J Ther Eng, Vol. 10, No. 5, pp. 1266−1274, September, 2024

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000857

Research Article

Estimation and analysis of exergy loss and performance evaluation of marine freshwater generating system

Jitendra Singh PAL[1,*], S. N. SAPALI[2], P. W. DESHMUKH[3]

[1]Department of Marine Engineering, Tolani Maritime Institute, Pune, Maharashtra, 410507, India
[2]Department of Mechanical Engineering, Shivaji University, Kolhapur, Maharashtra, 416004, India
[3]Department of Mechanical Engineering, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded, Maharashtra, 431606, India

ARTICLE INFO

Article history
Received: 10 November 2021
Revised: 12 March 2022
Accepted: 12 March 2022

Keywords:
Evaporator; Exergy Efficiency; Exergy Loss; Plate Type Heat Exchanger; Waste Heat

ABSTRACT

This paper provides the groundwork for the most efficient design of freshwater generating systems that take advantage of waste heat from the main engines. In the desalination process, freshwater generators, whether in the form of shell and tube-type or plate-type, are employed. Merchant vessels primarily utilize submerged shell and tube-type evaporators to generate fresh water. The foundation for comprehending separation processes, energetics, and economics lies in the quantitative interpretation of the second law of thermodynamics, with a specific focus on exergy and its dissipation. This research suggests employing exergy analysis to utilize waste heat as a valuable resource in a single-effect desalination process to meet freshwater needs, considering practical aspects. The study involves analyzing a freshwater generator of the Shell and tube type situated at the Tolani Maritime Institute in Pune, India. Thermal properties are calculated and visually represented through a flow diagram using a C^{++} program. The assessment of exergy unveils the extent and distribution of unattainable work within a freshwater generator employing a shell and tube design, particularly concentrated in its key components: the evaporator, condenser, and brine section. These findings are contrasted with those from a Plate Type Heat Exchanger (PTHE) freshwater generator. The rate of exergy destruction in Plate Type Heat Exchanger freshwater generators is 29.33%, whereas in shell and tube-type freshwater generators, it is higher at 44.88%.

Cite this article as: Pal JS, Sapali SN, Deshmukh PW. Estimation and analysis of exergy loss and performance evaluation of marine freshwater generating system. J Ther Eng 2024;10(5):1266−1274.

INTRODUCTION

Freshwater is required for domestic and technical purposes in marine vessels. The entirety of the generated heat energy serves as propulsion shaft power, with 5.2% of it dissipated through the jacket cooling water of the main engine. This heat energy from the jacket water is employed to produce freshwater through a low-pressure shell and tube-type

***Corresponding author.**
*E-mail address: jitendrasinghpal2011@gmail.com

This paper was recommended for publication in revised form by Regional Editor Hafiz Muhammad Ali

Published by Yıldız Technical University Press, İstanbul, Turkey

freshwater generator [1]. This low-pressure evaporation of seawater equation of state at one atmosphere was presented by Millero and Poisson [2], shown in Figure 1.

Kahraman et al. [3, 4], applied a cerci model to examine multi-stage flash desalination, achieving a second law efficiency of only 4.2%. They highlighted that the exergy associated with salinity turns negative when the stream salinity exceeds the incoming seawater salinity. Nafey et al. [5] utilized a sophisticated visual design and simulation package to assess the exergy loss of 4.04 mW in the Eoun Mousa MSF plant. Additionally, they employed a mathematical model to calculate the cost balance equation. Sharqawyet al. [6, 7, 8], calculated seawater exergy of reverse osmosis desalination plant by using MATLAB and thermodynamic properties of seawater given in IAPWS [9].

The two approaches are the first one by Cerci, the ideal mixture model, and the second approach by Mostafa seawater in which the chemical exergy is taken into consideration for the calculation of exergy of the desalination plant. The calculation of seawater enthalpy differs significantly between the models for seawater and aqueous sodium chloride solutions. The Mostafa model is used in this study to measure stream exergy at different plant locations, as shown in Figure 1 and Table 1. The derived equations are used to determine the hybrid components' irreversibility (exergy destruction). In the study conducted by Hosseiniet al. [10], the steam generated and fuel were described and expressed completely in the exergy analysis of the hybrid system. This description will explain how exergy efficiency is truly realized.

Gude [11] conducted an exergy analysis of desalination plants, identifying condensers as the primary source of the highest losses. Choudhari and Sapali [12] investigated the exergy aspects of a water-cooled refrigerator, concluding that the water-cooling system results in lower energy consumption and discharge gas temperatures for the compressor. Shikalgar and Sapali [13] presented experimental results comparing a water-cooled condenser unit with a hot-wall air-cooled condenser unit to identify exergy losses in refrigeration. The findings indicated higher exergy losses in the water-cooled condenser unit, and the analysis involved both energy and exergy methods. Koroglu and Sogut [14] examine a marine power plant utilizing an organic Rankine cycle energy and exergy assessments are performed to discover components and parameters that affect the system's efficiency. Rawabawale and Sapali [15] noted that the analytical exergy loss is less than the experimental exergy loss. They also found that the exergy loss fluctuates based on the duration and height of the cross-current cooling tower. According to Yuksel et al. [16] parametric 's analysis, seawater temperature of 31.88 ^{0}C and a jacket water mass flow rate of 72,000 kg/h are necessary to achieve the maximal freshwater generation capacity. According to Solanki and Pal [17], numerical execution uses pinch methods to fuse the solar energy system to generate thermal power in the dairy industry.

The aim of this study on freshwater generators for marine vessels are shell and tube type and plate type is to find the most efficient use of waste heat on board as well as for water generation. To locate the components that are more exergy deficient, a method is developed to quantify

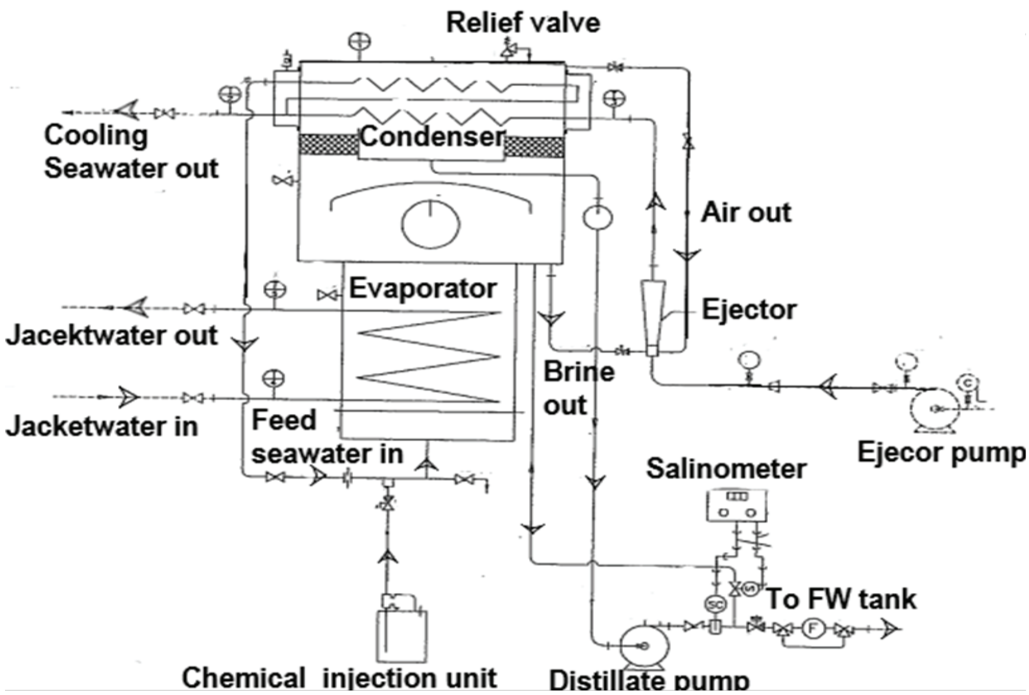

Figure 1. Balancing mass and energy in a shell and tube-type freshwater generator.

the thermal characteristics and specific exergy of a fluid stream. Exergy analysis is used to propose a freshwater generator using a plate-type heat exchanger, compared to the existing shell and tube-type freshwater generator [18].

Theory

The low-pressure steam distillation system was installed on several commercial and navy ships between 1940. Auxiliary exhaust steam was delivered at 5 kg/cm^2 and 160°C to these units. During that time, three fundamental types of low-pressure distillation units are available: shell and tube type heat exchangers, multi flash-type units, and vertical shell units. The most popular, the submerged tube unit, shell-tube type freshwater generator, was employed in this research.

Submerged tube distillation machines with capacities ranging from 4,000 to 50,000 litres per day were designed and manufactured. The effects could be single, double, or triple. A stage of the distillation process is called as an effect. A single effect evaporator evaporates seawater using the low-pressure steam fed in the submerged tube bundle. In a double-effect unit, the steam produced in the first effect is used to generate lower pressure steam from seawater in the second effect. The steam from the second effect is utilized to evaporate seawater in the third effect if a third effect is added. The vacuum maintained in the evaporator shell by the water ejector pump, the water ejector for air brine, etc., makes up the freshwater generator, which is represented by the evaporator shell and condenser in Figure 1. The distillate water is pumped out by the pump and then goes via the solenoid pump, electrical salinity indicator, and water flow meter, as seen in Figure 2.

The research begins with examining the freshwater generator, auxiliary boiler, and composite boiler in the Prabhu-Vidya ship-in-campus. After the investigation is completed, a steady-state model was created in Microsoft Excel. After the steady-state model in Microsoft Excel performs as predicted, a steady-state model in "C" is built. Each software's plant model produces a set of data that were validated with data received from intern cadet's ships data. The exergy of freshwater at a specific point in the system is expressed as system-specific exergy and represented by Eq. (1) [19].

a. Methodology
b. Material balances and energy balances
c. Boiling point elevation and thermodynamic losses
d. Exergy calculation of evaporator & other components of the freshwater generator
e. Boiler saturation temperature and pressure drop calculation of marine boiler
f. Exergy parameter calculation of freshwater generator and marine boiler. As per the assumptions that freshwater generator process is steady-state: Ψ (Specific Exergy) can be represented in a mathematical model as given by Sharqawy et al. [8]:

$$\begin{aligned}\Psi(\text{Specific Exergy}) = {} & (u - u_0) + P_0(v - v_0) - T_0(s - s_0) \\ & + w_s\{\varphi s * (To, Po, w) - \varphi^0 s(To, Po, w_0)\} \\ & + (1 - w_s)\{\varphi_w{}^*(T_0, T_0, w) - \varphi_w{}^0(T_0, T_0, w_0)\} \qquad (1)\end{aligned}$$

g. In the RUN mode, the screen asks for the data in the same order given in the flow chart. Once the data are fed in, the computer goes on to perform the various checks and iterations and calculate the specific exergy.
h. Print the values of chemical, physical, and total exergy of the steam. The values are shown in Figure 2 and Table 1.

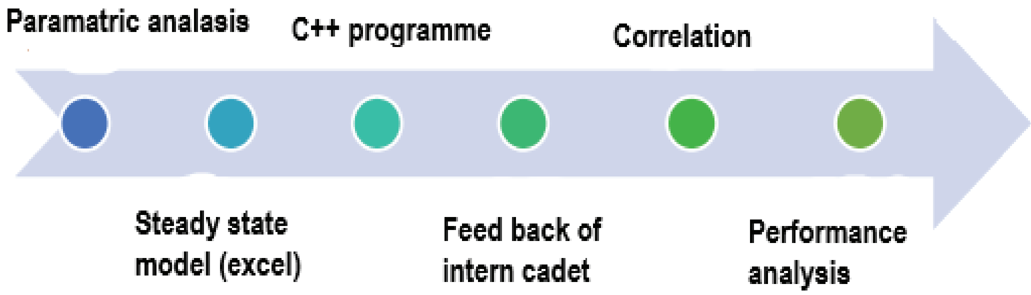

Figure 2. Flowchart to calculate the properties of the stream of freshwater generator.

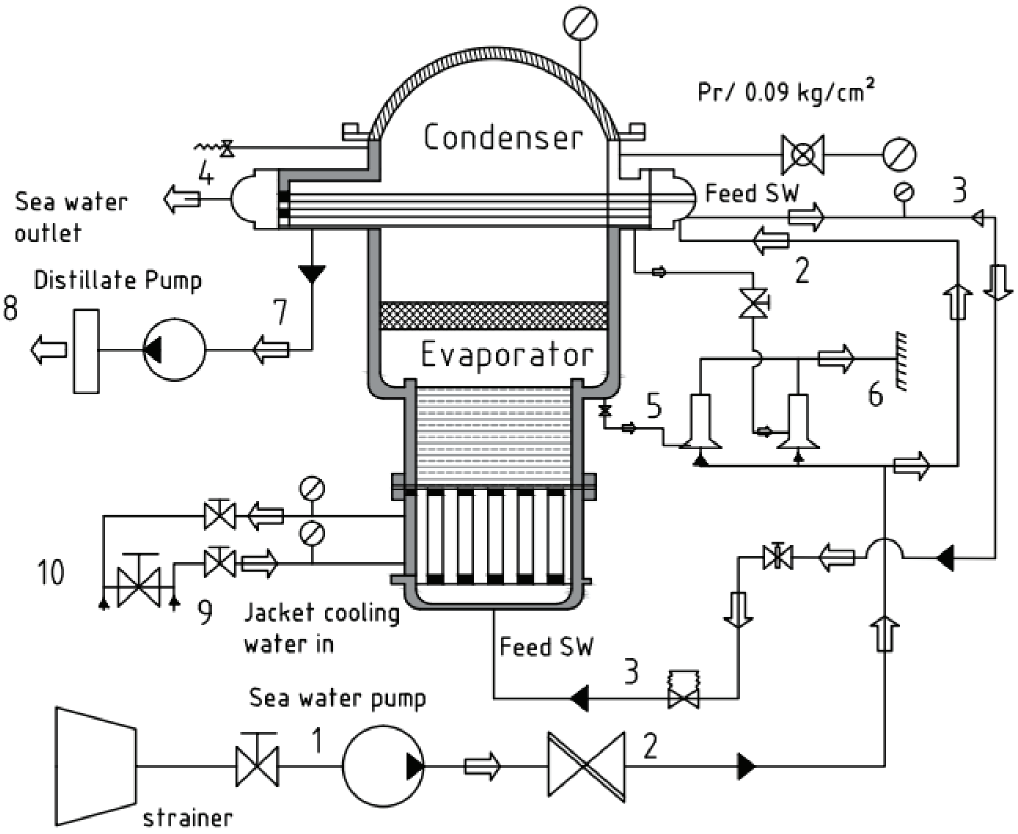

Figure 3. Shell and tube type freshwater generator system.

If no beneficial work is accomplished during the process, this alteration represents a depletion in available work as indicated by Eq. (2).

$$\dot{X}_{loss} = (\dot{X}_{input}) - (\dot{X}_{output}) \tag{2}$$

Mustafa and AI Ghamdi [20] introduced the Performance Ratio (τ_{ratio}).

$$\tau_{ratio} = \frac{\text{Net product water flow}}{\text{Maximum Exergy}} \tag{3}$$

Li [21] presents the second law efficiency (ϑ_{ex}), defined as the ratio of exergy output to exergy input.

$$\vartheta_{ex} = \frac{(\dot{X}_{output})}{(\dot{X}_{input})} \tag{4}$$

When evaluating different processes, the Improvement Potential proves valuable. The most significant enhancement in exergy efficiency for a process or system occurs when the rate of exergy loss or irreversibility is minimized. Hammond [22] introduces this improvement potential on a rate basis through Equation (5).

$$\epsilon_{IP} = (1 - \vartheta_{ex})(\dot{X}_{in\ by\ mass} - \dot{X}_{out\ by\ mass}) \tag{5}$$

Experimentation

The shell-and-tube freshwater generator achieved a steady-state condition within one hour of operation, with the fluid flowing steadily through a controlled volume in this processWater from the jacket enters the evaporator at approximately 85°C and exits at 71.1°C, facilitating freshwater production under vacuum conditions maintained by the ejector. Experiments were conducted to study parameters such as pressure, jacket water temperature, and the motive fluid (seawater) for the ejector in a parametric investigation. The readings from the experiments were taken at the freshwater generator's maximum capacity of 20 tons per day. Table 2 and Figures 2 and 3 demonstrate the various parameters of the experimental study. The condensate produced is if less than 10 PPM total dissolved solids then it will be delivered to the freshwater tanks.

RESULTS AND DISCUSSION

The integration of exergy analysis into the freshwater generation system entails incorporating exergy-block calculations subsequent to conventional energy-balance calculations. A 'C++' program is employed to determine the exergy characteristics of a shell-and-tube freshwater generator. Exergy input and losses for shell-and-tube-type freshwater generators are illustrated in Tables 1 to 2 and Figure 4. Additionally, Figure 5, along with Tables 3 and 4, presents a specific flow exergy diagram for a plate-type freshwater generator, depicting its exergy input and losses. Figures 4 and 5 highlight the origin of errors associated with considering processes solely from an energy balance perspective.

By utilizing waste heat from the propulsion engine's fuel energy, the energy derived from the propulsion engine jacket cooling water is utilized to convert seawater into freshwater. Cross-hatched triangles represent the exergy streams of major components of the freshwater generator, illustrating the distribution of exergy losses.

This depiction visually represents the available work as it moves through various system components. The different widths of the flow work lines serve as a visual indicator of the extent of streamflow, encompassing both useful work and exergy losses within these components. Figures 4 and 5 vividly and precisely depict the size and locations of exergy losses in crucial components such as the evaporator, condenser, and ejector. The flow diagram for the freshwater production system depicted in Figure 1 is derived from the first-law thermal balance. A comparison of these two flowcharts underscores the substantial impact of the exergy approach in precisely identifying the location and extent of inefficiencies within the energy system. Figures 4 and 5 accurately depict the actual distribution of losses, avoiding inaccuracies inherent in the energy-balance approach. Quantitative values for individual losses contributing to the overall component loss are outlined in Tables 2 and 4. These visuals will play a crucial role in discussions on energy-saving strategies utilizing exergy analysis, emphasizing that shell-and-tube-type freshwater generators exhibit a higher improvement potential of 83.28 kW, whereas plate-type freshwater generators require only 27.07 kW. The flow exergy diagram highlights a significant exergy loss of 90.63 kW in the ejector section of the shell-and-tube-type freshwater generator. It should be noted that the divergence is acknowledged when transitioning from the ideal reversible cycle to the actual irreversible cycle. The analysis of this freshwater generation system elucidates the exergy losses inherent in a particular plant configuration. Figure 6 presents a comparison of the second-law efficiency between plate-type and shell-type freshwater generator systems. It

Table 1. Thermal characteristics of streams 1 to 11 at different points within the shell-and-tube freshwater generator

Stream	Temp (°C)	Pressure (N/m^2)	Mass (kg/s)	Salt content	Enthalpy	Entropy	Exergy
					(kJ/kg)	(kJ/kg)	(kJ/kg)
1	32	101.325	17.88	0.0465	125.59	0.43	0.45
2	32	4000	17.88	0.0465	134.19	0.46	4.23
3	32	4000	1.22	0.0465	125.59	0.43	4.23
4	42.4	4000	16.66	0.0465	166.68	0.56	5.86
5	49	10.13	0.93	0.0701	186.67	0.31	4.64
6	43	4000	17.59	0.0701	167.74	0.59	4.65
7	49	10.13	0.28	0	205.22	0.69	6.47
8	52.4	2000	0.28	0	219.43	0.73	9.62
9	85	3000	13.88	0	356.01	1.13	28.5
10	71.1	3000	13.88	0	297.64	0.96	19.2
11	49	10.13	0.289	0	2592.1	7.371	749.11

Table 2. Exergy characteristics rate calculations at various components of the shell and tube type freshwater generator

Component	Exergy Input	Exergy Output	Exergy loss	Improvement Potential	II law efficiency
	(kW)	(kW)	(kW)	(kW)	
Evaporator	129.9	119.1	10.81	0.9	91.6
Condenser	114.4	44.83	69.6	42.31	39.2
Ejector	153.7	63.08	90.63	53.47	41
Seawater pp	11.08	0.42	10.65	10.33	3.1
Distillate pp	4.1	0.31	3.78	0.87	7.7
Total FWG	413.3	227.7	185.5	83.28	55.11

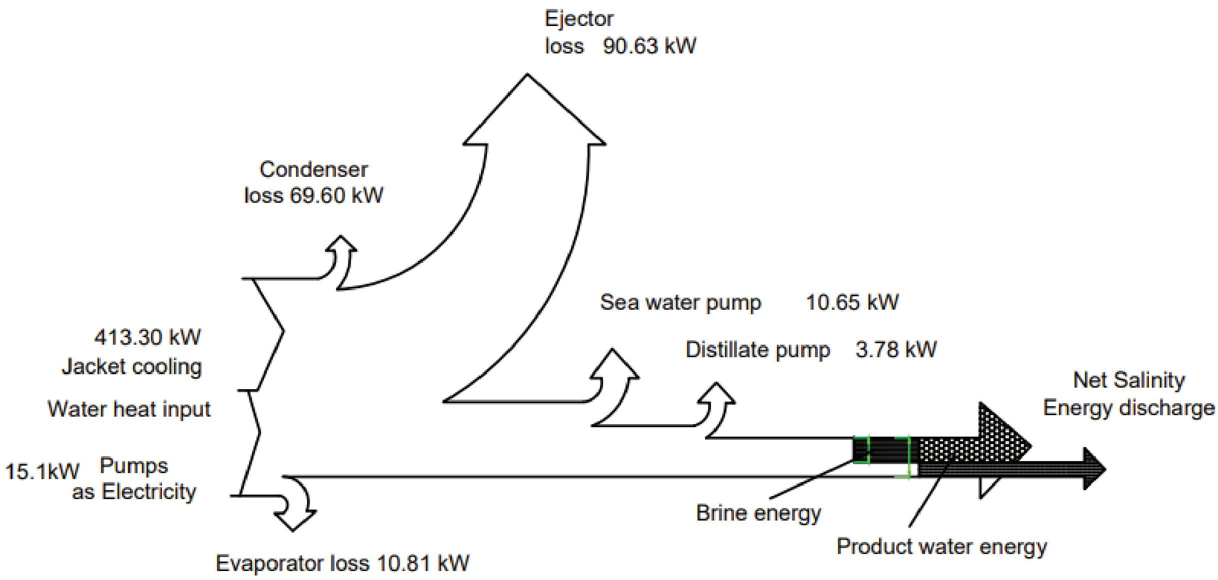

Figure 4. Exergy characteristics flow diagram of shell and tube type freshwater generator system.

Table 3. Thermal characteristics properties of streams 1 through 11 at various locations of the plate type freshwater generator

Stream	Temp (°C)	Pressure (N/m^2)	Mass (kg/s)	Salt content	Enthalpy (kJ/kg)	Entropy (kJ/kg)	Exergy (kJ/kg)
1	32	101.325	17.88	0.0465	125.59	0.43	2245.54
2	32	4000	17.88	0.0465	134.19	0.46	2399.31
3	32	4000	1.22	0.0465	134.19	0.46	163.71
4	42.3	4000	16.66	0.0465	166.28	0.55	2770.22
5	55	10.13	0.932	0.0701	230.23	0.767	214.57
6	43	4000	17.59	0.0701	168	0.567	2955.12
7	55	10.13	0.28	0	230.302	0.767	64.48
8	58.4	2000	0.28	0	244.51	0.811	68.46
9	78	3000	13.88	0	326.54	1.051	4532.37
10	69	3000	13.88	0	288.851	0.942	4009.25
11	49	10.13	0.289	0	2592.1	7.371	749.11

Table 4. Exergy characteristics rate calculations at various components of the plate type freshwater generator

Component	Exergy Input kW	Exergy Output kW	Exergy loss kW	Improvement Potential kW	II law efficiency
Evaporator	72.27	70.08	2.193	0.06	96.96
Condenser	117.05	87.88	29.16	7.299	75.05
Ejector	109.3	63.08	46.27	43.63	57.68
Seawater pp	11.08	0.429	10.65	10.33	3.1
Distillate pp	4.106	0.316	3.78	0.87	7.7
Total of FWG	313.86	221.78	92.08	27.07	70.66

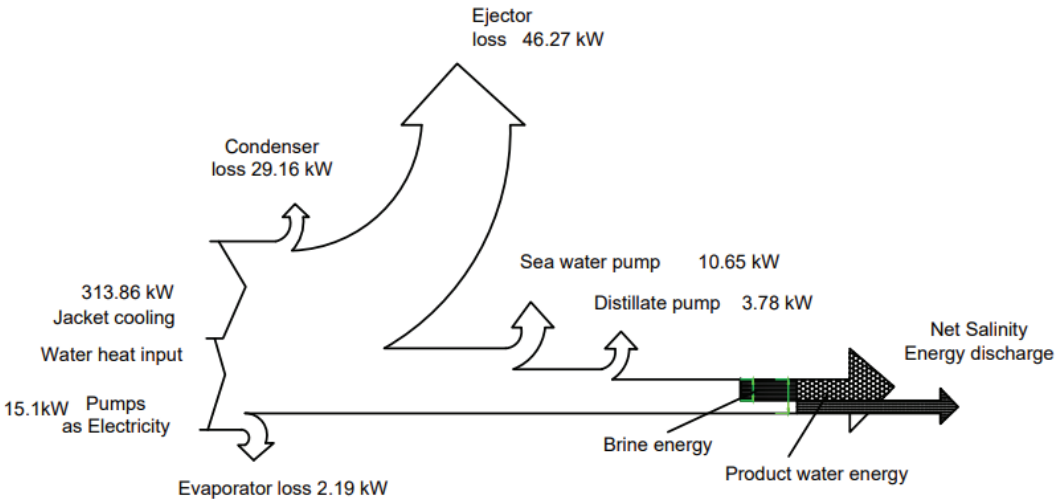

Figure 5. Exergy flow diagram of plate type freshwater generator system.

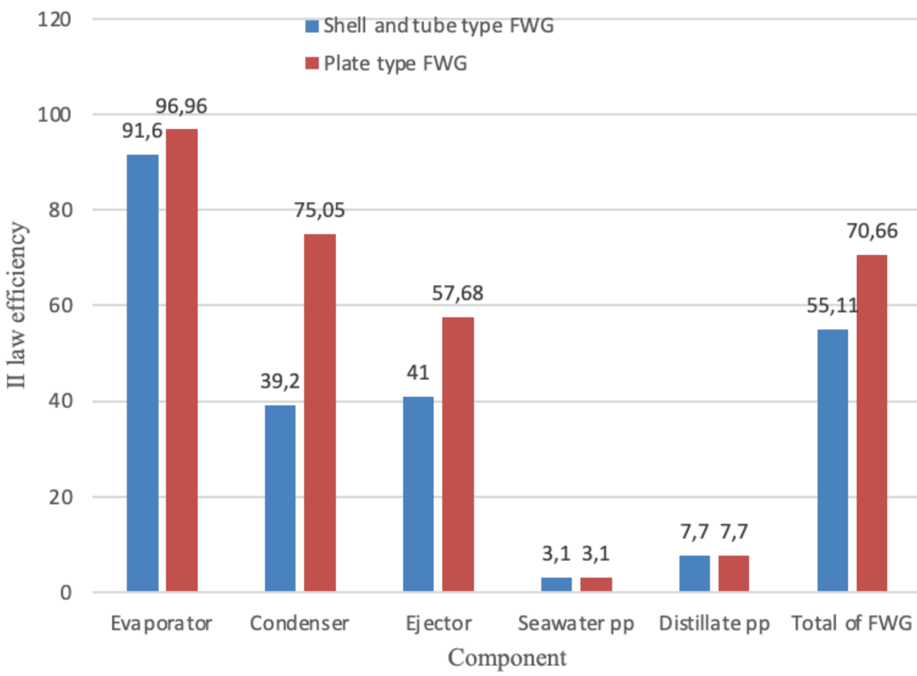

Figure 6. Comparison of II law efficiency of shell and tube and plate type freshwater generator system.

is evident that the plate-type FWG system exhibits higher efficiency than the shell-type FWG system.

CONCLUSION

The energetic and exegetic experimental performance analysis of a freshwater generator with shell-tube type and plate-fin type heat exchanger is studied to check the possibility of energy conservation and for the improvement of exergy efficiency.: -

1. The plate-type freshwater generator has an exergy input of 313.86 kW and a total exergy loss of 92.08 kW, whereas the shell and the tube-type freshwater generator has an exergy input of 413.3 kW and a total exergy loss of 185.5 kW.
2. It reveals that freshwater generator plate type heat exchangers have 15.32% less exergy destruction than shell and tube type freshwater generators. The plate type freshwater generator has an improvement potential of 27.07 kW with a second law efficiency of 70.66

%, whereas the shell and tube type freshwater generator have an improvement potential of 83.28 kW with a second law efficiency of 55.11 %. Which make freshwater generator plate type heat exchanger is more suitable for marine vessels.

3. The fraction of exergy loss in the pump-motor of seawater is 3.1% and the distillate pump is 7.7%. Using a variable frequency drive pump in place of existing pumps is recommended. This exergy analysis of freshwater generation systems is to minimize the irreversible losses through an exergy analysis is a prime area for effective improvement of the efficient use of energy.

ACKNOWLEDGEMENT

The authors thank the management of Tolani Maritime Institute for providing the facility of Ship-in-campus freshwater generator for this study purpose.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

This study makes use of data from a freshwater generator. All graphics collected or generated throughout the study are included in the published publication.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest concerning this article's research, authorship, and/or publication.

ETHICS

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

NOMENCLATURE

$\dot{W}$	Minimum work input: kW
$\dot{X}$	Exergy flow rate: kW
$\dot{m}_{jcw}$	Mass flow rate of jacket water: kg/sec
$\dot{m}_{dw}$	Mass flow rate of distillate water (product freshwater): kg/sec
$\dot{m}_{bew}$	Mass flow rate of brine ejector water: kg/sec
$\dot{m}_{sw}$	Mass flow rate of seawater used as coolant of condenser: kg/sec
$\dot{m}_{s}$	Mass flow rate of salt in seawater generated in evaporator: kg/sec
$\dot{m}_{fsw}$	Mass flow rate of feed seawater of evaporator: kg/sec
$\dot{m}_{fsteam}$	Mass flow rate of steam generated in evaporator: kg/sec
V	Velocity of sea water in the ejector nozzle: m/sec
h	Specific enthalpy of pure water: kJ/kg
s	Specific entropy of sea water: kJ/kgK
v	Specific volume: m^3/kg
p	Pressure at reference state kg/cm^2
u	Specific internal energy of water: kJ/kg
g_{sw}	Specific Gibb's energy: kJ
p	Pressure at reference state kg/cm^2
$\dot{X}_{loss}$	Rate of exergy destruction: kW
w_s	Salt content is sea water: kg/kg
E	Energy: kJ/kg
T	Temperature: K

Greek symbols

Ψ	Exergy flow: kJ/kg
ϑ_{ex}	Second law efficiency
φs	Chemical exergy of water in seawater: J/kg
φw	Chemical exergy of water in sea water: J/kg
τ_{ratio}	Performance ratio
ϵ_{IP}	Improvement potential: kW

Subscripts

m	Mass of stream
s	Salt
w	Water
sw	Seawater
in	Inlet stream
out	Outlet stream

Superscripts

*	Restricted dead state
o	Global dead state

REFERENCES

[1] Ibrahim S, Al-Mutaz I, Wazeer I. Development of a steady-state mathematical model for MEE-TVC desalination plant. Desalination 2014;351:9-18. [CrossRef]

[2] Millero FJ, Poisson A. International one-atmosphere equation of state of seawater. Deep Sea Res A Oceanogr Res Pap 1981;28:625-629. [CrossRef]

[3] Kahraman N, Cengel YA, Wood B, Çerçi Y. Exergy analysis of a combined RO, NF, and EDR desalination plant. Desalination 2005;171:217-232. [CrossRef]

[4] Kahraman N, Cengel YA. Exergy analysis of an MSF distillation plant. Energy Conver Manage 2005;46:2625-2636. [CrossRef]

[5] Nafey AS, Fath HES, Mobrouk A. Exergy and thermoeconomic evaluation of MSF process using a new visual package. Desalination 2006;201:224-240. [CrossRef]

[6] Sharqawy MH, Zubair SM, Lienhard VJH. Formulation of seawater flow exergy using accurate thermodynamic data. Proc ASME Int Mech Engineer Congr Expo 2010;2010:675-682. [CrossRef]

[7] Sharqawy MH, Zubair SM, Lienhard V JH. Second law analysis of reverse osmosis desalination plants: An alternative design using pressure retarded osmosis. Energy 2011;36:6617-6626. [CrossRef]
[8] Sharqawy MH, Lienhard VJH, Zubair SM. On exergy calculations of seawater with applications in desalination systems. Int J Therm Sci 2011;50:187-196. [CrossRef]
[9] International Association for the Properties of Water and Steam. Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater. Available at: https://www.teos-10.org/pubs/IAPWS-08.pdf. Accessed August 2, 2024.
[10] Hosseini SR, Amidpour M, Behbahaninia A. Thermoeconomic analysis with reliability consideration of a combined power and multi-stage flash desalination plant. Desalination 2011;278:424-433. [CrossRef]
[11] Gude VG. Exergy evaluation of desalination processes. Chem Engineer 2018;2:28. [CrossRef]
[12] Choudhari CS, Sapali SN. Testing of environment-friendly refrigerant R290 for water cooler application. Int J Engineer 2018;31:157-163. [CrossRef]
[13] Shikalgar ND, Sapali SN. Energy and exergy analysis of a domestic refrigerator: Approaching a sustainable refrigerator. J Therm Engineer 2019;5:469-481. [CrossRef]
[14] Koroglu T, Sogut OS. Advanced exergy analysis of an organic Rankine cycle waste heat recovery system of a marine power plant. J Therm Engineer 2016;3:1136-1148. [CrossRef]
[15] Rawabawale N, Sapali SN. Exergy analysis of the cross current cooling tower. J Therm Engineer 2020;6:499-510. [CrossRef]
[16] Yuksel O, Gulmez Y, Konur O, Aykut S, Erdogan KA, Colpan CO. Performance assessment of a marine freshwater generator through exergetic optimization. J Clean Prod 2019;219:326-335. [CrossRef]
[17] Solanki A, Pal Y. A comprehensive review to study and implement solar energy in dairy industries. J Therm Engineer 2021;7:1216-1238. [CrossRef]
[18] Ahern JE. The exergy method of energy systems analysis. New Jersey, US: John Wiley & Sons; 1980. pp. 102-106.
[19] Kotas TJ. The Exergy Method of Thermal Plant Analysis. London, UK: Exergon Publishing Company; 2012. pp. 33-44.
[20] Mustafa I, AI Ghamdi A. Exergy analysis of thermal seawater desalination - A case study. Renewable Energy Powered Desalination Handbook. Oxford, Butterworth-Heinemann; 2018. pp. 491-515. [CrossRef]
[21] Li KW. Applied Thermodynamics: Availability Method and Energy Conversion. New York: Taylor & Francis; 1989.
[22] Hammond GP. Engineering sustainability: Thermodynamics, energy systems and the environment. In: Winnett A, ed. Towards an Environment Research Agenda. London: Palgrave Macmillan; 2004. [CrossRef]