       | -                                |
| 4   | pH          | %         | standard method                   | REX PHS-3C                       |
| 5   | salinity    | ‰         | standard method                   | AZ8371                           |
| 6   | ozone       | mg/h      | standard method                   | COM-AD-02                        |

3. Results and discussion

3.1. Effects of salinity, UV intensity and flow rate on the process efficiency without ozone

Because of the evaporation and precipitation of the seawater, freezing and melting ice, the inflow of river water, seawater vortex convection and other factors, the changes of salinity in worldwide seawater are inevitable. Therefore, a ballast water treatment device should prove its efficiency under different salinity. In this study, the salinity of the influent was set to 30‰, 33‰, 35‰, 37‰, and 40‰ to examine the effects of salinity on the process efficiency of MVOM. The experimental results indicated that the variation of salinity cause less effects on removal efficiency of planktonic bacteria. Under different salinity, the numbers of total bacteria and E.cole in the effluent was no more than 200 cfu/100 ml and 40 cfu/100 ml, which can meet the D-2 standard.

In order to examine the synergistic effect of ozone and UV treatment effect, the experiment did in the case of non-ozone added. In MVOM process, membrane filter was used to remove more than 50 μm microorganisms in ballast water. The results indicated that no matter how fast the water flow during the experiment, no enteromorpha (larger than 50 μm) was found in the filtered ballast water, and the number of microbes between 10 μm and 50 μm was less than 10 /mL. The results indicates that the NVOM process had a perfect effect on the removal of large microbes, which can be contributed to the efficient filtering by the membrane filter.

Therefore, in the case of no ozone injected, the flow rate and UV intensity were used as two major factors to investigate their efforts on total bacteria and E.coli. Figure 2 and figure 3 illustrated the numbers of E.coli and total bacteria in the effluent under different flow rates and UV intensity, respectively.
Figure 2 and 3 showed that with increasing UV intensity, the number of bacteria after treatment was significantly fewer than before. When the UV intensity increases, the sterilization ability by UV radiation was heightened. In addition, as ultraviolet light and titanium dioxide were combined, the catalytic titanium dioxide generated hydroxyl free radicals, which causes strong bactericidal effect on this basis. With the constant UV intensity, it could be seen that the number of bacteria after processed also increased significantly with the increase of the flow rate. The phenomenon was mainly because when flow rate increases, the velocity of ballast water through the ultraviolet radiation sterilization was correspondingly increased, which shortens the inactivated time.

From the data of total bacteria and E. coli in Figure 2 and Figure 3, when the UV intensity was 0 W and 32 W, all of the results could not meet the requirements of the D-2 standard. When the UV intensity was 50 W and the flow rate was less than or equal to 200 L/h, the total bacteria and the E. coli amount in the discharged ballast water could all meet the D-2 standard. When the UV intensity was 75 W, and the flow rate was less than or equal to 400 L/h, the total bacteria and the E. coli amount in the discharged ballast water could all meet the D-2 standard.

3.2. The simulation of the process performance of UVOM with ozone added
In this study, BPNN was used to simulate the process performance of UVOM with ozone added. The BPNN is a kind of learning algorithm used for the error back propagation of the forward multi-layer neural network, and the BPNN uses a parallel network structure, including the input layer, hidden layer and output layer, the input signal will transfer to the output node through the effect function and the hidden node, then the output is given at last.

Since any continuous function or mapping can be achieved by using three layers of network, in this simulation, a three layers BP neural network was built according to the actual situation, including the input layer, hidden layer and output layer. The structure of the network was shown in figure 4. The numbers of nodes in input layer, hidden layer and output layer were 2, 4, and 2, respectively. The flow rate and UV intensity were set as the input and total bacteria and E. coli were set as output.

Table 3 listed the data of 12 tests with different flow rate and UV intensity. In order to do the simulation, and better reflect the actual situation better, part of the actual data from the experiments were used to train the model. In particular, data from test 1, 6 and 11 were used for testing the model and the other 9 sets of data were used as the training samples. From the table 3, we can find that the MVOM with ozone was capable of treating the ballast water. With the combination the ozone and other units, the treatment effect was correspondingly improved. With the UV intensity of 32 W, and the flow rate of less than or equal to 400 L/h, the total bacteria and the Escherichia coli amount in the discharged ballast water could meet the D-2 standard. When the UV intensity were 50 W and 75 W, and the flow rate was less than or equal to 600 L/h, the total bacteria and the Escherichia coli amount in the discharged ballast water could all meet the D-2 standard.
Table 3. The 12 tests under different flow rate and UV intensity used for making the BPNN model

| Test | UV(W) | Flow(L/h) | Total Bacteria (cfu/100mL) | E. coli (cfu/100mL) |
|------|-------|-----------|----------------------------|---------------------|
| 1    | 32    | 200       | 130                        | 80                  |
| 2    | 32    | 400       | 280                        | 180                 |
| 3    | 32    | 600       | 600                        | 400                 |
| 4    | 32    | 800       | 900                        | 800                 |
| 5    | 50    | 200       | 140                        | 60                  |
| 6    | 50    | 400       | 250                        | 140                 |
| 7    | 50    | 600       | 300                        | 220                 |
| 8    | 50    | 800       | 500                        | 350                 |
| 9    | 75    | 200       | 120                        | 20                  |
| 10   | 75    | 400       | 200                        | 100                 |
| 11   | 75    | 600       | 290                        | 160                 |
| 12   | 75    | 800       | 400                        | 240                 |

After the model foundation, data from test 1, 6 and 11 in table 3 was used for testing the model. Table 4 indicated the deviation between predictive values and real values. It showed that the maximum deviation of the total bacteria was 6.16%, and the minimum was 4.14%; the maximum deviation of the E. coli was 7.2%, and the minimum was 3.6%. The results indicated that the model can better describe the process performance of MVOM.

Actually, The UVOM reactor included several units with mechanical, physical and chemical effects, so the traditional model is difficult to effectively predict its running effect, especially when the internal physical and chemical conditions changed. In contrary, the BPNN was capable of putting the operational data into training set and then made the non-liner model. It can not only diagnose the state of the integration system, but also forecast the running effect of the reactor, thus to develop a theoretical foundation for the optimized control of the reactor. In this study, the BPNN performed its advantages in simulating the process operation, and this method has high applicability and much practical value.

After the training of the simulation, the weight of each layer and the threshold of each neuron was fixed and the results were shown in table 5 and table 6. According to the weights, the relative importance of the input parameters were calculated and shown in table 7. The results showed that the relative importance of flow rate was significantly larger than UV intensity. The results can be due to the inactivation time influenced by flow rate. While the ballast water entered the MVOM in higher flow rate, the retention time of microbes in the system was relatively shortened. The short retention time led to the weak contact with radicals and ozone, and more microbes can survive the conditions at all. Therefore, we should pay more attention to the choosing of suitable flow rate to make sure the process efficiency.

Table 4. The error analysis between predictive values and real values

| No | Test | 1  | 6  | 11 |
|----|------|----|----|----|
|    | Total bacteria | 4.14% | 6.13% | 6.16% |
|    | E.coli       | 3.6%  | 6.68% | 7.2% |
Table 5. The weights of input layer and hidden layer

| Hidden layer | Input layer |
|--------------|-------------|
|              | 1           | 2           |
| 1            | 2.793071638 | 3.960528537 |
| 2            | 2.245097505 | 2.148447665 |
| 3            | 1.857886624 | 5.048076581 |
| 4            | 1.092980735 | 5.412536706 |

Table 6. The weights of output layer and hidden layer

| Hidden layer | Output layer |
|--------------|--------------|
|              | 1   | 2   | 3   | 4   |
| 1            | 2.965553964 | -2.965118227 | 0.292352935 | 2.488322804 |
| 2            | 0.605956449 | -3.065426857 | 0.440639753 | 0.249601941 |

Table 7. The relative importance of the input parameters

| Variables     | UV intensity | Flow rate |
|---------------|--------------|-----------|
| RI (%)        | 34.04        | 65.96     |

4. Conclusion
In this study, the UVOM device, combining membrane filter, venture tubes, the UV catalytic TiO$_2$ unit and an ozone generator, was used to treat ballast water. Results indicated that salinity cause less effects on the removal efficiency of UVOM, and flow rate and UV intensity played more important roles. For UV intensity of 50 W and the flow rate no more than 200 L/h, and UV intensity of 75 W and the flow rate no more than 400 L/h, the discharged ballast water can meet the D-2 standard. For simulating the process performance by data under different flow rate and UV intensity, BPNN was constructed and can better describe the process. For predictive values and real values, the deviation of the total bacteria was from 4.14% to 6.16%, and the deviation of E. coli was from 3.6% to 7.2%. In addition, the results showed that the relative importance of flow rate was significantly larger than UV intensity.

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References
[1] Cai YH, Li X, Zaidi AA, Shi Y, Zhang K, Feng RZ, Lin AQ, Liu C (2019) Effect of hydraulic retention time on pollutants removal from real ship sewage treatment via a pilot-scale air-lift multilevel circulation membrane bioreactor. Chemosphere. 236:124338.
[2] Cai YH, Ben T, Zaidi AA, Shi Y, Zhang K (2019) Nitrogen removal augmentation of ship sewage by an innovative aerobic-anaerobic micro-sludge MBR technology. Process Biochemistry 82:123-134.
[3] Cai YH, Zaidi AA, Shi Y, Zhang K, Li X, Lin AQ (2019) Influence of salinity on biological treatment of ship domestic sewage using an air-lift multilevel circulation membrane reactor. Environmental Science and Pollution Research. (In press).
[4] Jiang XQ, Lin AQ, Ma HL, Li XY, Li YY (2020). Minimizing the thermal bridge through the columns in a refrigeration room. Applied Thermal Engineering 165: 114565.
[5] Lin AQ, Sun YG, Zhang H, Lin X, Yang L, Zheng Q (2018). Fluctuating characteristics of air-mist mixture flow with conjugate wall-film motion in a compressor of gas turbine. Applied Thermal Engineering 142: 779-792.

[6] Lin AQ, Zheng Q, Jiang YT, Lin X, Zhang H (2019). Sensitivity of air/mist non-equilibrium phase transition cooling to transient characteristics in a compressor of gas turbine. International Journal of Heat and Mass Transfer 137: 882-894.

[7] Jiang XQ, Lin AQ, Malik A, Chang XY, Xu YY (2019). Numerical investigation on aerodynamic characteristics of exhaust passage with consideration of multi-factor components in a supercritical steam turbine. Applied Thermal Engineering 162: 114085.

[8] Lin AQ, Zhou J, Fawzy H, Zhang H, Zheng Q (2019). Evaluation of mass injection cooling on flow and heat transfer characteristics for high-temperature inlet air in a MIPCC engine. International Journal of Heat and Mass Transfer 135: 620-630.