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Investigation of the Effect of the Regenerative Organic Rankine Cycle System on Decarbonization for a Bulk Carrier

Dökme yük gemisi için Rejeneratif Organik Rankine Çevrimi Sisteminin Dekarbonizasyon Üzerindeki Etkisinin Araştırılması

Türk Denizcilik ve Deniz Bilimleri Dergisi

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ABSTRACT

Shipping has a very important share in world trade. However, it has an inevitable effect on global greenhouse gas emissions. Therefore, there is a great motivation for the reduction of fuel consumption and exhaust emissions. Waste heat recovery systems based on Organic Rankine Cycle (ORC) technology have a significant potential to reduce fuel consumption and exhaust emissions. In this study, the optimization of the regenerative ORC was carried out for a bulk carrier. Multi-objective optimization was performed using a Grey Wolf Optimization algorithm that is a powerful and novel algorithm. Thermo-economic evaluations were carried out by considering the design and off-design working conditions of the ship. In addition, the impact of the optimized ORC system on decarbonization was investigated. The results showed that the annual average W_{net} was determined as 372.78 kW. The annual average fuel saving and the annual average CO_2 reduction were calculated as 522.83 tfuel/year and 1628.09 tCO_2/year, recpectively. The findings indicated that using the RORC system on ships is a promising solution for increasing emission restrictions and environmental concerns.

Keywords: Organic Rankine Cycle, waste heat recovery, multi-objective optimization, fuel saving, CO_2 emission

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ÖZET

Deniz taşımacılığı dünya ticaretinde çok önemli bir paya sahiptir. Ancak, küresel sera gazı emisyonları üzerinde kaçınılmaz bir etkiye sahiptir. Bu nedenle yakıt tüketiminin ve egzoz emisyonlarının azaltılması için büyük bir motivasyon bulunmaktadır. Organik Rankine Çevrimi (ORC) teknolojisine dayalı atık ısı geri kazanım sistemleri, yakıt tüketimini ve egzoz emisyonlarını azaltmak için önemli bir potansiyele sahiptir. Bu çalışmada, bir dökme yük gemisi için rejeneratif ORC atık ısı geri kazanım sisteminin optimizasyonu gerçekleştirilmiştir. Çok amaçlı optimizasyon, güçlü ve yeni bir algoritma olan Gri Kurt Optimizasyon algoritması kullanılarak gerçekleştirilmiştir. Geminin tasarım ve tasarım-dışı çalışma koşulları dikkate alınarak termoekonomik değerlendirmeler yapılmıştır. Ayrıca, optimize edilmiş ORC sisteminin dekarbonizasyon üzerindeki etkisi araştırılmıştır. Sonuçlar, yıllık ortalama W_{net}'in 372.78 kW olarak hesaplandığı göstermiştir. Yıllık ortalama yakıt tasarrufu ve yıllık ortalama CO_2 azaltımı ise sırasıyla 522.83 tyakıt/yıl ve 1628.09 tCO_2/yıl olarak hesaplanmıştır. Elde edilen bulgular, gemilerde RORC sisteminin kullanılmasının, artan emisyon kısıtlamaları ve çevresel kaygılar için umut verici bir çözüm olduğunu göstermiştir.

Anahtar sözcükler: Organik Rankine çevrimi, atık ısı geri kazanımı, çok amaçlı optimizasyon, yakıt tasarrufu, CO_2 emisyonu

1. INTRODUCTION

The maritime sector, which is responsible for approximately 90% of world trade, is of vital importance for the world economy (Töz et al. 2022). However, it has an impact of approximately 3% on global greenhouse gas (GHG) emissions. Maritime trade volume is expected to increase by 3.5% 2019-2024 compared to 2018. This indicates that emissions from ships will gradually increase. The international maritime organization (IMO) has introduced some strict rules such as EEDI (Energy Efficiency Design Index), SEEMP (Ship Energy Efficiency Management Plan), and EEOI (Energy Efficiency Operational Indicator) to solve this global problem.

Most of the ships (about 90%) use diesel engines as the main propulsion system. Diesel engines with an efficiency of around 50% release almost half of the fuel energy as waste heat. Therefore, the use of waste heat recovery systems is a very important solution for increasing efficiency. This will reduce fuel consumption and emissions, and will make a significant contribution to the target of decarbonization in maritime (Civgin and Deniz, 2021; Mallouppas and Yfantis, 2021). Different waste heat recovery technologies such as exhaust gas turbine system (EGT), Organic Rankine Cycle (ORC), Kalina Cycle (KC), thermoelectric generators (TG) can be used for marine diesel engine. In recent years, ORC has received increasing attention. The main difference between ORC and the basic Rankine Cycle is the use of organic refrigerants as the working fluid. ORC outperforms other methods, especially for waste heat recovery from low-temperature heat sources.

Ships are sailing with different main engine loads. This is one of the major challenges for a waste heat recovery system design. The design and off-design analysis should be carried out for more accurate analysis. Then, an operational profile-based simulation should be performed, taking into account the times spent at different main engine loads. Thus, annual net power output, fuel saving, and emission reduction amounts can be determined. On the other hand, there are limited studies that off-design analysis is performed in marine ORC studies (Yang and Yeh, 2015a; Yang and Yeh, 2015b; Yang and Yeh, 2014; Song *et al*., 2015).

There are very few studies that profile-based simulation is carried out by making design and off-design analyzes. Ahlgren *et al*. (2016) carried out an operational profile-based simulation for the passenger ship M/S Birka. Different working fluids were used for both simple and regenerative ORC in the study. The speed range of 12 to 14 kn, which corresponds to approximately 34% of the voyage time, was accepted as the design condition for ORC optimization. As a result of the study, it was seen that the largest mean net power output was given by the regenerative ORC cycle. In addition, the highest mean net power output for the regenerative cycle was obtained with benzene. The proposed ORC system provided fuel and cost savings by meeting approximately 22% of the ship's total electricity demand. Lümmen *et al*. (2018) compared ORC concepts for waste heat recovery in the hybrid powertrain of a fast passenger ferry. Different working fluid candidates were compared using a simple optimization based on the maximum amount of recoverable work. The regenerative ORC was determined as the most suitable solution to extract energy from the exhaust gases. In addition, R1234ze (Z) was found to be the most promising candidate. Shu *et al*. (2017) performed an ORC system simulation, taking into account the operational profile of M/S Birka. In the study, the working profile of the ship was examined under 6 different main engine load conditions. 45-55% engine load was chosen as the design condition, and off-design analyses were carried out for other operating conditions. As a result of the study, it was determined that R123 and R365mfc fluids provide more net power output than other fluids in all conditions. However, R123 produced more power at heavy engine loads, while the R365mfc was been shown to be more suitable for light engine loads. Mondejar *et al*. (2017) carried out an operational profile-based simulation by implementing a regenerative ORC for a cruise ship. The main purpose of the study was to evaluate the off-design performance of the optimized ORC. It was emphasized that the determined design conditions affect the total net power output for different operating conditions and the importance of the choice of design conditions is underlined. As a result of the study, it was determined that approximately 22% of the total electricity demand on board was met by using the maximum net energy production of the ORC system.

In recent years, optimization studies have attracted attention for the determination of the optimum ORC system parameters. These studies are divided into two as single-objective optimization and multi-objective optimization. Previous studies have generally been carried out with the single-objective of thermal efficiency, exergy efficiency, or net power output. In the next studies, multi-objective optimization studies have been carried out by adding parameters such as economy, environment, and safety to the thermodynamic indicators. De la Fuente *et al*. (2017a) carried out ORC optimization with particle swarm optimization algorithm for a container ship with a capacity of 4100 TEU. In the study, which was carried out considering the design and off-design operating conditions, the annual CO_2 reduction amount was used as the objective function. Four different working fluids, R1233zd(E), R236fa, R236ea, and R245fa, were used. The results showed that an ORC unit using sea water as the cooling water and R1233zd (E) as the working fluid was the best option. The annual CO_2 reduction amount was approximately 599 tons for the ORC unit using sea water as the cooling water. The annual CO_2 reduction amount was approximately 471 tons for the ORC unit using air as the cooling water. Akman and Ergin (2020) conducted an ORC study with genetic algorithm for a tanker with a capacity of 49990 DWT. The objective function was determined as exergy efficiency. The energy, exergy, and environmental parameters were analyzed at different main engine loads. The results showed that it was possible to increase the overall thermal efficiency of the ship power generation system by more than 2.5% under optimum conditions by using the onboard ORC system. Besides, the CO_2 reduction amount was achieved as 678.1 tons per year. It was also determined that the main engine should be operated between approximately 70% and 75% MCR in order to maximize exergy efficiency and minimize fuel consumption. Baldasso *et al*. (2019) investigated the effects of EGR and SCR on the performance of waste heat recovery units to be installed on new ships by using genetic algorithm for an LNG ship with a capacity of 2500 TEU. The annual electricity production, the volume of heat exchangers, and the net present value of the investment were taken as the objective function. De la Fuente *et al*. (2017b) performed ORC optimization with genetic algorithm for the Aframax tanker. In the study, simulations were carried out considering the design and five off-design conditions by using five different working fluids: benzene, heptane, hexamethyldisiloxane, toluene, and R245fa. Objective functions were selected as thermal efficiency, equipment dimensions (pipe and heat exchangers), and net power output. As a result of the study, it was determined that the use of ORC provided approximately 17% savings in both fuel consumption and CO_2 emissions compared to conventional steam RC.

The main purpose of this study is to investigate the annual fuel saving and CO_2 reduction amounts with the regenerative ORC (RORC) for the bulk carrier with a capacity of 109731 DWT. Main engine exhaust gas was used as waste heat. Design and off-design analyzes were carried out for different engine load conditions. Firstly, optimum RORC system parameters were obtained with Multi-Objective Grey Wolf Algorithm (MOGWA) for design working condition. Afterward, off-design analyzes were carried out using off-design models. Finally, the operational profile-based simulation was performed. Lastly, the annual fuel saving and CO_2 reduction amounts of the ship were determined.

2. MATERIAL AND METHOD

2.1. Bulk Carrier Waste Heat Analysis

In this study, the optimum waste heat recovery system for the bulk carrier Atlantic Dragon with a capacity of 109731 DWT was investigated. MAN 6G70ME-C9.5 is used as the main engine in the Atlantic Dragon. In order to apply a waste heat recovery system for a ship's main engine, waste heat information of the relevant main engine is required. The data of the MAN 6G70ME-C9.5 were obtained with the CEAS software provided by MAN (CEAS, 2021). The CEAS application provides power, speed, specific fuel consumption, exhaust gas mass flow rate, and exhaust gas temperature according to the main engine load in ISO standard (sea: 25°C, air: 25°C). Today, on most ships, the heat obtained from the exhaust gas is primarily used to meet the auxiliary heat demand on the ship. Therefore, firstly, the steam demand of the ship should be determined. In the doctoral thesis by De la Fuente (2016), an approximate correlation for the determination of steam demand was presented. In this study, De la Fuente's approximate correlation was used. The variation of the temperature and mass flow rate of the exhaust gas according to the main engine load after steam production was given in Figure 1.

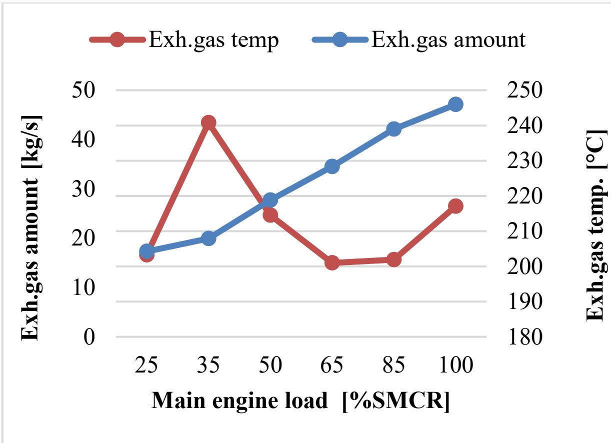

Figure 1. Exhaust gas properties after steam production for MAN 6G70ME-C9.5

2.2. RORC Thermodynamic Model

In this study, a waste heat recovery system for a bulk carrier was realized with the RORC system. The exhaust gas from the main engine enters firstly the boiler to meet the steam demand of the ship. The exhaust gas, which lost some of its heat, then entered the evaporator, and waste heat recovery was achieved. The schematic representation of the RORC system and the main engine was given in Figure 2.

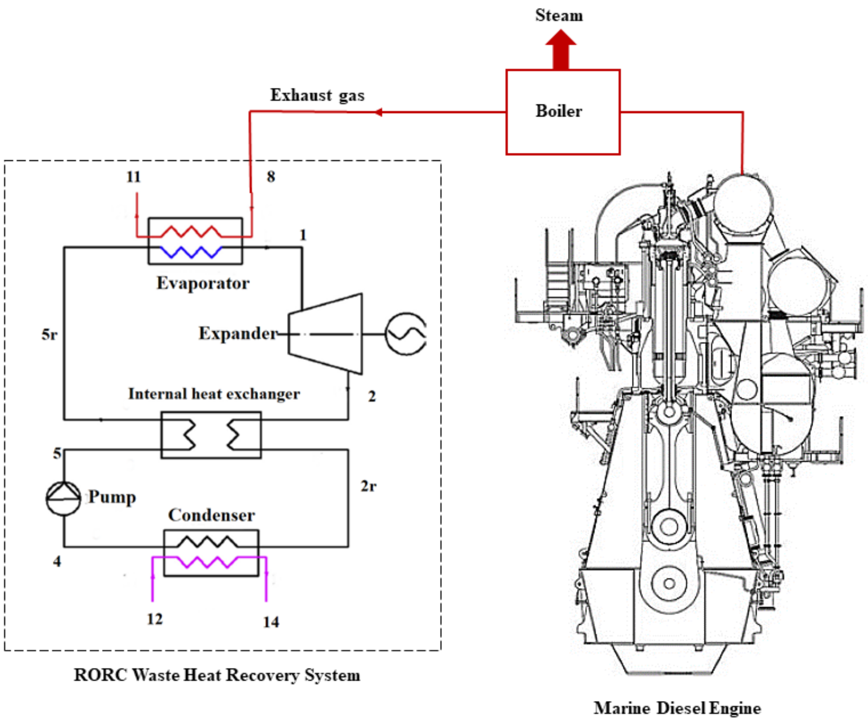

Figure 2. The layout of the RORC system and main engine for bulk carrier

The net power output of the RORC system ($\dot{W}_{net}$) is obtained as in Equation 1.

$$\dot{W}_{net} = \dot{W}_t \eta_g - \dot{W}_p - \dot{W}_{p,sw} \quad (1)$$

where η_g is generator efficiency. In addition, the effectiveness of recuperator (ε_{rec}) is calculated as follows:

$$\varepsilon_{rec} = \frac{T_2 - T_{2r}}{T_2 + T_5} \quad (2)$$

The thermal efficiency and exergy efficiency of the RORC system can be calculated as follows:

$$\eta_t = \frac{\dot{W}_{net}}{\dot{Q}_{eva}} \quad (3)$$

$$\eta_{ex} = \frac{W_{net}}{W_{net} + I_{tot}} \quad (4)$$

where I_{tot} is total exergy destruction in the system.

The exergy destruction of each component is calculated as follows:

$$I_p = m_f \cdot T_0 \cdot (s_5 - s_4) \quad (5)$$

$$I_{eva} = m_f \cdot T_0 \cdot \left[(s_1 - s_5) - \frac{h_1 - h_5}{T_H} \right] \quad (6)$$

$$I_t = m_f \cdot T_0 \cdot (s_2 - s_1) \quad (7)$$

$$I_{con} = m_f \cdot T_0 \cdot \left[(s_4 - s_2) - \frac{h_4 - h_2}{T_L} \right] \quad (8)$$

$$I_{rec} = m_f \cdot T_0 \cdot \left[(s_{2r} - s_2) + (s_{5r} - s_5) \right] \quad (9)$$

2.3. Heat Transfer Analysis

A shell-tube heat exchanger was used for the condenser, evaporator, and recuperator, which are the three main heat exchangers used in the RORC system. The evaporator is divided into three parts heating, evaporation, and superheating, and the condenser is divided into two parts as cooling and condensation to calculate the heat transfer coefficient and heat transfer area. Since the recuperator has a single-phase flow, it is analyzed in one part.

The working fluid in the heating and

superheating section in the evaporator unit and seawater in the condenser unit exhibit single-phase turbulent flow. Thus, the Nusselt number is calculated with the expression suggested by Gnielinski (1976). In addition, single-phase heat transfer occurring in the recuperator was also analyzed with this equation:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)} \quad \begin{matrix} 0.5 \le \text{Pr} \le 2000 \\ 3\times10^3 \le Re \le 5\times10^6 \end{matrix} \qquad (10)$$

where, Re and Pr represent the dimensionless Reynolds and Prandtl numbers, respectively. In addition, f is the friction factor and can be calculated with the Petukov equation (1970):

$$f = (0.79\ln(\text{Re}) - 1.64)^{-2} \quad 3\times10^3 \le Re \le 5\times10^6 \qquad (11)$$

In the evaporation section, the working fluid is in two phases and the heat transfer takes place in the form of boiling heat transfer. In the study, boiling heat transfer calculations were performed with the approach presented by Güngor and Winterton (1986). The main boiling heat transfer expression is given in Equation 12.

$$h_t = E\cdot h_{lo} + S\cdot h_{pool} \qquad (12)$$

h_{lo} is the liquid phase convection heat transfer coefficient and is calculated using the Dittus-Boelter correlation as follows:

$$h_{lo} = 0.023\cdot \text{Re}_{t,l}^{0.8}\cdot \text{Pr}_{t,l}^{0.4}\cdot \frac{k_{t,l}}{d_i} \qquad (13)$$

The two-phase convection factor E is calculated as in Equation 14.

$$E = 1 + 24000\cdot Bo^{1.16} + 1.37\cdot(1/X_{tt})^{0.86} \qquad (14)$$

Bo and X_{tt} are the boiling and Martinelli numbers, respectively.

The equation proposed by Cooper (1984) was used for pool boiling and shown as following equation.

$$h_{pool} = 55\cdot P_{rdc}^{0.12}\cdot(-\log_{10}P_{rdc})^{-0.55}\cdot M^{-0.5}\cdot q^{0.67} \qquad (15)$$

P_{rdc} is obtained by dividing the operating pressure of the working fluid by the critical pressure (P_{ope}/P_{crt}). The compression factor S is obtained by the expression below:

$$S = (1 + 1.15\cdot10^{-6}\cdot E^2\cdot \text{Re}_{t,l}^{1.17})^{-1} \qquad (16)$$

The exhaust gas flowing by the shell side and the working fluid in the cooling section of the condenser unit exhibit a single-phase flow, and the heat transfer coefficient is calculated as follows (Bergman *et al*., 2011):

$$Nu = 0.71\cdot \text{Re}^{0.5}\cdot \text{Pr}^{0.36}\cdot\left(\frac{\text{Pr}}{\text{Pr}_w}\right)^n \qquad (17)$$

In the condensing section in the condenser unit, the working fluid is two-phase and the condensation process is analyzed as film condensation. The heat transfer coefficient for condensation can be calculated as in Equation 18.

$$h = 0.728\cdot\left(\frac{g\cdot\rho_l\cdot(\rho_l - \rho_g)\cdot \text{k}_l^3\cdot h_{\text{lg}}}{\mu_l(\text{T}_{sat} - \text{T}_w)\cdot \text{d}_o}\right)^{1/4}\cdot N_r^{-1/6} \qquad (18)$$

where T_w is the wall temperature and T_{sat} is the saturation temperature. Nr is the average number of tubes in the vertical tube row, which can be considered as follows (Sinnott *et al*., 2015):

$$N_r = \frac{d_b}{p_t}\cdot(2/3) \qquad (19)$$

2.4. Economic Analysis

The total cost of the RORC system was obtained with the Module Costing Technique. In this method, there are several steps. First, the purchase cost (Cp) for any equipment is obtained as follows:

$$\log C_{p,X} = K_{1,X} + K_{2,X} \cdot \log Y + K_{3,X} \cdot (\log Y)^2 \quad (20)$$

where K_1, K_2, and K_3 show the equipment cost coefficients and Y is the power in kW for the turbine and the pump, or the heat transfer area in m^2 for the heat exchangers. X index shows the related equipment. The bare module cost for the turbine is calculated with Equation 21 and for heat exchangers and the pump with Equation 22.

$$C_{BM,tur} = C_{p,tur} \cdot \left(F_{BM} \cdot F_{p,tur}\right) \quad (21)$$

$$C_{BM,X} = C_{p,X} \cdot \left(B_{1,X} + B_{2,X} \cdot F_{M,X} \cdot F_{P,X}\right) \quad (22)$$

where B_1, B_2, and F_{BM} are the coefficients of the relevant equipment, F_M is material factor and F_P is the pressure factor and is calculated for all elements as follows:

$$\log F_{p,X} = C_{1,X} + C_{2,X} \cdot \log P + C_{3,X} \cdot (\log P)^2 \quad (23)$$

P is the working pressure of its respective element. C_1, C_2, and C_3 are the pressure factor coefficients. All the above-mentioned coefficients were given in Table 1 for each element based on the year 2001

The generator cost ($C_{BM,g}$) was determined as follows (Wang *et al.*, 2015):

$$C_{BM,g} = 1850000 \cdot \left(\frac{W_{net}}{11800}\right)^{0.94} 1.5 \quad (24)$$

Finally, the total cost of the RORC plant (C_{tot}) is obtained as follows:

$$C_{tot} = \begin{pmatrix} C_{BM,eva} + C_{BM,\text{con}} + \\ C_{BM,\text{rec}} + C_{BM,\text{p}} + \\ C_{BM,\text{t}} + C_{BM,g} \end{pmatrix}_{2001} \cdot \frac{CEPCI_{2020}}{CEPCI_{2001}} \quad (25)$$

CEPCI is a chemical engineering plant cost index. $CEPCI_{2001}$ and $CEPCI_{2000}$ are taken as 397 and 599.5, respectively (Baldasso *et al.*, 2019; Lee *et al.*, 2020). In this study, electricity production cost (*EPC*) was used as an economic indicator and *EPC* is calculated as follows:

$$EPC = \frac{A_{inv} + COM}{W_{net} \cdot t_{op}} \quad (26)$$

where t_{op} is annual operating time of the RORC system and was taken as 7500 hours. *COM* is the operation and maintenance cost and was accepted as 1.5% of the total investment cost. Besides, A_{inv} is the annuity of the investment and determined as follows:

$$A_{inv} = C_{tot} \cdot CRF \quad (27)$$

where *CRF* is the capital recovery factor and is calculated as follows:

$$CRF = \frac{i \cdot (1+i)^t}{(1+i)^t - 1} \quad (28)$$

where, t and i show the RORC plant life and the interest rate, respectively. RORC plant life is taken as 20 years and the interest rate is 5% for this study.

2.5. Off-design Analysis

Ships work at different main engine loads during their voyage.

Table 1. Equipment cost coefficients (Turton *et al.*, 2008).

X	Y	$K_{1,X}$	$K_{2,X}$	$K_{3,X}$	$B_{1,X}$	$B_{2,X}$	$F_{M,X}$	F_{BM}	$C_{1,X}$	$C_{2,X}$	$C_{3,X}$
Evap.	A_{eva}	4.3247	-0.303	0.1634	1.63	1.66	1.4	-	0.0388	-0.11272	0.08183
Cond.	A_{con}	4.3247	-0.303	0.1634	1.63	1.66	1.4	-	0.0388	-0.11272	0.08183
Recup.	A_{rec}	4.3247	-0.303	0.1634	1.63	1.66	1.4	-	0.0388	-0.11272	0.08183
Pump	W_p	3.3892	0.0536	0.1538	1.89	1.35	1.6	-	-0.3935	0.3957	-0.00226
Turbine	W_t	2.7051	1.4398	-0.1776	-	-	-	3.4	0	0	0

This situation changes the mass flow rate and temperature of the exhaust gas. Therefore, the quality of waste heat also changes. While designing the RORC system on ships, both the design operating condition and off-design conditions should be considered. In this study, sliding pressure mode was adopted for off-design analysis. The off-design operating condition for the heat exchanger is analyzed by the equation given below.

$$UA_{od} = UA_d \cdot \left(\frac{\dot{m}_{od}}{\dot{m}_d} \right)^{\alpha} \tag{29}$$

where α exponent was taken as 0.6. This value was used in many studies and produced reasonable results for a shell and tube heat exchanger in marine ORC application (Shu *et al.*, 2017; Mondejar *et al.*, 2017; Baldasso *et al.*, 2019; Baldi *et al.*, 2015; Andreasen *et al.*, 2017). The following expression is used for the off-design model of the pump.

$$\frac{\eta_{p,od}}{\eta_{p,d}} = c_1 \cdot \left(\frac{\dot{V}_{p,od}}{\dot{V}_{p,d}} \right)^3 + c_2 \cdot \left(\frac{\dot{V}_{p,od}}{\dot{V}_{p,d}} \right)^2 + c_3 \cdot \left(\frac{\dot{V}_{p,od}}{\dot{V}_{p,d}} \right)^1 + c_4 \tag{30}$$

The coefficients c_1, c_2, c_3 and c_4 are determined according to the performance curve of the pump. It was taken as $c_1 = -0.439$, $c_2=0.466$, $c_3=0.453$ and $c_4=0.519$ in the literature and was shown to produce sufficiently accurate results for ORC applications on ships (Baldi *et al.*, 2015; Andreasen *et al.*, 2017; Pierobon *et al.*, 2014). The efficiency of the turbine for off-design operating conditions was obtained with the following equation:

$$\frac{\eta_{t,od}}{\eta_{t,d}} = \frac{N_{od}}{N_d} \cdot \sqrt{\frac{\Delta h_{is,d}}{\Delta h_{is,od}}} \cdot \left(2 - \frac{N_{od}}{N_d} \cdot \sqrt{\frac{\Delta h_{is,d}}{\Delta h_{is,od}}} \right) \tag{31}$$

For the off-design model of the turbine, the relationship between temperature, pressure and mass flow was determined as follows:

$$C = \frac{\dot{m} \cdot \sqrt{T_{in}}}{\sqrt{P_{in}^2 - P_{out}^2}} \tag{32}$$

2.6. Grey Wolf Optimization Algorithm

Grey wolf algorithm (GWA) was introduced by Mirjalili *et al.* (2014). The algorithm was developed with inspiration from the hunting technique and social hierarchy of grey wolves. Grey wolves have a 4-level hierarchical structure. At the first level, there is the alpha wolf called leader wolf. This is followed by beta, delta, and omega wolves, respectively. The duties and authorities of the wolf in each hierarchical group are different from each other. Grey wolves group hunting is another feature that makes them special. According to Muro *et al.* (2011), the main stages of grey wolf hunting are:

- Tracking, chasing and approaching the prey.
- Pursuing, encircling, and harassing the prey until it stops moving.
- Attack

Mirjalili *et al.* (2016) mathematically modeled the hunting mechanism of grey wolves and presented the literature for the solution of optimization problems. The encircling behavior of grey wolves was modeled as follows:

$$\vec{D} = \left| \vec{C} \cdot \vec{X}_p(t) - \vec{X}(t) \right| \tag{33}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \tag{34}$$

where t is the current iteration, $\vec{A}$ and $\vec{C}$ are the coefficient vectors, $\overrightarrow{X_p}$ is the position vector of the prey, and $\vec{X}$ is the position vector of the grey wolf. The vectors $\vec{A}$ and $\vec{C}$ are calculated as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{35}$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{36}$$

where $\vec{a}$ is a coefficient decreasing linearly from 2 to 0 over the iteration and $\overrightarrow{r_1}$, $\overrightarrow{r_2}$ are random vectors ranging from zero to one. It is assumed that alpha, beta, and delta have better knowledge of the potential location of the prey to mathematically model the hunting behavior of grey wolves. Therefore, the top three best solutions obtained so far are recorded and other search agents update their positions according to the positions of these three wolves. Thus, the following formulas are offered:

$$\overrightarrow{D_\alpha} = \left|\overrightarrow{C_1} \cdot \overrightarrow{X_\alpha} - \overrightarrow{X}\right| \quad (37)$$

$$\overrightarrow{D_\beta} = \left|\overrightarrow{C_2} \cdot \overrightarrow{X_\beta} - \overrightarrow{X}\right| \quad (38)$$

$$\overrightarrow{D_\delta} = \left|\overrightarrow{C_3} \cdot \overrightarrow{X_\delta} - \overrightarrow{X}\right| \quad (39)$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1} \cdot \overrightarrow{D_\alpha} \quad (40)$$

$$\overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2} \cdot \overrightarrow{D_\beta} \quad (41)$$

$$\overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3} \cdot \overrightarrow{D_\delta} \quad (42)$$

$$\overrightarrow{X}(\mathrm{t}+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \quad (43)$$

Mirjalili *et al*. (2016) was introduced the Multi-Objective Grey Wolf Algorithm (MOGWA) in 2016 for multi-objective problems. Mirjalili *et al*. (2016) added two new components to the basic GWA. The first component is an archive responsible for storing non-dominant Pareto optimal solutions. The second component is a leader selection strategy.

3. IMPLEMENTATION

One of the main challenges for ORC design is determining the working fluid. It is desired that the working fluid is environmentally friendly and non-hazardous. In this study, R245fa was selected as the working fluid. The global warming potential of R245fa is 950 and ozone depletion potential is 0, and it is frequently used in the literature. Hazard levels of working fluids are evaluated using the Hazardous Materials Identification System (HMIS) and the hazard level is scaled between 0 and 4. R245fa is defined as health hazard 2, reactivity hazard 1 and flammability hazard 0. Therefore, R245fa is environmentally friendly and safe.

After the working fluid was determined, the first stage of the implementation section was started. In the first stage, the multi-objective optimization of the RORC system parameters was performed with MOGWA for the design condition. W_{net} and EPC indicators were taken as objective function. The decision variables were evaporator pressure (P_{eva}), turbine inlet temperature ($T_{t,i}$), condensing temperature (T_{con}) and condenser pinch point temperature difference ($\Delta T_{PP,con}$) and recuperator effectiveness (ε_{rec}). The limit values of these decision variables were given in Table 2.

Table 2. Lower and upper boundary values of decision variables

Decision variables	Lower boundary	Upper boundary
P_{eva}	1500 kPa	$0.95P_{crt}$
$T_{t,i}$	$T_{sat,Peva}$	T_{exh}-20
T_{con}	30 °C	40 °C
$\Delta T_{PP,con}$	5 °C	15 °C
ε_{rec}	0.1	0.95

The limit value of the exhaust gas outlet temperature from the evaporator unit was selected as 140°C to prevent acid corrosion. All modeling and optimization processes were performed in Matlab environment. Also, the thermodynamic and transport properties of the working fluids were provided by integrating the CoolProp (Bell *et al*., 2014) database into the Matlab environment via Python.

As a result of multi-objective optimization, non-dominated solutions were obtained. The final solution from these candidate solutions was obtained by the Euclidean distance (D) approach. This approach was based on how close the solution candidates are to the ideal solution. The Euclidean distance of all candidate solutions was calculated and the smallest value was accepted as the final solution. The Euclidean distance expression was shown below:

$$D = \sqrt{\left(\dot{W}_{net} - \dot{W}_{net}^{ideal}\right)^2 + \left(LEC - LEC^{ideal}\right)^2} \quad (44)$$

In the second step of the implementation part, off-design analysis was performed. As it is known, it is essential to apply off-design models since ships often operate in off-design conditions depending on the changing main engine load and environmental conditions during their voyage. The operational profiles of ships generally vary according to the type of ship. Real-time measurements should be taken and statistical calculations should be carried out to determine the operational profiles of ships. However, it is also possible to create an approximate operational profile for each ship type. The approximate operational profile for the bulk carrier was given by MAN as in Figure 3.

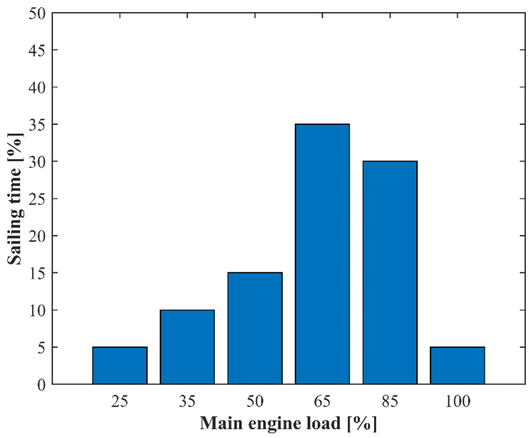

Figure 3. Main engine load profile for bulk carrier

The 65% main engine load was accepted as the design condition, the remaining engine loads were analyzed as off-design conditions. For the off-design conditions, maximizing W_{net} was taken as the only target, and optimization was carried out with an iterative process. An operational profile-based simulation was performed using the results obtained for all working conditions.

In this study, the energy obtained from the RORC facility is used to meet the ship's electricity demand. Therefore, the diesel generators on the ship will operate less, which will both provide fuel saving and make significant contributions to the prevention of environmental pollution. Therefore, considering that the specific fuel consumption of an average diesel generator is 0.187 kg/kWh and the annual operating time of the ORC plant is 7500 hours, the annual fuel saving of RORC systems is obtained as follows:

$$Fuel\ Saving = \dot{W}_{net} \times SFC \times t_{op} \left[\frac{t_{fuel}}{year}\right] \tag{45}$$

where SFC is specific fuel consumption and t_{op} is annual operating time. Using the annual fuel saving, the annual amount of CO_2 reduction can be calculated as follows:

$$CO_2\ reduction = Fuel\ Saving \times C_F \left[\frac{t_{CO_2}}{year}\right] \tag{46}$$

where C_F was carbon conversion factor and taken as 3.114 t_{CO_2}/t_{fuel} for heavy fuel (MEPC 245(66), 2014).

4. RESULT AND DISCUSSIONS

Pareto solutions were obtained as a result of the optimization process using MOGWA. In order to determine the final solution among the Pareto solutions, the Euclidean distance of each solution was calculated and the final solution was obtained as in Figure 4.

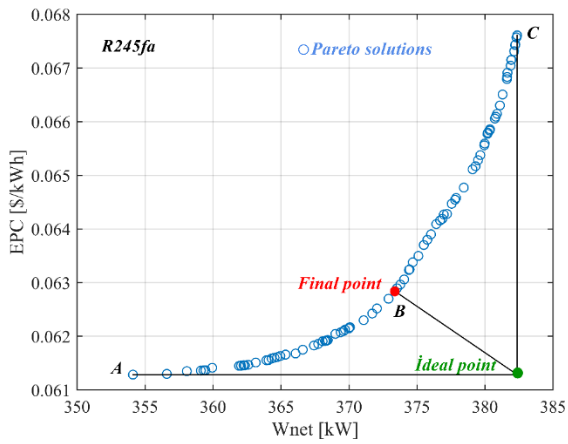

Figure 4. Pareto solutions for R245fa

In Figure 5, the blue circles represent the Pareto solutions, the green circle is the ideal point, and the red circle is the final point. The point at which EPC is minimum was marked A, the point at which W_{net} is maximum is C and the final solution was shown as point B. For the optimum RORC facility, EPC is required to be minimum and W_{net} to be maximum. W_{net}, exergy efficiency, and thermal efficiency were increasing from point A to point C. EPC and total cost were decreasing from point C to point A. As a result, point C was the most suitable in terms of thermodynamics, and point A was the most suitable solution economically. Since these two criteria cannot be met at the same time, point B is determined as the final solution by making a certain trade-off. Thus, the analyzes for the design operating condition of the RORC system with the R245fa working fluid were completed and the off-design analysis was performed for the performance under off-design operating conditions. There are two main constraints for off-design analyzes performed with the sliding pressure mode.; to prevent corrosion on turbine blades, the working fluid coming out of the evaporator is completely evaporated and the exit temperature of the exhaust gas from the evaporator is higher than 140°C to prevent acid corrosion in the ship's funnel. In the sliding pressure method, the condenser pressure was constant and the evaporator pressure was variable. Turbine inlet temperature (T_1), $\Delta T_{PP,con}$ and ε_{rec} parameters were calculated by the iterative solution method so that the heat exchanger areas calculated for the design condition at a given evaporator pressure would be the same as those in the off-design conditions. Table 3 shows the optimum value of the decision variables according to the overall main engine load.

Table 3. Optimum RORC system parameters of all operating conditions

Engine load [%]	**P_{eva} [Pa]**	**T_1 [K]**	**ε_{rec} [-]**	**$\Delta T_{PP,con}$ [K]**
25	1759000	475.335	0.844	2.9
35	3070000	495.08	0.792	4.9
50	3190000	470.71	0.792	5
65	3354558	454.12	0.866	5.06
85	3468450	459.03	0.786	5.4
100	3468450	480.2	0.783	5.4

As the main engine load increased, the optimum value of P_{eva} and $\Delta T_{PP,con}$ also increased. T_1 and ε_{rec} had different values according to RORC design constraint and heat load. Figures 5 and 6 show the variation of thermal efficiency and exergy efficiency according to main engine load, respectively.

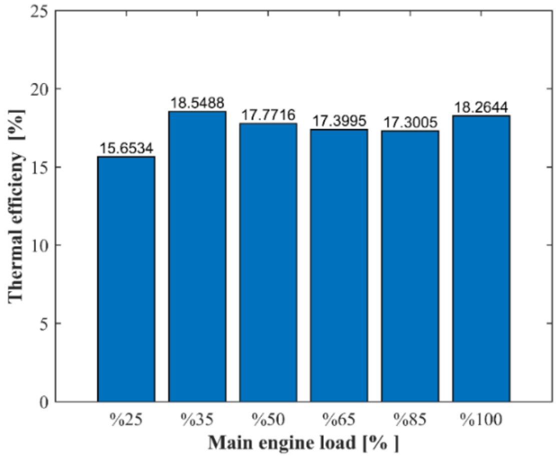

Figure 5. The variation of thermal efficiency for all main engine load

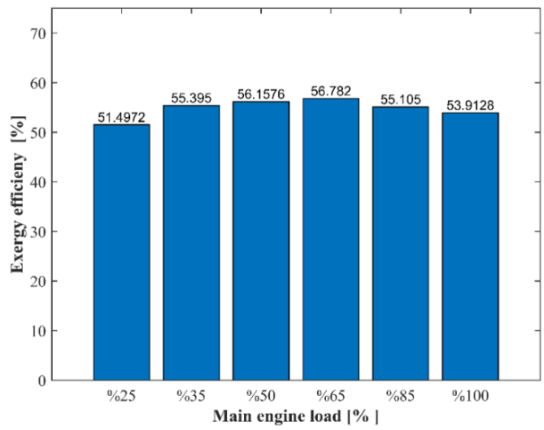

Figure 6. The variation of exergy efficiency for all main engine load

The highest value of thermal efficiency was determined as 18.55% at 35% engine load. The exergy efficiency was obtained as a maximum value of 56.78% at 65% engine load (i.e. design operating condition). After obtaining thermodynamic indicators for all main engine load, an operational profile-based simulation was performed. Table 4 shows the annual average W_{net} and EPC value, as well as fuel saving and CO_2 reduction.

Table 4. Operational profile based simulation for container ship

Parameter	Value
W_{net} [kW]	372.783
EPC [$/kWh]	0.0629
Fuel saving [t_{fuel}/year]	522.8292
CO_2 reduction [t_{CO2}/year]	1628.09

These results showed that the use of the RORC system for bulk carrier provides important contributions both in terms of economy and prevention of environmental pollution.

5. CONCLUSIONS

This study investigates the effect of installing a RORC system on a bulk carrier on fuel consumption and CO_2 reduction. Design and off-design analyzes were performed for the bulk carrier's main engine exhaust gas recycling. Firstly, optimum RORC system parameters were obtained with MOGWA for design working condition. Then, off-design analyzes were carried out using the iterative optimization method. Finally, the operational profile-based simulation was performed and the annual fuel saving and CO_2 reduction amounts of the ship were determined. The main conclusions of this study can be summarized as follows:

- W_{net} was determined as 373.37 kW for design condition.
- EPC was calculated as 0.06284 $/kWh for design condition.
- The total cost was determined as 1847598 $ for design condition.
- Exergy efficiency and thermal efficiency were calculated as 56.78% and 17.39%, respectively.
- The annual average W_{net} was determined as 372.78 kW.
- The annual average EPC was calculated as 0.0629 $/kWh.
- The annual average fuel saving was calculated as 522.83 t_{fuel}/year.
- The annual average CO_2 reduction was calculated as 1628.09 tCO_2/year.
- This study showed that using the RORC system on ships is a promising solution for increasing emission restrictions and environmental concerns.

In this study, the heat exchanger parameters were taken as constant. In future studies, heat exchanger optimization can be integrated into the main optimization process. In the present study, the gray wolf algorithm was used. However, new algorithms are added to the literature every year. Comprehensive performance studies can be conducted by using newly introduced algorithms in optimizing the ORC system. In the presented study, only ship exhaust gas was used as waste heat source. In future studies, different waste heat sources such as jacket cooling water and scavenging air cooling can be included in the ORC system and their effects can be investigated.

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AUTHORSHIP CONTRIBUTION STATEMENT

Samet GÜRGEN: Conceptualization, Methodology, Writing - Original Draft, Writing-Review and Editing, Software **İsmail ALTIN:** Writing-Review and Editing.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions is required for this study

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6. REFERENCES

Ahlgren, F., Mondejar, M.E., Genrup, M., Thern, M., (2016). Waste heat recovery in a cruise vessel in the Baltic Sea by using an organic Rankine cycle: a case study. *Journal of Engineering for Gas Turbines and Power* 138 (1): 011702. doi: 10.1115/1.4031145.

Akman, M., Ergin, S., (2020). Thermo-environmental analysis and performance optimisation of transcritical organic Rankine cycle system for waste heat recovery of a marine diesel engine. *Ships and offshore structures* 16(10): 1104-1113. doi: 10.1080/17445302.2020.1816744.

Andreasen, J.G., Meroni, A., Haglind, F., (2017). A comparison of organic and steam Rankine cycle power systems for waste heat recovery on large ships. *Energies* 10(547): 1-23. doi:10.3390/en10040547.

Baldasso, E., Andreasen, J.G., Mondejar, M.E., Larsen, U., Haglind, F., (2019). Technical and economic feasibility of organic Rankine cycle-based waste heat recovery systems on feeder ships: Impact of nitrogen oxides emission abatement technologies. *Energy Conversion and Management* 183: 577-589. doi: 10.1016/j.enconman.2018.12.114.

Baldi, F., Larsen, U., Gabrielii, C., (2015). Comparison of different procedures for the optimisation of a combined Diesel engine and organic Rankine cycle system based on ship operational profile. *Ocean Engineering* 110: 85-93. doi: 10.1016/j.oceaneng.2015.09.037.

Bell, I.H., Wronski, J., Quoilin, S., Lemort, V., (2014). Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp. *Industrial Engineering Chemistry Research* 53: 2498-2508. doi: 10.1021/ie4033999.

Bergman, T.L., Incropera, F.P., Lavine, A.S., DeWitt, D.P. (2011). *Introduction to heat transfer*, John Wiley & Sons, 960 p.

CEAS, (2021). Accessed Date: 11.11.2021, https://www.manes.com/marine/products/planning-tools-and-downloads/ceas-engine-calculations is retrieved.

Civgin, M.G., Deniz, C., (2021). Analyzing the dual-loop organic rankine cycle for waste heat recovery of container vessel. *Applied Thermal Engineering* 199(117512), 1-10. doi: 10.1016/j.applthermaleng.2021.117512

Cooper, M., 1984. Saturation nucleate pool boiling-a simple correlation. International Chemical Engineering Symposium, Vol. 86, pp. 786.

de la Fuente, S.S., (2016). Reducing Shipping Carbon Emissions under Real Operative Conditions: A Study of Alternative Marine Waste Heat Recovery Systems based on the Organic Rankine Cycle, PhD. Thesis, University College London, Department of Mechanical Engineering, 326 p.

de la Fuente, S.S., Larsen, U., Pierobon, L., Kærn, M. R., Haglind, F., Greig, A., (2017a). Selection of cooling fluid for an organic Rankine cycle unit recovering heat on a container ship sailing in the Arctic region. *Energy* 141: 975-990. doi: 10.1016/j.energy.2017.09.125.

de la Fuente, S.S., Roberge, D., Greig, A.R., (2017b). Safety and CO_2 emissions: Implications of using organic fluids in a ship's waste heat recovery system. *Marine Policy* 75: 191-203. doi: 10.1016/j.marpol.2016.02.008.

Gnielinski, V., (1976). New equations for heat and mass transfer in turbulent pipe and channel flow. *International Chemical Engineering* 16 (2): 359-368.

Gungor, K.E., Winterton, R., (1986). A general correlation for flow boiling in tubes and annuli. *International Journal of Heat and Mass Transfer* 29 (3): 351-358. doi: 10.1016/0017-9310(86)90205-X.

Lee, S.H., Lim, D.H., Park, K., (2020). Optimization and Economic Analysis for Small-Scale Movable LNG Liquefaction Process with Leakage Considerations. *Applied Sciences* 10(15): 5391, 1-25. doi: 10.3390/app10155391.

Lümmen, N., Nygård, E., Koch, P.E., Nerheim, L.M., (2018). Comparison of organic Rankine cycle concepts for recovering waste heat in a hybrid powertrain on a fast passenger ferry. *Energy Conversion and Management* 163: 371-383. doi: 10.1016/j.enconman.2018.02.063.

Mallouppas, G., Yfantis, E.A., (2021). Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals. *Journal of Marine Science and Engineering* 9(4): 415, 1-40. doi: 10.3390/jmse9040415.

MEPC 245(66), (2014). Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships.

Mirjalili, S., Mirjalili, S.M., Lewis, A., (2014). Grey wolf optimizer. *Advances in engineering software* 69: 46-61. doi: 10.1016/j.advengsoft.2013.12.007.

Mirjalili, S., Saremi, S., Mirjalili, S.M., Coelho, L.D.S., (2016). Multi-objective grey wolf optimizer: a novel algorithm for multi-criterion optimization. *Expert Systems with Applications* 47: 106-119. doi: 10.1016/j.eswa.2015.10.039.

Mondejar, M.E., Ahlgren, F., Thern, M., Genrup, M., (2017). Quasi-steady state simulation of an organic Rankine cycle for waste heat recovery in a passenger vessel. *Applied Energy* 185 (2): 1324-1335. doi: 10.1016/j.apenergy.2016.03.024.

Muro, C., Escobedo, R., Spector, L., Coppinger, R., (2011). Wolf-pack (Canis lupus) hunting strategies emerge from simple rules in computational simulations. *Behavioural processes* 88 (3): 192-197. doi: 10.1016/j.beproc.2011.09.006.

Petukhov, B. (1970). Heat transfer and friction in turbulent pipe flow with variable physical properties. In: "Advances in heat transfer 6th Edition", pp. 503-564, Elsevier.

Pierobon, L., Benato, A., Scolari, E., Haglind, F., Stoppato, A., (2014). Waste heat recovery technologies for offshore platforms. *Applied Energy* 136: 228-241. doi: 10.1016/j.apenergy.2014.08.109.

Shu, G., Liu, P., Tian, H., Wang, X., Jing, D., (2017). Operational profile based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine's exhaust waste heat. *Energy Conversion and Management* 146: 107-123. doi: 10.1016/j.enconman.2017.04.099.

Sinnott, R.K., Coulson, J.M., Richardson, J.F. (2005). *Chemical engineering design*, Oxford: Elsevier Butterworth-Heinemann.

Song, J., Song, Y., Gu, C.W., (2015). Thermodynamic analysis and performance optimization of an Organic Rankine Cycle (ORC) waste heat recovery system for marine diesel engines. *Energy* 82: 976-985. doi: 10.1016/j.energy.2015.01.108.

Töz, A., Büber, M., Köseoğlu, B., Şakar, C. (2022) Analysis of Collision Accidents in Maritime Transportation by FTA Method. Turkish Journal of Maritime and Marine Sciences, 1-16.

Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A. (2008). *Analysis, synthesis and design of chemical processes*. Pearson Education.

Wang, X.Q., Li, X.P., Li, Y.R., Wu, C.M., (2015). Payback period estimation and parameter optimization of subcritical organic Rankine cycle system for waste heat recovery. *Energy* 88: 734-745. doi: 10.1016/j.energy.2015.05.095.

Yang, M.H., Yeh, R.H., (2014). Analyzing the optimization of an organic Rankine cycle system for recovering waste heat from a large marine engine containing a cooling water system. *Energy Conversion and Management* 88: 999-1010. doi: 10.1016/j.enconman.2014.09.044.

Yang, M.H., Yeh, R.H., (2015a). Thermo-economic optimization of an organic Rankine cycle system for large marine diesel engine waste heat recovery. *Energy* 82: 256-268. doi: 10.1016/j.energy.2015.01.036.

Yang, M.H., Yeh, R.H., (2015b). Thermodynamic and economic performances optimization of an organic Rankine cycle system utilizing exhaust gas of a large marine diesel engine. *Applied Energy* 149, 1-12. doi: 10.1016/j.apenergy.2015.03.083.