Enhancing Maritime Energy Efficiency: A Multi-Physics Digital Twin Approach for Waste Heat Recovery Systems

[1]Geng Qin, [1]Songlin Bai, [1]Hung-Pin Chien, [2]Ming-Chao Yang, [2]Ming-Chao Lin, [2]Ling-Pang Tseng

[1]*American Bureau of Shipping, Singapore*

[2]*China Steel Express Corporation, Taiwan*

Abstract – This research develops a detailed multi-physics digital twin for ship energy systems, focusing on oil boilers and steam boiler Waste Heat Recovery (WHR) systems to address maritime energy efficiency and carbon emission reduction. The model integrates complex physical processes including thermo-dynamics, chemical reactions, electrical dynamics, and control systems, validated using operational data from China Steel Express Corporation. Simulations across various key operational conditions demonstrate the steam boiler WHR system's efficacy, consistently yielding over 50% reduction in oil boiler fuel consumption and 2-3% overall fuel savings for ship propulsion systems. This physics-based approach diverges from data-driven methods, ensuring system agnostic evaluation of ship designs and offering a robust framework for system performance prediction.

Keywords: Digital Twin, Modeling and Simulation, Propulsion Equipment, Waste Heat Recovery System, Decarbonization

1. INTRODUCTION

As the main drivers for change in the maritime industry, decarbonization efforts as well as fuel cost reduction are among the most significant trends that shape the improvement of fleet management and its performance [1]. Waste heat recovery systems, and more specifically, waste heat recovery boilers are thus proving to be crucial in this process. Their purpose is to extract waste heat from engines and transform it into usable energy, thereby enhancing energy efficiency and reducing reliance on alternative fuel sources [2]. Conventional engine systems generate waste heat and release it into the atmosphere, resulting in significant energy loss. Waste heat recovery systems can utilize this heat to meet various operational requirements, thereby greatly improving fuel-to-energy conversion efficiency and promoting environmental conservation [3].

In this study, we employ the concept of digital twin, defined as “a virtual representation of a physical asset, along with its environment and processes, comprised of integrated models that are updated through the exchange of information” [4]. In our context, the digital twin refers to a set of virtual models that accurately represent the physical WHR components. These models are validated with operational data to reflect the actual behavior, working condition, and performance of the physical systems, aligning with NASA's standards for models and simulations [5]. The general thrust of this study is to develop physics-based WHR models by constructing a steam boiler, as well as three of the auxiliary engines in bulk carriers. Therefore, within the scope of this study, we have simulated the fuel oil consumption and steam flow rates of this integrated system to ensure the accuracy of our estimates. Furthermore, the study aims to assess the waste heat recovery system's performance under various working conditions and provide comprehensive findings on possible fuel consumption and emissions reduction.

In the same context, the present study will expand knowledge on the topic by enhancing the development of a structural physics-based model to evaluate the WHR system applied to the auxiliary engine of a bulk carrier. This paper examines the possibilities of introducing new waste heat recovery boilers to auxiliary engines, as well as a comprehensive analysis of fuel consumption variability and emissions. This approach allows us to leverage advanced modeling techniques to address complex challenges in maritime energy systems, enabling optimization and validation in a virtual environment before real-world implementation.

The idea of recovering waste heat is well understood and relatively well researched in the literature applicable to industrial processes, power stations, and vehicle engines. Suárez De La Fuente [6] focuses on providing several options for shipping carbon emissions reduction based on Organic Rankine Cycle (ORC) waste heat recovery technology. The study by Oyekale [7] looks at the thermodynamic irreversibility of subcritical and supercritical ORC power plants for waste heat recovery in marine vessels. Oyekale's study showed how efficiency could be improved. Niknam [8] examines how waste heat recovery works when combined with new thermal systems, as well as how multi-energy systems work on ships. Di Battista [9] presents waste energy recovery and valorization in internal combustion engines, focusing on fuel savings and emissions reduction potential in transportation. Inal [10] focuses on the present developments and future trends of hybrid power and propulsion systems in ships, as well as delineating the existing issues for implementing waste heat recovery. Jyethi [11] also appropriately reviews the global and regional emissions of particulate matter, SOx, and NOx to justify practical and useful emissions control techniques like waste heat recovery. Elkafas [12] analyses the environmental and economic effects of the measures that reduce the speed of container ships, especially the waste heat recovery systems. Analyzing the broader picture of waste heat recovery adoption, Hendrickson [13] conducts a review of the environmental life cycle assessment of goods and services. Abo-Khalil [14] looks at how digital twin real-time hybrid simulation platforms can be used to keep power systems stable and suggests that waste heat recovery systems should be able to be supervised to work at their most efficient. This literature review explores various technologies such as the Organic Rankine Cycle, integration with hybrid systems, and addresses environmental and economic impacts. Despite these theoretical advancements, this paper presents a systematical physics-based model of waste heat recovery boilers combined with the auxiliary engines of an actual bulk carrier, and provides a specific quantitative analysis of fuel consumption and emission using real data. The integration of empirical data from an operational vessel not only validates the model's accuracy but also establishes a robust benchmark for subsequent studies in maritime energy efficiency.

The remainder of this paper is organized as follows: Section 2 of this research work reveals the methodology adopted for the conduct of this research. The simulations as well as further discussion on the developed model are presented in Section 3 and Section 4 gives the results of the work. Lastly, Section 5 highlighted the overall findings and future possible works.

2. METHODOLOGY

This study employs a digital twin approach, integrating elements from the Real World, Problem World, and Models, Simulations, and Digital Twins (MS&DT) World [15]. Our methodology begins with the real-world need for improved maritime energy efficiency and reduced emissions, which we translate into the specific goal of optimizing Waste Heat Recovery (WHR) systems in the Problem World. In the MS&DT World, we develop a comprehensive digital twin of the ship's energy systems, including oil boilers, steam boilers, and auxiliary engines. By simulating various scenarios, we derive insights that could be transferred back to the Real World, where they can be implemented to enhance the performance of actual WHR systems on bulk carriers. The following sections detail each step of this methodology, from data processing to model development and simulation.

Firstly, we obtained real operation data from the ship owner in the form of noon reports. The one-year data includes the operational time, main engine power and load, propeller speed, auxiliary engine fuel oil consumption, and oil boiler fuel oil consumption, etc. We preprocessed these raw data to ensure data authenticity and accuracy, which included cleaner operation, data imputation, identification of the operational mode, and an approximation of the upper bound of oil boiler fuel consumption. This process prevented excessive error from arising in the input data of the simulation models used in the subsequent step. Next, we created a baseline model for the existing oil boiler system as shown in Figure 1. This study thoroughly analyzed it to identify the parameters and corresponding values to simulate a similar operation environment.

This digital twin model replicated the process of the existing oil boiler system, to provide heat resource to the operation need or hotel load. The process begins with feedwater heating in the oil boiler, generating steam that serves as an energy source for onboard consumers (effectively heat exchangers). Post-energy release, steam condenses and returns to the boiler. Fuel supports both the auxiliary engine and oil boiler operations.

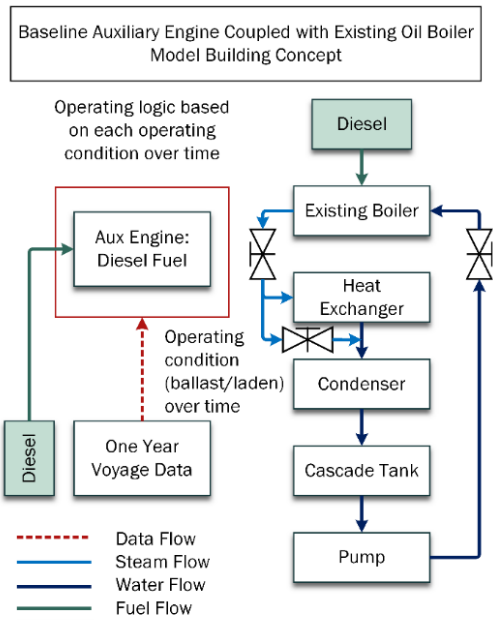

Figure 1: Conceptual Model of the Existing Oil Boiler

The baseline scenario represents the auxiliary engine's state prior to steam boiler installation. Figure 2 illustrates the digital twin model performance curve of the oil boiler after calibration as compared to manufacturer data.

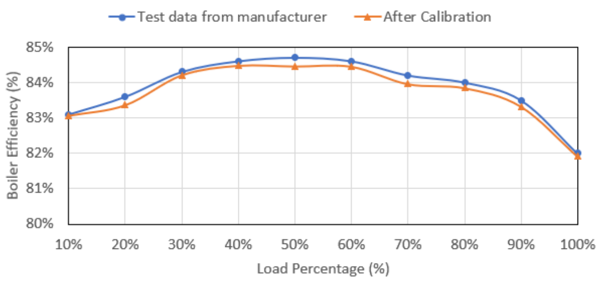

Figure 2. Oil boiler efficiency curve comparison

Following this, as shown in Figure 3, a comprehensive steam boiler digital twin model was developed to simulate the conversion of waste heat from auxiliary engines into steam. This model encapsulates the intricate energy transfer processes within the system. It incorporates the process of transferring waste heat generated by auxiliary engines to the steam boiler.

This model included calculations of temperature gradients, pressure differentials, and heat transfer rates, which enabled a comprehensive assessment of the steam boiler's performance. The steam boiler model was calibrated using manufacturer data, assuming no heat loss to the ambient environment. Other assumptions made are mass flow rate of water entering the boiler is equal to that of the steam exiting, and for every 10 kPa increase in backpressure, there is a 3% increment in fuel consumption [16].

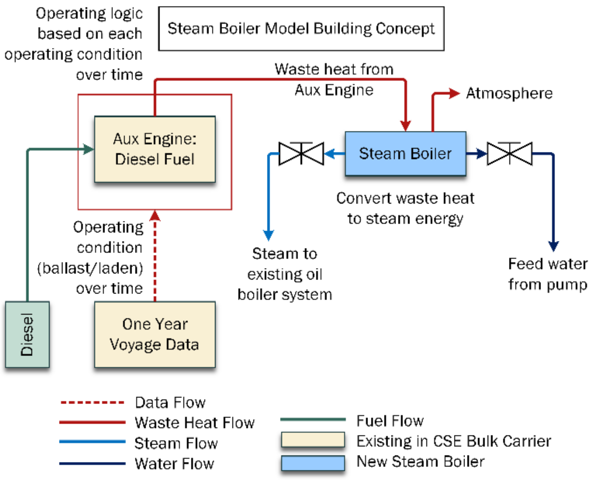

Figure 3: Steam boiler system model

Figure 4 illustrated the digital twin model performance curve of the oil boiler after calibration as compared to manufacturer data.

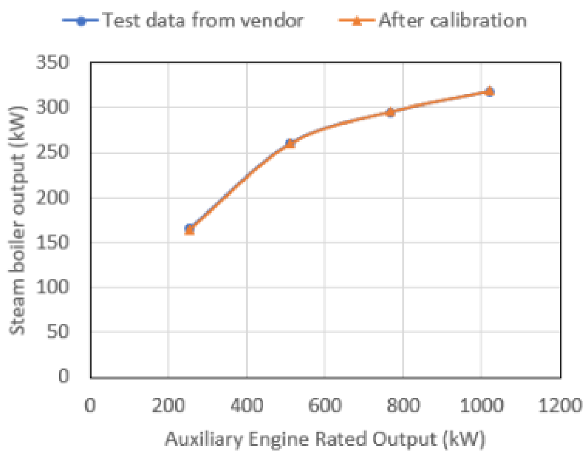

Figure 4: Steam boiler output curve

3. WHR Full System Simulation

This overall system model aimed to evaluate the system's ability to utilize waste heat to generate steam, comparing this with the energy demands previously met solely by the oil boiler. The flowchart in Figure 5 illustrates the process of calculating fuel oil consumption in the system. Oil boiler will only be activated when the Auxiliary Engine's WHR system cannot meet energy demands. This process helps us understand when and how much the oil boiler needs to run, which affects the total amount of fuel the ship uses.

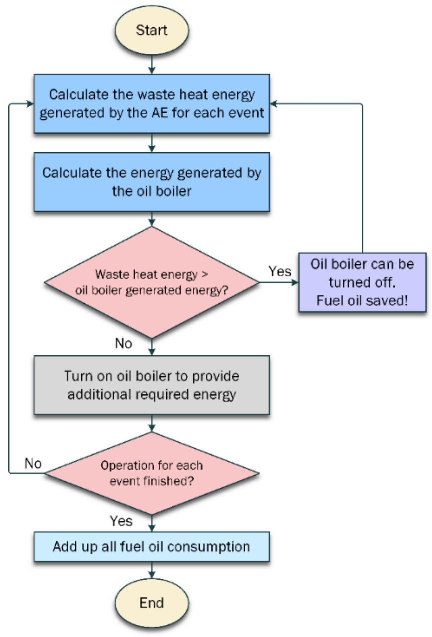

Figure 5: Flow chart for fuel oil consumption calculation

The overall physics-based WHR system digital twin is depicted in Figure 6. This system consists of three key components: three auxiliary engines which serves as the primary source of waste heat generation during operation; One oil boiler to provide steam energy for daily operations; Three steam boilers and one of them is to efficiently convert the captured waste heat into steam energy. Therefore, the steam boilers play a pivotal role in enhancing the overall efficiency of the WHR process.

Simulations were conducted to estimate system performance parameters, including WHR efficiency, energy output, and fuel consumption. These simulations considered different steam boiler efficiencies and various operational conditions such as anchorage, in-port, and at-sea operations. In addition, waste heat conversion logics are explained below:

- Waste Heat Generation: Auxiliary engines produce waste heat during operation.
- Waste Heat Transfer: The waste heat generated by the auxiliary engine is transferred to steam boilers.
- Steam Boiler Heat Conversion: The waste heat convert into steam through the water/steam piping system integrated within the boiler.
- Energy Assessment: Steam volume is compared to operational needs. Excess steam is used for other purposes to enhanced energy efficiency.
- Oil Boiler Activation: In cases where the generated steam falls short of the required quantity, the oil boiler is activated to supplement the steam supply.

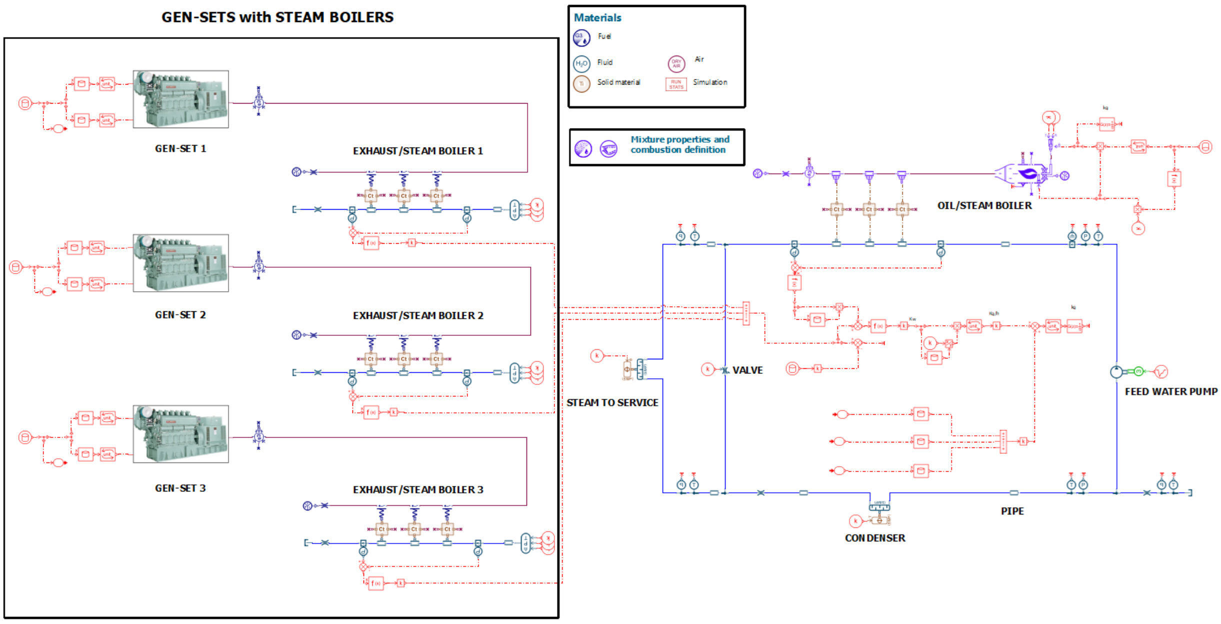

Figure 6: Diagram of the WHR System Digital Twin Model

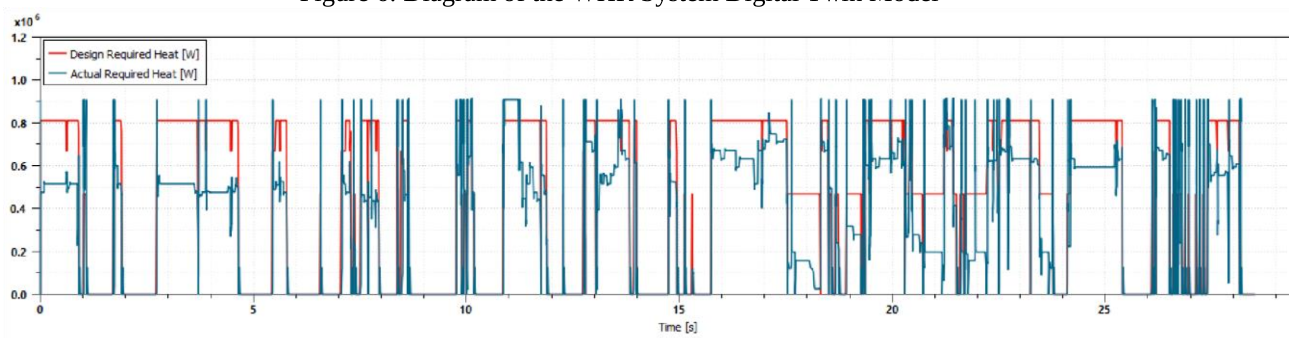

Figure 7: Steam requirements comparison between actual and simulated environment

4. RESULTS AND DISCUSSIONS

The simulations conducted in this study reveal the potential fuel savings and emissions reduction through the implementation of a WHR system on bulk carrier. The figures from 7 to 13 illustrate various aspects of the system's performance and efficiency under different operational conditions.

The simulated results have been explored using two datasets. One of these contains the data on designed steam requirements under different operational conditions, and the other one specifies the actual Fuel Oil Consumption (FOC), which allows us to derive the actual steam requirements by correlating the fuel consumption with the energy needed for steam production. The comparison of these two steam requirements is visually presented in Figure 7.

The comparisons reveal that the designed steam requirements exceed the actual operational needs. Furthermore, upon comparing the designed steam requirements with the actual steam requirements calculated from the FOC data in Figure 8, it is notable that the FOC associated with the designed steam requirements significantly exceeds the actual FOC for the same operations, which suggests a variance between the designed parameters and the digital twin developed using real-world operational efficiency.

In addition, we have considered various steam boiler efficiency scenarios, including 100%, 90%, 85%, 80%, 70%, and 50%. Figure 9 illustrates the history of FOC and provides a clearer perspective on the variation observed across different steam boiler efficiency scenarios. While a 100% steam boiler efficiency is not achievable in real-world conditions, we included this scenario to illustrate the theoretical upper limit of fuel savings. Our findings showed that with the 100% scenario representing the maximum potential savings and the 50% scenario demonstrating the lower bound of the system's benefits.

This trend is particularly pronounced during periods of high steam demand, such as anchorage and in-port operations, where the efficiency of the steam boiler plays an important role in determining overall fuel savings.

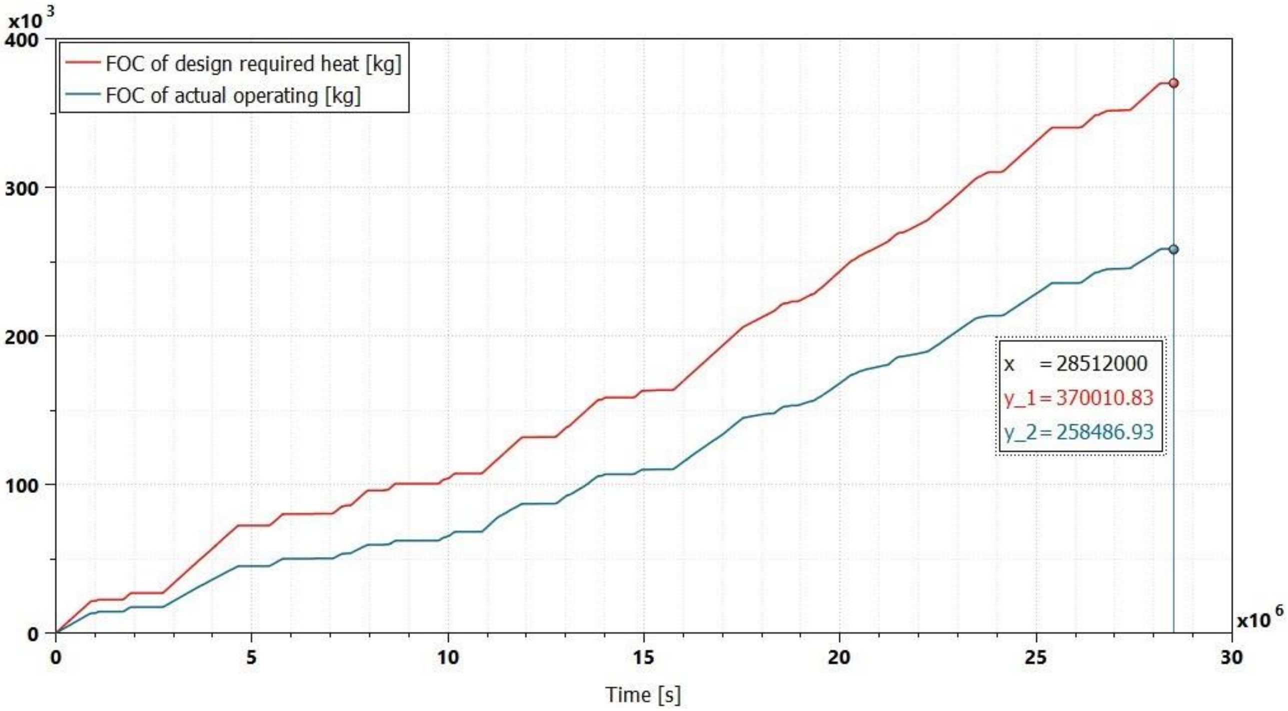

Figure 8: Fuel oil consumption history against design and actual steam requirement

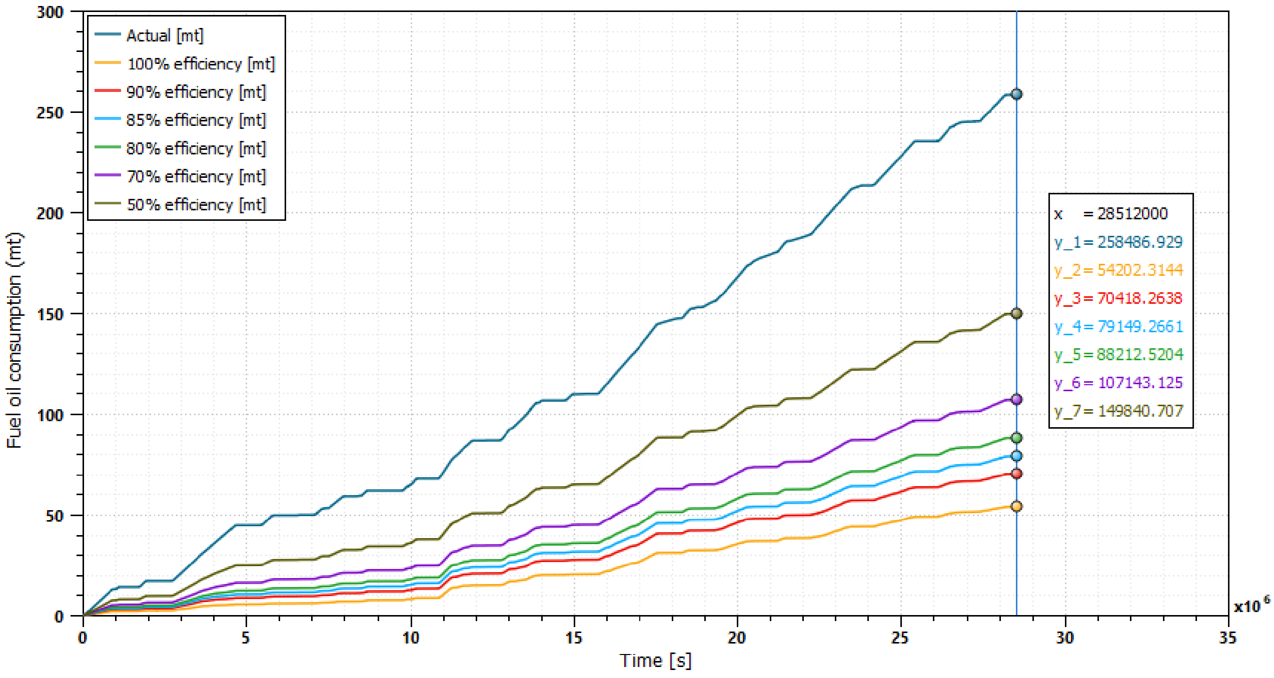

Figure 9: Fuel oil consumption history against different steam boiler efficiency

Next, Figure 10 depicts the percentage of fuel oil savings for oil boiler only. This calculation is based on the fuel savings divided by the actual FOC of the oil boiler. In more practical terms, our simulations showed that at an 80% efficiency level, which is considered achievable in well-maintained industrial steam boilers, the WHR system could potentially reduce oil boiler fuel consumption by up to 65%.

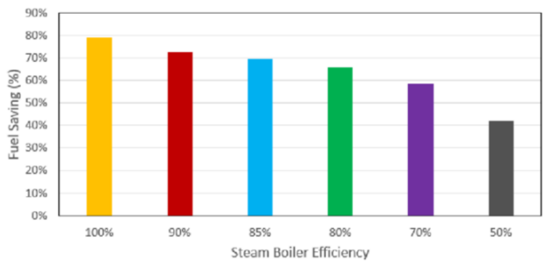

Figure 10: Fuel Saving Percentage

This finding underscores the substantial impact of steam boiler efficiency on the fuel economy of the oil boiler, highlighting the importance of maintaining high efficiency to maximize fuel savings.

Finally, to understand the factors contributing to the observed fuel savings across various steam boiler efficiency scenarios. We take the realistic case of an 80% steam boiler efficiency for example, as depicted in Figure 11. With the installation and use of the steam boiler, the results show that there will be a 2.3% reduction total fuel oil consumption (considering fuel consumed by oil boiler, auxiliary engines and main engine). This result is in line with IMO's green voyage 2050 study [17] that WHR System could save up to 5% or steam production on ships that have oil boilers installed.

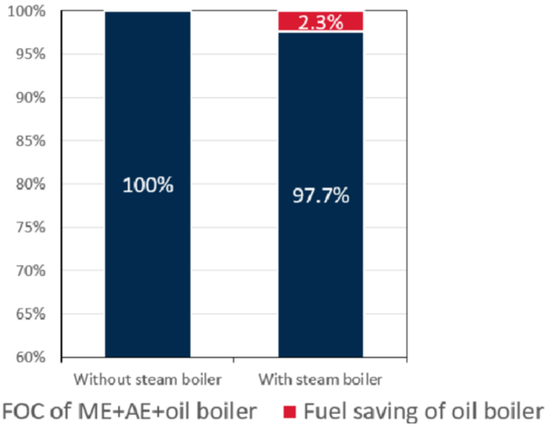

Figure 11. FOC Comparisons Based on Main Engine, Auxiliary Engine, and Oil Boiler

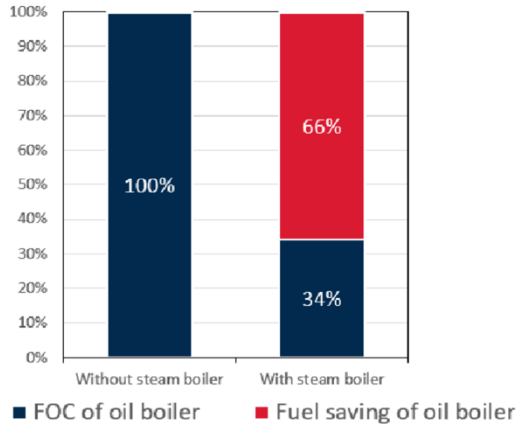

Figure 12: FOC Comparison Based on Oil Boiler

If we consider only the FOC of oil boiler as shown in Figure 12, the implementation of the steam boiler can reduce the oil boiler's fuel consumption by 66%, emphasizing the direct benefits of WHR in reducing the operational costs and environmental impact of maritime vessels.

Lastly, to compare the fuel saving for various operation scenarios, as shown in Figure 13, Fuel oil saving percentage is calculated based on saving divided by FOC for each operation. The data indicates that “at sea” operation yields the highest fuel saving in terms of percentage, reflecting the higher steam demands of these modes.

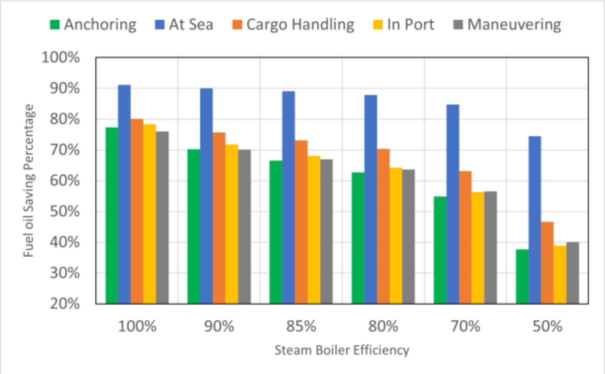

Figure 13. Fuel Oil Savings for Individual Operation Against Different Steam Boiler Efficiency

5. Conclusion

This study presented the development and analysis of an innovative WHR system digital twin model. It shows that WHR has the potential of revealing the enhancement of the fuel and emission on the bulk carriers. The paper employs the state-of-the-art multi-physics digital twin models of the oil and steam boilers, as well as their integration with the auxiliary engines. The energy recovery process from waste heat, encompassing heat capture, transfer, and utilization, etc. has been studied in the simulation. The results and performance analysis presented in this paper show that up to 80% efficiency is achievable in WHR steam boilers. The results and performance shows that for a realistic 80% efficiency WHR steam boilers system, fuel consumption by oil boilers can be reduced by 66%. The impact on the ship’s total fuel saving is 2.3%. Our digital twin approach and methodology used for assessing WHR possesses the potential for extension to various boiler efficiency scenarios and other maritime systems.

Furthermore, the rigorously verified and validated digital twins developed in this study can be effectively repurposed and incorporated into other ship system models. This scalability and adaptability open up possibilities for holistic ship energy system optimization, potentially leading to even greater efficiency gains and emission reductions across various vessel types and operational profiles. Future research directions could include the integration of this WHR digital twin model with real-time operational data for dynamic system optimization, exploration of its application to different ship types and sizes, and investigation of its potential in conjunction with other energy-saving technologies.

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