RELIABILITY ESTIMATION AND MODELLING OF AN LNG CARRIER STEAM PLANTS' BOILER EFFICIENCY USING REGRESSION METHOD

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Abstract

This study evaluates the thermodynamic performance of a steam generator to improve operational efficiency. A detailed analysis of the Rankine cycle revealed key parameters, including heat addition, heat rejection, and mechanical work output. The turbine expansion process produced 997.13kJ/kg of mechanical work, resulting in a boiler thermal efficiency of 83.11% and a net power output of 27320.8kW. Regression and reliability models were developed to predict performance under various conditions. The regression model showed that increasing the turbine inlet temperature from 450°C to 550°C improved cycle efficiency from 80.4% to 83.5% and power output from 2680Kw to 2800Kw. Optimal operating conditions were established at a turbine inlet temperature of 500°C, achieving efficiency of 83.45% and a power output of 28030.33kW. The system's reliability was calculated to be of 86.26%, supporting its long-term viability. The study highlights the importance of predictive modeling in minimizing downtime and maximizing energy.

Keywords: Steam turbine, Boiler, Heat, Regression model, Reliability, cycle efficiency

Introduction

A closed vessel that uses fuel combustion to heat water and turn it into steam is known as a boiler. The boiler's goals to efficiently and economically create steam under the ideal circumstances (Mohd, 2017). High pressure superheated steam is used to power turbines, while low pressure steam is used in processes and applications. For optimal heat transfer, it also features several tubes. These tubes run between the boiler's water collection drum at bottom and the steam distribution drum at the top. Steam is provided to the steam distribution system after been received by the super hater from the steam drum.

The purpose of this research was to evaluate an LNG Carrier team plant's boilers' thermal efficiency using operating data. The ship's steam plant provided the data utilized in this study, which was later used for the calculation of the boiler's thermal efficiency. The 30mW steam turbine for propulsion is powered by two look-alike Mitsubishi Heavy Industry boiler that is able to produce 60t/hr of steam each at 60 bar and 510^{0}C. This literature presents a conceptual framework for estimating and modelling the reliability of marine steam plant boiler efficiency using regression methods.

Various studies have been made on thermodynamic analysis of turbines. According to Erdem et al (2009), the first rule of thermodynamics is especially used to ascertain the energy performance of thermal power plants. Exergy performance is suitable for analysis, design and improvement of thermal power plant according to Naseri et al (2017). This approach helps designers to get a more specific tool for the evaluation of the steps that should be taken to improve this situation (Regulagadda et al, 2010).

Loss can be noticed in system by using the exergy analysis as opined by Ashouri et al, (2017). By using the exergy analyses, they were able to ascertain the energy conversion at different levels, the areas that had high energy losses, the effectiveness of different parts of the system and lastly the ways of minimizing losses. The method of the most appropriate approach in the cycle optimization based on given input data was applied by Rosen and Bulucea (2009). Srinivas et al (2007) conducted a study on a methane-fueled combined cycle power plant and evaluated its performance by using the first and second principles of thermodynamics. It was highlighted that a simple and accurate method of estimating the power output of the Rankine bottoming cycle can be obtained by exploiting the exhaust exergy of the gas turbine and the second law of thermodynamics. Two new graphs of the exergy efficiency of thermal power plant was developed by Noroozian et al (2017). Datta et al (2010) carried out an energy evaluation of an extremely gas fired turbine cycle with a biomass gasifier for power generation. In this research, the exergy concept has been used to explain the combustion gas turbine power production system. The engineering and energy point of view and also the use of gas to stimulate a cogeneration facility was presented by Bilgen (2000).

The need to construct a more comprehensive repression and reliability model that can effectively capture the interdependent and dynamic nature of steam boiler system is really necessary. Addressing these bridges will help in the advancement of this field of study by providing a more accurate and reliable tool for optimizing steam boiler performance.

Materials and Methods

In order to analyze the thermodynamic performance of the steam generator, operational data were obtained from a marine steam boiler. Computational tools and thermodynamic software were used for exergy and energy analysis. The development of a regression and reliability model was made, statistical software, historical performance data and programming environments of MATLAB were employed to establish predictive relationships between efficiency metrics and operational parameters.

Thermodynamic Process Analysis

The methodology outlines thermodynamic processes of the steam generator and their representation in the Rankine cycle. The cycle involves four key processes which are; the isentropic expansion process in the turbine, the heat rejection process in the condenser, the isentropic compression process in the pump, and the heat addition process in the boiler (Pawel et al, 2021).

At this stage, high-pressure, high-temperature steam exits the boiler and enters the turbine. The thermodynamic properties at this point include the enthalpy (h_1) is determined by the pressure (P_1) and temperature (T_1) of the steam (Zare, 2015). The enthalpy (h_1) is calculated as:

$$h_1 = h(P_1, T_1) \quad (1)$$

And the entropy (S_1) is calculated as:

$$s_1 = s(P_1, T_1) \quad (2)$$

This state represents the maximum energy content of the working fluid, providing the energy source for the turbine. It is the starting point for the turbine expansion process. During this process, steam expands in the turbine, producing work. Assuming the process is isentropic (no entropy generation), the entropy remains constant ($S_2 = S_1$). The enthalpy at the turbine exit (h_2) is determined using the isentropic relation (Dincer and Cengel, 2001). The turbine exit enthalpy is expressed as:

$$h_1 = h(P_2, T_2) \quad (3)$$

Where (P_2) is the pressure at the turbine outlet. At this stage, thermal energy converts the steam into mechanical work. Which can later be converted to electrical energy. The work done by the turbine is given by

$$W_t = h_1 - h_2 \quad (4)$$

At the condenser outlet, the steam is converted into a saturated liquid at low pressure. The thermodynamic properties at this point include the enthalpy (h_3) which is the saturated liquid enthalpy at the condenser pressure (P_3) and entropy (**S_3**) is the Saturated liquid entropy at (P_3) (Ahmadi et al, 2008). The enthalpy and entropy are respectively expressed as:

$$h_3 = h_{sat,liquid}(P_3) \quad (5)$$

$$s_3 = s_{sat,liquid}(P_3) \quad (6)$$

This state is the starting point for the pump compression process. The energy rejected to the environment in the condenser is:

$$Q_{out} = h_2 - h_3 \quad (7)$$

The saturated liquid is compressed entropically in the pump to the boiler pressure. Assuming no entropy generation ($S_4 = S_3$), the enthalpy at the pump outlet (h_4) and the work required by the pump is determined (Bora and Nakkeeran, 2014). The enthalpy is expressed as:

$$h_4 = h(P_1, S_3) \quad (8)$$

And the work required by the pump is:

$$W_p = h_4 - h_3 \quad (9)$$

At constant pressure, the compressed liquid is heated in the boiler till it turns to superheated steam. The energy added to the boiler is determined. This stage represents the main energy input to the cycle, providing the necessary thermal energy to generate high-pressure steam (Zare, 2015). The heat addition is:

$$Q_{in} = h_1 - h_4 \quad (10)$$

The ratio of the net work output to the heat is known as the thermal efficiency of the Rankine Cycle. This equation quantifies how efficiently the cycle converts thermal energy into useful work (Zhao et al, 2017). Thermal efficiency is expressed as:

$$\eta = \frac{W_{net}}{Q_{in}} * 100 \quad (11)$$

Where

$$W_{net} = W_t - W_p \quad (12)$$

This represents the mechanical or electrical power generated by the cycle (Ayad et al, 2017) and can be expressed as:

$$P_{output} = \dot{m}W_{net} \quad (13)$$

The T-S diagram visualizes the thermodynamic processes of the Rankine cycle. The stages of the Rankine cycle are modeled using thermodynamic equations, enabling the calculation of key metrics such as efficiency and power output.

Regression Model

Multiple linear regression was used to establish relationships between independent variables (T_{nilet}, P_{inlet}, P_{cond}) and dependent variables (η for efficiency and P_{out} for power output). The regression model supposed that there is a linear relationship between the independent variables and the dependent variables (Phan & Nguyen, 2024) as follows:

$$Y = X\beta + \epsilon \quad (14)$$

Where:

Y represents the dependent variables (η or Pout), X is the matrix of independent variables (T_{nilet}, P_{inlet}, P_{cond}), B is the vector of regression coefficients representing the effect of each independent variable and ϵ is the error term accounting for model deviations.

Model fitting

The regression coefficients (β) are estimated using the least squares method of Equation 15, minimizing the sum of squared errors as follows:

$$\hat{B} = (X^T X)^{-1} X^T Y \quad (15)$$

2.2.4 Prediction and optimization

The regression model used in this research is a data-driven approach to predict turbine performance (η for efficiency and Pout for power output) based on the operating parameters (T_{inlet}, P_{inlet}, P_{cond}). Below is a detailed explanation of the process, including the equations and steps for prediction and optimization. The general multiple regression model (Kaya & Guler, 2013) is as follow:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \epsilon \quad (16)$$

Where

Y is the Dependent variable (η or P_{out}), and all predictors are zero, β0 is the Intercept representing the baseline value of Y. β_1,β_2,β_3 is the Regression coefficients for T_{inlet} (X_1),P_{inlet} (X_2), P_{cond} (X_3), representing their individual contributions to Yand ϵ is the Error term capturing deviations due to unaccounted factors.

The regression coefficients are estimated by minimizing the sum of squared residuals (errors) as follows:

$$\sum_{i=1}^{n} \left(Y_i - \widehat{Y_1}\right)^2 \quad (17)$$

Where

n is the number of observations in the datasets using the estimated coefficients (β^, β1, β2, β3), the model predicted the turbine efficiency (η) and power output for given operating conditions (T_{nilet}, P_{inlet}, P_{cond}) as shown below in Equation 18 and 19 respectively.

$$\eta = \beta_0 + \beta_1 T_{inlet} + \beta_2 P_{inlet} + \beta_3 X_{cond} \quad (18)$$

$$P_{0ut} = \beta_0 + \beta_1 T_{inlet} + \beta_2 P_{inlet} + \beta_3 X_{cond} \quad (19)$$

To optimize turbine performance, the model identifies parameter values (T_{nilet}, P_{inlet}, P_{cond}) that maximize η and Pout . , it will ensured that T_{nilet}, P_{inlet}, P_{cond} stay within practical and operational limits:

$450 \leq Tinlet \leq 550$, $40 \leq Pinlet \leq 50$, $0.1 \leq Pcond \leq 1$ (20)

Reliability Model

Reliability analysis quantifies the likelihood that the steam generator and its components will function without failure over a specific operational period. The failure rates (λ) represent the average number of failures per hour and are influenced by operational control and predictive maintenance strategies.

Component reliability over time

The reliability of each component is calculated using the exponential reliability function and for a component operating for t=8000 hours (1 year), the reliability is computed for the boiler and can be expressed similarly for the condenser and pump (Sabri et al., 2020) as follows:

$$R(t) = e^{-\lambda t} \quad (21)$$

Where:

R(t) is the reliability as a function of time, λ is the failure rate (failures/hour) and t is the operational time (hours).

System reliability

The system's overall reliability depends on the configuration of its components. In a series system, this assumes that a failure in any single component leads to system failure. The system reliability decreases as the number of components increases or as individual component reliability decrease.

$$R_{system} = R_{component1} * R_{component2} * \ldots .* R_{componentn} \quad (23)$$

Reliability over time

The time-dependent reliability of each component and the overall system is computed to visualize performance degradation over extended periods. Using the exponential reliability function is expressed as (Dewangan et al., 2014).

$$R(t) = e^{-\lambda t} \quad (24)$$

A time vector (t=0 to t=8000hrs) is used to calculate R(t) for each component and the system.

Results and Discussion

Thermodynamic Analysis of the Steam Generator

The thermodynamic analysis of the steam generator as analysed from equation 1-13 and the steam turbine data shown in App.A, depicts the steam generator operational characteristics and performance metrics. Fig.1 shows the Temperature-Entropy (T-S) diagram, this vividly represents the thermodynamic cycle stages; the isentropic expansion process in the turbine, the heat rejection process in the condenser, the isentropic compression process in the pump and heat addition process. The bright blue curve indicates the working fluid's thermodynamic journey through these processes. The near-vertical and horizontal lines represent constant pressure, heat addition and rejection processes respectively.

Heat addition happens between points of lower entropy (compressed liquid) to higher entropy as the water is converted to superheated steam in the boiler. The transition is important because it increases the working fluid's energy content, adding to the turbines work output. The boiler adds heat at about 3107.10kJ/kg as depicted. The isentropic expansion happens in the turbine, where the high enthalpy steam delivers mechanical work at 997.13kJ/kg, while its pressure and temperature reduce.

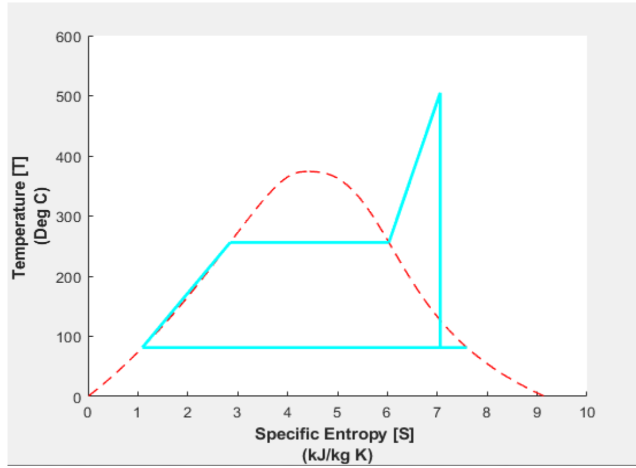

Figure 1: T-S Diagram of the Steam Generator

The condenser depicts the heat rejection stage where waste heat at 2115.23kJ/KG is released to convert steam to a liquid form at low pressure. This stage ensures that the cycle is closed and ready for compression. The pump compresses the low-pressure liquid to boiler pressure, requiring a reduced work at 5.27kJ/kg. The red dashed line depicts the saturation curve, which separates the wet and superheated steam regions. The system operates efficiently in the superheated zone, this is evident from the high-quality steam entering the turbine.

Fig.2 illustrates the variation of cycle efficiency and power output with respect to turbine inlet temperature. it also shows the relationship between turbine inlet temperature, power output versus cycle efficiency. A linear trend can be observed where both power output and efficiency increase with turbine inlet temperature. At 450^{0}C, the efficiency is about 80.2% and the power output is about 26.83MW. When the temperature reaches 550^{0}C, efficiency improves to 82.6%, and power output increases to 28.04MW.

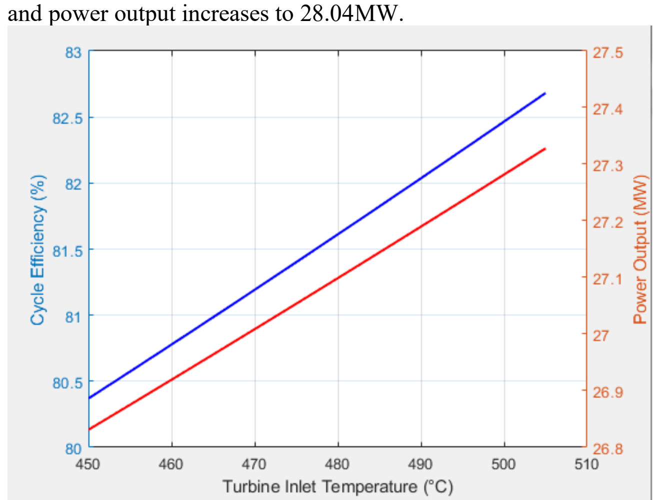

Figure 2: Efficiency and Power Output vs Turbine Inlet Temperature

This trend shows the fundamental principle that higher turbine inlet temperature improves the cycle's thermal efficiency by increasing the mean temperature at which heat is introduced. This agrees with the steam generator efficiency, emphasizing that the thermodynamic performance improves as the temperature difference between the heat source and sink increases. The detailed numerical outputs corroborate the graphical insights. The thermal efficiency of 82.6% shows the percentage of input energy that is converted to useful work, while the power output of 27320.8kW represents the not mechanical energy available for external use.

Reliability Model

In contrast, analysing the reliability of the steam engine using equation 21 and 22, the reliability adjusted model reveals a slightly varying perspective, which highlights the practical implications of system reliability on performance. The reliability-adjusted model adds factors such as; component degradation, and operational stability which has a tangible impact on the steam engine's efficiency and power output. The reliability adjusted efficiently very closely follows the trend of the steam generator, ranging from 80.4% to 81.34% across the turbine inlet temperature range. As depicted in Fig.3, the adjustments ensure that the system operates within realistic boundaries of reliability.

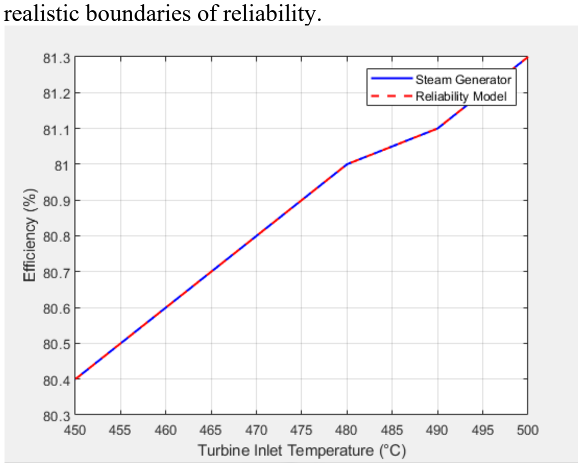

Figure 3**:** Steam Generator and Reliability Efficiency Result

By the time the T_{inlet} reaches 500^0C, the efficiency is predicted to be 83.4%. The nearly linear progression, with a consistent increase of about 0.00097% - 0.001% when compared to that of the steam generator, shows that higher turbine inlet temperature improves the thermal efficiency of the steam generator. This improvement occurs because more of the thermal energy is converted into mechanical work rather than being lost as waste heat.

The reliability data depicts the substantial impact of component dependability on overall system performance as shown in Table1 and Fig. 4. The reliability values of the turbine (0.9749), boiler (0.9608), condenser (0.9403), and pump (0.9794) contributes to an overall system reliability of 0.8626. The figures highlight the turbine and condenser as the least reliable components, significantly influencing the system's operational reliability.

Table 1: Reliability of Various Steam Turbine Components

Component	MTBF (hrs)	MTTR (h
Boiler	24,981.60	43.98
Feed Pump	48,028.57	32.05
Turbine	39,279.76	36.86
Condenser	16,240.75	48.65

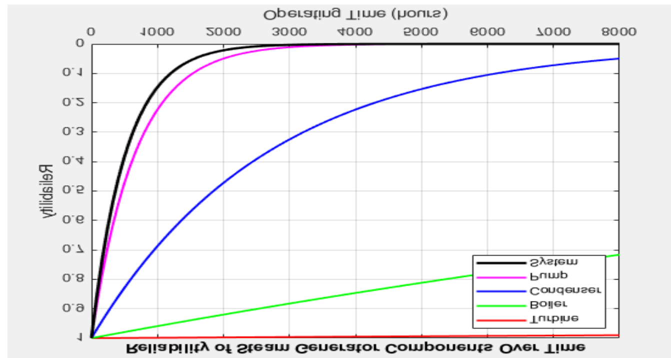

Figure 4*:* Reliability of Steam Generator Component over Time

Enhanced reliability ensures that the system operates closer to its designed efficiency and power output, minimizing losses due to suboptimal conditions or unplanned. The reliability-adjusted efficiency and power output results reflects a robust system capable of consistent performance overtime. Notwithstanding the overall system being relatively high at 72.62%, this depicts that this steam generator is highly reliable. By addressing component reliability challenges, operators can optimize the lifecycle performance of the steam turbine system, ensuring sustained power generation and operational efficiency.

Regression Model

The regression parameters described by equation 16 is illustrated in Table 2 with regression determinant as 80.9%. When comparing the steam engine data to the regression model, using equations 4 to 20, a clear pattern arises in which the regression model captures the overall trends in both efficiency and power output with high degree of accuracy. For example, the regression efficiency shows a steady increase from 80.4% at a turbine inlet temperature of 450^0C to 81.32% at 500^0C as illustrated in Fig.5.

Table 2: The regression parameters for boiler efficiency.

Regression Parameter		Fuel flowrate	Excess air ratio	Flue gas temperature	Feedwater Temperature	Steam flow rate	Boiler load
R-squared: 0.809	β_0 = 90	β_1 = 0.004	β_2 = 0.004	β_3 = 0.025	β_4 = 0.06	β_5 = 0.0004	β_6 = 0.12

The almost constant increment in both efficiency and power output underscores the ability of multiple regression to generalize the system's response to the changes in thermal input, providing a reliable framework for predicting system performance. The option to limit the analysis to 500^0C as the peak regression turbine inlet temperature that the steam generator can operate safely, rather than extending it to 505^{0}C, the research remains within the bounds of operational safety while capturing significant performance enhancement.

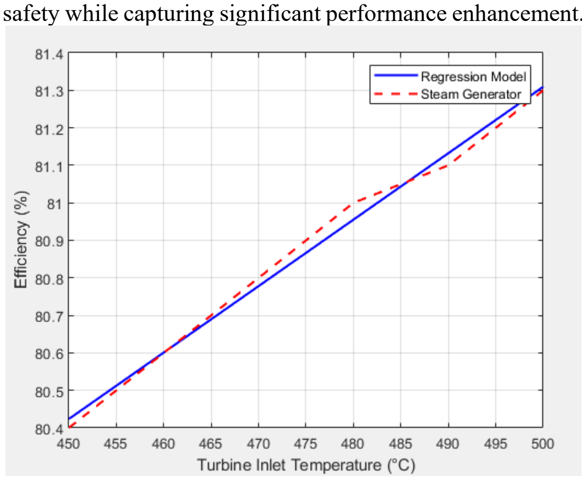

Figure 5**:** Steam Generator and Regression Efficiency against Turbine inlet Temperature

Beyond 500^{0}C, the potential gains in efficiency and power output may start to reduce because often thermodynamic limits making the additional increase in temperature less beneficial relative to the added costs and risks. This balance of performance gains and system reliability makes 500^{0}C an optimal choice for the regression analysis.

Comparative Analysis

The power output results depicted in Fig.6 further explains the influence of reliability. For a turbine inlet temperature of 500^{0}C, the regression model predicts a power output of about 28030.33kW, while the reliability-adjusted output is slightly lower at 28000.00kW. Across the temperature range, the regression power output increases steadily from 26830.33kW AT 450^{0}C to 28030.3kW at 500^{0}C, whereas the reliability-adjusted power output closely errors this trend, ranging from 26800.00kW to 28000kW.

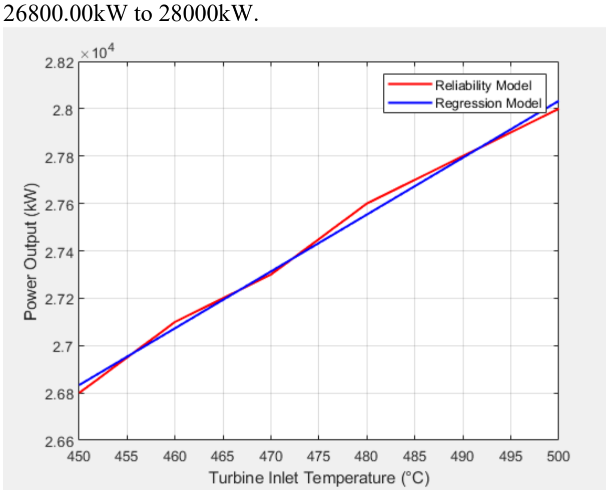

Figure 6: Comparative Analysis of Power

The close alignment of these values depicts that reliability adjustments primarily stabilizes performance rather than significantly boosting power output. This stabilization ensures that the system performance remains efficient under real-world operation conditions, showing how operational reliability mitigates potential performance loses caused by component failure and wear. This study confirms that higher turbine inlet temperatures improve thermodynamic performance by improving the conversion of thermal energy into work, although the adjustments due to reliability metrics yield only small amount of incremental benefits.

The comparison between the steam engine data, the regression model, and the reliability-adjusted model reveals complementary insights into the performance of the steam generator system. While the regression model provides a robust framework for the prediction of theoretical performance trends. The reliability model incorporates practical considerations that ensure operational stability and consistency.

Validation

In terms of validation, boiler performance shows a strong correlation between stimulation and model predictions confirming the reliability and accuracy of the processes studied. Fig 7 illustrates the boiler efficiency as a function of evaporation rate (ton/hr), the efficiency increases steadily with rising evaporation, getting to a height of 81% between 25 to75ton/hr. The curve illustrates a typical performance trend where efficiency is enhanced with load up to an optimal point and then stabilizes. The presence of a data point (drop symbol) on the curve suggests experimental or simulation data used for model validation.

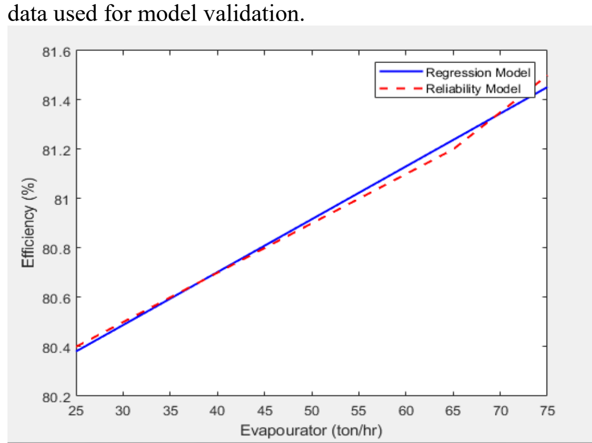

Figure 7: Result Validation

Conclusion

The study concludes that increasing the turbine inlet temperature directly improves the steam generator's performance, with power output rising from 26,800 Kw to 28,000 Kw and efficiency improving from 80.40% to 81.50% when the temperature is increased from 450^{0}C to 505^{0}C. The analysis highlights the importance of thermodynamic principles in understanding and optimizing steam generator performance. The development of regression and reliability models provides valuable insights into improving steam engine operation, with the regression model capturing the linear relationship between temperature, efficiency, and power output.

The study determines that a turbine inlet temperature of 500^0C is the optimal operating condition, achieving the highest efficiency (81.50%) and power output (28,000 KW) while maintaining safe operational parameters. The integration of reliability and regression models effectively predicts performance metrics and accounts for real-world constraints, reducing downtime and improving energy recovery. This comprehensive approach ensures the steam turbine operates at peak efficiency while maintaining long-term stability and reducing maintenance costs, highlighting the importance of incorporating dependability metrics in steam.

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Appendix A

The thermodynamic data acquired from the LNG Carrier are the following;

Performance Data for Main Boiler (Hyundai H.14069, Boiler Type MB – 3E) Oil Firing

Load			B.MAX	NOR	75% NOR	50% NOR	25% NOR
Evaporation	Total	kg/h	55,000	47,000	35,250	23,500	11,750
	SH Steam	kg/h	55,000	47,000	35,250	23,500	11,750
	DSH Steam	kg/h	0	0	0	0	0
Pressure	Drum	bar	68.0	65.9	63.5	61.7	60.7
	SH Outlet	bar	60.3	60.3	60.3	60.3	60.3
Water & Steam Temperature	Eco Inlet	^0C	145	145	145	145	145
	SH Inlet	^0C	284	282	279	277	276
	SH Outlet	^0C	515	515	515	499	468
	DSH Outlet	^0C	285	285	285	285	285
Air Temperature	FDF Outlet	^0C	45	45	45	45	45
	SAH Outlet	^0C	120	120	120	120	120
Efficiency	(HHV Base)	%	88.4	88.5	88.4	87.8	85.6
Caloric value	HHV	kcal/kg	10280	10280	10280	10280	10280
	LHV	kcal/kg	9713	9713	9713	9713	9713
Fuel Oil Consumption		kg/h	4001	3416	2564	1696	844
Excess Air Rate		%	10.0	10.0	12.5	19.2	36.0
O2 Rate		%	1.9	1.9	2.3	3.4	5.6
Combustion Air Flow		kg/h	60,350	51,530	39,550	27,720	15,740
Fuel Gas Flow		kg/h	64,351	54,946	42,114	29,416	16,584
Eco inlet Gas Temp.		^0C	391	373	348	322	297
Eco Outlet Gas Temp		^0C	182	177	171	167	167
Total Draft Loss		mbar	48.3	35.2	20.8	10.2	3.3