NIPES

Advances in Engineering Design Technology

Journal homepage: www.nipesjournals.org.ng

Comparative Thermodynamic Analysis of Marine Propulsion Systems Under Varying Loads and Operational Conditions

Peter Akhator[1], Loyalty Akpeti[2], Imoudu Moses Ohikhuemi[3]*, Voke Franklyne Okpohworho[4], Obanor Jeffrey Osarumese[5], Kadiri Aweni Aweni[6]

[1,2,3,4,5,6]Department of Mechanical Engineering, University of Benin, P.M.B. 1154, Benin City, Nigeria.

ARTICLE INFORMATION

Article history:
Received 20 June 2024
Revised 19 August 2024
Accepted 24 September 2024
Available online 30 September 2024

Keywords:
Energy, Exergy, Marine Propulsion, Modelling, Simulation

https://doi.org/10.5281/zenodo.13842955

ISSN-2682-5848/© 2024 NIPES Pub.

ABSTRACT

This study undertakes a meticulous examination of marine propulsion systems' efficiency and performance across diverse load scenarios and operational conditions. Through a comprehensive methodology encompassing energy and exergy analyses, comparative analysis methodologies, and detailed modeling and simulation using EBSILON Professional, this study uncovers crucial insights into the impact of load variations and operational conditions on propulsion system performance. This study reveals that there isn't a significant drop-off in system efficiency at 80% load when pressure relief valves are included across the system, indicating the effectiveness of these valves in maintaining performance under different operational scenarios. By presenting and analyzing its findings, this project contributes valuable recommendations for optimizing marine propulsion systems, thereby enhancing their efficiency and sustainability in maritime operations.

1. Introduction

The study of marine propulsion systems is crucial for enhancing the efficiency and sustainability of maritime transportation. The maritime sector faces significant challenges, such as environmental impact and fuel consumption, necessitating the development and optimization of advanced propulsion technologies. This research delves into the efficiency and adaptability of a marine propulsion system under varying loads and operational conditions, aiming to provide actionable insights for improving sustainability.

Several studies have explored different aspects of marine propulsion technologies [1] focused on the design and thermodynamic analysis of a Solid Oxide Fuel Cell (SOFC) system for naval surface ships, highlighting the high efficiency and low emissions of SOFCs as promising alternatives to conventional systems [2] conducted conventional and advanced exergy analyses of marine steam power plants, examining both traditional thermodynamic metrics and advanced exergy-based techniques to assess system efficiency [3] investigated waste heat recovery using an Organic Rankine Cycle (ORC) integrated with a two-stroke low-speed marine Diesel engine, demonstrating the potential of ORC systems to enhance overall efficiency [4] analyzed pressure reduction valves in marine steam power plants, offering insights into optimizing steam plant performance through improved pressure control.
Previous studies have not thoroughly examined the impact of pressure relief valves on marine propulsion system efficiency across varying loads and operational conditions. This research addresses this gap by demonstrating that these valves effectively maintain system performance, even at 80% load.

This research also aims to bridge the gap in understanding how marine propulsion systems perform under realistic operational scenarios, particularly concerning load variations and environmental influences. A thorough comparative thermodynamic analysis will be conducted, assessing the efficiency and adaptability of the propulsion technology improved in the work of [4]. The methodologies employed include energy and exergy analyses, leveraging previous research contributions such as those by [5] on numerical models for marine engines.
This research has significant implications for the maritime industry's operational efficiency and environmental stewardship. The findings and recommendations will empower industry stakeholders to make informed decisions regarding propulsion system selection and integration. The relevance of this research extends beyond academic discourse, directly impacting the maritime sector's efforts to advance sustainable energy systems and enhance operational efficiency, as emphasized by [6].

2. Methodology

2.1 Modeling and Simulation with EBSILON Professional

EBSILON Professional is a modeling software. "Energy Balance and Simulation of the Load Response Power Generating or Process Controlling Network Structures" is a term that can be shortened to "EBSILON." This tool is useful for stationary simulation of various thermodynamic power cycles and processes.

A program for calculating mass and energy balance in thermodynamic cycles is called EBSILON. The performance of a combined cycle power plant under design and part-load conditions can be simulated using EBSILON **[7]**. Standard components, when used to model typical power plant components, form the basis of the EBSILON model framework. Also, programmable parts with user-defined behaviour for simulating intricate power plant operations are useful tools.

The International Association for the Properties of Water and Steam, or IFC67 steam table, is the source of data used by Ebsilon along with cp-polynomial for flue gas and air.

EBSILON is a variable program system that uses a closed solution based on a sequential solution method to balance all power plant circuits that occur. Objects are used to construct the cycles. The many object kinds include Components, Text fields, Pipes, Macros (like the gas turbines in the library), Value crosses, and Graphical elements.

Figure 1 shows the basic user interface of EBSILON® Professional by highlighting the control elements and toolbars.

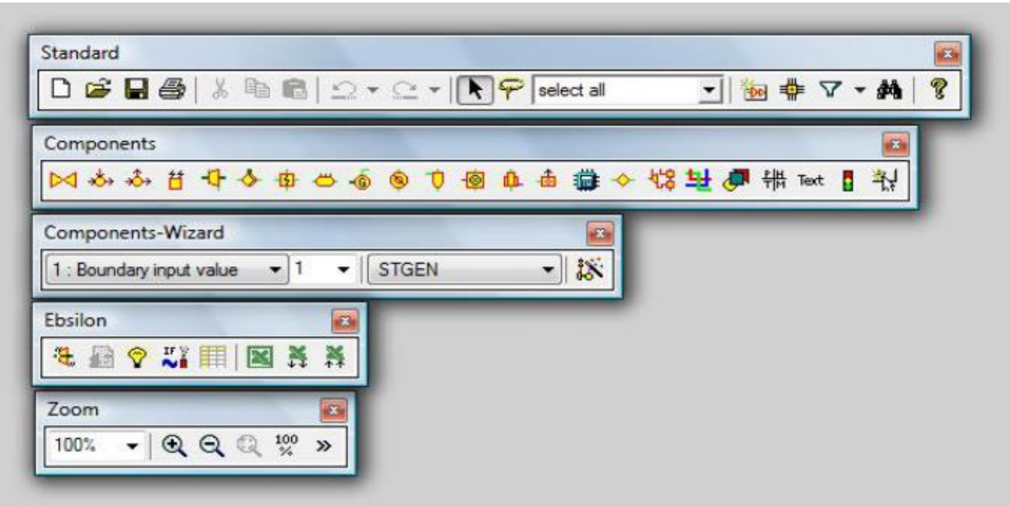

Figure 1 - Basic control elements and toolbars of EBSILON software [8]

2.2 Model Validation

Model validation is crucial in ensuring the accuracy and reliability of the simulations conducted using EBSILON for the comparative thermodynamic analysis of marine propulsion systems. To validate the models, a comparison was made between the simulated results and real-world performance data from the LNG carrier steam power plant with pressure reduction valves analyzed by **[4]**.
The validation process involves using historical engine data from marine vessels being modeled. This data includes key indicators such as enthalpy, pressure, temperature, mass flow rate, and power output. By aligning the simulated outputs with this empirical data, we can adjust the model parameters and improve the accuracy of the simulations. This iterative process of model refinement was essential for ensuring that the predictions made by EBSILON are reliable and applicable to real-world scenarios, thereby enhancing the credibility of the comparative analysis. The formulae used to calculate key thermodynamic properties, such as enthalpy, pressure, temperature, mass flow rate, and power output, are within the EBSILON software. These calculations are essential for generating the simulated outputs that were then compared with the real-world performance data of the LNG carrier steam power plant.

2.3 Energy Analysis

EBSILON allows engineers to model the thermodynamic processes within marine engines with high accuracy and detail **[9]**.

The energy assessments of the combined cycle revolve around the Rankine cycle.

The energy analysis of the study was carried out using the result obtained from the modeling in Table 1 and the governing equations as expressed in Eqn. 1 to 13 below.

BOILER

The energy balance across the boiler (Q_B) is calculated as

$$Q_B = B_{HPB} + B_{IPB} \quad (1)$$

$$Q_{HPB} = \dot{m}_w (H_1 - H_{28}) \quad (2)$$

$$Q_{IPB} = \dot{m}_w (H_8 - H_7) \quad (3)$$

STEAM TURBINE

The steam turbine has triple pressure, High-Pressure, Intermediate Pressure, and Low Pressure. The total power output from the low, Intermediate and high-pressure steam turbines is calculated as

$$W_{ST} = (W_{HPST} + W_{IPST} + W_{LPST}) \quad (4)$$

$$W_{HPST} = \dot{m}_{S1}(H_1 - H_7) \quad (5)$$

W_{IPST} = $\dot{m}_{S8}(H_8 - H_{11})$ (6)

W_{LPST} = $\dot{m}_{S11}(H_{11} - H_{14})$ (7)

CONDENSER

The energy balance across the condenser (Q_{COND}) is calculated as

Q_{COND} = $\dot{m}_w$ (H_{14} - H_{15}) (8)

= 8.607 (2397.71– 166.872)

= 19.2 MW

FEED WATER PUMP

The energy balance across the feed water pump is calculated as

W_{FWP} = $\dot{m}_w$ (H_{26} - H_{25}) (9)

The total network done by the steam turbine ($W_{net,ST}$ **)** is

$W_{net,ST} = (W_{ST} - W_{FWP}) \text{ x } \eta_{mech}$ (10)

The thermal efficiency of steam turbine on is calculated as

$\eta_{ST} = \frac{W_{net,ST}}{Q_{supplied,hrsg}} \text{ x } 100$ (11)

Specific steam consumption (SSC)

$SSC = \frac{\dot{m}_{w} \text{ x } 3600}{W_{net,ST}}$ (12)

Work Ratio (WR)

$WR = \frac{W_{net,ST}}{W_{ST}}$ (13)

2.4 Exergy Analysis

By simulating different operating scenarios and load profiles, engineers can assess how operating conditions affect the exergy efficiency of the propulsion system **[10]**. The Exergy analysis is a technique based on the concept of exergy, which is defined as a universal measure of the work potential or quality of different forms of energy in relation to a given environment **[11].** In this study, the exergy rate, the exergy destruction, and exergy efficiency of each component were evaluated using the result obtained from the modeling in Table 2 and the governing equations as expressed in Eqn. 14 to 38.

BOILER

Exergy Destruction (ExD_B)

$ExD_B = T_o \ \dot{m}_S (S_7 - S_1) + T_o \ \dot{m}_S (S_8 - S_7)$ (14)

Energy Rate

$ExQ_B = \dot{m}_S (E_1 - E_7) + \dot{m}_S (E_7 - E_8)$ (15)

Exergy Efficiency

$\acute{\eta}_{Ex} = 1 - \frac{ExD_B}{Ex_{QB}} \times 100$ (16)

STEAM TURBINE

Steam comprises of High-Pressure steam turbine (HPST), Intermediate-Pressure steam turbine (IPST), and Low-Pressure steam turbine (LPST)

Exergy Destruction in the steam turbine

$ExD_{ST} = ExD_{HPST} + ExD_{IPST} + ExD_{LPST}$ (17)

$ExD_{HPST} = T_o \ \dot{m}_S (S_7 - S_1)$ (18)

$ExD_{IPST} = T_o \ \dot{m}_S (S_8 - S_7)$ (19)

$ExD_{LPST} = T_o \ \dot{m}_S (S_{14} - S_{11})$ (20)

The Energy Rate in the steam turbine is calculated as

Exergy Rate = Exergy Rate in HPST + Exergy Rate in HPST + Exergy Rate in LPST (21)

Exergy Rate in HPST = $\dot{m}_s \ (E_1 - E_7)$ (22)

Exergy Rate in IPST = $\dot{m}_s \ (E_8 - E_7)$ (23)

Exergy Rate in LPST = $\dot{m}_s \ (E_{14} - E_{11})$ (24)

Exergy Efficiency

$\acute{\eta}_{ExST} = 1 - \frac{ExD_{ST}}{Ex_{WST}} \times 100$ (25)

CONDENSER

Exergy destruction in the condenser is calculated as

$ExD_{cond} = \dot{m}_S (H_{14} - H_{15}) - T_o \ \dot{m}_S (S_{14} - S_{15})$ (26)

Exergy Rate=$\dot{m}_w(E_{14}$-$E_{15})$ (27)

Exergy Efficiency

$(ή_{Ex,cond}) = 1 - \frac{ExD_{cond}}{W_{cond}}$ x 100 (28)

FEED WATER PUMP

Exergy destruction in the feed water pump is calculated as

$Exd_{FWP}=T_o ṁ_w(S_{26}-S_{25})$ (29)

Exergy Rate in Feed water pump

$Ex_{wFWP}=ṁ_w(E_{26}-E_{25})$ (30)

Exergy Efficiency $ή_{Ex,FWP} = 1 - \frac{ExD_{FWP}}{Ex_{WFWP}}$ x 100 (31)

Marine power plant Exergy Efficiency ($ή_{Ex,mpp}$) is expressed as

Exergy Efficiency ($ή_{Ex}$)$=\frac{useful\ Exergy}{exergy\ supplied}$ (32)

$= 1 - \frac{Total\ Exergy\ destroyed}{exergy\ supplied\ by\ the\ unit}$ **[12]** (33)

PERCENTAGE OF EXERGY DESTRUCTION (%ExD)

Percentage of Exergy Destruction (%ExD) is calculated as

$(\%ExD)=\frac{Exergy\ Destruction\ per\ unit\ component}{Total\ Exergy\ Destruction}$x100 (34)

Total Exergy Destruction (ExD_{total} **)** $= ExD_B + ExD_{ST} + ExD_C + ExD_{FWP}$

FOR BOILER;

$\%\ ExD_B = \frac{ExD_B}{ExD_{total}}$ x 100 (35)

FOR STEAM TURBINE;

$\%\ ExD_{ST} = \frac{ExD_{ST}}{ExD_{total}}$ x 100 (36)

FOR CONDENSER;

$\%\ ExD_C = \frac{ExD_C}{ExD_{total}}$ x 100 (37)

FOR FEED WATER PUMP;

$\%\ ExD_{FWP} = \frac{ExD_{FWP}}{ExD_{total}}$ x 100 (38)

2.5 Design & Off-Design Mode

The purpose of this research is to carry out a performance assessment of a marine steam power plant that operates on conventional LNG (Liquefied Natural Gas) carriers. The performance assessment will be carried out on condensate and superheated steam pressure reduction valves while the steam plant operates in design and part load conditions by examining the energy generated, exergy destruction and thermal efficiency using EBSILON professional software.

The steam turbine model description is based on the simple cycle performance guarantee, thermodynamic equations, modelling and simulation of the steam turbine model on design and off design (part-load) conditions, and simulation analysis form the basis of this project's methodology.

The data used in the modelling and simulation of the marine steam power plant was obtained from a research paper by **[4]** which is similar to our research topic.

Figure 2 shows the simulated design at peak load with EBSILON® data trees on every pipe, showing the basic properties of the steam/water before and after each major component. Each major component is labeled with a letter. Pipes are labeled with numbers.

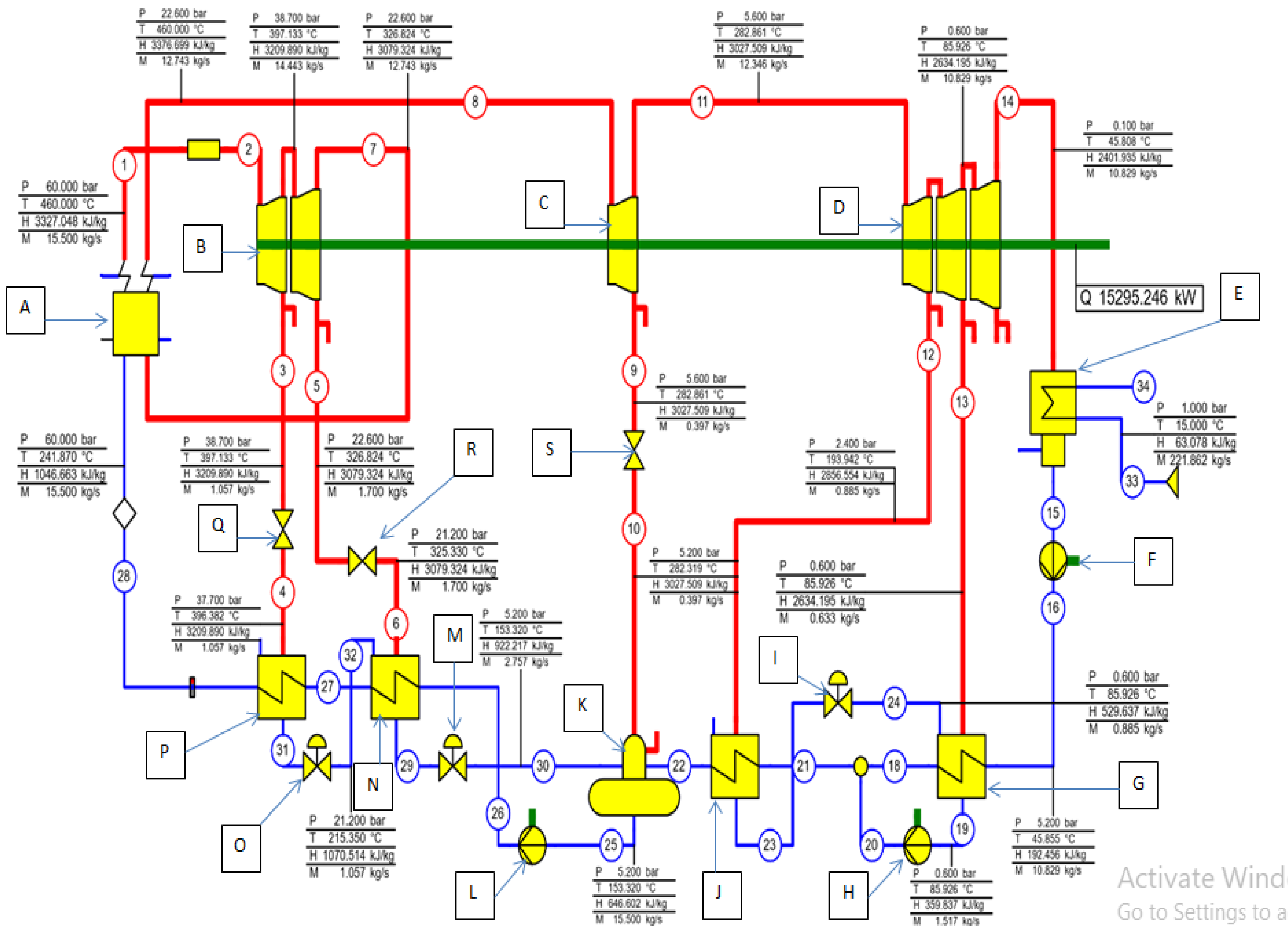

Figure 2 - Labeled Model at 100% Load

A – Boiler
B – High Pressure Turbine
C – Intermediate Pressure Turbine
D – Low Pressure Turbine
E – Condenser
F – Pump 1
G – Closed Feed Heater 1
H – Pump 2
I – Control Valve 1
S – Throttle Valve
J – Closed Feed Heater 2
K – Open Feed Heater / Deaerator
L – Pump 3
M – Control Valve 2
N – Closed Feed Heater 3
O – Control Valve 3
P – Closed Feed Heater 4
Q – Throttle Valve 1
R – Throttle Valve 2

Table 1 shows the properties of steam/water at different specified locations in the cycle for 100% load

Table 1: Summary of Operational Design Condition Data for the Marine Power Pl

Plant units	Parameters	Units	Value
Steam Turbine	HP steam pressure	bar	60
	HP steam temperature	℃	460
	HP steam mass flow rate	kg/s	15.5
	IP steam pressure	bar	22.6
	IP steam temperature	℃	460
	IP steam mass flow rate	kg/s	12.743
	LP steam temperature	℃	340.645
	LP steam pressure	bar	5.6
	LP steam mass flow rate	kg/s	12.346
Condenser	Turbine exhaust duct pressure	bar	0.1
	Condensate mass flow rate	kg/s	10.829
	Condenser duct Temperature	℃	45.808
Deaerator	Heating Steam Inlet pressure	bar	5.2
	Heating Steam Inlet mass flow rate	Kg/s	0.397
	Heating Steam inlet temperature	℃	282.319
	Feed water outlet pressure	bar	5.2
	Feed water outlet mass flow rate	Kg/s	15.5
	Feed water outlet temperature	℃	153.32

3. Results and Discussion

Table 2 shows the properties of steam/water at different specified locations in the cycle for 80% load.

Table 2: Results from Simulating under 80% Part-load condition, 12.236MW

S/N	Components	Pressure	Temp.	Enthalpy	Mass Flow	Exergy	Entropy	Energy Flow
	Unit	bar	℃	kJ/kg	kg/s	kJ/kg	kJ/kg-k	MW
	Symbol	P	T	H	ṁ	E	S	Q
1	Boiler HP Outlet/ HP Turbine Inlet	47.496	460	3344.055	12.139	1464.564	6.88	40.595
2	HP Turbine Outlet/ Boiler IP Inlet	17.958	328.357	3093.921	10.101	1199.606	6.935	31.253
3	Boiler IP Outlet/ IP Turbine Inlet	17.958	460	3382.620	10.101	1369.719	7.369	34.169
4	IP Turbine Outlet/ LP Turbine Inlet	4.46	283.682	3032.379	9.807	995.539	7.456	29.74
5	LP Turbine Outlet /Cond. Inlet	0.073	39.84	2397.71	8.607	294.95	7.698	20.637
6	Condenser Outlet	0.073	39.84	166.872	8.607	10.995	0.57	1.436
7	Deaerator heating steam Inlet	4.183	283.310	3032.379	0.294	987.554	7.486	0.891
8	Deaerator heating steam outlet/ Feed water pump Inlet	4.183	145.236	611.712	12.139	121.775	1.793	7.426
9	Feed water pump outlet	47.496	145.965	617.582	12.139	126.879	1.796	7.497
10	Boiler HP Inlet	47.496	231.786	998.932	12.139	282.421	2.623	12.126

Figure 3 shows the simulated design at 80% load with EBSILON® data trees on every pipe showing basic properties of the steam/water before and after each major component. Pipes are labeled with numbers.

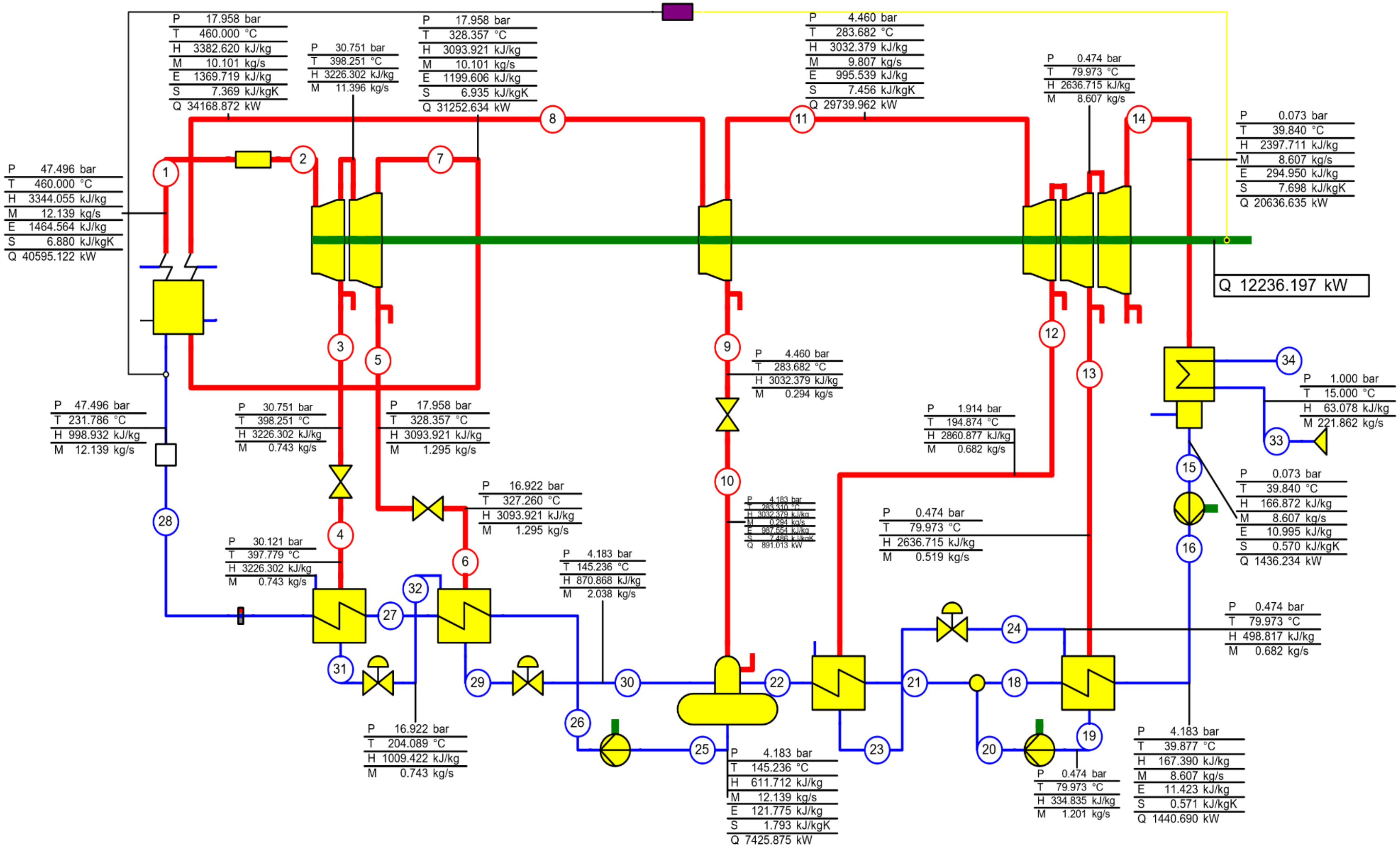

Figure 3: Marine power plant in 80% off – Design Mode

3.1 Energy Analysis (Off-Design)

Table 3 shows the result obtained from the energy analysis of the marine power plant

Table 3: Result from the energy analysis of the Marine power plant

S/N	**Parameters**	**Units**	
1	Power Output (MW)	MW	12.797
2	Cycle Efficiency (%)	%	40.149
4	Specific Steam Consumption (Kg/kWh)	Kg/kWh	3.468
5	Heat Added (MW)	MW	31.383
6	Work Ratio		0.985

3.2 Exergy Analysis (Off-Design)

Table 4 shows a summary of the results obtained from the exergy analysis of the marine power plant.

Table 4 - Result from the exergy analysis of the CCPP

S/N	**Components**	**Exergy Available**		**exergy**	**Exergy**	**% of exergy**	**Exergy**
		Work done	**Heat Supplied**	**Rate**	**Destruction**	**Destruction Rate (ExD)**	**Efficiency**
		MW	MW	MW	MW	%	%
1	BOILER	0	31.383	16.068	3.7	39.72	76.97
2	STEAM TURBINE	12.797	0	13.866	5.023	53.92	63.77
3	CONDENSER	0	19.2	2.444	0.578	6.2	96.99
4	FEED WATER PUMP	12.6	0	0.062	0.015	0.16	75.81

Following the modeling and simulation, the results were tabulated and used to analyze the exergy destruction and exergy efficiency in each component of the power plant. These results were further processed using Microsoft Excel to create clear pictorial charts for visual representation. In the performance assessment of the research work, the exergy destruction among different components was evaluated, as demonstrated in Table 5 and Figure 4.

Table 5 - Exergy Destruction Table

Components	Exergy Destruction (MW)
BOILER	3.700
STEAM TURBINE	5.023
CONDENSER	0.578
FEED WATER PUMP	0.015

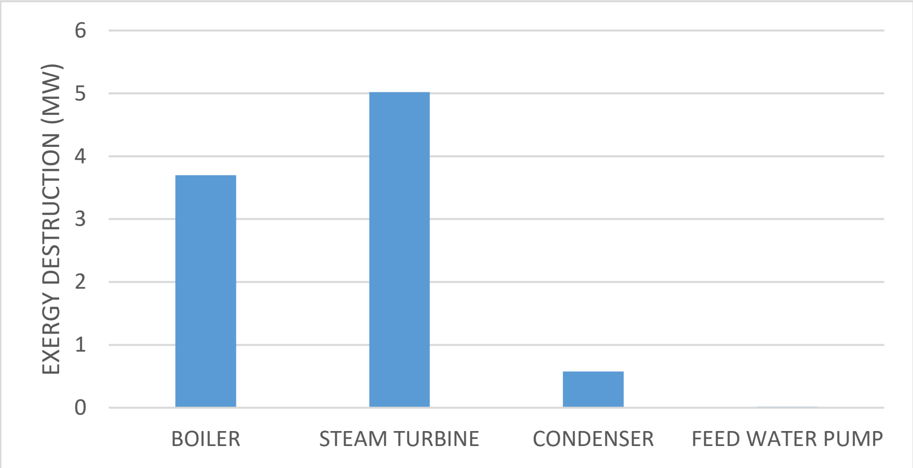

Figure 4 - Exergy Destruction Bar Chart

The bar chart above clearly shows the inefficiency of different components of the thermal power plant. Exergy is the maximum amount of usable work that can be obtained from a system. In a thermal power plant, energy is lost due to inefficiencies in the conversion of thermal energy to electrical energy. The graph shows that the feed water pump has the lowest exergy destruction, and the steam turbine has the highest exergy destruction.

A comparison can also be drawn between the percentages each component contributes to the overall exergy destruction in the system. The analysis provides detailed insights into the rate and proportion of exergy destruction attributed to various components within the power plant. The steam turbine emerges as the primary contributor to exergy destruction, accounting for 53.92% of the total exergy loss. This loss can be attributed to factors such as frictional losses within the turbine blades and components, along with irreversible heat transfer during the expansion process. Following closely, the boiler stands as the second-highest contributor, responsible for 39.72% of the total exergy destruction. Other components contribute in the following order: the condenser at 6.2% and the feed water pump at 0.16%, which is the least significant source of irreversibility within the system. The results presented in Table 6 and Figure 5 below depict this information diagrammatically.

Table 6 - % Exergy Destruction Table

Components	Exergy Destruction (%)
BOILER	39.72
STEAM TURBINE	53.92
CONDENSER	6.2
FEED WATER PUMP	0.16

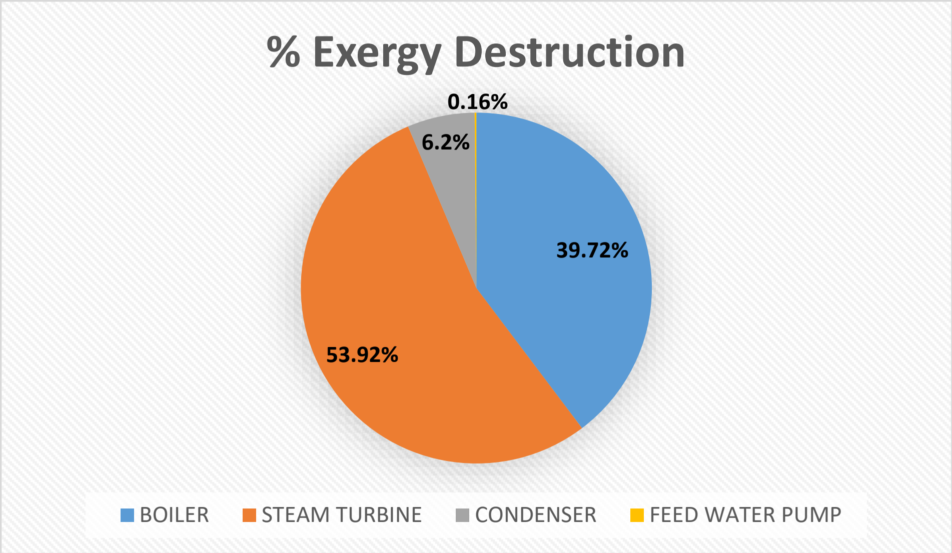

Figure 5 - % Exergy Destruction Pie Chart

Similar representations are made for Exergy Efficiency and Exergy Rate and are highlighted in Tables 7 and 8 as well as Figures 6 and 7.

Table 7 - % Exergy Efficiency Table

Components	% Exergy Efficiency (%)
BOILER	76.97
STEAM TURBINE	63.77
CONDENSER	96.99
FEED WATER PUMP	75.81

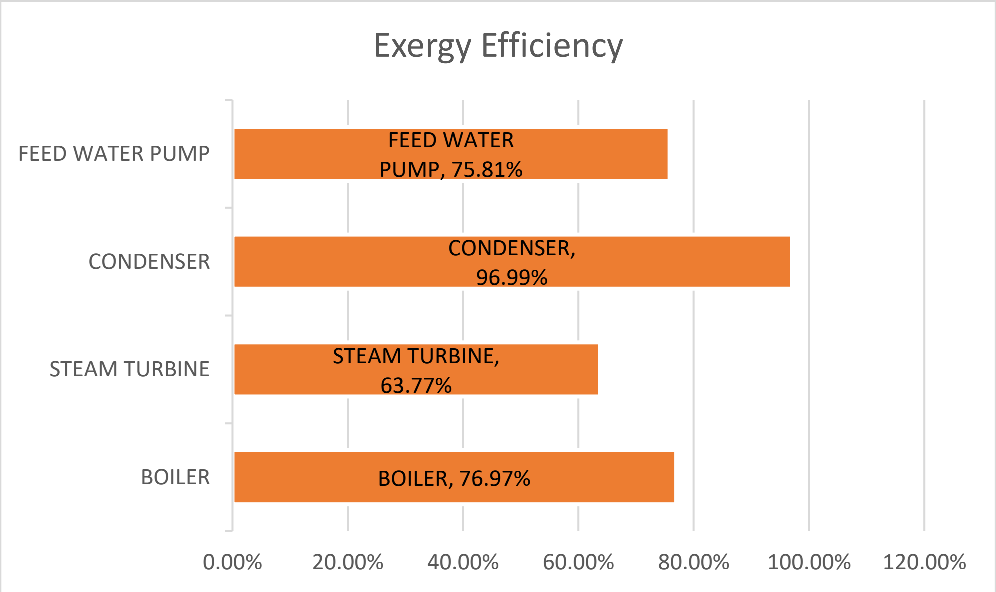

Figure 6 - % Exergy Efficiency Horizontal Bar Chart

Table 8 - Exergy Rate Table

Components	**Exergy Rate (MW)**
BOILER	16.068
STEAM TURBINE	13.866
CONDENSER	2.444
FEED WATER PUMP	0.062

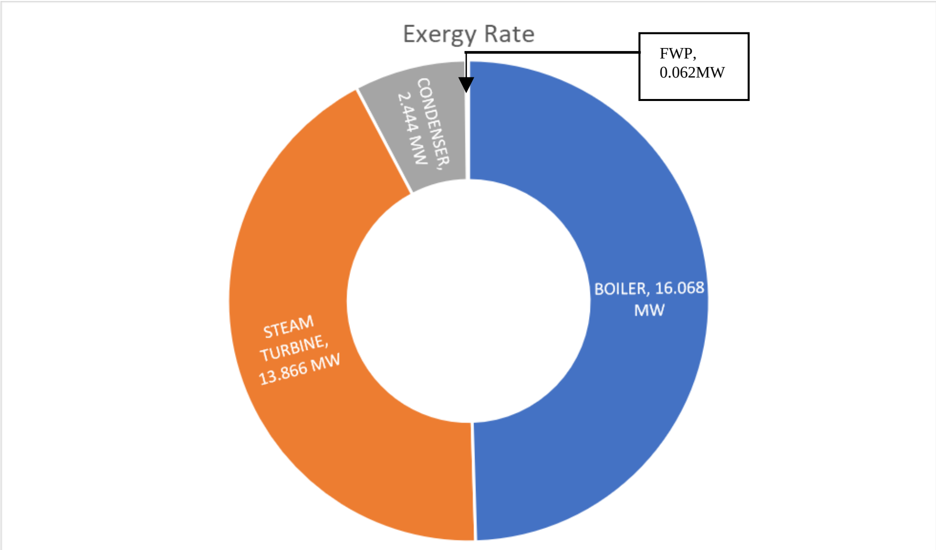

Figure 7 - Exergy Rate Sunburst

From the analysis, we can see that even though the steam turbine had the highest % exergy destruction, it also had the highest % exergy efficiency due to its relatively high exergy rate

4. Conclusion

In conclusion, a comparative thermodynamic analysis on a marine propulsion system under varying loads and operational conditions, incorporating an off-peak analysis at 80% peak load was conducted. The off-peak analysis was done with the aid of EBSILON® Professional. This study revealed that system efficiency does not significantly drop at 80% load when pressure relief valves are integrated, demonstrating the effectiveness of these valves in maintaining consistent performance across varying loads and conditions. This study underscores the critical role of advanced technologies, such as pressure relief valves, in enhancing marine propulsion system efficiency, suggesting that incorporating such components can optimize performance and sustainability even under diverse operational scenarios. Moving forward, this study provides a foundation for further advancements in the design and optimization of marine propulsion systems, promoting better efficiency and performance in maritime operations.

Acknowledgement

Grateful acknowledgement is given to STEAG Energy Services GmbH for providing the EBSILON® Professional software for simulations, which greatly contributed to the success of this project.

References

[1] Ezgi, C., Turhan Çoban, M. & Selvi, Ö., 2013. Design and thermodynamic analysis of an SOFC system for naval surface ship application. Journal of fuel cell science and technology, 10(3), p. 031006.

[2] Koroglu, T. & Sogut, O., 2018. Conventional and advanced exergy nalyses of a marine steam power plant. Energy, Volume 163, pp. 392-403.

[3] Lion, S. et al., 2019. Thermodynamic analysis of waste heat recovery using Organic Rankine Cycle (ORC) for a two-stroke low speed marine Diesel engine in IMO Tier II and Tier III operation. Energy, Volume 183, pp. 48-60.

[4] Mrzljak, V., Anđelić, N., Poljak, I. & Orović, J., 2019. Thermodynamic analysis of marine steam power plant pressure reduction valves. Pomorski zbornik, 56(1), pp. 9-30.

[5] Altosole, M. & Figari, M., 2011. Effective Simple Methods For Numerical Modelling Of Marine Engines In Ship Propulsion Control Systems Design. Journal of Naval Architecture and Marine Engineering, Volume 2, pp. 129-147.

[6] Shu, G. et al., 2017. Operational profile based thermal-economic analysis on an Organic Rankine Cycle using for harvesting marine engine's exhaust waste heat. [Online]. Available at: https://www.elsevier.com. [Accessed November 23 2023].

[7] Hans-Peter, D., 2012. Accompanying Material for the EBSILON®Professional. s.l.:s.n.

[8] Andrea, 2010. Use of EBSILON Professional. Berlin.

[9] Nahim, H., Younes, R., Shraim, H. & Ouladsine, M., 2016. Oriented review to potential simulator for faults modeling in diesel engine. Journal of Marine Science and Technology, Volume 21, pp. 533-551.

[10] Mahian, O., Mirzaie, M., Kasaeian, A. & Mousavi, S., 2020. Exergy analysis in combined heat and power systems: A review. Energy conversion and management, Volume 226, p. 113467.

[11] Kotas, T., 1985. Teaching The Exergy Method To Engineers. In: Teaching Thermodynamics. Boston: Springer US, pp. 373-385.

[12] Cengel, Y. & Boles, M., 2010. Thermodynamics: An Engineering Approach. 7th ed. s.l.:s.n.