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Research Article

Operation cost analysis of UV-based ballast water treatment system used on a bulk carrier ship

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ABSTRACT

According to IMO rules, when a new machine system needs to be integrated into the ship, it is required to have low fuel consumption in terms of energy efficiency and emissions. The same is true for ballast treatment. Many different types of ballast water treatment systems (BWTS) are available on the marine market. Ship operators want to choose BWTS that will consume minimum fuel and operate at maximum efficiency. Therefore, in this study, fuel consumption under both IMO and USCG conditions, and hence the operational cost, is calculated if the UV-based BWTS system is integrated into a bulk carrier ship. As a result, the highest cost is $9773 when the most expensive fuel, MGO, is used and operation is performed with a single ballast pump. In USCG mode, the minimum cost is $6382 and the maximum cost is $18929 under the same conditions. It is seen that if the fuel price increases to 1.4 $/kg, the cost of using BWTS in IMO mode can increase to $11392, and if it drops to 0.3 $/kg, the cost of using BWTS in IMO mode can decrease to $1826. It is seen that the highest cost can go up to $22066 and the lowest cost can go down to $3983, with the change of fuel prices in the use of BWTS in USCG mode. With the resulting formulation, with the power consumption of the BWTS and the diesel generator shop trail test fuel consumption values, researchers or shipping companies can repeat the calculations for all kinds of different fuels and different amounts of ultraviolet (UV) chambers for variable ballast operations with different ballast tank capacities. Consequently, it is thought that this study is useful in determining the additional operational cost of UV-based BWTSs.

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INTRODUCTION

Ballast water is seawater carried by ships to provide stability, trim and structural integrity. When a ship loads cargo, it discharges the ballast water in its tanks. Likewise, when a ship is unloaded, it fills its ballast tanks with ballast water. In literature, it is stated that about 3 to 5 billion tons of ballast water are transferred worldwide every year [1]. When ballast water is transferred from one region to another, it creates direct and indirect effects on regional ecology, economy, and human health, due to species such as microorganisms, phytoplankton, and zooplankton [2].

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For all these reasons, the International Maritime Organization (IMO) put into effect the Ballast Water Management Convention (BWMC) on 8 September 2017. Thanks to this convention, all ships in international traffic are required to manage their ballast water and sediment to a certain standard according to a ship-specific ballast water management plan. From now on, new ships will need to meet the ballast water treatment standard, while existing ships will be required to replace mid-ocean ballast water but meet the ballast water treatment standard until a specified renewal survey date. As a result, most ships will need to install an onboard ballast water treatment system (BWTS) [3]. Therefore, maritime businesses and shipping companies have started to search for which type of BWTS would be more effective. It is known that in BWTSs, mechanical methods (filtration, hydro cyclone, and magnetic separation), physical methods (heat treatment, UV, ultrasound, and cavitation), and chemical methods (hydrogen peroxide, biocides, electro-chlorination, and ozone) are combined and used as hybrids methods. The initial investment cost of these systems, as well as the treatment efficiency and operating costs, can be different from each other because the equipment and energy amounts they need are different. There are studies on BWTS in many different aspects in the literature [4–8]. In this context, Gerhard et al. [9] investigated the impact of policy on the use of BWTSs by examining IMO Type Approval registries and country-level databases in the United States and Australia. The authors found that most ships with BWTS had either electrolytic or UV purification systems. Altug et al. [10] have taken samples from the ballast water of 21 ships coming to the Sea of Marmara, Türkiye from different parts of the world. Samples were tested and 38 bacterial species, 27 pathogenic bacteria belonging to 17 families, were identified. Vorkapić et al. [11] carried out the analysis and comparison of the economic feasibility of BWTS systems operating with UV irradiation and electrochlorination methods on merchant ships. The authors noted that systems using electrochlorination can be almost five times more cost-effective than those based on UV irradiation and almost eight times more cost-effective than ballast water exchange using the sequential method. It is known that different BWTSs are preferred in different regions. For example, Animah [12] examined 17 ballast water treatment technologies and features such as technological readiness, commercial readiness, operational readiness, seafarer skills readiness, biological efficiency readiness, and cost of ballast water treatment technologies, and stated that BWTS using membrane filters would be the best option for Ghana. Doğru et al. [13] emphasized the harmful effects of ballast water and analyzed the systems used in ballast water treatment. Vural and Yonsel [14] examined two ships with different ballast water capacities built in Türkiye and the most suitable systems for ships were proposed using the Key Performance Indicators method. Elçiçek et al. [15] evaluated the effect of ballast water on marine and coastal ecology and compiled IMO regulations on ballast water in this context. Ren [16] carried out a study with an evaluation criteria system consisting of eight criteria in four categories used to evaluate BWTS. An example case involving four technologies for ballast water treatment, namely Alfa Laval, Hyde, Unitor, and NaOH was studied with the proposed method and Hyde was considered the best choice. Jang et al. [17] conducted a ship ballast water test using extremely turbid seawater (>300 mg total suspended solids (TSS)/L) collected from the Shanghai Port and normal seawater (<100 mg TSS/L) collected from other ports. For ballast water retained for long storage periods, the results suggest the use of UV units or electrolysis-containing BWTSs during deballasting. This indicates the importance of using the UV unit. UV irradiation inactivates organisms by disrupting chemical bonds in DNA and RNA and cellular proteins [18]. Although the UV method is known to be very effective in the inactivation or destruction of microorganisms, it is recommended to be used after an efficient pre-treatment. UV-based BWTS technology creates acoustic cavitation by creating high-frequency radiation in the liquid and takes advantage of the disinfectant effect of the physical and chemical processes that take place during this time. When the microscopic gas bubbles formed during cavitation burst, very high local heat is released, and it also causes the formation of disinfectants such as hydroxyl radicals and hydrogen peroxide [19]. However, the cavitation created varies depending on the frequency, power density, duration of action, and properties of the water in question. On the other hand, high-intensity ultrasound energy is required to provide the desired standard in microbiological disinfection in large-scale waters [20]. Therefore, the cost of ultrasound technology per ballast water volume is considered to be relatively high [21, 22]. Before BWTS systems, only ballast pumps constituted the operating cost in ballast operations. Başhan et al. [23] calculated the operational cost of ballast operation for a case bulk carrier ship at different diesel generator loads and different fuel unit prices. In this study, apart from prior studies, it has been studied the additional operational cost of a UV-based BWTS is considered to be added to this bulk carrier ship.

MATERIALS AND METHODS

The capacities of all ballast tanks belonging to M/V İnce İnebolu (52376 DWT) and also technical specifications of the ballast pump are given in the previous study [23]. The vessel's technical particulars are provided in Table 1.

The simple system diagram of the UV-based BWTS that is planned to be integrated into the bulk carrier ship is shown in Figure 1. Developed by Optimarin [24], this system works in ballasting and deballasting modes. During ballast, ballast water first passes through a 20-micron

Table 1. M/V İnce İnebolu's ship particulars

IMO no	9254472
Call sign	TCPK7
Build	2002
DWT (summer)	52376 M/T
Length overall	189.99 m
Breadth	32.26 m
Ballast capacity	28930 m^3
Diesel genera-tors	Daihatsu 5DK-20

Table 2. Design conditions of the BWTS

Description	Specification
Water type	Ballast water
Flow range	Ballast: 155–1000 m^3/h
	Deballast: 60–1000 m^3/h
Filter Capacity	95–1040 m^3/h
Back flush pump capacity	100 m^3/h @ 2,5 bar
Design pressure	10 bar
Ballast water temperature range	-2 → +37 °C
Ambient temperature range	0 → +50 °C
System pressure loss	Filter: 0,3 bar
	UV system: 0,12 bar
	FPV: 0,2 bar
	Total: 0,62 bar
OBS power supply range	440 VAC, 60 Hz, 3 phase+E
Power requirement	6 × 40 kW
Average power consumption	6 × 17 kW (in IMO mode)
	6 × 35 kW (in United States Coast Guard (USCG) mode
Heat dissipation	Approx. 1,5 kW per UV Power Cabinet (6 pcs.)
	The rest of the system is negligible

filter. This filter removes larger particles, including the majority of zooplankton. After the filter, the water passes through the UV chamber(s), where the water is exposed to high doses of UV light. The number of UV chambers is related to the capacity of the ship's ballast tanks. In this study, BWTS with 6 UV chambers is considered. UV exposure kills/inactivates bacteria/viruses as well as the rest of the plankton. In the deballasting process, the filter is bypassed and the ballast water once again passes through the UV chamber(s). This ensures that plankton and bacteria/viruses are neutralized if any of them pass the initial treatment in the ballasting process. Detailed design conditions of the UV-based BWTS are provided in Table 2.

Table 3. Maximum flow rate correlation according to the number of UV chambers

Number of UV chambers	Max flow rate (m^3/h)
2	334
3	500
4	667
5	834
6	1000
7	1167
8	1334
9	1500
10	1667
11	1834
12	2000
13	2167
14	2334
15	2500
16	2667
17	2834
18	3000

Besides, the maximum flow rate correlation according to the number of UV Chambers is provided in Table 3. This is directly related to the ship's ballast water tank capacities. Considering M/V İnce İnebolu, the total capacity of the topside and ballast tanks is 15407.1 m^3 with the aft peak tank. No: 3 cargo ballast amount is 13522.9 m^3. The ship has a total ballast tank capacity of 28930 m^3.

The energy needs of almost all auxiliary machinery on ships, except propulsion, are provided by diesel generators. Thus, diesel generators provide the energy needs of ballast pumps and BWTS to be integrated into the system. The total load on the generators on ships is known, and the total fuel consumption is also known. However, it is not known how much energy each of the auxiliary machines fed by the generator consumes. Therefore, in order to determine the energy consumption (direct fuel consumption) of an auxiliary machine fed by the generator, a function is fitted by regression analysis from the fuel consumption values of the generator at different loads. Thanks to this function, it is determined by calculating how much fuel consumption has increased considering that the relevant auxiliary machine is activated and, on which load range the generator is operating.

The fuel consumption values of a DAIHATSU generator with the machine model of 6DC-17A x 500 kW belonging to the M/V İncebolu ship were used. Fuel consumption is 36.6 kg/h for 125 kW, 58.2 kg/h for 250 kW, 81.4 kg/h for

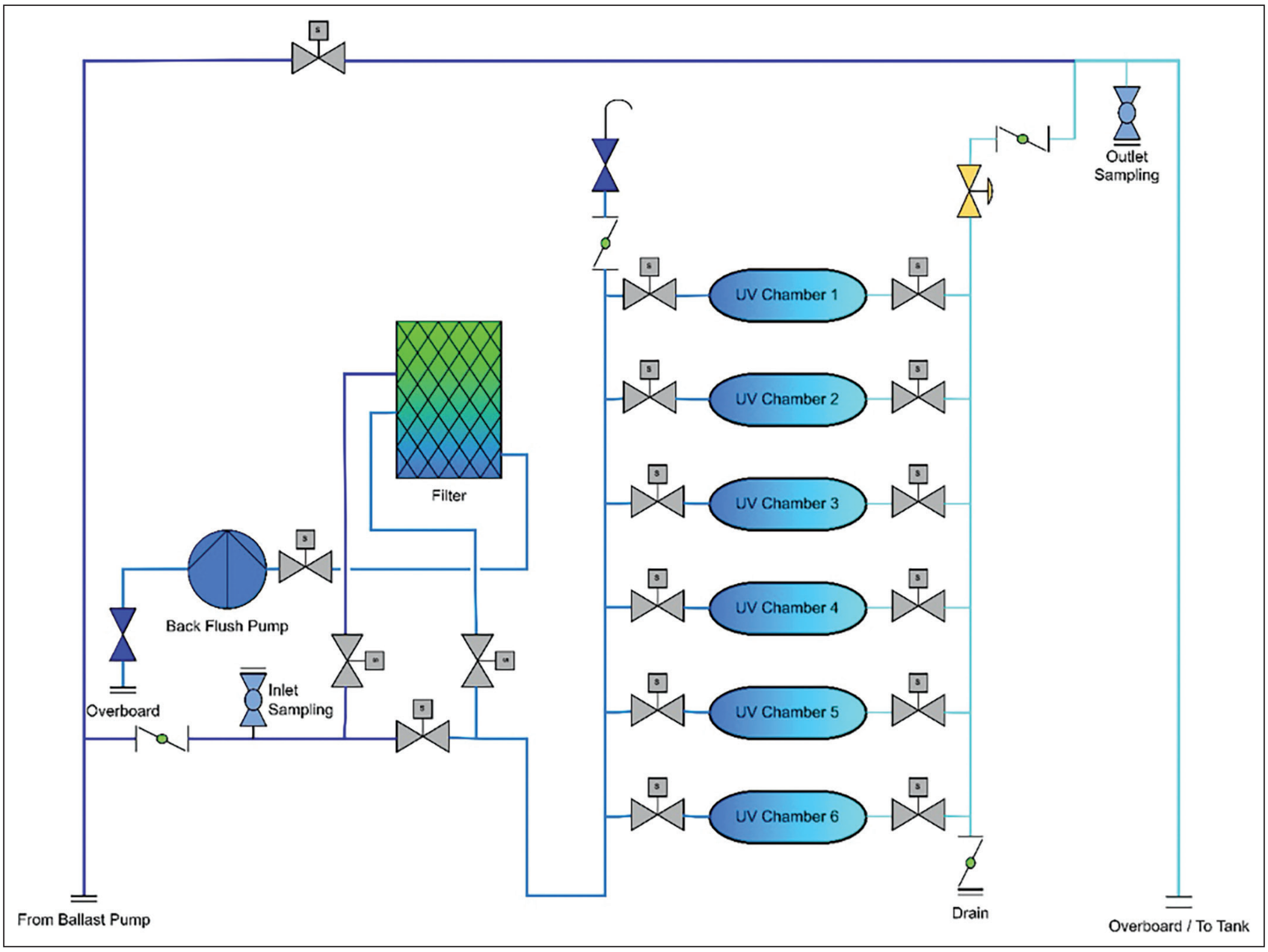


Figure 1. Basic schematic flow diagram of the BWTS.

375 kW, and 105.1 kg/h for 500 kW. A figure and function were obtained by using the fuel consumption values at different loads from the shop trail test information of the diesel generator and given in Figure 2. The new fuel consumption data is shown in Figure 2 when BWTS is started on the generator operating at 25%, 50%, and 75% loads. When the regression analysis is made from these consumption values, the fuel consumption of the BWTS can be found in Table 4. P denotes power, dg subscript is diesel generator and bwts is ballast water treatment system.

Global average bunker prices can be found at [25]. This average is from major global bunkering ports of Busan, Colombo, Durban, Fujairah, Gibraltar, Hong Kong, Houston, İstanbul, LA/Long Beach, Las Palmas, Mumbai, New York, Panama, Piraeus, Rotterdam, Santos, Shanghai, Singapore, St Petersburg, and Tokyo. The prices are $760.50, $1201 and $481 for Very Low Sulphur Fuel Oil (VLSFO), Marine Gas Oil (MGO), and Intermediate Fuel Oil, 380 cSt (IFO380), respectively. The three fuel types mentioned here are taken into account while making the calculations. For IFO180 and other types of fuel, additional calculations can be made with price and fuel consumption data.

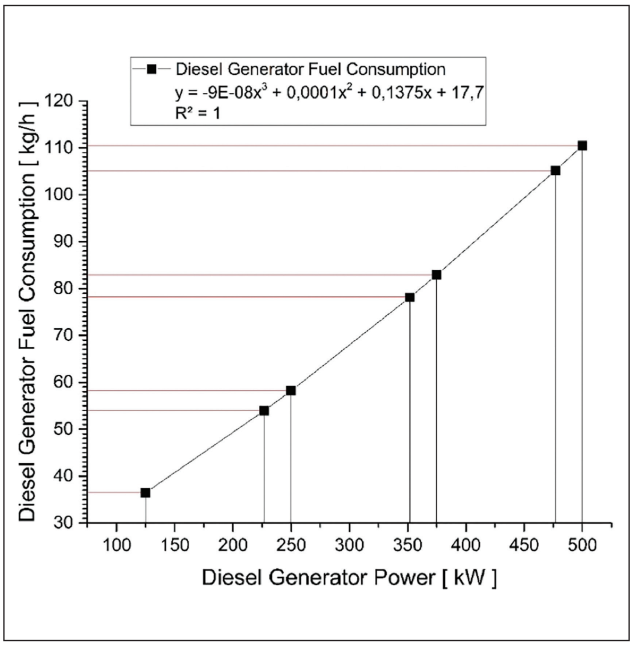
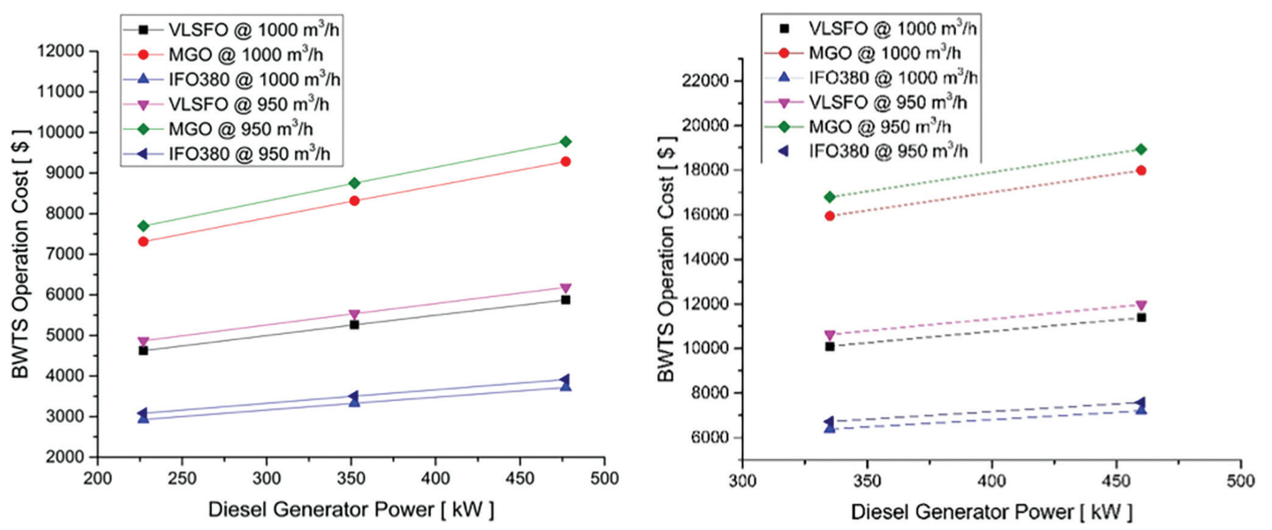


Figure 2. Fuel consumption dependent on diesel generator power in IMO mode.

Table 4. Calculation of the BWTS operation cost

Total ballast tanks volume	28930 (m^3)
BWTS capacity	6x167 (m^3/h) or 950 (m^3/h)
Fuel consumption of BWTS	-9×10^{-7} [($P_{dg}{}^{3}$-P_{bwts3})+(0,0001 × $P_{dg}{}^{2}$-$P_{bwts}{}^{2}$)]+[(0,1375 × P_{dg}-P_{bwts})] (kg/h)
Number of ballast operation	b
Average fuel price	VLSFO - 760.50 $/MT, MGO - 1201 $ and IFO 380 -481 $
BWTS operation cost	($)



a) IMO mode b) USCG mode

Figure 3. Cost of operating BWTS at variable loads with different fuels.

RESULTS AND DISCUSSION

In ballast operations on ships, when there was no BWTS, the operation cost was incurred by the fuel consumption of the ballast pump(s). When UV-based BWTS is used, UV systems consume energy in both IMO mode and USCG mode of the USA. According to the capacities of the BWTS and the ballast pumps, calculations were made in this study as 950 m^3/h or 1000 m^3h treatment. Ships generally operate with different fuels according to their voyage regions. Therefore, in this study, cost analysis of BWTS was made according to 3 different fuels and according to the 25%, 50%, and 75% load of the diesel generator. In Figure 3, in case of running BWTS at 3 different generator loads, a cost analysis is made regarding three different fuels. It is assumed that the system operates in IMO and USCG modes and performs 12 ballast operations in 1 year.

Figure 3 shows the annual cost of BWTS, when used at different loads of the generator in IMO and USCG modes. Calculations are made for the ship to fully fill the ballast tanks 12 times a year. It is also seen in the figure that the ballast operation is carried out at two different flow rates and the use of different fuels during the operations. The reason for choosing these two different flow rates is that the maximum flow rate of the BWTS system is 1000 m^3/h and the maximum flow of a ballast pump on board is 950 m^3/h. It is seen that the minimum cost in IMO mode is $2928 when using the cheapest fuel, IFO380, and operating at the maximum flow rate of the BWTS. In addition, it is seen that the highest cost is $9773 when the most expensive fuel, MGO, is used and operation is performed with a single ballast pump. In USCG mode, the minimum cost is $6382 and the maximum cost is $18929 under the same conditions. Considering the highest cost case, i.e., using MGO in USCG mode, the extra cost of not using the maximum capacity of the BWTS appears to be $946.

Figure 4 shows the cost of using BWTS with different fuel prices for IMO and USCG modes. Calculations are made for the ship to fully fill the ballast tanks 12 times a year. In addition, as seen in Figure 3, it is seen that the cost increases as the load of the generator increases. It is seen that if the fuel price increases to 1.4 $/kg, the cost of using BWTS in IMO mode can increase to $11392, and if it drops to 0.3 $/kg, the cost of using BWTS in IMO mode can decrease to $1826. It is seen that the highest cost can go up to $22066 and the lowest cost can go down to $3983, with the change of fuel prices in the use of BWTS in USCG mode.

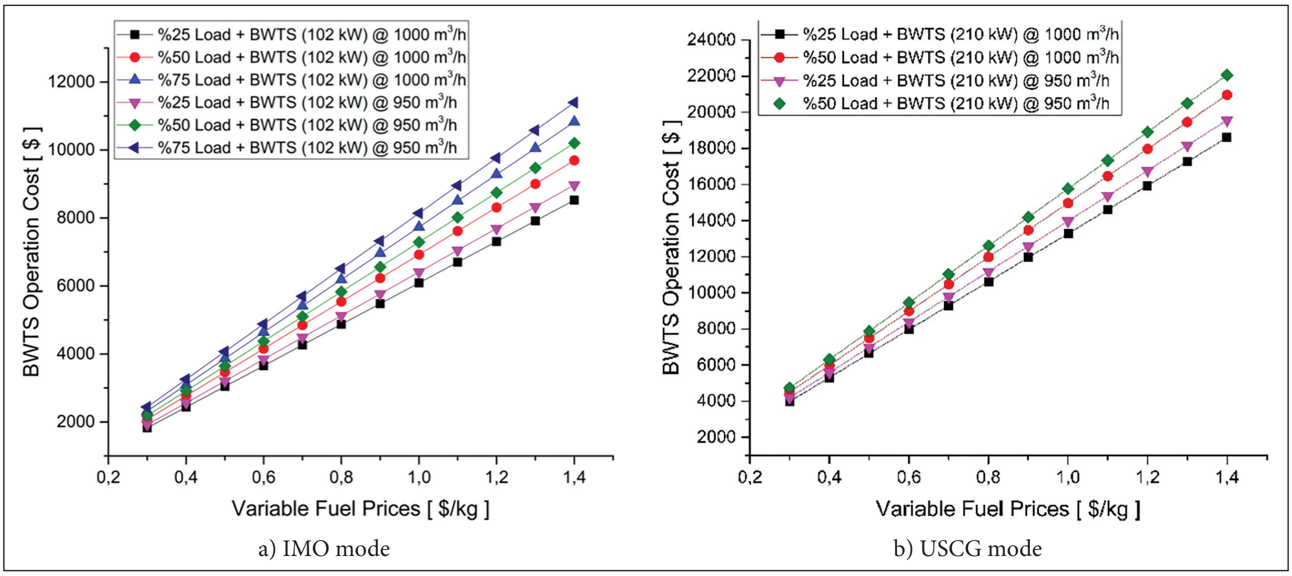


Figure 4. BWTS operation cost at different loads for variable fuel prices.

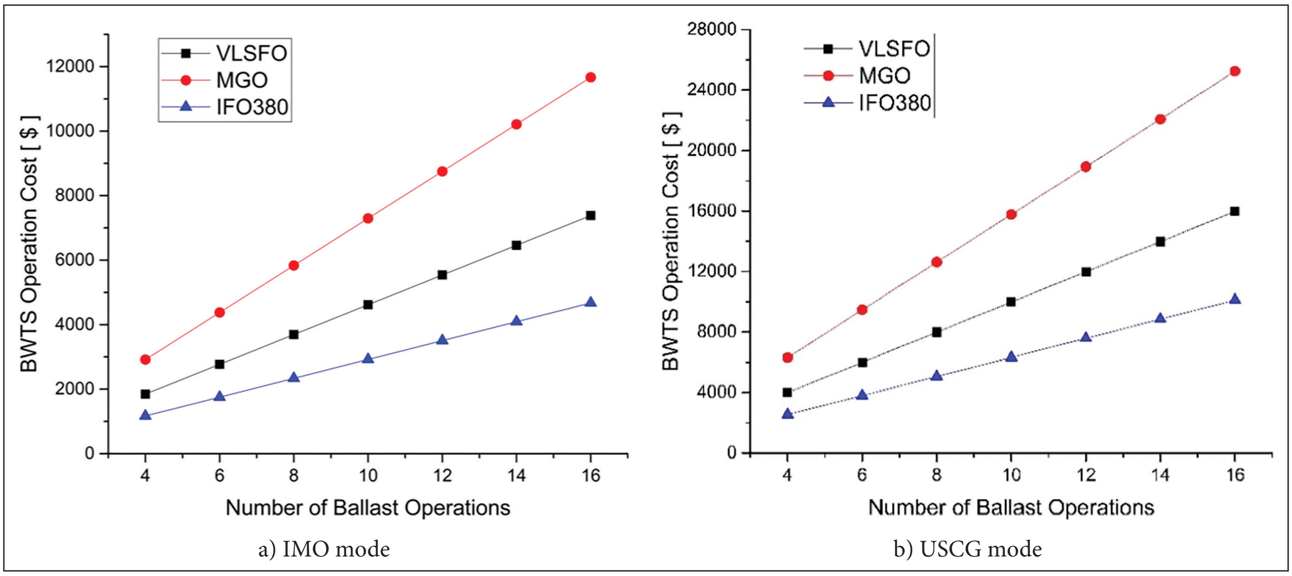


Figure 5. BWTS operation cost with different fuels for variable numbers of ballast operations.

Figure 5 shows the annual costs of using BWTS in IMO and USCG modes, depending on the number of ballast operations per year. Calculations are made for the case that the generator is at 50% load excluding BWTS and the ballast operation is carried out with a flow rate of 950 m^3/h. With the annual number of ballast operations increasing to 16, the cost of using BWTS in annual IMO mode increased to $11693 with MGO. In addition, it was observed that when the number of operations decreased to 4 while using IFO380, the cost decreased to $1168.

Figure 6 shows the annual cost of operating the BWTS in USCG mode, depending on the load on the single generator when two generators are running. The fuel consumption by the BWTS is covered by two generators while the generators are operating in parallel, that is, in synchronization, and therefore the extra fuel consumption has been calculated. Under these conditions, it is seen that the annual cost of using BWTS increases up to a maximum of $20146 and decreases to a minimum of $6039.

CONCLUSIONS

There are BWTSs developed with many different mechanical, physical, and chemical methods for ballast water treatment. Each of these methods has its own advantages and disadvantages. In addition to complying

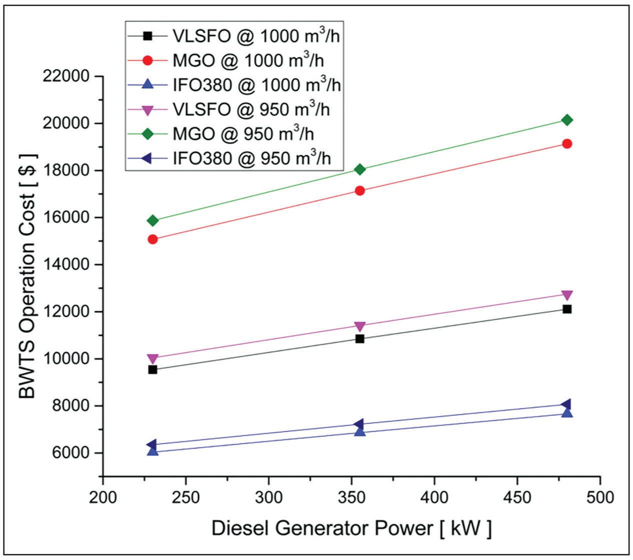


Figure 6. Cost of operating BWTS at variable loads on 2 generators with different fuels.

with the standards set by the IMO, shipowners want the BWTSs they will integrate on their ships to be systems with high energy efficiency, low fuel consumption, and therefore low operational cost. Therefore, the additional operational cost of integrating a UV-based BWTS, which is frequently preferred in the maritime market, into a bulk carrier ship has been calculated in different scenarios. As the load of the diesel generator increases, fuel consumption also increases. However, as the load increases, the specific fuel consumption decreases to a certain level. Therefore, calculations were made at different generator loads. In addition, calculations were made considering VLSFO, MGO and IFO380 fuel prices as ships use different fuels. Since fuel prices are constantly changing in the world, fuel prices have been parametrically changed and it has been shown how much BWTS operation costs can increase in case of an increase in fuel prices. Since the number of ballast operations may vary depending on the voyage area of the ship and the load it carries, cost analysis has also been carried out for different ballast operations to give an idea. In addition, these analyzes were repeated according to both IMO and USCG situations. Because the manufacturer stated that BWTS consumes more power to meet the standards in USCG mode. Thanks to all these calculations and formulation, shipping companies can similarly be able to deduct the operating cost of the UV-based BWTSs they plan to integrate into their ships.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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