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A Comparison Between the Performance of Multi-Stage Flash Desalination Once-Through and Brine Recirculation in Extracting Marine Diesel Engines Waste Energy

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ABSTRACT

There are numerous methods for utilizing waste heat energy from marine diesel engines; however, selecting these methods depends on the load and capacity of these engines, as well as the available area. As a result, the purpose of this paper is to utilize waste heat energy from scavenge air to operate the multi-effect evaporator forward feed (MEE-FF) and assess its performance based on the distillate water's mass flow rate at various engine loads. A comparison is also made between the multistage flash desalination once-through (MSF-OT) and multistage-desalination brine recirculation (MSF-BR) to determine which is best in extracting engine exhaust waste energy within the available area. Detailed mathematical models were built for three different plants using MATLAB software. On these plants, the effect of various variables like steam temperature, intake water flow rate, and the temperature on the plant performance have been studied. The main result showed that the performance ratio, surface area and distilled mass amount in the MSF-BR are increased by 55%, 50.19%, and 55% for the same input data respectively, while the feed water mass and brine mass are decreased by 50.87% and 34.36%, respectively in comparison to MSF-OT.

1. Introduction

As a main source of living, water is indispensable for everyone, however, providing clean drinking water is becoming a global problem as fresh clean water is not distributed equally worldwide. The world's main concern now is about delivering clean and safe drinking water to everyone to cope with the increased water scarcity. The problem of water shortage could also be seen clearly on-board ships as the average use of drinking water on those ships is more than 260000 gallons per day [1-3]. Therefore, enough clean drinking water should be provided for all the passengers with less expenses and without using much energy. This could be achieved by exploiting seawater and extracting from

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it freshwater. This process is known as desalination of seawater which is used by most of the world's population especially the Middle East countries [4,5].

The desalination of seawater requires huge amounts of energy to produce enough clean drinking water for those who suffer from water shortage [6-8]. Recent studies are investigating the ability of exploiting various types of energy sources to desalinate seawater [9]. To solve this energy problem, heat lost from diesel engines could be used to generate thermal energy and power to desalinate seawater [6,10,11].

The diesel engine produces huge amounts of waste energy [12,13] since it only produces 49.3% shaft power to operate any vehicle, and the rest is waste heat energy which is estimated to be 50.7%. This waste heat energy includes different forms of wastes which could be used in generating energy and power such as about 0.6% radiation, about 4.3% lubricating oil, about 6.3% jacket water, about 14.1% scavenge air water cooling, and about 25.4% of exhaust gas [12,13]. The thermal energy of the exhaust gas and the scavenge air cooling can be exploited in seawater desalination because the diesel engine provides forms of heating methods to desalinate seawater [8].

Thermal desalination includes different types: Multistage-Flash Desalination (MSF), Multi Effect Evaporation (MEE), and Single Effect [2,14,15]. This paper discusses two thermal desalination which are multistage flash and multi effect evaporation. The first system has two configurations which are once-through (MSF-OT) [16] and brine recirculation (MSF-BR) [17]. The latter one is classified into three categories: forward feed, parallel feed, and backward feed.

The multistage flash process, whether it is once-through or brine recirculation, has multiple advantages. It has a high capacity out which is provided at relatively higher thermal efficiency and reliability, and this results in lower production costs and higher performance in desalinating seawater [18]. It requires simple system equipment to be installed.

The MSF-OT is distinguished by operating at low salinity with values of 42000 ppm for the feed and of 46106.6 ppm for the flashing brine steams which results in reducing the fouling and the boiling problems occurring in the condenser and the heater [14]. The specific heat transfer area is reduced from (45.1 $m^2/(kg/s)$) to (12.7 $m^2/(kg/s)$) due to the MSF-OT performance ratio since the heat in the brine heater system is distributed over a larger amount of distillate water [14]. This shows how the specific heat transfer decreases when the performance ratio increases and vice versa [14].

The MSF-BR is characterized by having a proper design which allows for variable loads that range between 70 to 110% of the rated capacity [19]. It has simple manufacturing and installation properties [14].

The MEE-FF has many advantages such as having a stable layout, performing at a wide range as well as being a simple process. It also has a low energy consumption, and it can operate at a low temperature. It is also known for its high efficiency of production as it has efficient the distribution of water and tube wetting. Moreover, it uses all types of vapours with pressure higher than 0.5 bars, and it separates vapours and non-condensable gases [20].

The MSF desalination unit is very efficient as it provides quantities of distillate water. This unit uses exhaust gas as waste heat energy which is extracted from the diesel engine to operate it [21]. The study also highlights that in summer the distillate water production is more than winter due to the variation of the feed water temperature as in summer the temperature is high and affects the production of the distillate water [22]. The studies showed that MSF unit produces sufficient quantities of distillate water with less expenses because it utilizes the thermal energy produced from the diesel engine to operate it [10].

This paper focuses mainly on the idea of using exhaust gas, extracted from diesel engine as a form of Waste Heat Recovery (WHR) [19,22]. Due to the mass flow rate and high temperature the exhaust gas, it is used as a heating fluid source which can be used in operating multi-stage flash distillation

(MSF) system as this system requires high temperature to operate to produce distillate water. The scavenge air can be used as a heating fluid source to operate multiple-effect distillation (MEE) system in producing distillate water [12]. Compared to the exhaust gas, the scavenge air has lower mass flow rate and temperature; accordingly, it is suitable to be used as a heating fluid source for MEE units which do not need high temperature and mass flow rate [14] to operate multiple-effect distillation (MEE) system in producing distillate water.

In addition, this paper also draws a comparison between the MSF-OT and MSF-BR which gives the consumer an opportunity to choose which unit will be the best in desalinating water according to the desired requirements and needs. The comparison also presents the space required for the desalinating units and the amount of the produced desalinated water.

2. Process Description

This study is using the diesel engine 6RT-flex58T-E made by HYUNDAI-WARSTILA [23]. This marine diesel engine is a two-stroke one with constant pressure turbocharging and has a maximum power output of 13.94 MW. Its operating parameters are acquired from the official shop test that was performed experimentally by the manufacturer as a procedure for quality control upon installation aboard the ship. The continuous service rating of the engine as shown in Table 1 is used in designing the systems of this study.

Table 1
Temperature and mass flow rate distribution of exhaust gas and charge air at different operating load

Load (%)		25	50	75	90	100
Exhaust Gas	m' (kg/s)	7.0627	15.137	24.052	28.818	32.666
	T (˚C)	290	262	249	251	261
Charge Air	m' (kg/s)	6.883	14.793	23.546	28.207	31.969
	T (˚C)	52	134	190	213	230
After Air Cooler	T (˚C)	23	29	33	36	37

The scavenge air and the exhaust gas, which are extracted from diesel engine as waste heat energy, will be used to operate the MEE-FF and the MSF respectively to desalinate seawater. The temperature of scavenge air at small loads such as 25, 50 and 75 is not high compared to the temperature of the exhaust gas; as a result, having low temperature makes the scavenge air suitable for MEE-FF, and having high temperature makes the exhaust gas suitable for MSF-OT and MSF-BR.

A heat exchanger is used to reduce the temperature of the scavenge air produced from the compressor of the turbo charger depending on the requirements of the diesel engine according to every load. It is also used to change the temperature of the water used to cool the scavenge air to 100 ˚C which changes it to vapor. The vapor of 100 ˚C temperature and the mass flow rate which differs according to the diesel engine's load are used as thermal sources to operate the MEE-FF unit of six stages. The amount of distillate water produced from the MEE-FF unit differs according to the given load of the diesel engine. It is calculated by using modelling excel sheet and MATLAB program to estimate the amount of M_f, M_b, M_d dimension of stages and the performance of the MEE-FF unit according to the diesel engine load.

The exhaust gas is used to operate the MSF-OT or the MSF-BR to desalinate the seawater and then they are compared together to decide on the best one in modelling. The exhaust gas has specific mass flow rate and temperature which differ according to the diesel engine load. The exhaust gas is used as thermal source to operate both MSF-OT and MSF-BR to produce distillate water as presented in Figure 1 and Figure 2.

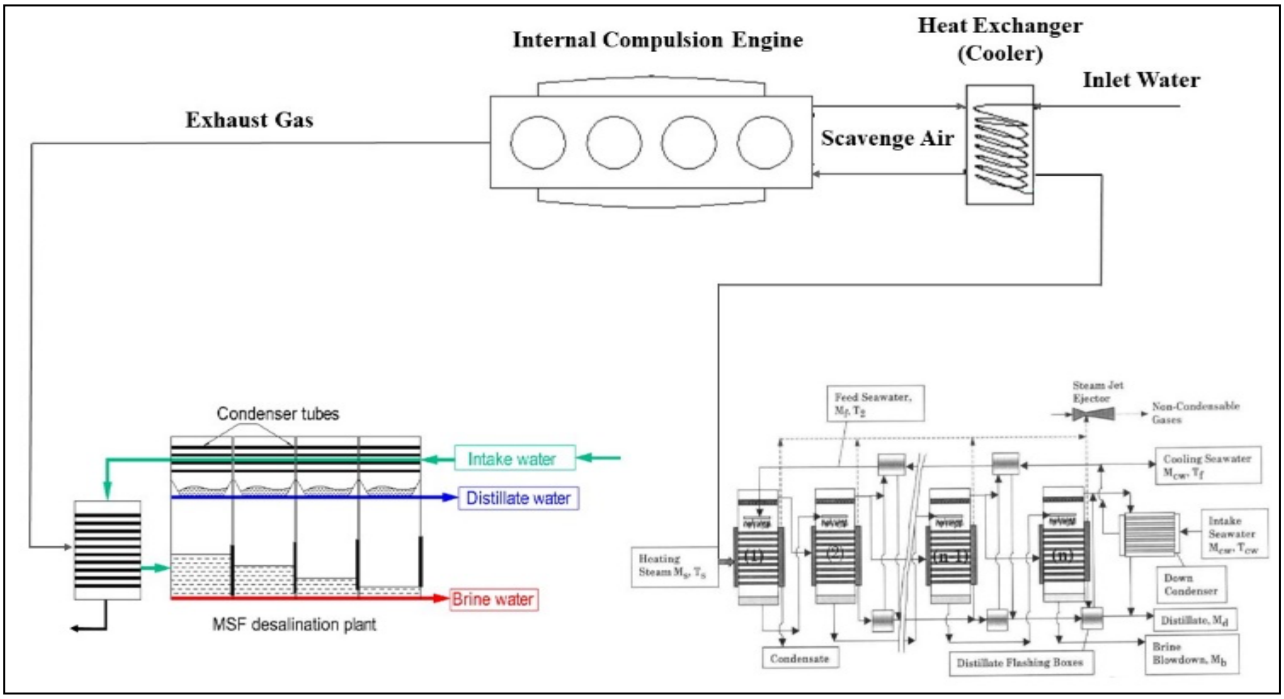

Fig. 1. Proposal 1

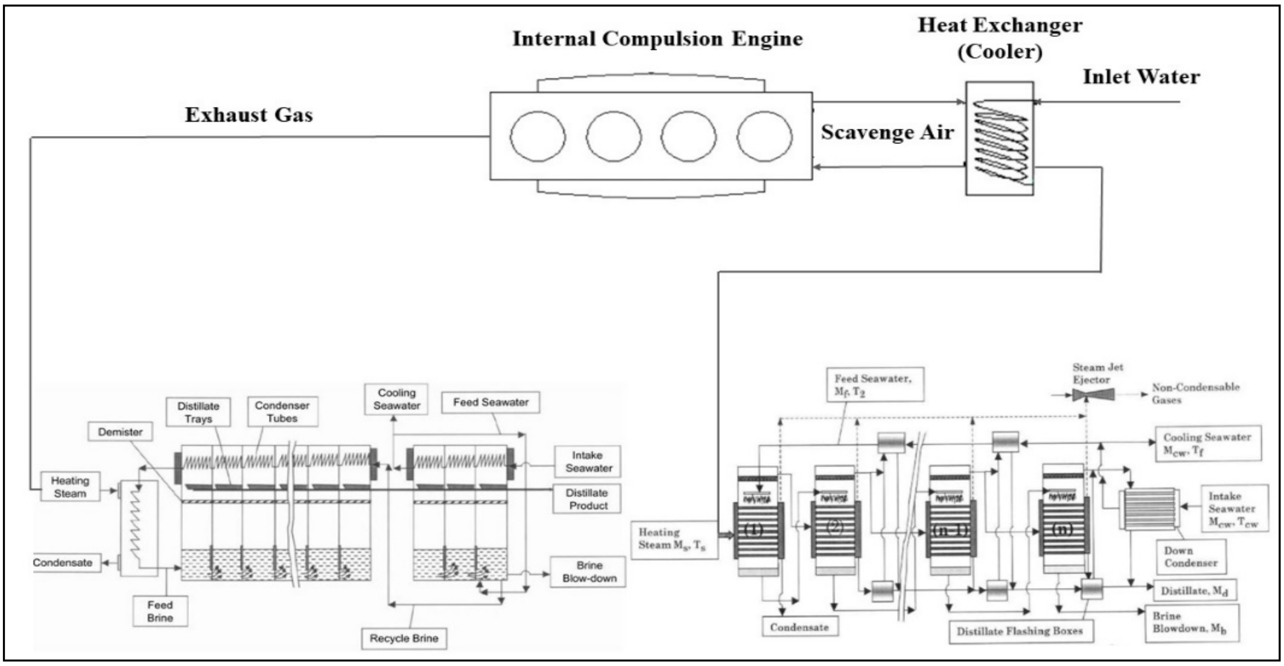

Fig. 2. Proposal 2

Accordingly, the waste heat energy produced from the diesel engine can be used to desalinate seawater and solve the global problem of water shortage.

3. Modelling Approach

The marine diesel engine has different sources of waste heat energy, two of which are the scavenge air and the exhaust gas. These two sources could be used to operate some plants for desalinating seawater to solve the global problem of water shortage as shown in Figure 3.

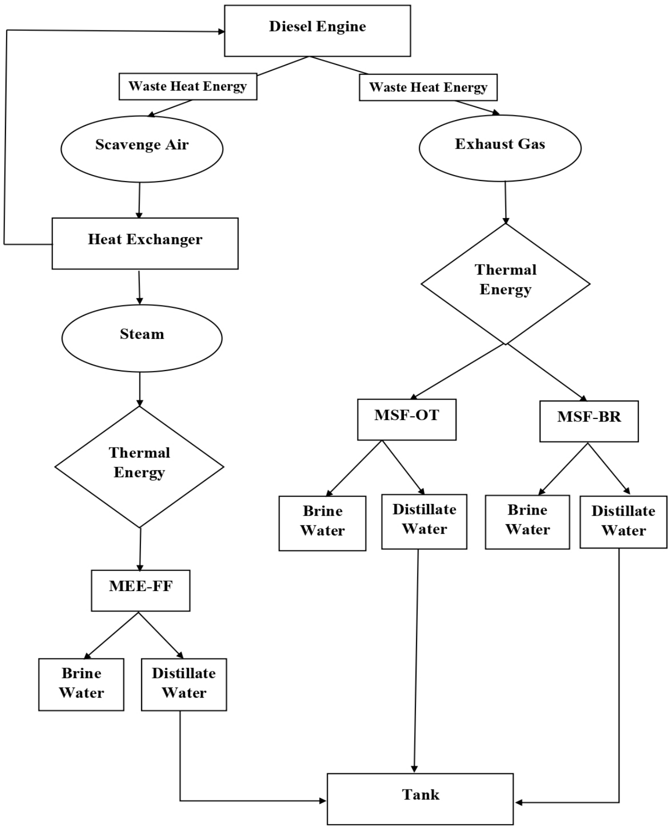

Fig. 3. Flowchart of the Model

Regarding the scavenge air, a heat exchanger is used to reduce its temperature by using saltwater as it transfers into a steam of 100 $^{\circ}C$. The scavenge air goes back with a temperature owing to the marine diesel engine. Steam is used as a thermal source for operating the MEE-FF which produces distillate water and brine water. The former is stored in the tank as shown in Figure 3, while the latter is neglected.

The exhaust gas is also used as a thermal source to operate two configurations: MSF-OT and MSF-BR. They also produce distillate water, which is stored in the tank as shown in Figure 3 and brine water, which is neglected.

4. Mathematical Model

4.1 Procedures

The following mathematical model for MSF-OT, MSF-BR, and MEE-FF is adopted from El-Dessouky and Ettouney [14] Darwish *et al.,* [20] and Al-Mutaz and Wazeer [24] to present the salt balance, stage material, the profile of stages, condenser temperature, stage dimensions, performance parameters as well as material balance. The equations are also adopted from El-Dessouky *et al.,* [26] and Al-Mutaz and Wazeer [27].

4.2 Mathematical Model for Heat Exchanger (Cooler)

The scavenge air enters the heat exchanger with a high temperature T_{in} which is cooled through exploiting the saltwater as it gets in with its normal sea temperature $T_{in(sw)}$. Then, the scavenge air flows out of the heat exchanger with a different temperature T_{out} and mass flow rate owing to the requirements of the marine diesel engine at every load. The saltwater also gets out with a higher temperature as it reaches 100 ˚C which is measured through using sensors and its mass flow rate differs according to the load of the marine diesel engine. Afterward, the output continues flowing to form the heating source for the MEE-FF desalination plant [25].

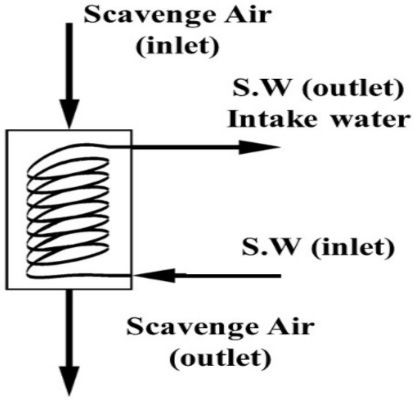

Fig. 4. The Cooler of the Main Engine

$$Q = M_{SA} \, . \, C_{p_{SA}} \, . (T_{in} - T_{out}) = M_{SW} \, . \, C_{p_{SW}} \, . (T_{SW_{out}} - T_{SW_{in}}) \tag{1}$$

From the previous equation, the M_{SW} is conducted at $T_{SW_{out}}$ which is equal to 100 ˚C. The sea-water pumps must be driven electrically. The pumps' capacity is indicated by the type of coolers used and the dissipated heat. The mathematical model for MEE-FF is adopted from El-Dessouky *et al.,* [26] and Al-Mutaz and Wazeer [27] and is used to produce distillate water at different loads of the marine diesel engine.

4.3 Solution Procedure of the Mathematical Model for MSF-OT

The mathematical model for MSF-OT is adopted from El-Dessouky *et al.,* [26] and Al-Mutaz and Wazeer [27] and is used to produce distillate water depending on different loads of the marine diesel engine.

4.3.1 Heat balance

From the following equation, the M_f is detected according to different loads of the marine diesel engine due to the change of T_{gas} and M_{gas}. Note that $T_{gas,2}$ cannot be less than 150 ˚C to avoid the formation of sulfuric acids.

$$M_{gas}. C_{p,gas}. \left(T_o - T_{gas,2}\right) = M_f . C_{p,saltwater}(T_o - t_1) \tag{2}$$

$$M_d = M_f(1 - (1 - y)^n) \tag{3}$$

4.3.2 Material balance

$$M_f = M_d + M_b \tag{4}$$

The salt balance equation is:

$$M_f \, . X_f = M_b \, . X_b \tag{5}$$

4.4 Solution Procedure Mathematical Model for MSF-BR

While developing the simplified model, the same assumptions, considered in the simplified model of the MSF-OT, are also considered for the MSF-BR [27].

4.4.1 Heat balance

$$M_{gas} = \frac{M_r \, .Cp_{saltwater} \, (T_0 - T_F \,)}{C_{p,gas} \, (T_{gas} - T_{gas,2})} \tag{6}$$

$$M_d = M_r . (1 - (1 - y)^n) \tag{7}$$

The given overall material balance equation:

$$M_f = M_b + M_d \tag{8}$$

$$M_f = \frac{M_d \, .X_b}{X_b - X_f} \tag{9}$$

5. Model Validation

This paper presents a new approach utilizing the waste heat energy of marine diesel engine to operate different desalination techniques: MEE-FF, MSF-OT, and MSF-BR. In this study, the scavenge air was used as a thermal source to operate the MEE-FF plant of six stages and the exhaust gas was also used as a thermal source to operate the MSF-OT and the MSF-BR plants. After searching in the previous literature, no experimental nor theoretical results could be found for the proposed system configuration. Consequently, the components of the main model are validated alone to assure the authentication of the created excel sheet and the MATLAB model.

First, MEE-FF model is validated by using the inputs of the case study mentioned by El-Dessouky and Ettouney [14] which are presented in Table 2.

Table 2
Validation results of MEE-FF

Effect	1	2	3	4	5	6
D (kg/s)	0.1708	0.1693	0.1677	0.1662	0.1646	0.1614
B (kg/s)	2.3292	2.16	1.9922	1.826	1.6614	1.5
X (ppm)	45078.9	48611.5	52704.4	57501.2	63198.6	70000
T (˚C)	92.67	84.96	76.84	68.29	59.29	40
A (m2)	22.1446	22.1445	22.1445	22.1446	22.1446	22.1446

The results of the MEE-FF model made by the excel sheet and the MATLAB program are identical to the results of the case study made by EL-Dessouky and Ettouney [14] as shown in Table 3.

Table 3
Validation results of MSF-OT

Parameter	Results of Nassor's Model	Model Results	Error
Mgas, kg/s	29.5	28.37	3.8%
Md, kg/s	162.5	169.28	4%
Mb, kg/s	2337.5	2330.714	0.2%
ppm	44920	45050.5	0.2%
D1, kg/s	10.98	10.93	0.44%
PR	5.49	5.96	7.9%

Second, MSF-OT model is validated by using the inputs of the case study mentioned by West [11] which are presented in Table 4.

Table 4
The parameter inputs of MSF-OT and MSF-BR

Units	MSF-OT	MSF-BR
Parameter	Input	Input
Top brine temperature (TBT) °C	106	106
Brine blowdown temperature °C	40	40
Feed seawater temperature °C	25	25
Seawater salinity, ppm	42000	42000
Number of stages	24	24
Brine load kg/ms	180	180
Vapor velocity m/s	6	6
Weir coefficient Cd	0.5	0.5
Number of diesel engine	1	1
Brine blowdown salinity, ppm	-	70000
Number of units recycling brine	-	3

The results of the MSF-OT model made by the excel sheet and the MATLAB program are compared to the results of the case study made by West [11] as shown in Table 5.

Table 5
Validation results of MSF-OT

Parameter	Results of Nassor's Model	Model Results	error
M_{gas}, kg/s	29.5	28.37	3.8%
M_d, kg/s	162.5	169.28	4%
M_b, kg/s	2337.5	2330.714	0.2%
ppm	44920	45050.5	0.2%
D_1, kg/s	10.98	10.93	0.44%
PR	5.49	5.96	7.9%

Finally, MSF-BR model is validated by using the inputs of the case study mentioned by EL-Dessouky and Ettouney [14] which are intake seawater temperature 25 ˚C, steam temperature 116 ˚C, top brine temperature 106 ˚C, brine temperature in the last stage 40 ˚C, heat capacity of liquid streams 4.18 KJ/kg˚C, salinity of intake seawater 42000 ppm, salinity of the brine blow-down 70000 ppm, vapor velocity in the last stage 6 m/s, brine mass flow rate per stage width 180 kg/s, and weir friction coefficient 0.5. The results of the MSF-BR model made by the excel sheet and the MATLAB program are identical to the results of the case study made by EL-Dessouky and Ettouney [14] as shown in the following Table 6.

Table 6
Validation results of MSF-BR

Flow Rates		Heat Transfer Area		Stage Dimensions		Performance Parameters	
M_d	378.8 kg/s	A_b	4256.6 m^2	W	18.8 m	PR	7.21
M_f	947 kg/s	A_r	4156.9 m^2	L	2.56 m	sA	259.6 m^2
M_b	568.2 kg/s	A_j	2266.4 m^2	GH1	0.078 m	sMcw	2.41 kg/s
M_r	3384 kg/s	A_c	94094.1 m^2	H1	0.278 m		
M_s	52.52 kg/s						
M_{cw}	914.64 kg/s						

6. Case Study

As mentioned before, the scavenge air is being cooled by the heat exchanger through using cooling water which changes into steam at 100 ˚C. The mass flow rate of the steam differs according to the different loads of the marine diesel engine as shown in Table 1.

Figure 5 highlights the amount of the mass flow rate of steam at different loads at temperature of 100 ˚C, and it also clarifies that the amount of the mass flow rate of the steam increases due to the increase of the load of the diesel engine as a result of the rise in the temperature of the scavenge air which is affected by the load of the diesel engine.

The following input data in Table 4 in addition to the mass flow rate of the steam in Table 3 are used to operate the MEE-FF. The results are also obtained from using the prementioned data of the diesel engine in Table 1. It is noticed that due to the increase of the load of the diesel engine there is an opportunity for using more amount feed seawater; accordingly, this allows for producing more amounts of distillate water as shown Figure 6.

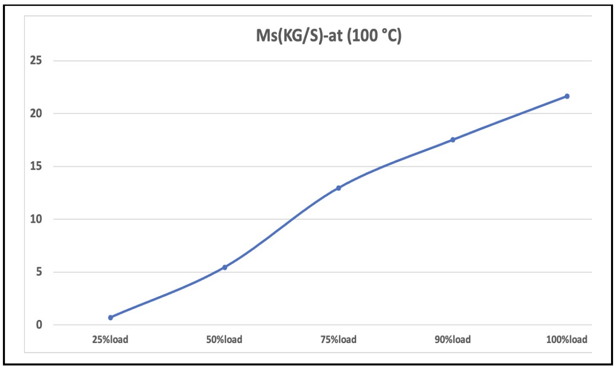

Fig. 2. The amount of the mass flow rate of steam at different loads at temperature of 100 ˚c

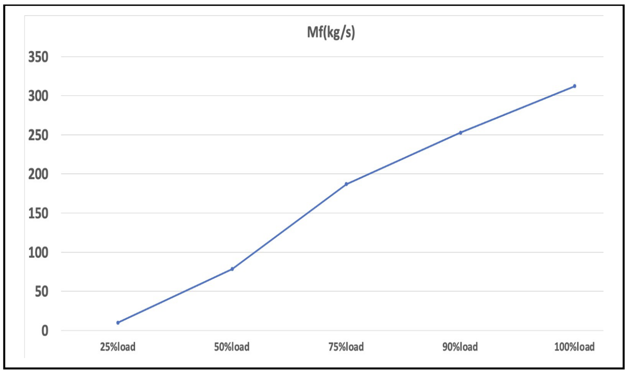

Fig. 3. Feed Seawater

The amount of the distillate water increases because of the increase in the load of the diesel engine as shown in Figure 7. Moreover, the average heat transfer area increases due to the increase in the load of the diesel engine as shown in Figure 8.

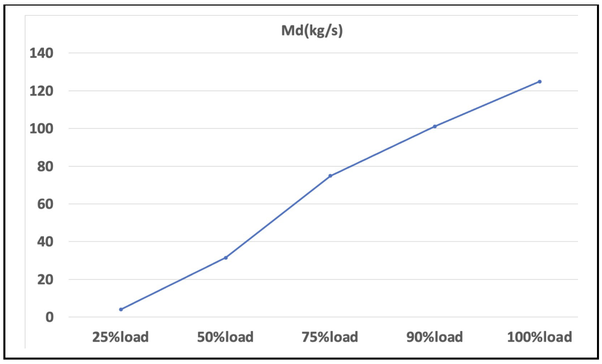

Fig. 4. Distillate Water

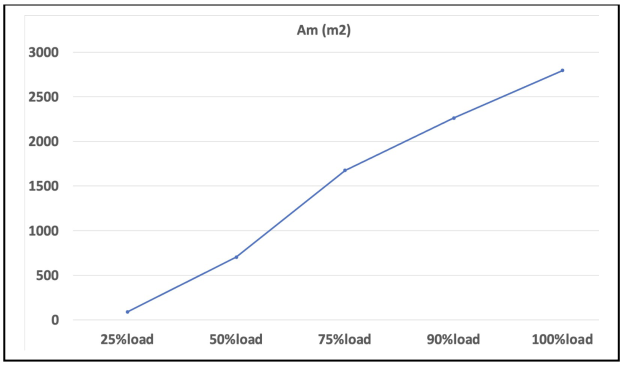

Fig. 5. Average Heat Transfer Area

It is noticed that the amount of the distillate flow rate for each unit n increases at every load as shown in Figure 9. The results show that the amount of brine flow rate for each unit n increases at every load as shown in Figure 10.

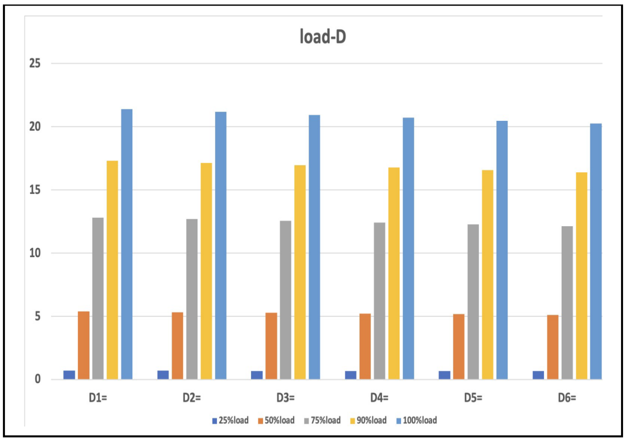

Fig. 6. Distillate Flowrate

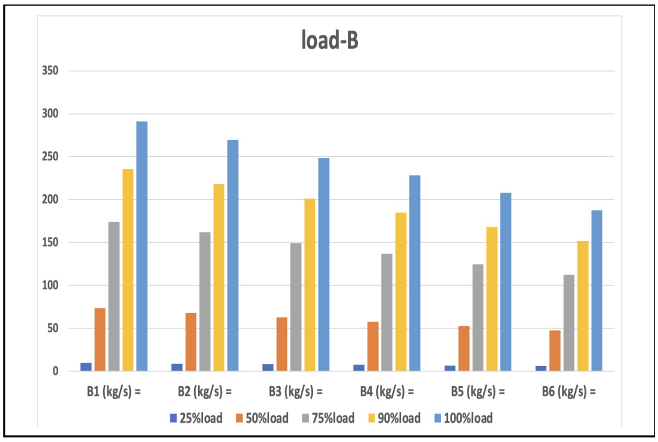

Fig. 7. Brine Flowrate

As mentioned before, the exhaust gas is used as a thermal source to operate one of the two configurations MSF-OT or MSF-BR. A comparison is drawn to decide on which of those two configurations is better. Note that they have the same number of units which is n=24. Moreover, a program is made for each configuration on MATLAB program and a mathematical excel sheet model. The same inputs are used for both programs to compare the results. Those inputs are previously mentioned in Table 4.

The results of the case study are based on the models of the MATLAB program and the excel sheet which use the mentioned input data of the previous marine diesel engine and the pre-mentioned input data of the MSF-OT and MSF-BR. These results are used to compare these two configurations and decide on the most efficient one.

The specific heat transfer area of the MSF-BR is higher than the specific heat transfer area of the MSF-OT by 50.19% according to the different given loads of the marine diesel engine as shown in Figure 11. This means that MSF-OT requires less space for construction compared to the MSF-BR. The performance ratio of the MSF-BR is higher than the MSF-OT by 55% on different loads of the marine diesel engine as shown in Figure 12.

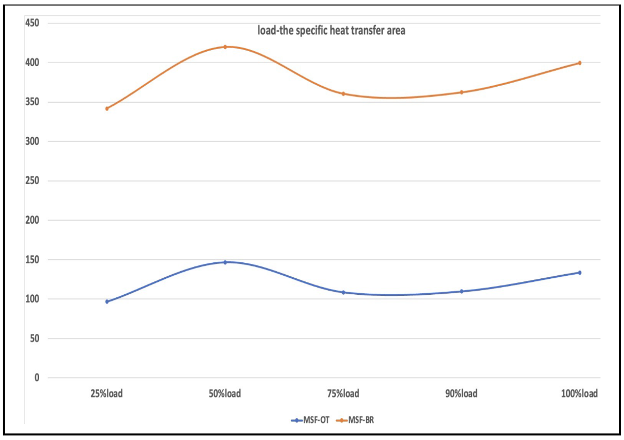

Fig. 8. The Specific Heat Transfer Area of MSF-OT and MSF-BR

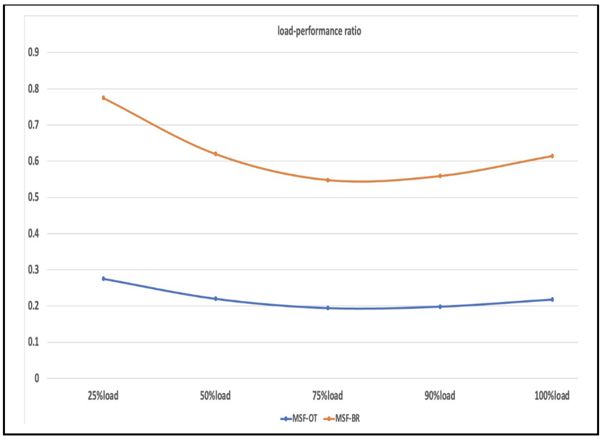

Fig. 9. The Performance Ratio of MSF-OT and MSF-BR

The brine mass flow rate of the MSF-OT is remarkably more than the MSF-BR which decreases by 34.36% on different loads of the marine diesel engine as shown in Figure 13. It is also noticed that the feed seawater of the MSF-OT is more than the feed seawater of the MSF-BR which decreases by 50.87% on different loads of the marine diesel as shown in Figure 14. Moreover, The MSF-BR produces higher distillate water than the MSF-OT by 55% although it has a lower mass flow rate of feed seawater than the MSF-OT as shown in Figure 15.

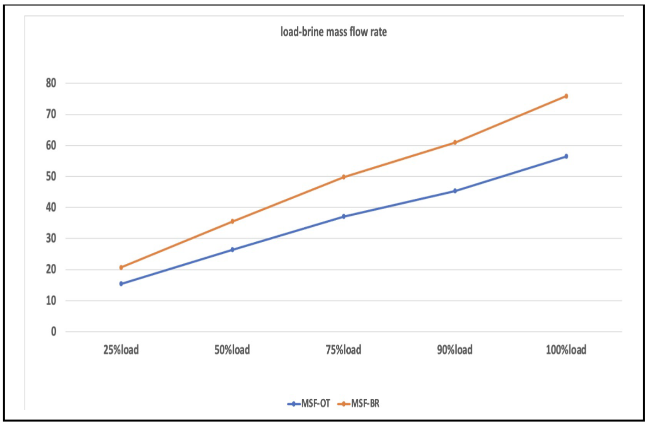

Fig. 10. Brine Mass Flow Rate Of MSF-OT and MSF-BR

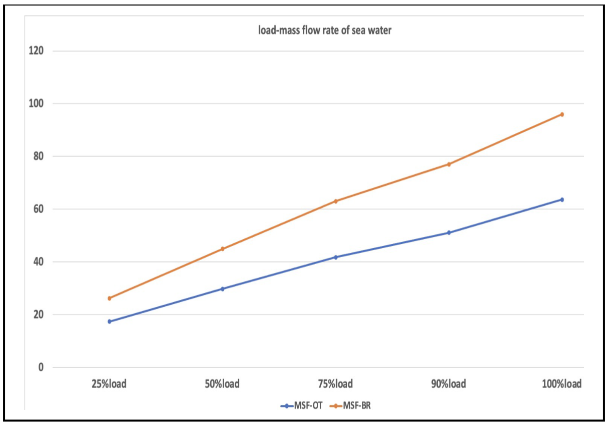

Fig. 11. Feed Seawater of MSF-OT and MSF-BR

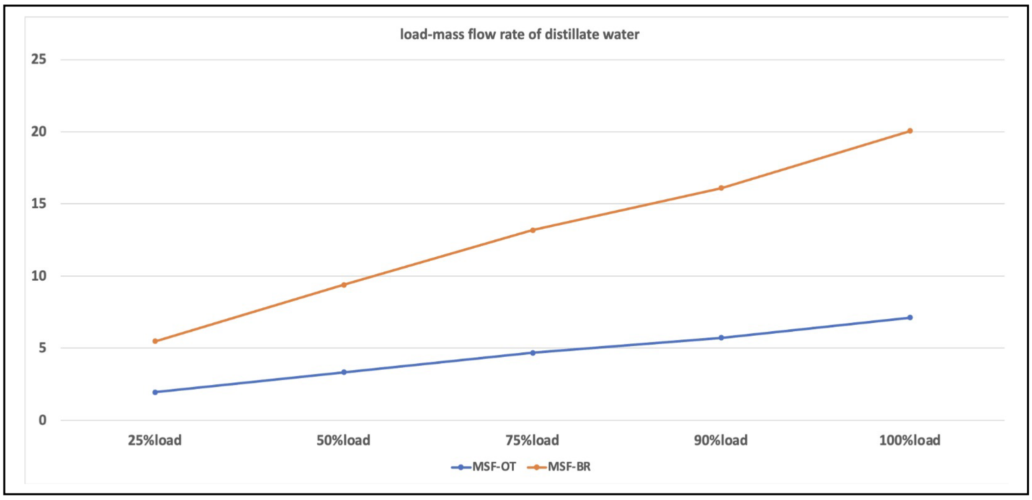

Fig. 12. Distillate Mass Flow Rate of MSF-OT and MSF-BR

7. A Comparison Between the Suggested Desalination Models and the Reverse Osmosis Desalination Units

In this study, a comparison is made between the suggested desalination models and the familiar types of desalination which is reverse osmosis desalination system on board ships. The comparison is made in terms of consumed power, consumed fuel, cost of fuel and CO_2 emissions.

7.1 Evaluating the Consumed Power

To calculate the power consumed from the diesel engine, the mass flow rate of the total production of the distillate water produced from proposal (1) and proposal (2) should be calculated first. A comparison is made for the power consumed from the diesel engine between the reverse osmosis and the two proposed models. These calculations are shown in the following table:

Table 7
Power consumed for both proposals

Cases	Proposals	$M_{\dot{d}\,t}$ (kg/s)	$M_{\dot{d}\,t}$ (m^3/h)
Case 1	$M'_{d\,(MSF-OT)} + M'_{d\,(MEE-FF)}$	5.71 + 101.06 = 106.77	384.37
Case 2	$M'_{d\,(MSF-BR)} + M'_{d\,(MEE-FF)}$	10.39 + 101.06 = 111.45	401.22

The following equation which is adapted from Schmid [8] could be used to calculate the power consumption:

$$P_{consumption} = S.E.C * M'_{d\,(t)} \tag{10}$$

The specific energy consumption (S.E.C) is assumed to be equal 3 kwh/m^3 in this study, so the results for both cases are shown as the following depending on Eq. (10):

$\mathbf{P_{consumption\ (case1)}}$ = 3 * 384.37 = 1153.11 kwh
$\mathbf{P_{consumption\ (case2)}}$ = 3 * 401.22 = 1203.66 kwh

The previous results show how much power consumed from the diesel engine is saved because the two proposals use waste heat energy, which is the scavenge air and the exhaust gas produced from the diesel energy.

7.2 The Economical Aspect of the Proposals

The economical aspect for the two proposals is presented by the form of reduction in the fuel consumption (heavy fuel oil, 1% of Sulphur) which is used to operate the diesel engine 6RT-flex58T-E made by HYUNDAI-WARSTILA. The reduction in the power from the diesel engine leads to using less fuel as the waste heat energy is used as a thermal source to operate the two proposed models. The following equation, which is adapted from Schmid [8], is used to calculate the consumption of the fuel used to operate the diesel engine:

$$Fuel_{consumption} = Fuel\ g * P_{consumption} \tag{11}$$

The results of fuel consumption for both cases are shown as the following depending on Eq. (11):

Case 1= 171.5 * 1153 = 197.758 kg/h
Case 2 = 171.5 * 1203.66 = 206.427 kg/h

A significant reduction in fuel cost is remarkably recognized due to the reduction in fuel consumption. According to the French National Institute of Statistics and Economic Studies (INSEE), the price of HFO in August 2023 was 545.96 $/Ton [29].

$$Fuel_{saving} = Fuel\ kg/h * Cost\ (U.S.\ dollars) \qquad (12)$$

$\mathbf{Fuel_{saving\ (case\ 1)}}$ = 197.758*545.96= 107967.959 $
$\mathbf{Fuel_{saving\ (case\ 2)}}$ = 206.427 * 545.96= 112700.885 $

The previous results show how much fuel is saved in operating the diesel engine because the two proposals used in desalinating seawater depend on the waste heat energy which is the scavenge air and the exhaust gas.

7.3 Reduction in CO_2 Emission

The CO_2 emission reduction reveals the environmental impact of the two proposals because utilizing the waste heat energy of the scavenge air and the exhaust gas produced from the diesel engine leads to using less fuel in operating the diesel engine and desalinating the seawater on the board ship unlike the reverse osmosis which requires much fuel resulting in producing much CO_2. The specific CO_2 emission for burning HFO is 3.114 kg-CO_2/kg-fuel [8]. Therefore, when the CO_2 emission decreases, the fuel saving decreases too and vice versa as shown in the following two proposals:

$$CO_{2\ reduction} = Fuel_{consumption} * Specific\ CO_2\ emission\ for\ HFO \qquad (13)$$

Case 1 = 3.114 * 197.758 = 615.818 kg/h
Case 2 = 3.114 * 206.4276 = 642.81 kg/h

From the previous equations, it is shown that Case 1 saved 615.818 kg/h, and Case 2 saved 642.81 kg/h. It is noticed that Case 2 saves more fuel consumption which leads to reducing CO_2 emissions.

8. Conclusions

In this paper, the freshwater generation from marine diesel engine has been studied. The proposal of this study depends on exploiting exhaust gas and scavenge air in water desalination, and they are both waste heat energy extracted from diesel engine.

Three methods have been used for desalination and they were compared together: Multiple Effect Evaporation-Forward Feed (MEE-FF), Multi-Stage Flash-Once Through (MSF-OT), and Multi-Stage Flash-Brine Recirculation (MSF-BR). Waste heat from the marine diesel engine is used for the operation of those desalination plants.

A MATLAB program and A mathematical excel sheet model have been developed for each desalination unit, and the programs were also validated and then they were used to calculate the heat transfer. They also deal with various diesel engines as well as conditions of water for all seasons. In this study, they work with the three mentioned configurations. Regarding the MEE-FF, it deals with six stages, while the MSF-OT and MSF-BR, it can deal with a stage number up to 32 stages according to demand, cost, and available area.

The results show that in the MEE-FF, it is noticed that M_f, M_d, and A_m are increased by the increase of the diesel engine load. Regarding the comparison between MSF-OT and MSF-BR, the *PR*, *sA*, M_d of MSF-BR are increased by 55%, 50.19%, 55% respectively for the same input data by increasing the marine diesel engine load, while the M_f and M_b of the MSF-BR decreased by 50.87% and 34.36% respectively.

The results also show that there is a remarkable reduction in the consumed power, consumed fuel, cost of fuel and CO_2 emissions because the two proposals use waste heat energy, which is the scavenge air and the exhaust gas produced from diesel energy.

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References

[1] Köfteci, Sevil. "Experimental study on the low-cost iron wire fiber reinforced asphalt concrete." *Teknik Dergi* 29, no. 4 (2018): 8515-8535. https://doi.org/10.18400/tekderg.350135

[2] Habib, Somar Moaen, Ahmed Hamed, Ahmed Yahia Youssef, Mahmoud Kassem, and Abdalla Hanafi. "Dynamic Modeling and Simulation of the Forward Feed MED-TVC Desalination Plant." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 92, no. 1 (2022): 190-211. https://doi.org/10.37934/arfmts.92.1.190211

[3] Dzaky, Muhammad Irfan, Engkos Achmad Kosasih, and Ahmad Zikri. "Thermodynamic Simulation in Eco-Friendly Aquadest Production Through Compression System Method Combined with Steam Power Plant as Heat Source." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 100, no. 1 (2022): 63-76. https://doi.org/10.37934/arfmts.100.1.6376

[4] International Energy Agency (IEA). “World Energy Investment,” *International Energy Agency (IEA)*, (2022).

[5] Wirangga, Ristanto, Dan Mugisidi, Adi Tegar Sayuti, and Oktarina Heriyani. "The Impact of Wind Speed on the Rate of Water Evaporation in a Desalination Chamber." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 106, no. 1 (2023): 39-50. https://doi.org/10.37934/arfmts.106.1.3950

[6] Abd Wahid, Khairul Anuar, Ilham Fahmi, Zaid Puteh, Muhammad Nur Farhan Saniman, Kamal Rusulan, Khairul Azhar, and Wan Mansor Wan Muhammad. "Self-desalination seawater jig based on solar thermal energy." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 1 (2022): 92-101. https://doi.org/10.37934/arfmts.91.1.92101

[7] Grljušić, Mirko, Vladimir Medica, and Nikola Račić. "Thermodynamic analysis of a ship power plant operating with waste heat recovery through combined heat and power production." *Energies* 7, no. 11 (2014): 7368-7394. https://doi.org/10.3390/en7117368

[8] Schmid, Heinrich. "Less emissions through waste heat recovery." In *Wartsila Switzerland Ltd, Green Ship Technology Conference, London, 2004*. 2004.

[9] U. S. G. Survey. “The World’s Water.” (2016). http://water.usgs.gov/edu/earthwherewater.html

[10] Thabit, Qahtan, Abdallah Nassour, and Michael Nelles. "Water Desalination Using the Once-through Multi-Stage Flash Concept: Design and Modeling." *Materials* 15, no. 17 (2022): 6131. https://doi.org/10.3390/ma15176131

[11] Charitar, Deepti, and Amos Madhlopa. "Integration of waste heat in thermal desalination technologies: A review." *Journal of Energy in Southern Africa* 33, no. 1 (2022): 68-84. https://doi.org/10.17159/2413-3051/2022/v33i1a5434

[12] Mito, Mohamed T., Mohamed A. Teamah, Wael M. El-Maghlany, and Ali I. Shehata. "Utilizing the scavenge air cooling in improving the performance of marine diesel engine waste heat recovery systems." *Energy* 142 (2018): 264-276. https://doi.org/10.1016/j.energy.2017.10.039

[13] Varshil, P., and D. Deshmukh. "A comprehensive review of waste heat recovery from a diesel engine using organic rankine cycle." *Energy Reports* 7 (2021): 3951-3970. https://doi.org/10.1016/j.egyr.2021.06.081

[14] El-Dessouky, Hisham T., and Hisham Mohamed Ettouney. *Fundamentals of salt water desalination*. Elsevier, 2002.

[15] Shu, Gequn, Youcai Liang, Haiqiao Wei, Hua Tian, Jian Zhao, and Lina Liu. "A review of waste heat recovery on two-stroke IC engine aboard ships." *Renewable and Sustainable Energy Reviews* 19 (2013): 385-401. https://doi.org/10.1016/j.rser.2012.11.034

[16] Moharram, Nour A., Seif Bayoumi, Ahmed A. Hanafy, and Wael M. El-Maghlany. "Hybrid desalination and power generation plant utilizing multi-stage flash and reverse osmosis driven by parabolic trough collectors." *Case Studies in Thermal Engineering* 23 (2021): 100807. https://doi.org/10.1016/j.csite.2020.100807

[17] Roy, Yagnaseni, Gregory P. Thiel, and Mohamed A. Antar. "The effect of increased top brine temperature on the performance and design of OT-MSF using a case study." *Desalination* 412 (2017): 32-38. https://doi.org/10.1016/j.desal.2017.02.015

[18] Al-Sahali, Mohammad, and Hisham Ettouney. "Developments in thermal desalination processes: Design, energy, and costing aspects." *Desalination* 214, no. 1-3 (2007): 227-240. https://doi.org/10.1016/j.desal.2006.08.020

[19] Hussein, Arwa, and Hasnaa Kandil. "Seawater desalination using waste heat recovery on passenger ship." *Port-Said Engineering Research Journal* 24, no. 1 (2020): 82-101.

[20] Darwish, M. A., Fouad A. Yousef, and N. M. Al-Najem. "Energy consumption and costs with a multi-stage flashing (MSF) desalting system." *Desalination* 109, no. 3 (1997): 285-302. https://doi.org/10.1016/S0011-9164(97)00075-1

[21] Jammoul, R., and O. A. El-Samni. "The design of a small-scale multi-stage desalination plant driven by the exhaust of diesel generators." *Int. J. Comput. Methods Exp. Meas* 59 (2015): 419-432. https://doi.org/10.2495/CMEM150381

[22] Jadhao, J. S., and D. G. Thombare. "Review on exhaust gas heat recovery for IC engine." *International Journal of Engineering and Innovative Technology (IJEIT)* 2, no. 12 (2013).

[23] Hyundai Heavy Industry. "Application for Inspection and Test: Engine and Machinery Division." (2013).

[24] Al-Mutaz, Ibrahim S., and Irfan Wazeer. "Comparative performance evaluation of conventional multi-effect evaporation desalination processes." *Applied Thermal Engineering* 73, no. 1 (2014): 1194-1203. https://doi.org/10.1016/j.applthermaleng.2014.09.025

[25] Butcher, C. J., and B. V. Reddy. "Second law analysis of a waste heat recovery based power generation system." *International Journal of heat and mass transfer* 50, no. 11-12 (2007): 2355-2363. https://doi.org/10.1016/j.ijheatmasstransfer.2006.10.047

[26] El-Dessouky, Hisham, Imad Alatiqi, S. Bingulac, and Hisham Ettouney. "Steady-state analysis of the multiple effect evaporation desalination process." *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology* 21, no. 5 (1998): 437-451. https://doi.org/10.1002/(SICI)1521-4125(199805)21:5<437::AID-CEAT437>3.0.CO;2-D

[27] Al-Mutaz, Ibrahim S., and Irfan Wazeer. "Comparative performance evaluation of conventional multi-effect evaporation desalination processes." *Applied Thermal Engineering* 73, no. 1 (2014): 1194-1203. https://doi.org/10.1016/j.applthermaleng.2014.09.025

[28] Hassanean, Mohamed, Ahmed Nafey, Rehab El-Maghraby, and Fatma Ayyad. "Simulation of multi-stage flash with brine circulating desalination plant." *Journal of Petroleum and Mining Engineering* 21, no. 1 (2019): 34-42. https://doi.org/10.21608/jpme.2020.73173

[29] Market Price and Insight. "Heavy fuel oil (Rotterdam Fuel Oil Price) - Prices in US dollars per tonne." (2023).