POLISH MARITIME RESEARCH 4 (120) 2023 Vol. 30; pp. 31-42
10.2478/pomr-2023-0056

# OPTIMAL UV QUANTITY FOR A BALLAST WATER TREATMENT SYSTEM FOR COMPLIANCE WITH IMO STANDARDS

**Nguyen Dinh Thach**
**Phan Van Hung** *
Faculty of Navigation, Vietnam Maritime University, Haiphong, Viet Nam

* Corresponding author: *phanvanhung@vimaru.edu.vn (Phan Van Hung)*

## ABSTRACT

*Ballast water management is an effective measure to ensure that organisms, bacteria and viruses do not migrate with the ballast water to other areas. In 2004, the International Maritime Organization adopted the International Convention on the Control and Management of Ballast Water and Ship Sediments, which regulates issues related to ballast water management. Many technologies have been researched and developed, and of these, the use of UV rays in combination with filter membranes has been shown to have many advantages and to meet the requirements of the Convention. However, the use of UV furnaces in ballast water treatment systems requires a very large capacity, involving the use of many high-power UV lamps. This not only consumes large amounts of electrical energy, but is also expensive. It is therefore necessary to find an optimal algorithm to enable the UV radiation for the UV controller in the ballast water sterilisation process to be controlled in a reasonable and effective manner. This controller helps to prolong the life of the UV lamp, reduce power consumption and ensure effective sterilisation. This paper presents a UV control algorithm and a controller for a UV furnace for a ballast water treatment system installed on a ship. The results of tests on vessels illustrate the effect of the proposed UV controller.*

**Keywords:** UV Quantity Controller, Ship, Ballast Water Management, Viable Organisms Threat, Marine Environment.

## NOMENCLATURE

$UV_{Dose}(k)$ – is the amount of UV at the current point
$UV_{Dose}(k-1)$ – is the amount of UV at the previous point
$\tau$ – is the amount of water entering and leaving this region
$V_a$ – is the amount of water injected in one cycle $\tau$
$UV^a_{dose}$ – is the amount of UV available in the amount of water injected into the $V_j$ area
$V_b = V_j - V_a$ – is the amount of water remaining in volume $V_j$ at time k−1
$UV^b_{dose}=UV^j_{dose}(k-1)$ – is the amount of UV in volume $V_j$ at time k−1
T – is the sampling time for the controller
dUV – is the difference between two values dUV1 and dUV2
U″(k) – is the value at the present time
U″(k−1) – is the value at the time of the previous product

## INTRODUCTION

Ships use ballast water to ensure stability and manoeuverability. This water is taken in and discharged as needed to counterbalance the hull stress caused by rough sea conditions, loading and unloading operations, or changes in fuel and water levels. In addition, ballast water helps to control the trim of the vessel, thereby ensuring it maintains the appropriate balance and posture during its voyage [1]–[5]. However, this water may harbour a diverse range of organisms, such as phytoplankton, zooplankton, bacteria, viruses, and macro-fauna. The unintentional transfer of potentially invasive alien species (of which there are around 7,000 to 10,000 different types, including marine microbes, plants, and animals) occurs worldwide on a daily basis, leading to economic losses of tens of billions of US dollars annually [6]–[10]. The International Maritime Organization (IMO) [11] has identified numerous undesirable and invasive species associated with ballast water operations. The introduction of non-indigenous species through ballast water discharge can inflict severe consequences on local ecosystems, as invasive species have the potential to outcompete native species for resources, leading to significant alterations in the structure and function of an ecosystem [12]–[22]. Moreover, they have the capacity to introduce diseases and parasites, which can pose a threat to native species and disrupt the delicate balance of the food web. Certain invasive species can even modify water chemistry, potentially leading to eutrophication and the proliferation of harmful algal blooms. The impacts of ballast water discharge on aquatic ecosystems can also have significant economic repercussions. The introduction of invasive species can inflict damage on both commercial and recreational fisheries, diminishing their yields and affecting the livelihoods of those who depend on them. Furthermore, invasive species can cause harm to infrastructure and property, resulting in increased maintenance costs and decreased property values. The expenses associated with controlling and eradicating invasive species can be substantial, and their effects may persist for many years [6], [7], [19],[13], [23]–[29].

The Ballast Water Management Convention (Ballast Water Management Convention, 2004) was adopted by an IMO Diplomatic Conference in February 2004, and finally came into force globally on 8 September 2017. This convention requires ships to effectively treat their ballast water to remove or neutralise aquatic organisms and pathogens before discharging it into new locations. Its aim is to prevent the spread of invasive species and potentially harmful pathogens. Ships operating under this convention may be subjected to port state control in any port or offshore terminal of a party to the Ballast Water Management Convention; this inspection process may involve verifying the presence of a valid certificate and an approved ballast water management plan on board, checking the ballast water record book, and possibly conducting ballast water sampling in accordance with the guidelines for ballast water sampling (G2) to meet standards D1 and D2.

Ballast water management systems (D3) must be approved by the administration, and must adhere to the IMO guidelines. In 2016, revised guidelines for the approval of ballast water management systems (G8) were adopted, and were later transformed into a draft mandatory code for the approval of ballast water management systems (BWMSs), with particular reference to the procedure for approval of BWMSs that use active substances (G9).

All ships are required to comply with the D2 standard by 8th September 2024, and must ensure that their BWMSs meet the required criteria to protect marine ecosystems from potential invasive species and pathogens [11], [30]. Some essential water quality parameters necessary for effective marine environment management include physico-chemical factors such as temperature, colour, turbidity, salinity, dissolved oxygen, conductivity, suspended solids, and radioactivity. Monitoring and understanding these parameters are crucial to ensure the proper and sustainable management of the marine ecosystem [16], [31]–[34].

Several ballast water treatment systems or combinations of systems have been developed and put into practical use to ensure compliance with the standards set by the BWM Convention. It is worth mentioning that ballast water treatment systems that utilise UV rays in conjunction with a membrane filter are highly regarded for their efficient microbial treatment capability and cost-effectiveness [35]–[39].

Ballast water treatment systems using UV reactors often employ multiple high-power UV lamps within a single reactor. To ensure effective bactericidal results, precise control over the UV reactor is necessary, which involves maintaining a consistent UV lamp dose that adheres to the specified standard. In practice, the dose of UV radiation relies on two critical factors: the flow rate of water passing through the reactor, and the intensity of UV radiation within the UV reactor itself [29],[36], [37], [39],[40]. Identifying these factors and devising a control method for the UV reactor is a crucial area of research that requires careful study and implementation. At present, the ballast water treatment systems of many global brands employ a basic ON/OFF control measure for the UV reactor, although some continuously run the reactor at full capacity regardless of variations in water flow. As a result, the UV dose becomes unstable, leading to inefficient energy consumption and a shorter lifespan for the UV lamps. This article focuses on formulating and establishing optimal control equations for the UV reactor, with the aim of addressing the aforementioned drawbacks and improve the performance of systems such as these [37],[38],[29],[41]-[43].

## CONTROL ALGORITHM FOR A UV FURNACE CONTROLLER

### UV QUANTITY MODEL

The ballast water of the vessel has zero UV when it enters the UV furnace. During the process of flowing through the furnace, the ballast water is treated with UV rays, so the amount of UV gradually increases and until the desired amount is reached at the outlet. The distribution of the amount of UV over the length of the furnace is illustrated in Figure 1. The lower the flow rate of the water, the higher the UV level at the outlet, or the steeper the characteristic of the UV quantity according to the furnace location.

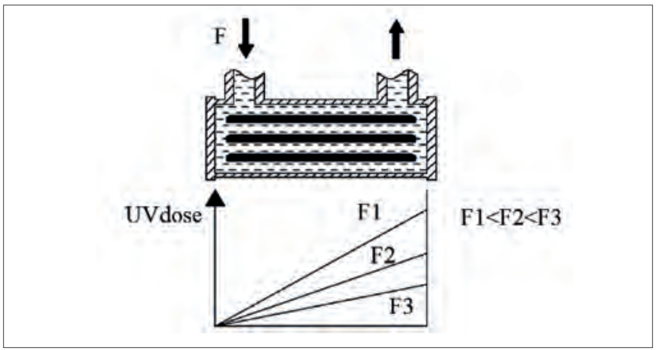


*Fig. 1. Distributions of UV in the furnace when treating ballast water*

To calculate the amount of UV involved, we divide the UV furnace into equal parts $V_1, V_2, \ldots, V_n$. If these are small enough, the amount of UV at all points in each one of these parts can be considered constant. That is, the amount of UV in the hypothetical furnace is approximately distributed in each volume fraction $V_j$ as shown in Figure 2.

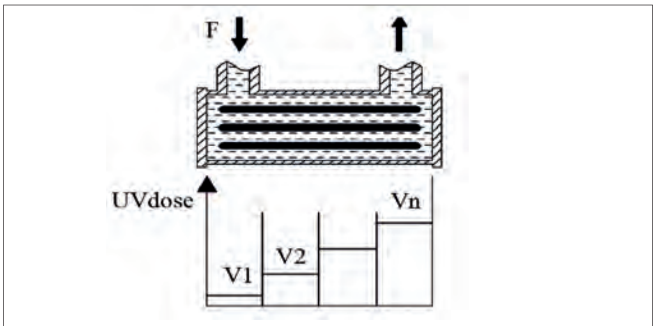


*Fig. 2. Distribution of UV in the furnace according to the hypothesis*

A PLC is a computing device based on a microcontroller, and the signals from the PLC are digital ones. Calculations with application operations for real-time control are performed by the PLC over a certain period of time called the calculation cycle τ. If the current time period of the PLC is the kth cycle (Figure 3), then the previous computation times are k–1, k–2, etc. and the subsequent computation times are k+1, k+2, etc.

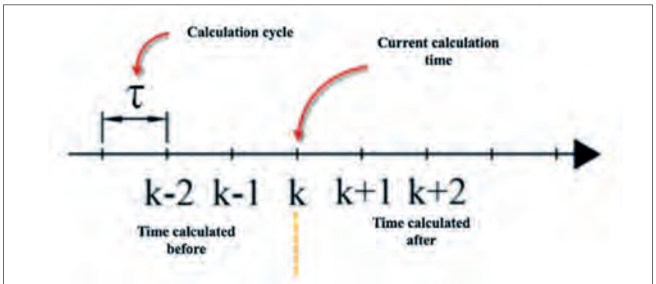


*Fig. 3. Calculation periods for the PLC*

As the PLC performs calculations with a period τ, we consider the variation in the amount of UV between two consecutive time points. If $UV_{Dose}(k)$ is the amount of UV at the current point, then $UV_{Dose}(k-1)$ is the amount at the previous point.

For a section $V_j$ of the UV furnace (Figure 4), the amount of water entering and leaving this region in each calculation cycle τ is $V_a = F \cdot \tau$ (litres). In one cycle τ, the amount of UV received by the ultraviolet lamp is $i \cdot \tau$. The amount of UV in section $V_j$ at time k $\left(UV^j_{dose}(k)\right)$ can then be approximated as follows:

$$UV^j_{dose}(k) = \frac{UV^j_{dose} \cdot V_a + UV^b_{dose} \cdot V_b}{V_j} + i \cdot \tau \qquad (1)$$

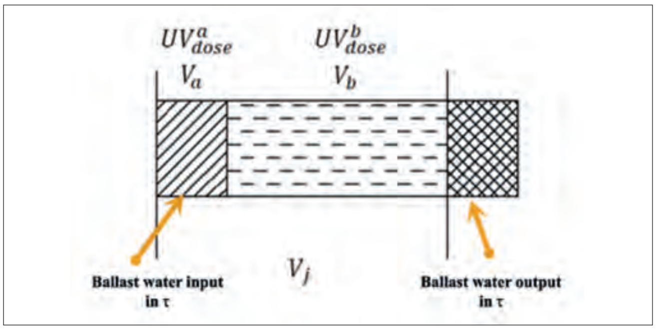


*Fig. 4. Calculation of the amount of UV in a section $V_j$ of the furnace*

Transforming Eq. (1) gives:

$$UV^j_{dose}(k) = \frac{UV^a_{dose} \cdot F \cdot \tau + UV^j_{dose}(k-1) \cdot (V_j - F \cdot \tau)}{V_j} + i \cdot \tau \qquad (2)$$

$$UV^j_{dose}(k) = UV^j_{dose}(k-1) \cdot \left(1 - \frac{F \cdot \tau}{V_j}\right) + UV^a_{dose} \cdot \frac{F \cdot \tau}{V_j} + i \cdot \tau \qquad (3)$$

The amount of water pumped out of part $V_j$ of the furnace in this time period τ will have a UV content equal to the amount of UV in part $V_j$ at the previous time $UV^j_{dose}(k-1)$.

To ensure the correctness of Eq. (3), the calculation time τ and the volume of each part $V_j$ must be chosen so that each time the PLC is updated, the amount of water flowing into each volume $V_j$ does not exceed this volume. In other words, the condition $F_{max.\tau} < V_j$ ensures the accuracy of the UV calculation in Eq. (3).

For systems using PLCs, the calculation period is generally taken as 0.1 s. With a design rated flow rate of 55 litres per second, the maximum design flow for the furnace is 70 litres per second. Thus, the volume of each division $V_j > 70 \cdot 0.1 = 7$ litres. Thus, a UV oven with volume 78 litres can be divided into 10 parts at most. The smaller the component parts, the higher the accuracy, but the larger the computational volume; thus, we need to choose the lowest feasible volume with an acceptable calculation error.

In this study, we carry out a simulation where the amount of UV is calculated according to Eq. (3) for a number of divisions ranging from three to 10. Since the construction of the model is the same for each number of divisions, we only present an illustration for a model with five parts. Using Eq. (3), a mathematical model of the amount of UV at time k can be constructed as shown in Figure 5, where the UV furnace is divided into five equal parts, V1 to V5.

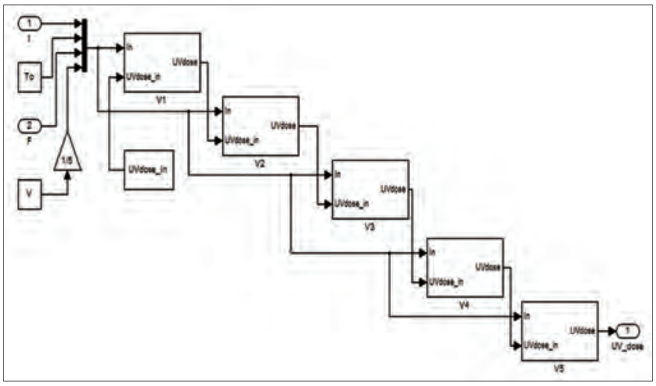

*Fig. 5. Example of a model constructed to calculate the amount of UV in the furnace*

To calculate the amount of UV at time k, we need to know the amount of UV at time k−1. The model in Figure 6 uses a memory block to save the value at the previous calculation time. In other words, if the input to the memory block is the value of $UV_{dose}(k)$, the output is the value of $UV_{dose}(k-1)$.

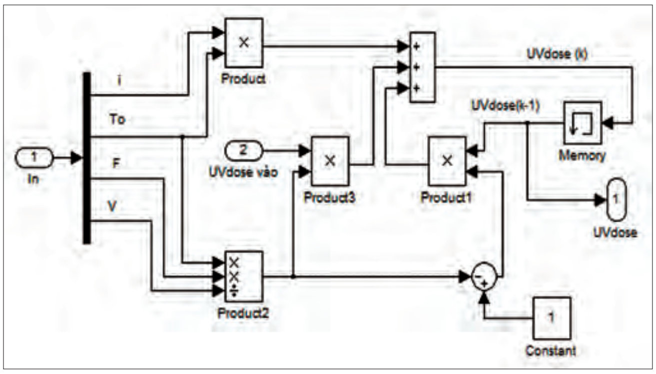


*Fig. 6. Details of the calculation in block $V_j$*

## CONSTRUCTING THE CONTROL ALGORITHM

The entire UV furnace space is divided into five parts, $V_1$, $V_2$, …, $V_5$, and the amount of UV in each part is defined in Eq. (3). $V_1$ receives ballast water from outside the furnace, while $V_5$ contains the amount of water coming out of the furnace after treatment. The variables of the fuzzy control structure are defined as shown in Figure 7.

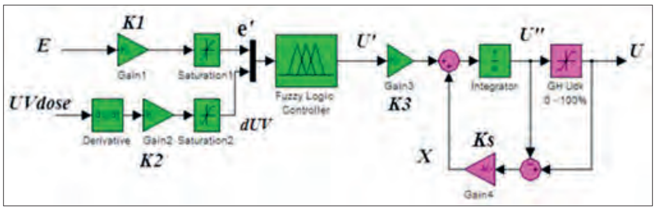


*Fig. 7. Variables used by the fuzzy controller structure for the UV furnace*

The two values e′ and dUV are determined as follows:

$$e' = \begin{cases} 1 & if\ \ E \cdot K_1 > 1 \\ E \cdot K_1 & if\ \ -1 \le E \cdot K_1 \le 1 \\ -1 & if\ \ E \cdot K_1 < 1 \end{cases} \tag{4}$$

$$e' = \begin{cases} 1 & if\ \ \Delta U_{dose} \cdot {}^{K_2}/_{T} > 1 \\ \Delta U_{dose} \cdot {}^{K_2}/_{T} & if\ \ -1 \le \Delta U_{dose} \cdot {}^{K_2}/_{T} \le 1 \\ -1 & if\ \ \Delta U_{dose} \cdot {}^{K_2}/_{T} < -1 \end{cases} \tag{5}$$

The output signal of the fuzzy controller U′ for varying values of the two inputs e′ and dUV can be calculated in many ways, for example based on the shape of the membership function, based on a transformation matrix, or by using an output signal table.

For PLC devices, constructing membership functions for the input and output variables requires considerable system resources and long computation times, which can affect the controllability of the PLC; hence, to calculate the value of the fuzzy control output U′ we use a table lookup method, as follows.

*Step 1: Tabulate the output value U′ according to the input e′and dUV*

From the fuzzy controller results obtained from the simulation using Matlab software, we enter some representative values in the ranges of the input variables e′ and dUV. The simulation then gives the output values U′ shown in Table 1.

*Tab. 1. Output value U′ for varying values of input e′ and dUV*

| U′ | | dUV | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | −1 | −0.8 | −0.6 | −0.4 | −0.2 | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
| e′ | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.3 | 0.15 | 0.05 | 0.02 | 0 |
| | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.46 | 0.38 | 0.22 | 0.1 | 0.03 | 0 | −0.4 |
| | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.2 | 0.1 | 0.03 | 0 | −0.1 | −0.1 |
| | 0.4 | 0.5 | 0.5 | 0.5 | 0.36 | 0.23 | 0.1 | 0.03 | 0 | −0.1 | −0.4 | −0.6 |
| | 0.2 | 0.5 | 0.44 | 0.36 | 0.2 | 0.1 | 0.03 | 0 | −0.1 | −0.3 | −0.7 | −0.9 |
| | 0 | 0.5 | 0.38 | 0.2 | 0.1 | 0.03 | 0 | −0.1 | −0.3 | −0.8 | −0.9 | −1 |
| | −0.2 | 0.3 | 0.22 | 0.1 | 0.04 | 0 | −01 | −0.4 | −0.7 | −0.9 | −1 | −1 |
| | 0.4 | 0.15 | 0.1 | 0.03 | 0 | −0.1 | −0.3 | −0.7 | −0.9 | −1 | −1 | −1 |
| | −0.6 | 0.05 | 0.03 | 0 | −0.1 | −0.3 | −0.8 | −0.9 | −1 | −1 | −1 | −1 |
| | −0.8 | 0.02 | 0 | −0.1 | −0.4 | −0.7 | −0.9 | −1 | −1 | −1 | −1 | −1 |
| | 1 | 0 | −0.1 | −0.1 | −0.6 | −0.9 | −1 | −1 | −1 | −1 | −1 | −1 |

*Step 2: Determine the value of the fuzzy controller output U′*

There are two cases in regard to the values of e′ and dUV at the input.

*Case 1:* The values of e′ and dUV match those in the table, in which case looking up the value from the table is simple. The value of the control output U′ is exactly the same as the value in the table.

*Case 2:* The values of e′ and dUV do not coincide with any value in the table, and their values are between two values in the table. Suppose e′ is between two values $e'_1$ and $e'_2$, and dUV is between two values $dUV_1$ and $dUV_2$. Then, as e′ and dUV each have two values, there are four cells in Table 2 below.

*Tab. 2. Calculation of the value of U′*

| U′ | | dUV | |
|---|---|---|---|
| | | $dUV_1$ | $dUV_2$ |
| e′ | $e'_1$ | $A_1$ | $B_1$ |
| | $e'_2$ | $A_2$ | $B_2$ |

To construct a formula for the lookup table of U′ values, we first derive a formula to determine the value of $y_K$ corresponding to the value of $x_k$, knowing that the point $K(x_K, y_K)$ lies between two points $M(x_1, y_1)$ and $N(x_2, y_2)$, as shown in Figure 8. The equation for the line MN has the form:

$$\frac{y-y_2}{y_1-y_2} = \frac{x-x_2}{x_1-x_2} <-> y = \frac{y_1-y_2}{x_1-x_2} \cdot (x-x_2) + y_2 \qquad (6)$$

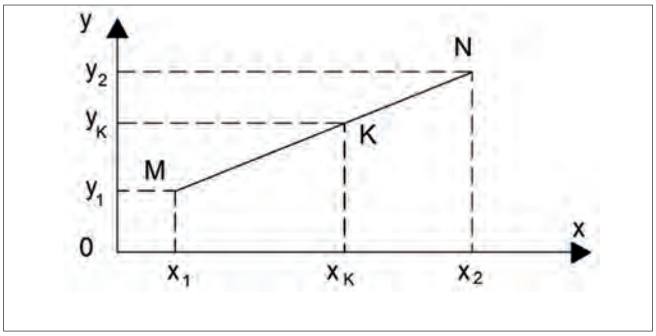

*Fig. 8. Determining the value of yK in a segment MN*

The value of $y_k$ is then determined from the value of $x_k$ using Eq. (7):

$$y_K = \frac{y_1-y_2}{x_1-x_2} \cdot (x_K-x_2) + y_2 \qquad (7)$$

The method used to determine the control output value U′ is illustrated in Figure 9. We apply Eq. (7) to calculate the value of $U_1$ for segment $A_1A_2$ and $U_2$ for segment $B_1B_2$ depending on the value of e′, as follows:

$$U_1 = \frac{A_1-A_2}{e'_1-e'_2} \cdot (e'_1 - e'_2) + A_2$$
$$U_2 = \frac{B_1-B_2}{e'_1-e'_2} \cdot (e'_1 - e'_2) + B_2 \qquad (8)$$

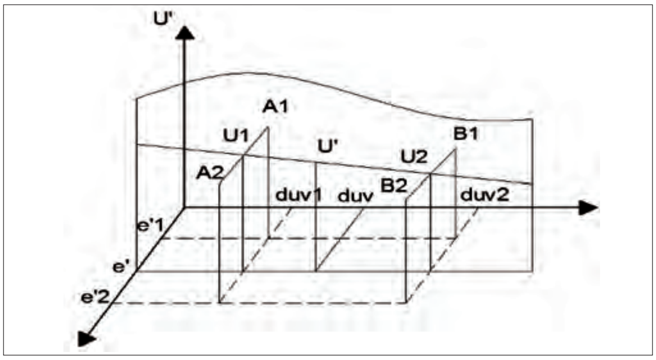

*Fig. 9. Method used to determine the value of the control output U′ from the lookup table*

We apply Eq. (7) to calculate the value of U′ on segment $U_1U_2$ in dUV as follows:

$$U' = \frac{U_1-U_2}{dUV_1-dUV_2} \cdot (dUV - dUV_2) + U_2 \qquad (9)$$

Here, we consider an example where we determine the value of U′ for two inputs, e′ = 0.1 and dUV = −0.35. In this case, e′will lie between two values $e'_1 = 0.2$ and $e'_2 = 0$, and dUV between two values $dUV_1 = -0.4$, $dUV_2 = -0.2$. We can use the lookup table to get four values, $A_1$, $A_2$, $B_1$, and $B_2$, as shown in Figure 10.

$$U_1 = \frac{A_1-A_2}{e_1-e_2} \cdot (E'-e_2) + A_2 = \frac{0.2-0.1}{0.2-0} \cdot (0.1-0) + 0.1 = 0.15$$
$$U_2 = \frac{B_1-B_2}{e_1-e_2} \cdot (E'-e_2) + B_2 = \frac{0.1-0.03}{0.2-0} \cdot (0.1-0) + 0.03 = 0.065$$
$$U' = \frac{U_1-U_2}{dUV_1-dUV_2} \cdot (dUV-dUV_2) + U_2 = \frac{0.15-0.065}{-0.4+0.2} \cdot (-0.35+0.2) + 0.065 = 0.129$$

| U' | | dUV | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -1 | -0.8 | -0.6 | -0.4 | -0.2 | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
| e | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.3 | 0.15 | 0.05 | 0.02 | 0 |
| | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.46 | 0.38 | 0.22 | 0.1 | 0.03 | 0 | -0.4 |
| | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.2 | 0.1 | 0.03 | 0 | -0.1 | -0.1 |
| | 0.4 | 0.5 | 0.5 | 0.5 | 0.36 | 0.23 | 0.1 | 0.03 | 0 | -0.1 | -0.4 | -0.6 |
| | 0.2 | 0.5 | 0.44 | 0.36 | 0.2 | 0.1 | 0.03 | 0 | -0.1 | -0.3 | -0.7 | -0.9 |
| | 0 | 0.5 | 0.38 | 0.2 | 0.1 | 0.03 | 0 | -0.1 | -0.3 | -0.8 | -0.9 | -1 |
| | -0.2 | 0.3 | 0.22 | 0.1 | 0.04 | 0 | -0.1 | -0.4 | -0.7 | -0.9 | -1 | -1 |
| | -0.4 | 0.15 | 0.1 | 0.03 | 0 | -0.1 | -0.3 | -0.7 | -0.9 | -1 | -1 | -1 |
| | -0.6 | 0.05 | 0.03 | 0 | -0.1 | -0.3 | -0.8 | -0.9 | -1 | -1 | -1 | -1 |
| | -0.8 | 0.02 | 0 | -0.1 | -0.4 | -0.7 | -0.9 | -1 | -1 | -1 | -1 | -1 |
| | -1 | 0 | -0.1 | -0.1 | -0.6 | -0.9 | -1 | -1 | -1 | -1 | -1 | -1 |

*Fig. 10. Lookup table of output values U′*

To determine the output signal U, it is necessary to calculate the value of the output U″. Based on the control structure in Figure 7, we have:

$$U''(s) = \frac{1}{s} \cdot \left(K_3 \cdot U'(s) + X(s)\right) \qquad (10)$$

where $X(s) = K_s\left(U(s) - U''(s)\right)$ is the value of the anti-saturation integral. We convert Eq. (10) to the Z domain using the Tustin method:

$$s = \frac{2}{T} \cdot \frac{z-1}{z+1} \qquad (11)$$

to get Eq. (12) in the Z domain:

$$U''(z) = \frac{T}{2} \cdot \frac{z+1}{z-1} \cdot \left(K_3 U'(z) + X(z)\right)$$

$$\left(1-\frac{1}{z}\right)\cdot U''(z)=\frac{T}{2}\cdot\left(1+\frac{1}{z}\right)\cdot\left(K_3\cdot U'(z)+X(z)\right) \quad (12)$$

To implement Eq. (12) in the PLC, we transform it into a differential equation as follows.

$$U''(k)-U''(k-1)=\frac{T}{2}\cdot\left(K_3\cdot U'(k)+K_3\cdot U'(k-1)+X(k)+X(k-1)\right)$$

$$U''(k)=U''(k-1)+\frac{T}{2}\cdot\left(K_3\cdot U'(k)+K_3\cdot U'(k-1)+X(k)+X(k-1)\right)$$

$$U''(k)=U''(k-1)+\frac{T}{2}\cdot\left(K_3\cdot U'(k)+K_3\cdot U'(k-1)+X(k-1)\right)+\frac{T}{2}\cdot X(k) \quad (13)$$

If we set $F=U''(k-1)+\frac{T}{2}\cdot\left(K_3\cdot U'(k)+K_3\cdot U'(k-1)+X(k-1)\right)$, then

$$U''(k)=F+\frac{T}{2}\cdot X(k) \quad (14)$$

To calculate U''(k), we consider three cases:

*Case 1:* $U''(k)\in[0,1]$

Then $X(k)=k_s\cdot(U(k)-U''(k))=0$. From Eq. (14), we have:

$$U''(k)=F \quad (15)$$

*Case 2:* $U''(k)>1$

Then $X(k)=k_s\cdot(1-U''(k))$, and from Eq. (14) we get:

$$U''(k)=\frac{2}{2+k_s\cdot T}\left(F+\frac{T}{2}\cdot k_s\right) \quad (16)$$

*Case 3:* $U''(k)<0$

Then $X(k)=k_s\cdot(0-U''(k))$, and from Eq. (14), we get:

$$U''(k)=\frac{2F}{2+k_s\cdot T} \quad (17)$$

The controller output after the limiting step is determined by the following system of equations:

$$U(k)=\begin{cases}1 & khi\ \ U''(k)>1\\ U''(k) & khi\ \ 0\le U''(k)\le 1\\ 0 & khi\ \ U''(k)<0\end{cases} \quad (18)$$

The algorithm for calculating the value of the fuzzy controller in the PLC for the UV furnace is summarised in Figure 11.

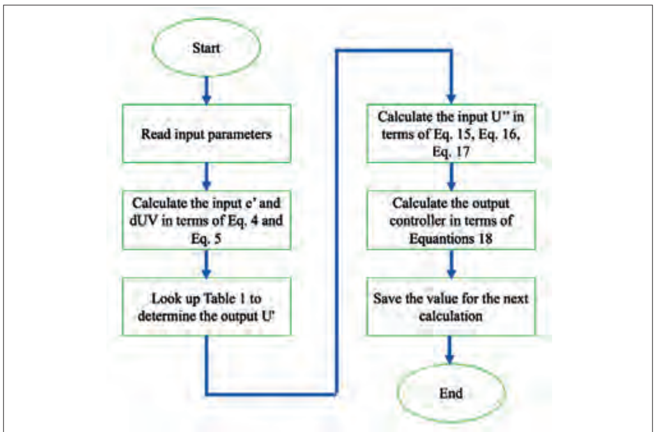


*Fig. 11. Algorithm for calculating the output value of the fuzzy control*

## DEVELOPMENT OF THE UV QUANTITY CONTROLLER

The basic components of a fuzzy controller are the fuzzy stage, the composition rule, and the defuzzification stage. Since basic fuzzy controllers are only capable of processing current signals, these are called static fuzzy controllers. To extend their application to dynamic control problems, the necessary kinematics are added to the basic fuzzy controller to provide it with the derivative or integral value of the signal. When used with these kinematics, the basic fuzzy controller is called a dynamic fuzzy controller.

For the ballast water treatment UV reactor, this is a nonlinear object. This nonlinearity is expressed in the relationship between the flow rate F and the amount of UV, and between the UV lamp control signal ($U_{dk}$) and the UV intensity. The relationship between $UV_{dose}$ and the flow F is described in general terms by the system of equations in (13) and (14). These systems are difficult to control with PIDs, and experiments are required to determine the accuracy of the controller. In this case, other controllers are often used (for example based on fuzzy control, neural control, or adaptive control) for the system. In the present paper, we build a fuzzy controller, as this has certain outstanding features: (i) the control is based on the operator's experience; (ii) there no need for an object model to set up the controller; and (iii) it can be applied to industrial control devices such as PLCs or microprocessors [43].

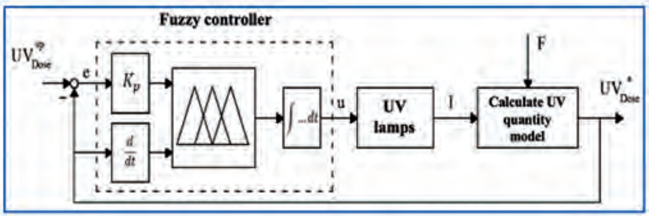


*Fig. 12. Structure fuzzy controller for UV reactor*

The fuzzy control structure for the UV reactor is shown in Figure 12. In this structure, the controller has two inputs and one output signal. The output signal of the controller is in the range [0,1], corresponding to a UV intensity of the lamp of between zero and $I_{max}$.

The two inputs of the fuzzy controller are: wrong order between the UV amount set and the UV amount of water treated in the reactor. Rate of variation of UV content of ballast water.

To facilitate the construction of the model and the signal processing step, all of the input values to the fuzzy controller are converted to standard values between –1 and 1. To do this, we need to pass additional inputs in the form of the coefficients $K_1$ and $K_2$, as shown in Figure 13.

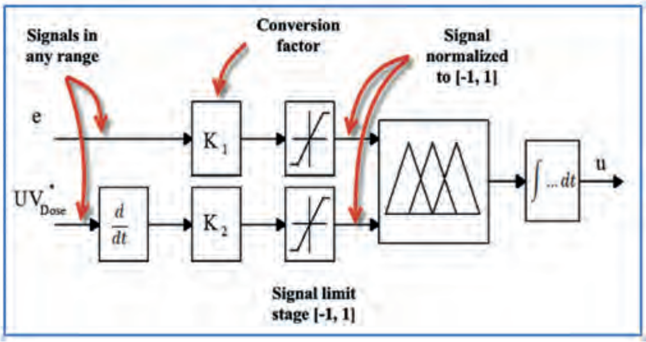


*Fig. 13. Fuzzy control structure with additional inputs in the form of value conversion factors*

We then determine the conversion factor $K_1$ for the control error input e. The coefficient $K_1$ is used to convert the range of the deviation e from $[-e_0, e_0]$ to the range $[-1, 1]$ for input into the fuzzy controller. The range $[-e_0, e_0]$ should be chosen so that for the smallest value of the limit $e_0$, the change in e is greatest in this interval.

To ensure the good operation and impact of the bias $e_0 = \frac{UV_{dose}^{dm}}{10}$, the coefficient $K_1$ is determined using Eq. (19):

$$K_1 = \frac{1}{e_0} = \frac{10}{UV_{dose}^{dm}} = \frac{10}{200} = 0.05 \tag{19}$$

We determine the conversion factor $K_2$ for the variable rate input $UV_{dose}$ as follows. $K_2$ is used to convert the range of values for the rate of change $dUV_{dose}/dt$ from $[-dUV_0, dUV_0]$ to the range $[-1,1]$ to feed into the fuzzy controller. Based on the simulated response of the rate of change of UV in the reactor, the rate of change of $UV_{dose}$ at the fastest time has the value $dUV_{dose}/dt = 10$. Thus, the $dUV_{dose}/dt$ variable takes values in the range $[-10, 10]$, or in other words, the coefficient $K_2 = 1/10 = 0.1$.

The construction of the fuzzy controller was first carried out in Matlab to simulate and verify the operation before applying it to real objects. Simulation can help to shorten the equipment testing time, reduce costs and allow us to gain experience in controlling the system. Here, we used a Sugeno fuzzy controller [46] with two inputs (the signal bias e and the variable $dUV_{dose}/dt$) and one output (Output 1). This controller was implemented in Matlab with the Fuzzy Toolbox, as shown in Figure 14. The next step was to build linguistic variables for the inputs/outputs and to create membership functions corresponding to these linguistic variables for each input/output. To simplify the process of building the membership function for the input linguistic variables, we define linguistic values as shown in Table 3.

*Tab. 3. Linguistic variables for signal input*

| Linguistic variable | Meaning | Value |
|---|---|---|
| GN | Great negative | –1 |
| LN | Large negative | –0.6 |
| SN | Small negative | –0.3 |
| ZE | Zero | 0 |
| SP | Small positive | 0.1 |
| LP | Large positive | 0.3 |
| GP | Great positive | 0.5 |

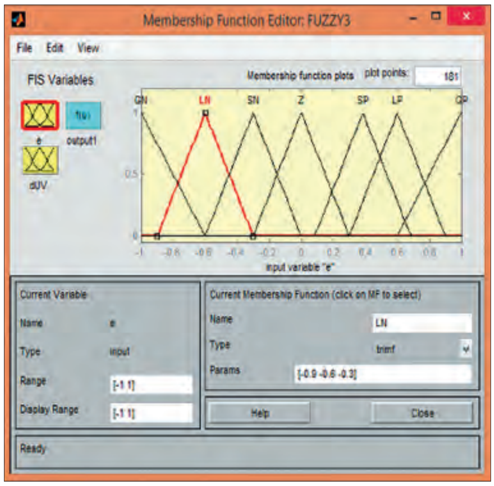


*Fig. 14. Fuzzy controller toolbox with the membership function of the input bias UV*

After building the membership function for the inputs, we constructed the membership function for the outputs. From the UV intensity response characteristics of the system, we know that the rate of increase in the UV intensity is limited by the response of the lamp, meaning that this is a factor that cannot be further increased. The rate of reduction in UV intensity is also high. We therefore created an asymmetric controller characteristic in which the control signal used to increase the UV intensity changed more slowly than the rate of decrease in the UV intensity of the reactor. This meant that the control characteristic could eliminate the problem whereby the system response cannot keep up with the changing speed of the control, which affects the output quality of the system. To build the output signal, we used language variables for the output with the values shown in Table 3.

When the two inputs (e, $dUV_{dose}/dt$) and the fuzzy rule had been built, the controller was able to completely determine the explicit value of the output $U_{dk}$ according to the values of the input. The relationship between U′ and the two input signals (e, $dUV_{dose}/dt$) is shown graphically in Figure 10. In this feature, Output 1 of the controller varies in the range $[-1, 0.5]$. With these characteristics, the controller will have a slower increase rate of 1/2 than the decrease rate of the signal. As mentioned above, this deviation in the rate of increase/decrease is found purely based on practical experience, and depends on the rates of increase and decrease in the UV intensity in the reactor being asymmetric. This surface is also the basis for building algorithms for fuzzy controllers on PLC.

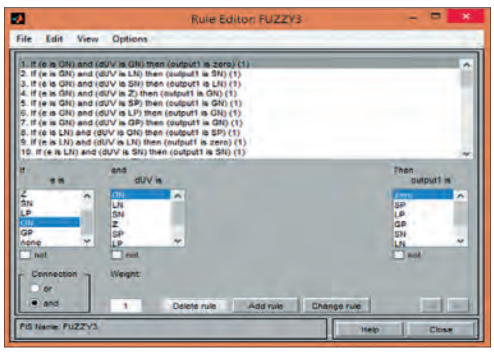


*Fig. 15. Developing the fuzzy rule in Matlab software*

Tab. 4. Fuzzy rule for controller

| Output 1 | | dUV$_{dose}$/dt | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | GN | LN | SN | Z | SP | LP | GP |
| e | GN | Z | SN | LN | GN | GN | GN | GN |
| | LN | SP | Z | SN | LN | GN | GN | GN |
| | SN | LP | SP | Z | SN | LN | GN | GN |
| | Z | GP | LP | SP | Z | SN | LN | GN |
| | SP | GP | GP | LP | SP | Z | SN | LN |
| | LP | GP | GP | GP | LP | SP | Z | SN |
| | GP | GP | GP | GP | GP | LP | SP | Z |

With the proposed control structure, after building the component models, we get the simulation model shown in Figure 11 and Table 3, where the input is in the range [−1,1], and the controller output after the integral is in the range [0%,100%].

## EVALUATION OF BIOCHEMICAL EFFICIENCY DURING TESTING OF BALLAST WATER TREATMENT SYSTEM ACCORDING TO IMO STANDARD G8

### CONFIGURATION FOR ON-BOARD TESTING

The IMO G8 provision pertains to the testing of ballast water treatment systems on board vessels. According to these regulations, testing of a ballast water treatment system requires the installation of such a system on a ship where the normal ballast operations are carried out. This means that the ballast system of the ship should be fully operational in the usual manner.

To conduct tests on the proposed ballast water treatment system, a specific procedure was followed. The ballast water treatment system was installed on the ship, and was configured as shown in Figure 16. This configuration diagram served as a guide for the proper installation and arrangement of the system components to ensure that it functioned as intended. This setup allowed for the systematic testing and evaluation of the system's performance under real-world conditions, and ensured that it met the requirements and standards set out in the IMO G8 regulations.

### ONBOARD TEST PROCEDURE

In accordance with the requirements outlined in G8, shipboard testing of ballast water treatment systems is a comprehensive process that is conducted over a minimum duration of six months. During this testing period, there are specific criteria that must be met, and a series of test cycles need to be completed successfully. Each test cycle comprises several distinct steps, which ensure a thorough evaluation of the performance of the treatment system, as follows:

- Pumping ballast water into the control tank: The initial step of the test cycle involves pumping ballast water into a designated control tank on the ship. This control tank serves as a reference point for monitoring the quality and condition of the ballast water before it undergoes treatment.
- Pumping ballast water into the ballast tanks for treatment: After filling the control tank, the next step is to pump ballast water from this tank into the ship's ballast tanks, which form part of the treatment system. It is at this point that the ballast water will be subjected to the treatment process designed to eliminate or reduce the concentration of aquatic organisms.
- Draining the ballast water from the control tank: Once the ballast water has been transferred to the tanks of the treatment system, the control tank is emptied or drained. This step is essential for maintaining consistency in the testing process, as it allows for comparison between treated and untreated water samples.
- Discharging ballast water from treated ballast tanks: Following the treatment process, the treated ballast water is discharged from the tanks. In this step, the effectiveness of the treatment system is evaluated in terms of rendering the ballast water compliant with environmental regulations, particularly concerning the control of invasive species and pathogens.

To meet the IMO G8 requirements, it is crucial that this sequence of work steps is repeated continuously for at least six months. The testing process must also yield a minimum of three consecutive successful test cycles to demonstrate the consistent and reliable performance of the ballast water treatment system for various operating conditions and environmental factors. This stringent testing protocol helps ensure that ships' BWMSs meet international standards for environmental protection.

### BALLAST WATER SAMPLING AND ANALYSIS DURING TESTING

*(1) Number of samples in one test cycle*

Three input water samples are taken during the process of pumping ballast water into the counter-egg tank (taken at the beginning, middle and end of the process).

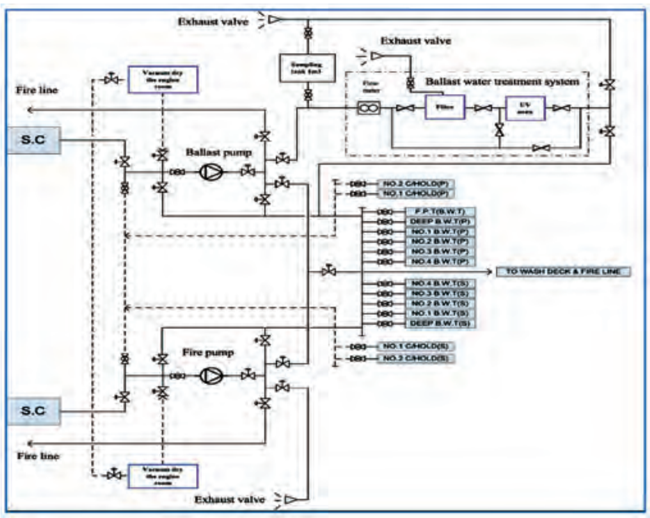


Fig. 16. Diagram showing an example of a test configuration for a ballast water treatment system on a ship

Three samples are taken from the discharge line during the process of discharging the ballast water from the egg tank (taken at the beginning, middle and end stages). A total of nine samples are taken from the discharge line during the process of discharging the ballast water from the treated ballast tank (three samples in the first stage, three in the middle stage, and three in the final stage).

*(2) Test criteria for samples*

For each sample, the following criteria need to be met:

Environmental parameters: temperature, salinity (PSU), TSS (mg/l), DOC (mg/l) and POC (mg/l);

Number of living organisms: 50 μm/m$^3$;

Number of living organisms: 10–50 μm/1 ml;

Vibrio cholerae (cholera): cfu/100 ml;

Escherichia coli group (intestinal bacilli): cfu/100 ml;

Intestinal enterococci group: cfu/100 ml;

Heterotrophic bacteria: cfu/1 ml.

*(3) Criteria for a successful test cycle*

*Step 1:* Inlet water requirement

The input water must satisfy the following criteria:

Number of living organisms with size ≥ 50μm: 100/m$^3$;

Number of living organisms 10–50 μm in size: 100/1 ml

*Step 2:* Requirements for water samples during discharge of the ballast water from the control tank

Number of living organisms 50 μm in size: 10/m$^3$;

Number of living organisms 10–50μm in size: 10/1 ml

*Step 3:* The requirements for water samples during the discharge of ballast water from the treated ballast tank are considered to comply with the D2 discharge standard (IMO BWM Convention).

## EXPERIMENTAL RESULTS AND DISCUSSION

On-board testing of the ballast water treatment system was completed over a test period exceeding six months. Testing was carried out in accordance with the IMO Guidelines for the Approval of Ballast Water Treatment Systems (G8). The collection and analysis of ballast water samples was carried out by the Institute of Marine Environment and Resources under the supervision of the Vietnam Register. The test results for the ballast water treatment system according to IMO's G8 standard are presented in Table 5, where the average value of a parameter for three samples is recorded in the corresponding cell in the results.

The test results in Table 5 show that the input parameters for the water were in accordance with the requirements of the IMO. The parameters for the ballast water discharge from the reference tank are also in accordance with the requirements of IMO, and the parameters of the treated water from the ballast tank met the IMO standard D2.

The measurement results corresponding to the actual amounts of UV when operating on board under different conditions show that the controller works well, and the parameters of the system are suitable at the design value. The Vietnam Institute of Marine Environment and Resources has confirmed that various samples of ballast water after treatment from the commissioning testing conducted with the subject BWMS are considered to comply with D2 discharge standard (IMO BWM Convention).

## CONCLUSION

Ballast water management is a vital measure to ensure that organisms, bacteria, and viruses do not spread to new areas when discharging ballast, in accordance with the International Convention on the Control and Management of Ballast Water and Ship Sediments established in 2004, which regulates ballast water management issues. The UV reactor used in a ballast water treatment system often requires multiple high-power UV lamps within a single unit, due to its large capacity. These high-power UV lamps consume significant electrical energy, and impose high costs.

Efficiently controlling UV radiation during the water disinfection process is therefore essential to extend the lifespan of UV lamps, reduce energy consumption, and ensure effective antimicrobial treatment. This research has focused on developing optimal equations 19 (and Eqs. (4)–(18)) and a controller for a UV reactor in a ballast water treatment system (Figs. 11–13) installed on a ship. Experimental results from five ships have been presented to demonstrate the efficiency achieved by the proposed UV controller. When the proposed control algorithm is applied, the UV lamp shines at the appropriate intensity to meet the ballast water treatment requirements, rather than continuously operating at high intensity. This results in significant energy savings compared to a system without a UV

*Tab. 5. Measured values*

| Name of ship | Treatment rated capacity (m$^3$/h) | IMO standard | | Sampling period |
|---|---|---|---|---|
| | | Viable organisms ≥50μm (org/m$^3$): <10 | Viable organisms 10-50μm (org/ml): <10 | |
| ANBIEN BAY | 500 | 4 | 6.8 | 10h50–14h00, 02/06/2022 |
| TTC PIONEER | 200 | No live organisms detected | 7.8 | 11h10–12h15, 06/06/2022 |
| ROYAL 89 | 100 | 6 | 4.5 | 09h50–10h40, 15/08/2022 |
| TRACY | 150 | 1 | 2.9 | 15h00–15h30, 20/09/2022 |
| AN THINH PHU 08 | 100 | 1 | 0.2 | 08h00–09h00, 14/10/2022 |
| THAI BINH 35 | 50 | 1 | 1.7 | 11h30–12h10, 02/11/2022 |

controller. Furthermore, operating at low intensity rather than continuously at high intensity can help prolong the life of the UV lamp.

The development of effective treatment approaches such as these can enhance ballast water management, thus mitigating the negative impacts of invasive species on marine environments, economies, and human well-being.


**ACKNOWLEDGMENTS**

The authors would like to thank their colleagues at Vietnam Maritime University, Vietnam Register, Institute of Marine Environment and Resources, and the shipping companies for their assistance in this work. We also appreciate the constructive suggestions from the anonymous reviewers, which were invaluable in improving the quality of the manuscript.


## REFERENCES


1. G. Altug, S. Gurun, M. Cardak, P. S. Ciftci, and S. Kalkan, "The occurrence of pathogenic bacteria in some ships' ballast water incoming from various marine regions to the Sea of Marmara, Turkey," *Mar. Environ. Res.*, vol. 81, pp. 35–42, Oct. 2012, doi: 10.1016/j.marenvres.2012.08.005.

2. L. J. Aridgides, M. A. Doblin, T. Berke, F. C. Dobbs, D. O. Matson, and L. A. Drake, "Multiplex PCR allows simultaneous detection of pathogens in ships' ballast water," *Mar. Pollut Bull.*, vol. 48, no. 11, pp. 1096–1101, Jun. 2004, doi: 10.1016/j.marpolbul.2003.12.017.

3. J. Chen, Y. Lin, J. Zhou Huo, M. Xia Zhang, and Z. Shang Ji, "Optimization of ship's subdivision arrangement for offshore sequential ballast water exchange using a non-dominated sorting genetic algorithm," *Ocean Engineering*, vol. 37, no. 11, pp. 978–988, Aug. 2010, doi: 10.1016/j.oceaneng.2010.03.012.

4. I. Staffell and P. Balcombe, "How to decarbonise international shipping: options for fuels, technologies and policies," *Energy Convers. Manag.*, [Online]. Available: https://www.academia.edu/38669854/How_to_decarbonise_international_shipping_options_for_fuels_technologies_and_policies

5. P. Van Hung, K.-S. Kim, L. Q. Tien, and N. M. Cuong, "Distribution of oil spill response capability through considering probable incident, environmental sensitivity and geographical weather in Vietnamese waters," *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, vol. 2, no. 1, pp. 31–41, Nov. 2018, doi: 10.1080/25725084.2018.1511240.

6. G. Drillet et al., "Improvement in compliance of ships' ballast water discharges during commissioning tests," *Mar. Pollut. Bull.*, vol. 191, p. 114911, Jun. 2023, doi: 10.1016/j.marpolbul.2023.114911.

7. P. E. Neill and M. Arim, "Human Health Link to Invasive Species," in *Encyclopedia of Environmental Health*, pp. 570–578, 2019, doi: 10.1016/B978-0-12-409548-9.11731-2.

8. S. Gollasch, C. L. Hewitt, S. Bailey, and M. David, "Introductions and transfers of species by ballast water in the Adriatic Sea," *Mar. Pollut. Bull.*, vol. 147, pp. 8–15, Oct. 2019, doi: 10.1016/j.marpolbul.2018.08.054.

9. O. Vidjak *et al.*, "Zooplankton in Adriatic port environments: Indigenous communities and non-indigenous species," *Mar. Pollut. Bull.*, vol. 147, pp. 133–149, Oct. 2019, doi: 10.1016/j.marpolbul.2018.06.055.

10. P. Van Hung, K.-S. Kim, and M. Lee, "Cooperative response to marine hazardous and noxious substances and oil spill incidents in the ASEAN region," *Australian Journal of Maritime & Ocean Affairs*, vol. 11, no. 1, pp. 61–72, Jan. 2019, doi: 10.1080/18366503.2018.1559524.

11. IMO, International Maritime Organization [IMO], 2004. International Convention for the Control and Management of Ships' Ballast Water and Sediments. International Maritime Organization, London. [Online]. Available: http://www.imo.org/en/About/Conventions/List ofConventions/Pages/International- Convention-for-the-Control-and-Management-of-Ships%27-Ballast-Water-and-Sediments-(BWM).aspx

12. G. Elidolu, S. I. Sezer, E. Akyuz, O. Arslan, and Y. Arslanoglu, "Operational risk assessment of ballasting and de-ballasting on-board tanker ship under FMECA extended evidential reasoning (ER) and rule-based Bayesian network (RBN) approach," *Reliab. Eng. Syst. Saf.*, vol. 231, p. 108975, Mar. 2023, doi: 10.1016/j.ress.2022.108975.

13. D. K. Gray, I. C. Duggan, and H. J. Macisaac, "Can sodium hypochlorite reduce the risk of species introductions from diapausing invertebrate eggs in non-ballasted ships?," *Mar. Pollut. Bull.*, vol. 52, no. 6, pp. 689–695, Jun. 2006, doi: 10.1016/j.marpolbul.2005.11.001.

14. P. P. Sangave, A. Mukherjee, and A. Pandit, "Ballast water treatment using hydrodynamic cavitation," Nov. 2014. [Online]. Available: https://www.semanticscholar.org/paper/Ballast-Water-Treatment-Using-Hydrodynamic-Sangave-Mukherjee/ ca3f5edcc2a28ba175b1a4c0093b70b49bb2a334

15. S. Rahman, "Implementation of ballast water management plan in ships through ballast water exchange system," *Procedia Eng.*, vol. 194, pp. 323–329, Jan. 2017, doi: 10.1016/j.proeng.2017.08.152.

16. E. Tsolaki and E. Diamadopoulos, "Technologies for ballast water treatment: A review," *Journal of Chemical Technology & Biotechnology*, vol. 85, no. 1, pp. 19–32, Jan. 2010, doi: 10.1002/jctb.2276.

17. S. A. Bailey and H. Rajakaruna, "Optimizing methods to estimate zooplankton concentration based on generalized patterns of patchiness inside ballast tanks and ballast water discharges," *Ecol. Evol.*, vol. 7, no. 22, pp. 9689–9698, Nov. 2017, doi: 10.1002/ece3.3498.

18. C. Grob and B. G. Pollet, "Regrowth in ship's ballast water tanks: Think again!" *Mar. Pollut. Bull.*, vol. 109, no. 1, pp. 46–48, Aug. 2016, doi: 10.1016/j.marpolbul.2016.04.061.

19. V. Raţă and L. Rusu, "Ballast water pollution risk assessment in the Black Sea," in *Mechanical Testing and Diagnosis*, Jan. 2021, pp. 35–40. doi: 10.35219/mtd.2020.4.05.

20. E. Briski *et al.*, "Combining ballast water exchange and treatment to maximize prevention of species introductions to freshwater ecosystems," *Environ. Sci. Technol.*, vol. 49, no. 16, pp. 9566–9573, Aug. 2015, doi: 10.1021/acs.est.5b01795.

21. A. Travizi *et al.*, "Macrozoobenthos in the Adriatic Sea ports: Soft-bottom communities with an overview of non-indigenous species," *Mar. Pollut. Bull.*, vol. 147, pp. 159–170, Oct. 2019, doi: 10.1016/j.marpolbul.2019.01.016.

22. P. Mozetič *et al.*, "Phytoplankton diversity in Adriatic ports: Lessons from the port baseline survey for the management of harmful algal species," *Mar. Pollut. Bull.*, vol. 147, pp. 117–132, Oct. 2019, doi: 10.1016/j.marpolbul.2017.12.029.

23. J.-H. Park, Y.-B. Sim, S.-Y. Kang, and S.-H. Kim, "Inactivation of indicating microorganisms in ballast water using chlorine dioxide," *Ecology and Resilient Infrastructure*, vol. 5, no. 3, pp. 111–117, Sep. 2018, doi: 10.17820/ERI.2018.5.3.111.

24. T. McCollin, G. Quilez-Badia, K. D. Josefsen, M. E. Gill, E. Mesbahi, and C. L. J. Frid, "Ship board testing of a deoxygenation ballast water treatment," *Mar. Pollut. Bull.*, vol. 54, no. 8, pp. 1170–1178, Aug. 2007, doi: 10.1016/j.marpolbul.2007.04.013.

25. L. A. Drake, M. A. Doblin, and F. C. Dobbs, "Potential microbial bioinvasions via ships' ballast water, sediment, and biofilm," *Mar. Pollut. Bull.*, vol. 55, no. 7, pp. 333–341, Jan. 2007, doi: 10.1016/j.marpolbul.2006.11.007.

26. S. Vodyanitskaya et al., "Methods of decontamination of ship ballast water with polyguanidine disinfectant," International Journal of Infectious Diseases, vol. 79, p. 77, Feb. 2019, doi: 10.1016/j.ijid.2018.11.195.

27. E. Lakshmi, M. Priya, and V. S. Achari, "An overview on the treatment of ballast water in ships," *Ocean Coast Manag.*, vol. 199, p. 105296, Jan. 2021, doi: 10.1016/j.ocecoaman.2020.105296.

28. M. N. Tamburri, K. Wasson, and M. Matsuda, "Ballast water deoxygenation can prevent aquatic introductions while reducing ship corrosion," *Biol. Conserv.*, vol. 103, no. 3, pp. 331–341, Mar. 2002, doi: 10.1016/S0006-3207(01)00144-6.

29. J.-T. Baek, J.-H. Hong, M. Tayyab, D.-W. Kim, P. R. Jeon, and C.-H. Lee, "Continuous bubble reactor using carbon dioxide and its mixtures for ballast water treatment," *Water Res.*, vol. 154, pp. 316–326, 2019, doi: https://doi.org/10.1016/j.watres.2019.02.014.

30. IMO, "Globallast guidelines for development of a national ballast water management Strategy, 1997. Guidelines for preventing the introduction of unwanted organisms and pathogens from ships ballast waters and sediment discharges. Resolution A.868 (20)." 2004.

31. G. H. Briton, B. Yao, and G. Ado, "Evaluation of the Abidjan lagoon pollution," *Journal of Applied Sciences and Environmental Management*, vol. 11, no. 2, 2007, doi: 10.4314/jasem.v11i2.55030.

32. J. Liu, P. Wang, G. Liu, J. Dai, J. Xiao, and H. Liu, "Study of the characteristics of ballast bed resistance for different temperature and humidity conditions," *Constr. Build. Mater.*, vol. 266, p. 121115, Jan. 2021, doi: 10.1016/j.conbuildmat.2020.121115.

33. N. A. Salleh *et al.*, "Pathogenic hitchhiker diversity on international ships' ballast water at West Malaysia port," *Mar. Pollut. Bull.*, vol. 172, p. 112850, Nov. 2021, doi: 10.1016/j.marpolbul.2021.112850.

34. G. Romanelli *et al.*, "Ballast water management system: Assessment of chemical quality status of several ports in Adriatic Sea," *Mar. Pollut. Bull.*, vol. 147, pp. 86–97, Oct. 2019, doi: 10.1016/j.marpolbul.2017.12.030.

35. M. R. First and L. A. Drake, "Life after treatment: detecting living microorganisms following exposure to UV light and chlorine dioxide," *J. Appl. Phycol.*, vol. 26, no. 1, pp. 227–235, Feb. 2014, doi: 10.1007/s10811-013-0049-9.

36. Z. Manxia, L. Shengjie, T. Xiaojia, L. Xiang, and Z. Yimin, "Evaluation of micro-pore ceramic filtration and uv radiation combination on ballast water treatment," in *2010 International Conference on Digital Manufacturing & Automation*, pp. 670–673, Dec. 2010, doi: 10.1109/ICDMA.2010.374.

37. P. P. Stehouwer, A. Buma, and L. Peperzak, "A comparison of six different ballast water treatment systems based on UV radiation, electrochlorination and chlorine dioxide," *Environ. Technol.*, vol. 36, no. 16, pp. 2094–2104, Aug. 2015, doi: 10.1080/09593330.2015.1021858.

38. I. Rivas-Zaballos, L. Romero-Martínez, I. Moreno-Garrido, J. Moreno-Andrés, A. Acevedo-Merino, and E. Nebot, "UV-LEDs combined with persulfate salts as a method to inactivate microalgae in ballast water," *Journal of Water Process Engineering*, vol. 51, p. 103361, Feb. 2023, doi: 10.1016/j.jwpe.2022.103361.

39. J. Xiao, Y. Xu, L. Hu, and H. Wu, "Evaluating the treatment performance of filtration & real-time UV irradiation

processes for bacteria and pathogens in fresh ballast water," *Reg. Stud. Mar. Sci.*, vol. 63, p. 102971, 2023, doi: https://doi.org/10.1016/j.rsma.2023.102971.

40. N. F. Gray, "Chapter Thirty-Four - Ultraviolet disinfection," in *Microbiology of Waterborne Diseases (Second Edition)*, S. L. Percival, M. V Yates, D. W. Williams, R. M. Chalmers, and N. F. Gray, Eds., Second Edition. London: Academic Press, 2014, pp. 617–630. doi: https://doi.org/10.1016/B978-0-12-415846-7.00034-2.

41. Y. Wang, L. Zou, L. Ma, Z. Zhao, and J. Guo, "A survey on control for Takagi-Sugeno fuzzy systems subject to engineering-oriented complexities," *Systems Science & Control Engineering*, vol. 9, no. 1, pp. 334–349, 2021, doi: 10.1080/21642583.2021.1907259.

42. "DESMI to manufacture ballast water treatment system under licence," *Pump Industry Analyst*, vol. 2012, no. 8, pp. 12–13, 2012, doi: https://doi.org/10.1016/S1359-6128(12)70370-1.

43. B. Sayinli, Y. Dong, Y. Park, A. Bhatnagar, and M. Sillanpää, "Recent progress and challenges facing ballast water treatment – A review," *Chemosphere*, vol. 291, p. 132776, 2022, doi: https://doi.org/10.1016/j.chemosphere.2021.132776.