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A Case Study on Sustainable Energy Use from Ballast Water Management System in Transport Vessels

Jeho HWANG, Sihyun KIM*

Abstract: A ballast water management system (BWMS) is an essential module that is directly influential for navigation efficiencies and safety for vessel operations. The net function of the BWMS is to maintain the stability of vessels. This study examines the possibility and applicability of self-generating power from the BWMS for sustainable energy use in vessels. The data from the CX0809 vessel which is a Panamax class bulk carrier between July 2020 and March 2022 were used for analysing the power generation volume. An in-pipe hydroelectric system that adopts a deflector and Savonius turbine was introduced at the location where ballast water (BW) flows in the same direction during ballasting and deballasting. Then, hydroelectric analysis was performed under the geometric condition setting. According to the research findings, the production range of electricity was 863 - 4090 kW/h and 1256 - 4744 kW/h, during ballasting and deballasting, respectively. There were some variations depending on the BWMS operational characteristics and time duration. Finally, this study proposes a new approach for expanding the applicability of BWMS to the power generation sector to improve vessel energy efficiency with environmental and vessel-operation terms. The conceptual approach for renewable energy production in this study contributes to advancing eco-friendly bulk shipping.

Keywords: ballast water management system; bulk shipping; eco-friendly vessel; self-generating power

1 INTRODUCTION

The Maritime Environmental Protection Committee 72 (MEPC 72) of International Maritime Organization (IMO) adopted strategies to reduce the greenhouse gases caused by vessel operations by more than 40% in 2030, in parallel with the overall emissions by 50%, and CO_2 emissions by 70% by 2050, compared to emissions in 2008 [1]. To reduce the greenhouse gases caused by maritime shipping, regulations such as the Energy Efficiency Design Index (EEDI) in Regulations 20, 21, 22, and 24, Energy Efficiency Existing Ship Index (EEXI) in Regulations 19, 23, and 25, and the Carbon Intensity Indicator (CII) in Regulations 26, 27, and 28 and Ship Energy Efficiency Management Plan (SEEMP) in Regulations 22 and 26 are introduced. In addition, the IMO promotes the Energy Efficiency Operational Indicator (EEOI) as a guideline from MEPC 59/Circ. 684 to improve the vessel's energy efficiency and prevent air pollution based on MARPOL ANNEX VI [2]. Accordingly, shipping companies are facing an economic burden due to the IMO's gradually strengthening atmospheric regulations. To cope with the trends, increasing the energy efficiency of vessels is essential considering that fuel costs account for the highest proportion of vessel operating costs. Improving vessel energy efficiency in the maritime industry is essential for the industry's long-term development and sustainability. Currently, various studies have been conducted on not only propulsion systems to replace existing fossil fuels with eco-friendly energy sources (hydrogen, methanol, ammonia, etc…) but also ship structure and equipment including hull and superstructure, hull biofouling management, modification of ship's bulbous bow, air lubrication system, fuel saving propeller Attachment, and on-board DC grid system [3, 4]. Moreover, studies in terms of energy recovery have been conducted regarding wasted heat [5, 6], reverse osmosis desalination (RO), and membrane-based desalination (MCDI) [7]. However, heat recovery equipment is customized to recover a certain level of energy, but when the engine operates at a low load, the recovery rate decreases. On the other hand, when the engine operates at a high load, performance may be limited depending on the specifications. In the case of desalination, the RO process requires high power consumption and emits GHGs and waste brine, which has harmful effects on marine ecology. In addition, the emission-blocking rate of contaminants like bromide is high when introducing MCDI, but the power consumption is higher than RO. In summary, shipping companies can contribute to social and environmental aspects by reducing the level of emissions caused by ships while increasing energy efficiency by introducing the eco-friendly ship technologies mentioned. However, a method to recover hydrodynamic energy by causing an artificial pressure difference in the pipe is proposed in the operation of BWMS without affecting the performance of the equipment in this study. By 2024, all international vessels are expected to comply with the performance standards of the BWM convention. In other words, most ships are recommended to install BWMS on board although alternative methods for complying with the standards are allowed except for ships using clear ballast water or using BWMS facilities at port to remove harmful marine organisms and pathogens in ballast water [8]. The BWMS is essential and critical for maintaining vessel stability by reducing the stress on the hull during a voyage or cargo handling process and improving overall navigation efficiencies, such as operability, propulsion, and maneuverability [9]. When the ballast water level in a carrier is equal to sea level after using water head pressure, BW pumps operate to generate mechanical pressure for enabling the ballasting and deballasting process during BWMS operating status. According to the BWMS operating principle, the net function of the BWMS was extended to a self-power generating plan using hydroelectric power to promote eco-friendly vessel operation. On the other hand, In-pipe hydroelectric power generation is already being introduced in other industries. However, limited studies have investigated energy efficiency improvement using additional energy supply generated by the Ballast Water Management System (BWMS) within vessels. Accordingly, this study attempted to analyse the applicability and effectiveness of self-generating power from the BWMS via in-pipe conditions as a conceptual prototype study targeting the vessel of CX0809 (IMO number: 9842504). In the case of bulk carriers, the overall stress level of the hull is adjusted by simultaneously handling cargo and ballast water, based on the status of the asymmetric cargo and ballast distributions in each compartment to ensure stability. In other words, ballasting and de-ballasting procedures are performed continuously during cargo operations according to the BWMS plan. In summary, the BWMS operations are performed more actively compared to other ship types. The concept of energy harvesting using BWMS in bulk carriers could be considered innovative in that it could make a sustainable contribution to not only existing bulk carriers but also eco-friendly bulk carriers in terms of energy efficiency as a new technical-driven sector. As a result, this study provides useful insights for improving vessel energy efficiency by employing BWMS as a potential energy production sector.

2 LITERATURE REVIEW

2.1 Ballast Water Management System in Vessels

The function of BWMS is not only maintaining the stability of a vessel but also ballast water sterilization. The invasive aquatic species have been transferred to other sea areas through ballasting and deballasting operations. Accordingly, it acts as the primary cause of marine environmental pollution, including the alteration and destruction of marine habitats [10]. Accordingly, the scope of subsequent research related to BWMS function is limited to methods to improve ballast water sterilization. Although treatment technologies can be categorized into primary treatment, mechanical separation, and chemical treatment, combinations of different sterilization methods have been shown more effective [11]. Most studies address combinatorial techniques for more effective BW processing, which are as follows. For example, multiple treatment combinations have been used, including ultraviolet light (UV) sterilization and filtration [12], UV radiation and hydro-cyclonic separation [13], UV treatment and electro-chlorination [14], ultrasound (US) and UV radiation [15], UV sterilization and hydrogen peroxide treatment [16], UV treatment and oxidation [17], bromine/oxidation treatment and filtration [18], and hydrogen peroxide and ozone treatment [19]. In other words, the research trend on BWMS has focused on technologies for the effective removal of biological organisms, residual chlorine, mud, and silt. However, this study was conducted to examine the possibility that the function of BWMS could be expanded to renewable energy harvesting unlike previous studies addressing BW treatment from a different perspective. In summary, the focus of this study is to envision the functionality of BWMS as a new energy harvesting sector as a green energy technology. Furthermore, this study is significant in that it attempted to establish energy production using BWMS in the high-efficiency ship technology sector.

2.2 Hydroelectric Power Generation in Industrial Sector

Researchers have investigated using hydroelectric power generation in various application areas. Renewable energy-related research conducted in terms of the shipping and port industry interface is as follows. Li et al. [20] suggested methods for converting wave energy into electric power as an auxiliary energy source for ports, along with a plan to assist decision-making on green investment through mathematical formulation. Acciaro et al. [21] suggested a macroscopic direction for adopting alternative maritime power (AMP), alternative fuels for port equipment, and wind and wave power plants in ports to improve the mutual energy efficiency of shipping and port industries. Some studies have expanded the function of the equipment to the range of self-power generation. Studies that attempted energy harvesting targeting facilities with fluid flow within the city are as follows. Gude [22] and Gu et al. [23] considered waste water supply and treatment systems as a potential opportunity for energy recovery and savings. Langroudi et al. [24] experimented with hydraulic power generation by installing lucid turbines in oil pipes, testing the effectiveness of hydroelectric power generation using water supply to cities, fire prevention facilities, and industrial sites. On the other hand, in the field of seawater desalination plants, Emam and Dincer [25] and Li et al. [26] investigated seawater desalination as a potential ocean-based source of electricity generation, an approach that was previously limited by technological and economic constraints. Furthermore, research on the efficiency of generating electricity by leveraging the water flowing in pipelines is as follows. Sahim et al. [27] investigated the effectiveness of power production based on the deflector and its angle using savonius turbines and other alternative turbines inside the pipeline. However, limited studies have investigated energy harvesting via in-pipe hydraulic power in the maritime industry. The authors' results regarding extensive studies indicated that an in-pipe hydroelectric system could extend the function of the BWMS potentially.

2.3 Conceptual Method for Self-generation from BWMS

Although various types of turbines could be used for hydroelectric power generation, this may result in significant variability in the functions of the BWMS and the systemic characteristic related to the flow of ballast water in pipe structure. Salleh et al. [28] tested the efficiency of the in-plane axis using darrieus, gorlov, and savonius turbines for hydroelectric power generation, demonstrating the efficiency of savonius turbines. Accordingly, this study adopted the savonius turbine system adopting a deflector for minimizing the variations in the function of the BWMS. Fig. 1 illustrates the BWMS-based power-generating method. The efficiency of using the hydraulic energy of a flowing liquid can be raised by incorporating a deflector into the savonius turbine to improve the energy harvesting performance. In detail, the combination of savonius hydro turbine and deflector plate minimizes the pressure drop of the ballast water flow. The energy harvesting performance is increased at the inlet boundary of the turbine depending on the effect of mounting the deflector plate with geometrical conditions [29]. The increasing rate of energy harvesting efficiency of the deflector installation is 30% - 40% [30].

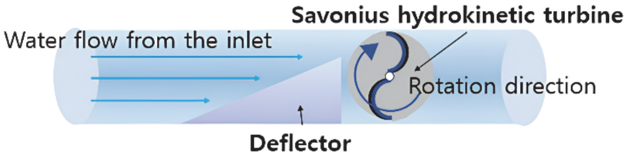

Figure 1 Self-power generating method based on BWMS

Overall, a significant amount of electricity could be generated while maintaining stable BWMS operation, not disrupting flow characteristics with the pressure difference without interfering with the pressure according to the water head pressure or BW pump. This method could be adopted to increase the energy production rate of the turbine, enhancing its applicability as an internal sub-generation module. In other words, under BWMS operational conditions, the surplus pressure energy produced by ballast water flow via the deflector represents the amount of potential energy extraction.

3 MATERIALS AND METHODS

3.1 Ballast Water Management System in Bulk Carrier

In this study, a target vessel type was considered to be a bulk carrier. BWMS for bulk carriers must be continuously monitored and controlled to ensure stability. Especially, the overall stress level of the hull should be adjusted by simultaneously handling cargo and ballast water volume within acceptable limits. In summary, ballasting and deballasting procedures should be performed continuously during cargo operations according to the BWMS plan. The vessel chosen for this study was the CX0809 (81200 DWT), which transports bulk cargo like coal and limestone, worldwide. Tab. 1 and Tab. 2 show the storage space in each cargo hold and ballast water tank. And, Tab. 3 demonstrates the pipe data. Fig. 2 illustrates the detailed locations of each cargo hold and the ballast water tank. Ballast water capacity accounts for 18.68% of the maximum volume that the vessel can accommodate.

Table 1 Capacity of each cargo hold (IMO number: 9842504)

Compartments	Volume / m^3	Compartments	Volume / m^3
NO.1 Cargo Hold	12558.0	NO.5 Cargo Hold	14015.9
NO.2 Cargo Hold	15003.9	NO.6 Cargo Hold	13959.2
NO.3 Cargo Hold	14538.4	NO.7 Cargo Hold	14347.3
NO.4 Cargo Hold	12892.2	-	-

Table 2 Capacity of each water ballast tank (IMO number: 9842504)

Compartments	Volume / m^3	Compartments	Volume / m^3
F.P.TK.	1615.9	NO.4 W.B.TK (P)	2266.8
NO.1 W.B.TK.P	1535.3	NO.4 W.B.TK (S)	2266.8
NO.1 W.B.TK.S	1535.3	NO.5 W.B.TK (P)	868.1
NO.2 W.B.TK.P	1738.2	NO.5 W.B.TK (S)	868.1
NO.2 W.B.TK.S	1738.2	A.P.TK.	2028.6
NO.3 W.B.TK.P	2946.0	-	-
NO.3 W.B.TK.S	2946.0	-	-

Table 3 Overflow and filling line data

Tank	No. of overflow lines	Overflow line nominal diameter / mm	Overflow lines total cross-sectional area / mm^2	Filling line nominal diameter / mm	Filling line total cross-sectional area/ mm^2
F.P.TK.	3	300/300/300	219213.4	300	70224.5
NO.1 B.W.TK.P	3	250/250/250	153231.4	300	70224.5
NO.1 B.W.TK.S	3	250/250/250	153231.4	300	70224.5
NO.2 B.W.TK.P	2	300/300	146142.3	300	70224.5
NO.2 B.W.TK.S	2	300/300	146142.3	300	70224.5
NO.3&4 B.W.TK.P	2	300/300	146142.3	300	70224.5
NO.3&4 B.W.TK.S	2	300/300	146142.3	300	70224.5
NO.5&6 B.W.TK.P	2	300/300	146142.3	300	70224.5
NO.5&6 B.W.TK.S	2	300/300	146142.3	300	70224.5
NO.7 B.W.TK.P	2	300/300	146142.3	300	70224.5
NO.7 B.W.TK.S	2	300/300	146142.3	300	70224.5
A.P.TK.	2	250/250	102154.3	200	32369.7

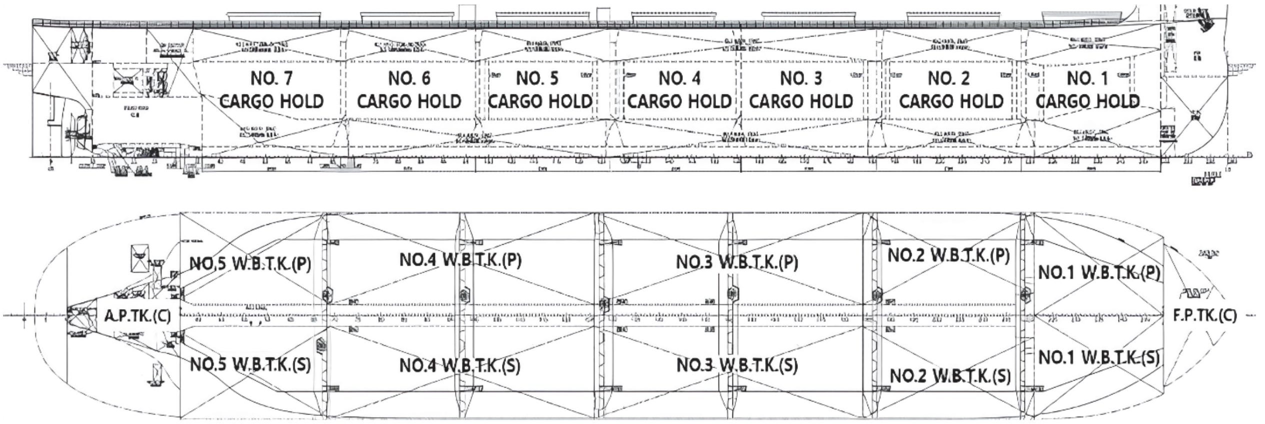

Figure 2 Layout of each compartment (IMO number: 9842504)

Fig. 3 shows the BWMS layout of the CX0809. The type of each BW pump is M.D. Vert. Centrifugal and the rated capacity is 1200 m^3/h. When the BWMS is activated, the flow velocity in the interlocking pipe structure is continuously measured using each Flow Measurement Unit (FMU). The drive source module can be installed in two pipe sections denoted by red lines whose specifications are 330 A with respective lengths of 2170 mm and 1830 mm. During BWMS operation, seawater flows into the ballast tanks through the sea chest or is discharged into the sea overboard. During the ballasting operation, ballast water is disinfected through an Electro-clean^{TM} System

(ECS). On the other side, a neutralizer is injected into the ECS in the initial stage. Subsequently, Total Residual Oxidant (TRO) concentration is controlled to maintain less than 0.2 mg/L and then discharged into the sea. Fig. 4 describes the overall ECS process [31].

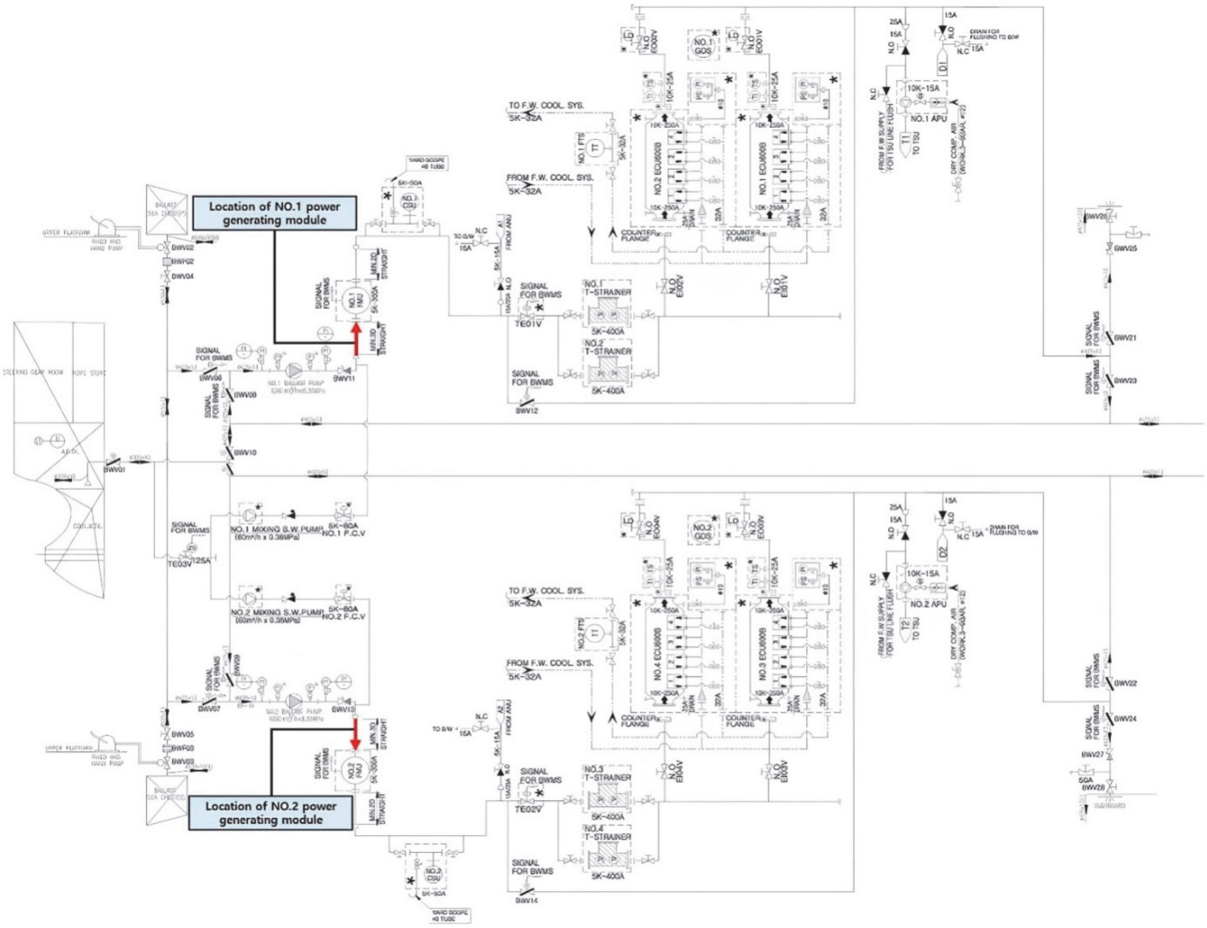

Figure 3 BWMS layout of the target carrier

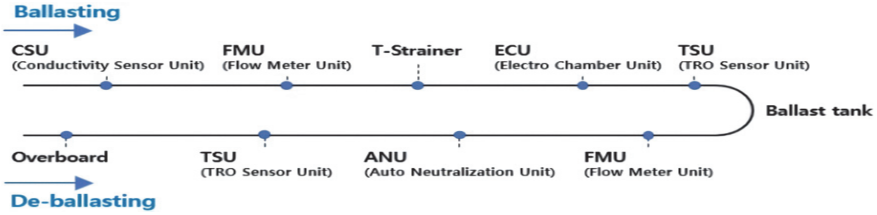

Figure 4 BWM operational process

3.2 Data Collection

The BWMS operational data used in this study were precisely recorded by each FMU. Tab. 4 and Tab. 5 show the working time and flow rate recorded in the FMUs. The data collection period for FMUs was from July 19, 2020, to March 4, 2022. Also, during the voyages, ballasting and deballasting were performed 18 and 23 times, respectively. Tab. 6 and Tab. 7 show the distribution of flow rates measured at each FMU during BWMS operation. The flow rate measured from FMU is a total of 31,651 data, and it is classified into 7,387 (FMU1), 5,857 (FMU2) in the ballasting process, and 10,354 (FMU1), 8,053 (FMU2) in the deballasting process.

Table 4 BWMS operation days during the ballasting process

NO	Start	End	Time duration / hr
1	23:08, 16.07.2020	09:18, 17.07.2020	10.2
2	01:45, 31.08.2020	09:28, 31.08.2020	7.7
3	01:47, 04.10.2020	08:22, 04.10.2020	6.6
4	00:15, 13.11.2020	01:15, 14.11.2020	25.3
5	23:38, 11.12.2020	10:37, 13.12.2020	35.0
6	23:45, 16.12.2020	08:37, 17.12.2020	8.9
7	01:29, 01.02.2021	10:41, 03.02.2021	33.2
8	05:25, 20.08.2021	08:04, 21.08.2021	25.7
9	00:51, 26.08.2021	01:27, 26.08.2021	0.6
10	03:24, 27.08.2021	04:24, 27.08.2021	1.0
11	00:16, 28.08.2021	01:34, 28.08.2021	1.3
12	13:22, 03.10.2021	07:53, 05.10.2021	42.9
13	02:24, 21.10.2021	04:52, 21.10.2021	2.5
14	07:38, 13.11.2021	12:01, 13.11.2021	4.38
15	17:29, 28.12.2021	5:53, 30.12.2021	36.4
16	12:39, 09.02.2022	13:25, 09.02.2022	0.8
17	07:47, 14.02.2022	23:00, 15.02.2022	39.2
18	13:13, 04.03.2022	14:06, 04.03.2022	0.9
Total time duration			282.58

Table 5 BWMS operation days during the deballasting process

NO	Start	End	Time duration / hr
1	23:11, 07.08.2020	08:16, 08.08.2020	9.1
2	00:00, 15.09.2020	06:34, 09.15.2020	6.6
3	05:16, 27.10.2020	13:04, 27.10.2020	8.1
4	00:21, 26.11.2020	19:24, 26.11.2020	19.0
5	02:20, 31.12.2020	04:36, 31.12.2020	2.3
6	19:04, 07.01.2021	05:46, 08.01.2021	10.7
7	05:40, 16.02.2021	07:33, 16.02.2021	1.9
8	20:24, 05.03.2021	04:21, 06.03.2021	8.0
9	13:36, 23.04.2021	22:11, 23.04.2021	8.6
10	23:11, 23.06.2021	05:01, 24.06.2021	5.8
11	05:23, 25.08.2021	05:48, 25.08.2021	0.4
12	02:14, 27.08.2021	03:21, 27.08.2021	1.1
13	04:31, 27.08.2021	00:12, 28.08.2021	19.7
14	03:31, 11.09.2021	16:23, 11.09.2021	12.9
15	05:20, 28.09.2021	06:05, 28.09.2021	0.8
16	16:31, 06.10.2021	22:27, 06.10.2021	5.9
17	03:03, 30.10.2021	08:46, 30.10.2021	5.7
18	06:54, 05.11.2021	07:16, 05.11.2021	0.4
19	12:34, 04.12.2021	06:31, 05.12.2021	18.0
20	17:23, 20.01.2022	00:12, 23.01.2022	54.8
21	09:44, 30.02.2022	10:31, 30.02.2022	0.8
22	10:34, 11.02.2022	10:58, 11.02.2022	0.4
23	08:04, 03.03.2022	13:26, 04.03.2022	29.4
Total time duration			230.4

Table 6 Flow rate distribution of each FMU

Division	Ballasting / m/h		De-ballasting / m/h	
	FMU1	FMU2	FMU1	FMU2
Min.	0	0	0	0
1st Qu.	5400.0	4038.0	5992.0	1620.0
Mean	5798.3	4824.8	6079.8	4869.1
Median	6378.0	6072.0	6834.0	6516.0
3rd Qu.	6810.0	6822.0	7284.0	7290.0
Max.	7998.0	8124.0	8634.0	8640.0

Table 7 Mass flow rate distribution of each FMU

Division	Ballasting / t/h		De-ballasting / t/h	
	FMU1	FMU2	FMU1	FMU2
Min.	0	0	0	0
1st Qu.	1223.5	914.9	1342.8	368.1
Mean	1313.7	1093.2	1377.7	1103.4
Median	1445.1	1375.8	1548.4	1476.4
3rd Qu.	1543.0	1545.7	1650.4	1651.8
Max.	1812.2	1840.7	1956.3	1957.6

3.3 Hydroelectric Analysis

The power output 'P' obtained from the hydroelectric system was calculated using Eq. (1). In this study, 1025 kg/m^3, the density of seawater 'ρ', was applied to the density of ballast water.

$$P = \eta_T \cdot \rho \cdot Q \cdot g \cdot h \tag{1}$$

where
P: producible power / W
η_T: total energy conversion efficiency / %
ρ: density of the liquid / kg/m^3
Q: volumetric flow rate of the liquid / m^3/s
g: acceleration of gravity, $g = 9.81$ m/s
h: turbine head / m

The turbine head 'h' in Eq. (1) corresponds to the surplus of the pressure difference 'Δp_u' in a power network employing a turbine. The difference in hydraulic pressure at this point corresponds to the difference between the pressure before entering the deflector 'P_{in}' and the pressure at the end of the deflector (P_{out}) at each point. In the process of introducing 'Δp_u', Eq. (1) was transformed into Eq. (2). As a result, Eq. (3) is derived when the unit of 'M' is converted from kg/s to t/h for the purpose of performing hour-based analysis. The gravitational acceleration was also calculated as a figure [32].

$$P = M \cdot g \cdot \Delta p_u \cdot \eta_T \tag{2}$$

where
P: producible power / W
M: mass flow rate of seawater / kg/s
g: acceleration of gravity, $g = 9.81$ m/s^2
Δp_u: useful difference head / MPa
η_T: total energy conversion efficiency / %

$$P = 0.2777 \cdot M \cdot \Delta p_u \cdot \eta_T \tag{3}$$

where
P: producible power / W
M: mass flow rate of seawater t/h
Δp_u: useful difference head / MPa
η_T: total energy conversion efficiency / %

The method for harvesting the pressure difference 'Δp_u' according to the deflector installation through the savonius turbine could contribute to the improvement of ship energy efficiency. The power output obtained from the combined operation of the turbine and deflector, which was calculated based on the pressure difference 'Δp_u' between point 'P_{in}' and 'P_{out}', is expressed in Eq. (4) which is an input variable to Eq. (3). As a result, the volume of the energy 'P_{total}' that could be harvested during BWMS operation could be expressed as Eq. (5).

$$\Delta p_u = k_a \frac{v_2^{\,2}}{2} = \frac{0.8\left|\sin\left(\frac{\pi}{4} - \frac{\alpha}{2}\right)\right|\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]}{\left(\frac{D_2}{D_1}\right)^4} \cdot \frac{v_1^{\,2}}{2} \tag{4}$$

where
Δp_u: pressure difference / MPa
v_1: flow velocity / m/s at P_{in}
v_2: flow velocity / m/s at P_{de}
k_α: loss coefficient / m^{-1}s^2
α: deflector angle / °
D_1: deflector blockage coefficient at P_{in}
D_2: deflector blockage coefficient at P_{out}

$$P_{total} = \sum_{i=1}^{I} \left[M_i \cdot \frac{0.8\left|\sin\left(\frac{\pi}{4} - \frac{\alpha}{2}\right)\right|\left\{1 - \left(\frac{D_{h2}}{D_1}\right)\right\}}{\left(\frac{D_{h2}}{D_1}\right)} \cdot \right. \tag{5}$$

$$\left. \cdot \frac{v_{1,i}^2}{2} \cdot \eta_T \cdot 0.2777 \right]$$

where
P_{total}: total power output / W

$v_{1,i}$: flow velocity m/h at P_{in} at time i
M_i: mass flow rate t/h at time i
α: deflector angle / °
D_1: deflector blockage coefficient at P_{in}
D_2: deflector blockage coefficient at P_{out}
η_T: total energy conversion efficiency / %

For validating the justification about the assumptions, the shape of the savonius turbine and deflector in Payambarpour, Najafi, and Magagnato [33] introduced the fact that can be expanded into the in-pipe to be installed in the BWMS. Accordingly, assumptions about the geometry variables and various parameters were derived from the study. However, the uncertainties that could be made by the materials of pipe, turbine, and deflector were not considered. So, it is necessary to reflect these conditions in future research. In detail, considering the pipe design specifications for the BWMS in CX0809, it is a suitable condition to introduce the self-generating module with a deflector angle of $50° \leq \alpha \leq 80°$, for which the required pipe length is acceptably 186 mm 239 mm regarding the geometrical conditions. In addition, a turbine aspect ratio of 0.9, which is the ratio between the vertical and horizontal lengths of the turbine, and a blockage coefficient of 0.8, which determines the deflector geometry were considered. In the case of each parameter range, the efficiency range of the generator 'η_g' was approximately 85% - 98%, and the efficiency of the electric power converter 'η_c' is 97% - 99% [32], and the efficiency range of the savonius turbine with deflector 'η_t' was 12% at 50° and 16% at 80° which was gradually increasing as the angle increased within the set angle range [33].

4 RESULTS

4.1 Hydroelectric Analysis

As a result, the amount of electricity produced during the ballasting and deballasting process in the total voyage was estimated by adjusting the deflector angle. Fig. 5 and Fig. 6 show the result of the total power harvesting.

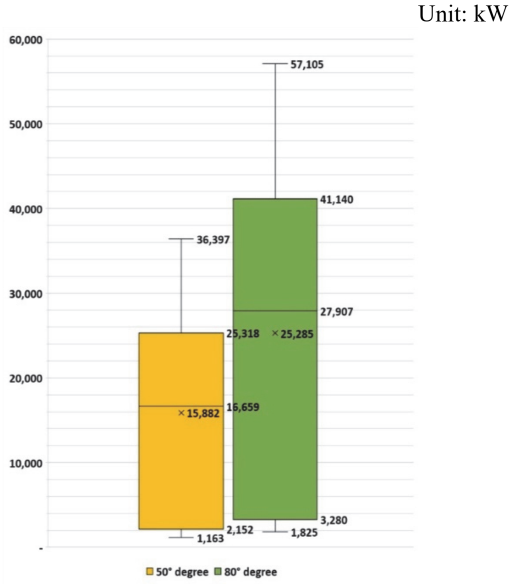

Figure 5 Total production during ballasting

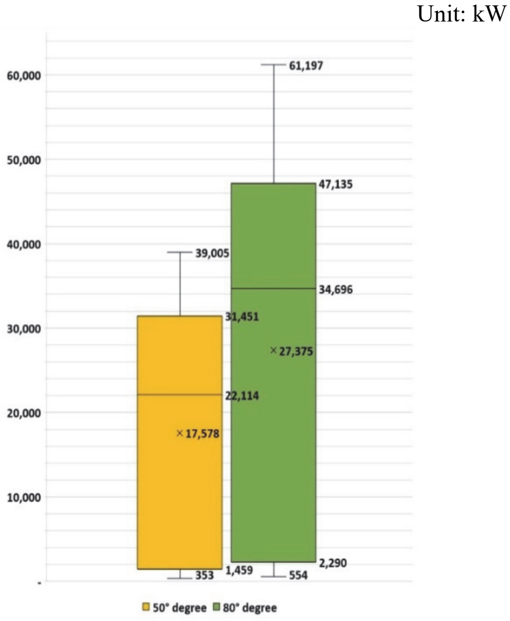

Figure 6 Total production during de-ballasting

During ballasting, the range of average volume was 15882 kW (50°) - 25285 kW (80°), and 16659 kW (50°) - 25285 kW (80°) in the case of median volume range. The range of average and median volumes was 17578 kW (50°) - 27375kW (80°) and 22114kW (50°) - 34696 kW (80°), respectively during de-ballasting. When the deflector angle was changed from 50° to 80°, the derived power production was 2152 kW - 41140 kW during ballasting and 1459 kW - 47135 kW during deballasting.

4.2 Energy Productivity

Fig. 7 and Fig. 8 describe the estimation results for the amount of produced power per hour. The results show that average range was 1724 kW/h (50°) - 2838 kW/h (80°) and median range was 1507kW/h (50°) - 2704 kW/h (80°) during ballasting.

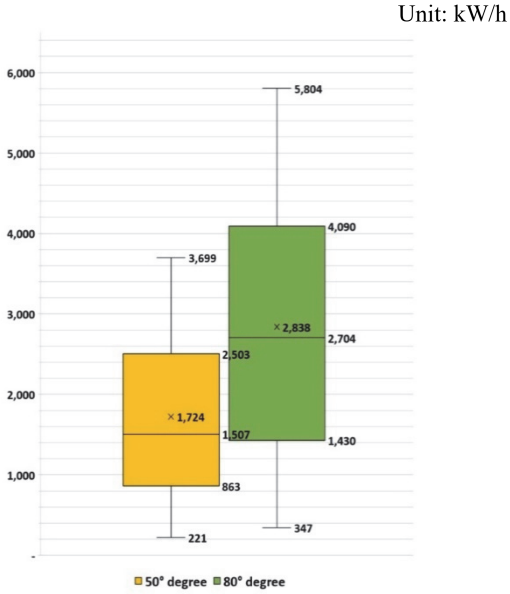

Figure 7 Energy production rate during ballasting

Unit: kW/h

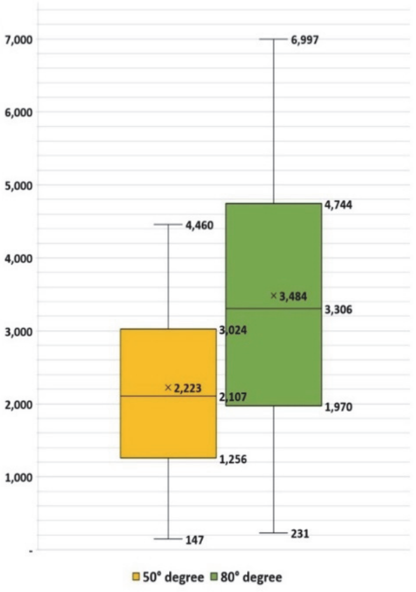

Figure 8 Energy production rate during de-ballasting

In addition, 2223 kW/h (50°) - 3484 kW/h (80°) for average range and 2107 kW/h (50°) - 3306 kW/h (80°) for median range could be produced during deballasting. In summary, 863 kW/h - 4090 kW/h during ballasting and 1256 kW/h - 4744 kW/h during deballasting could be generated considering the angle change of the deflector. This study performed a theoretical hydroelectric analysis by setting designable engineering parameters with the collected data according to the BWMS specifications and operation in CX0809 (IMO number: 9842504). The flow of seawater passing through the pipe structure within the BWMS and pipe design specifications were considered structurally for the credible estimation. The results showed that this study verified the effectiveness and applicability of the BWMS-based self-generating system as a suitable direction.

5 CONCLUSIONS AND LIMITATIONS

In this study, a conceptual study was conducted on energy production via BWMS for the initial stage. Examining the real-time operational data from the BWMS characteristics of bulk carriers revealed the possibility of generating a significant amount of power from the system. The power volume generated through the BWMS-based energy-recovery system is 722139 kWh during ballasting and 639029 kWh during de-ballasting over 21 months. According to [34], it is possible to save 1361 tons (1235 metrictons) when consuming heavy fuel oil (HFO) and 1295 tons (1175 metrictons) when consuming marine gas oil (MGO). Moreover, the operational cost could be effectively saved by 771358 USD for HFO and 858925 USD for MGO based on [35]. In other words, it means that 64818 kWh per month can be used for internal power generation adopted BWMS. The monthly cost-saving range could be 36727 - 40901 USD. In operational terms, it is possible to produce remarkable electricity by introducing the BWMS-based power generation system, with a positive effect on saving vessel operation costs and reducing air pollutant emissions. Additionally, it will contribute to improving the energy efficiency of ship operations in the long term, if eco-friendly fuels are introduced in the maritime industry. Especially, the BWMS-based small hydropower module is expected to have relatively high price competitiveness due to the minimal equipment investment for installation. Energy efficiency and reduction of the pollution caused by vessel operations are directly related to eco-friendly vessels. The BWMS-based self-generating system could have a considerable impact on the development of more effective eco-friendly vessels that enhance energy efficiency in the case of the bulk maritime transportation sector and related industries related to ship power. As a result, this research contributes to advancing eco-friendly technologies using internal equipment for vessel operation depending on the perspective to expand the net function of BWMS to the energy recovery sector. Despite its academic and practical implications, this study has some limitations. The theoretical estimation simplified with a conceptual framework for the energy harvesting method has the potential opportunity to be further detailed and explored by the simulation approach. In future research, more detailed research should be conducted by utilizing big data on BWMS operation in creating a simulation environment similar to the operational circumstance while performing technical and economic analysis for deriving more sophisticated analytical results.

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Contact information:

Jeho HWANG
Department of Logistics,
Korea Maritime and Ocean University,
Busan, South Korea, 49112
E-mail: jeho9288@g.kmou.ac.kr

Sihyun KIM
(Corresponding author)
Department of Logistics,
Korea Maritime and Ocean University,
Busan, South Korea, 49112
E-mail: sihyunkim@kmou.ac.kr