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Energy Efficiency Analysis of Main Cooling Pump System on Bulk Carrier Using VSD

Rashieka Alma Adalia[1], Fajri Ashfi Rayhan[1*]
[1]Department of Naval Architecture, Universitas Pembangunan Nasional Veteran Jakarta, 16514, Indonesia.

KEYWORDS
Energy efficiency; Cooling System; Variable Speed Drive; Pump Performance; Bulk Carrier

ABSTRACT – Improving energy efficiency in marine auxiliary systems has become increasingly important due to rising fuel consumption, stricter environmental regulations, and global green shipping initiatives. Conventional seawater cooling pumps on bulk carrier vessels generally operate at constant speed regardless of cooling demand, resulting in excessive energy consumption under partial-load conditions. Previous studies mainly focused on general Variable Speed Drive (VSD) applications, while limited research investigated the integrated performance of seawater cooling systems in bulk carriers, particularly the relationship between pump energy consumption, heat transfer performance, and operational efficiency. This study was conducted to evaluate the energy efficiency of the main cooling pump system on a bulk carrier vessel through the implementation of a Variable Speed Drive (VSD). The analysis was conducted using a thermodynamic simulation approach under steady-state conditions by applying pump affinity laws, heat transfer equations, and operational data from a MAN B&W S42MC marine diesel engine under various engine loads and seawater temperatures. The results show that VSD implementation reduced pump power consumption from approximately 26 kW to 2–10 kW under partial-load conditions, corresponding to improved pump efficiency, with a maximum efficiency of approximately 82% achieved near the Best Efficiency Point (BEP). The cooling system also maintained stable freshwater outlet temperatures around 36°C, indicating effective heat transfer performance, thermal stability, and improved cooling system energy efficiency. These findings confirm that VSD operation is highly effective under partial-load conditions and supports ship energy management systems to reduce fuel consumption and support sustainable green shipping practices.

*Corresponding Author | Fajri Ashfi Rayhan | ✉ (**fajri.ar@upnvj.ac.id**)

INTRODUCTION

In marine engine systems, the cooling system plays a fundamental role in maintaining thermal stability and ensuring reliable operation under varying operating conditions In bulk carrier vessels, a central cooling system is commonly employed to regulate engine temperature by removing excess heat through a heat exchanger, where seawater acts as the primary cooling medium. However, conventional seawater cooling pumps generally operate at a fixed speed independent of the actual cooling requirements. This operating characteristic leads to significant energy inefficiencies, particularly under partial load conditions, Previous studies have demonstrated that ship operational efficiency can be enhanced through optimization of speed and operating conditions, particularly by considering environmental and system performance factors. where excessive flow rates result in unnecessary power consumption and reduced overall system performance [1][2][3].

In recent years, improving energy efficiency in marine auxiliary systems has become increasingly important due to the growing demand for fuel efficiency and stricter ecological regulations in the maritime industry. The increasing demand for efficient energy utilization has driven the development of advanced technologies such as Variable Speed Drives (VSD), which are part of modern power electronic systems. The International Maritime Organization (IMO) has emphasized energy efficiency and emission reduction strategies [4][5], encouraging the adoption of energy-saving technologies onboard ships. Reported that the power usage of marine cooling pumps may account for approximately 65–70% of the total power consumption in centralized cooling systems, indicating significant potential for energy-saving improvements through pump optimization and Variable Speed Drive (VSD) implementation. One promising approach is the application of Variable Speed Drive (VSD), which enables pump operation to be adjusted according to real-time cooling requirements. Several studies have reported that VSD implementation can significantly reduce energy consumption in pump systems, especially under variable load conditions, while maintaining adequate heat transfer performance in heat exchangers. Furthermore, variable speed systems have demonstrated improved efficiency, adaptability to load variations, and significant fuel savings in marine applications [2][6][7].

In addition, thermodynamic modeling approaches using simulation tools such as Engineering Equation Solver (EES) have been widely applied to analyze cooling system performance under varying operational parameters, including seawater temperature, engine load, and flow rate. These approaches provide a systematic method to evaluate the interaction between fluid flow, heat transfer, and energy consumption in marine cooling systems. Although previous studies have focused on improving pump efficiency and the application of VSD in general systems, limited research has addressed the integrated performance of seawater cooling pump systems in bulk carriers. In particular, the interaction between pump energy consumption, heat exchanger performance, and overall system efficiency remains insufficiently explored. Furthermore, the trade-off between energy savings and potential impacts on engine thermal performance, such as variations in cooling effectiveness, has not been thoroughly investigated. Therefore, this research seeks to analyze the energy efficiency of the main cooling pump system in a bulk carrier by implementing a Variable Speed Drive (VSD). The analysis focuses on pump power consumption, cooling flow characteristics, heat transfer performance within the heat exchanger, and the overall system efficiency under various operating conditions [8]-[11].

METHODS

Bulk Carrier Specification

This study was conducted based on the operational characteristics of a bulk carrier vessel equipped with a MAN B&W S42MC main engine. The engine is classified as a two-stroke, slow-speed, crosshead-type marine diesel engine commonly used in large commercial bulk carriers due to its high propulsion efficiency and operational reliability. The engine operates at a maximum continuous rating (MCR) speed of approximately 158 rpm and utilizes Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) as the dominant fuel used. Bulk carriers are large commercial vessels equipped with high-power main engines that generate significant thermal loads during operation. As a result, these vessels require cooling systems with larger capacities to maintain engine performance, thermal stability, and operational reliability under varying operating conditions. Therefore, the bulk carrier cooling system represents an important application for evaluating the effectiveness of Variable Speed Drive (VSD) technology in improving cooling system energy efficiency.

The bulk carrier vessel employs a central cooling system consisting of freshwater and seawater circuits to maintain stable engine operating temperatures under varying main engine load conditions. The cooling system supports heat dissipation from the jacket water and scavenging air systems through a seawater cooling pump and heat exchanger arrangement. The main operational parameters used in this study are presented in Tables 3.1 and 3.2. The main engine has an output power of approximately 41,840 kW with a brake mean effective pressure (BMEP) of 1.8 MPa.

Table 1. Specification of the Bulk Carrier

Parameter/Unit	Value
Vessel Type	Bulk Carrier
Length Of All [m]	187.6
Length Of Between Pendicular [m]	181.2
Breadth [m]	24.7
Depth [m]	14.93
Draft [m]	9.87
Deadweight Tonnage [Ton]	28300
Main Engine	MAN B&W S42MC
Engine Type	2-Stroke Slow-Speed Marine Diesel
MCR Speed [RPM]	158
Fuel Type	HFO/MDO

The jacket water system operates with inlet and outlet temperatures of 80°C and 71°C, respectively, while the scavenging air temperatures range from 206°C at the inlet to 34°C at the outlet. In addition, the cooling system operates with a jacket water flow rate of 93 kg/s and a scavenging air flow rate of 83.78 kg/s. These operational data were used as the basis for the thermodynamic and cooling system performance analysis under varying seawater temperatures and main engine load conditions.

Cooling System description

The performance of main cooling system in a vessel notably in a bulk carrier is evaluated by using a central cooling configuration consisting of freshwater (FW) and seawater (SW) circuits. The system is equipped with a shell-and-tube type of heat exchanger, which functions as a central cooler to enable the transfer of heat from the freshwater circuit to seawater circuit. Seawater serves as the final heat rejection medium and is circulated by a seawater cooling pump, which is the primary focus of this study

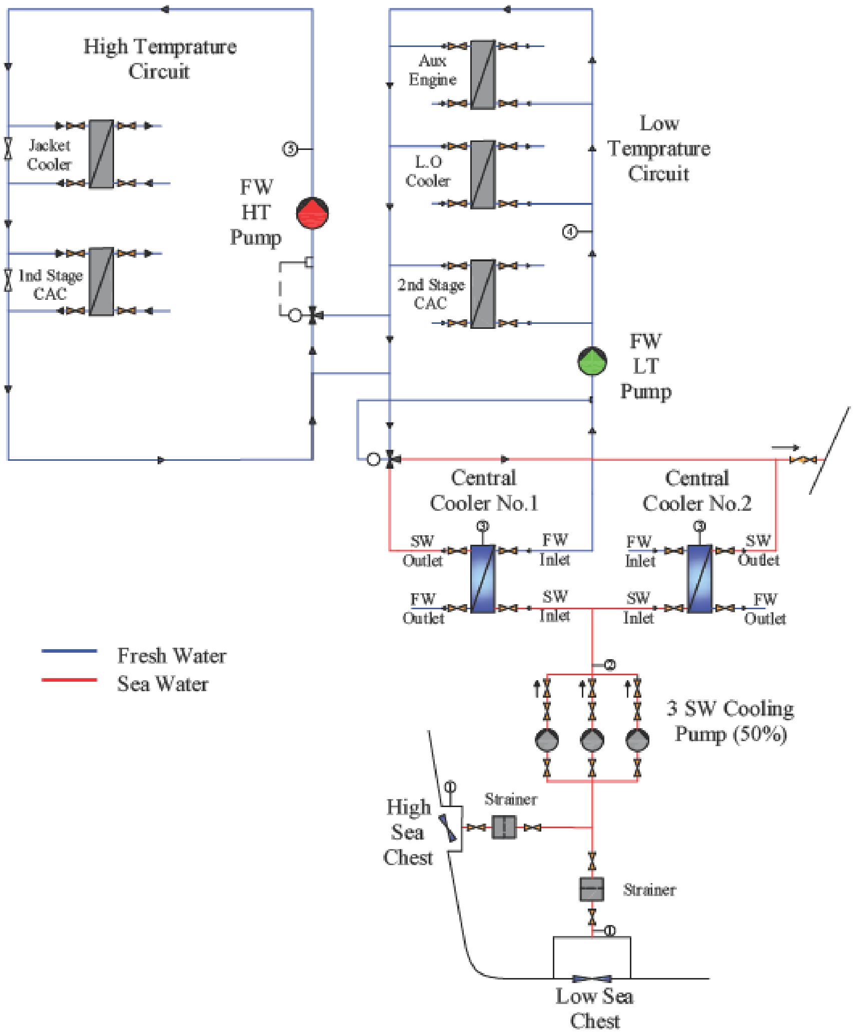

Figure 1. Central Cooling System Configuration of the Bulk Carrier

This system is analyzed under steady-state operating condition, and the interaction between the two cooling circuits is evaluated to assess the overall thermal performance. The freshwater circuit operates as a closed-loop system that absorbs heat from the main engine and various auxiliary components. As shown in Figure 1, freshwater circulates through several key components, including the jacket cooler, charge air cooler, and lubricating oil cooler. After absorbing heat from these components, the fluid is directed to the heat exchanger, where it is cooled before being recirculated within the system. The cooling system configuration adopted in this study follows the integrated seawater/freshwater cooling arrangement commonly used in bulk carrier vessels [10][12][13].

In contrast, the seawater circuit operates as an open-loop system that functions as the final heat rejection pathway to the marine environment. As illustrated in Figure 1, seawater is drawn through the sea chest and then passes through a strainer to remove debris and suspended particles. The seawater is subsequently pumped to the central cooler, where it absorbs heat from the freshwater through an indirect heat transfer process. After the heat exchange process, the seawater is discharged back to the sea through the overboard discharge line. The heat process between the two circuits occurs within the central cooler, where thermal energy is transferred from freshwater to seawater without direct mixing of the fluids. The present study adopts a central cooling system arrangement consisting of a seawater cooling loop, freshwater loop, plate heat exchanger, three-way valve, and variable-speed seawater pump. This mechanism ensures efficient heat transfer while maintaining the quality of the cooling fluids within the system. A MAN B&W S42MC two-stroke marine diesel engine is selected as the main engine considered in this study, slow-speed marine diesel engine, which is commonly employed in major commercial vessels due to its high torque and fuel efficiency [14]-[16]

The cooling system consists of several key components, including the seawater pump, freshwater low-temperature (FWLT) pump, freshwater high-temperature (FWHT) pump, and the central of heat exchanger. Seawater pump circulates seawater as the final cooling medium, the FWLT pump distributes low-temperature freshwater to auxiliary cooling equipment, the FWHT pump maintains the circulation of high-temperature freshwater within the engine cooling jacket, and the central heat exchanger facilitates heat transfer between the freshwater and seawater circuits.

Table 2. Specification of the Main Engine

Name/Unit	Value
Output Power [MW]	41.84
BMEP [MPa]	1.8
Jacket Water Inlet [°C]	80
Jacket Water Outlet [°C]	71
Jacket Water Flow [kg/s]	93
SFOC [g/kWh]	166.24
Scavenge Air Inlet [°C]	206
Scavenge Air Outlet [°C]	34
Scavenge Air Flow [kg/s]	83.78

System performance is assessed under various operating conditions, including changes in engine load, seawater temperature, cooling capacity, and flow rate. In addition, parameters such as heat transfer rate, temperature distribution, and pump energy consumption are examined to evaluate overall system efficiency.

System Modeling

The analysis is carried out using a thermodynamic modeling method for evaluating the effectiveness of the main cooling system under various operating conditions. The system assumed to function under steady state condition therefore, time-dependent variations are neglected, and the analysis focuses on equilibrium behavior. This assumption streamlines the analysis while not significantly affecting the accuracy of the results.

The governing equations applied in this study include energy balance equations, heat transfer correlations, and pump performance relationships [17].

The heat transfer rate in the cooling system is determine according to the energy balance equation:

$$Q = \dot{m}\, c_p\, (T_{out} - T_{in}) \tag{1}$$

where Q represent heat transfer rate, $\dot{m}$ is mass flow rate, C_p denotes specific heat capacity, and T_{in} is a inlet temperature and T_{out} outlet temperature, respectively The mathematical model applied in this study was developed based on thermodynamic equilibrium, pump performance relationships, and pressure loss analysis for marine central cooling systems. Similar modeling approaches involving pump power equations, heat transfer balance, and flow resistance analysis have been reported in previous ship cooling system studies [17][18].

Heat exchanger performance is characterized using the whole heat transfer coefficient, which reflects the combined thermal resistances on the inner tube side, outer surface, and fouling layers. The relationship is expressed as:

$$\frac{1}{U} = \frac{1}{h_{io}} + \frac{1}{h_o} + R_f \tag{2}$$

where U is the whole heat transfer coefficient, h_{io} and h_o are convective heat transfer coefficient on inner and outer surfaces, and R_f is the fouling resistance

The convective heat transfer coefficient on the inner tube side is corrected to the outer surface area basis using the following relation:

$$h_{io} = h_i \cdot \frac{D_i}{D_o} \tag{3}$$

where h_i is convective of heat transfer coefficient on the inner tube side, while D_i and D_o are the inner and outer tube diameters, respectively. This correction is made to maintain consistency in determining the total heat transfer coefficient.

The Prandtl number (Pr) It is expressed as follows:

$$Pr = \frac{c_p \cdot \mu}{k} \tag{4}$$

where $c_p$is specific heat capacity (J/kg·K), $\mu$is the dynamic viscosity, and k is the thermal conductivity. The thermophysical properties are used to describe the heat transfer behavior of the fluid as represented by the Prandtl number.

The Reynolds number (Re) It can be expressed as:

$$Re = \frac{\rho \cdot v \cdot D}{\mu} \tag{5}$$

where ρ is the density of fluid, v is the flow of velocity, D is diameter of the pipe, and μ is the dynamic viscosity. The Reynolds number is adopted to determine the flow pattern, whether transitional, laminar also turbulent. In general, the flow is considered laminar when $Re < 2300$, transitional when $2300 < Re < 4000$, and turbulent when $Re > 4000$.

The Reynolds number is essential in determining the appropriate heat transfer correlation used in the analysis, such as the Dittus–Boelter or Gnielinski correlations. In addition, it significantly influences the estimation of pressure drop and the overall performance of the heat exchanger.

The Number of Transfer Units (NTU) It is defined as:

$$NTU = \frac{U \cdot A}{(\dot{m}c_p)_{min}} \tag{6}$$

where NTU represents the heat transfer capacity of the heat exchanger, which is influenced by the collectively heat transfer coefficient (U) and the heat transfer surface area (A), both representating the physical characteristics of the heat exchanger.

The denominator, $(\dot{m}c_p)_{min}$, indicates the minimum heat capacity rate of the fluid streams, which determines the fluid (seawater or freshwater) that limits the heat transfer process. Therefore, NTU serves as a parameter that links the physical characteristics of the heat exchanger with the operating conditions of the fluid flow. The heat capacity ratio is defined as:

$$R = \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_{max}} \tag{7}$$

where $(\dot{m}c_p)_{min}$is the minimum and $(\dot{m}c_p)_{max}$ describe the maximum heat capacity rates of the fluid streams, respectively. The heat capacity ratio is used to determine the thermal effectiveness of the heat exchanger based on the flow configuration, such as counterflow or parallel flow.

The pump head is determined using the Bernoulli equation as a function of pressure, velocity, and elevation between the inlet and outlet of the pump:

$$H = \left(\frac{p_2}{\rho g} + \frac{v_2^2}{2g} + Z_2\right) - \left(\frac{p^1}{\rho g} + \frac{v_1^2}{2g} + Z_1\right) + h_f \tag{8}$$

where $P_1$and $P_2$are the inlet and outlet pressures, $v_1$and $v_2$are the flow velocities, $z_1$and $z_2$are the elevations, $\rho$is the fluid density, $g$is the gravitational acceleration, and $h_f$represents head losses due to friction. The pump power is defined as:

$$P_p = \frac{\rho g Q H_p}{\eta} \tag{9}$$

This method is widely used in thermodynamic analysis due to its capability to accurately predict system performance under various operating conditions. This research uses the method to evaluate the interaction between pump performance, heat transfer characteristics, and energy consumption within the marine cooling system. However, the limitation of this approach lies in the assumption of steady-state conditions, which may not fully capture transient behaviors in real ship operations. Despite this limitation, the method remains reliable and appropriate for analyzing system performance under controlled operating conditions, as implemented in this research.

Analytical Assumptions

To simplify the analysis is based on the assumptions are applied: 1) The system is maintained under steady-state conditions. 2) Heat losses to the surroundings are considered negligible. 3) Pressure drops in the system are assumed negligible. 4) Changes in kinetic and potential energy are ignored. 5) Thermophysical properties of the fluids are assumed constant. 6) The heat exchanger works under ideal conditions.7) Pump performance follows the affinity laws with constant efficiency. 8) The effect of the Variable Speed Drive (VSD) is considered only on pump speed and flow rate. These assumptions are commonly used in thermodynamic analyses of marine cooling systems and are consistent with previous studies on central cooling systems and pump performance in marine applications

VSD Application

The Variable Speed Drive (VSD) was applied to the seawater pump to regulate the pump speed according to the actual cooling demand. Unlike conventional constant-speed operation, the VSD enables dynamic adjustment of the pump rotational speed, allowing proportional control of the flow rate. In accordance with the pump affinity laws, The flow rate changes proportionally with rotational speed, the head varies with the square of the rotational speed, and the power consumption varies with the cube of the rotational speed The pump speed is controlled using a Variable Speed Drive (VSD). The VSD operates by converting AC power into DC and then back into AC with adjustable frequency, allowing precise control of motor speed and system performance [19].

Therefore, reducing the pump speed, even slightly, can significantly lower power consumption. This characteristic makes VSD an effective solution for improving energy efficiency under variable load conditions. The adjustment of flow rate also influences the heat transfer performance in the heat exchanger, as it affects the convective heat transfer coefficient and overall system efficiency [2][20].

This approach especially significant in marine cooling systems, where operating conditions such as engine load and seawater temperature continuously vary. Therefore, the performance of the cooling system with and without VSD was compared to evaluate potential energy savings and its impact on heat transfer performance.

Operating Conditions

The simulation was conducted under a range of operating conditions to represent realistic ship operation. The engine load was varied at 25%, 50%, 75%, and 100% to capture both partial and full-load conditions. The seawater inlet temperature was adjusted within the range of 30–40°C to represent tropical operating environments. All simulations were performed under steady-state conditions. The cooling system parameters include a heat exchanger capacity ranging from 1800 to 2400 kW, an overall heat transfer coefficient of 2000–2500 W/m²·K, and a heat transfer area of 300–400 m². The seawater mass flow rate was varied between 50 and 60 kg/s, while the freshwater mass flow rate ranged from 40 to 50 kg/s. The pump speed variation was adjusted based on the applied load conditions to simulate realistic operation of the Variable Speed Drive (VSD). In this study, the independent variables include engine load, seawater temperature, and pump speed, while the fixed parameters consist of the heat exchanger characteristics and system configuration. The selected operating ranges were determined based on typical operating conditions of bulk carrier vessels to ensure that the simulation results represent realistic marine environments. The inlet and outlet temperatures of both seawater and freshwater were examined to assess heat transfer performance and overall thermal stability. Furthermore, pump power consumption and efficiency were evaluated to determine the overall energy performance.

Table 3. Simulation Parameters

Parameters/Unit	Value
Heat Exchanger Cooling Capacity (kW)	1800-2400
Overall heat transfer coefficient (W/m²·K)	2000-2500
Heat transfer area (m²)	300-400
Seawater mass flow rate (kg/s)	50-60
Freshwater mass flow rate (kg/s)	40-50
SW inlet temperature (°C)	30-40
SW outlet temperature (°C)	40-50
FW inlet temperature (°C)	50-60
FW outlet temperature (°C)	30-40

RESULTS AND DISCUSSION

Heat transfer performance
Seawater vs. Freshwater: Cooling Performance at 25% Load

Under partial operating conditions at 25% engine load under increased thermal loading conditions, the performance of cooling system was analyzed based on variations in seawater temperature. This analysis utilizes the design data and thermodynamic methodology adopted in the reference study, where the heat transfer capacity is governed by fluid mass flow rate, fluid heat capacity, and temperature differential, as defined by the energy balance equation. As we can see on the first graph, the inlet seawater temperature (Tsw-in) increases linearly with the rise seawater temperature from 14°C to 32°C. The outlet seawater temperature (Tsw-out) is presented using two approaches, namely the numerical model and the thermodynamic model, both showing a relatively linear increasing trend.

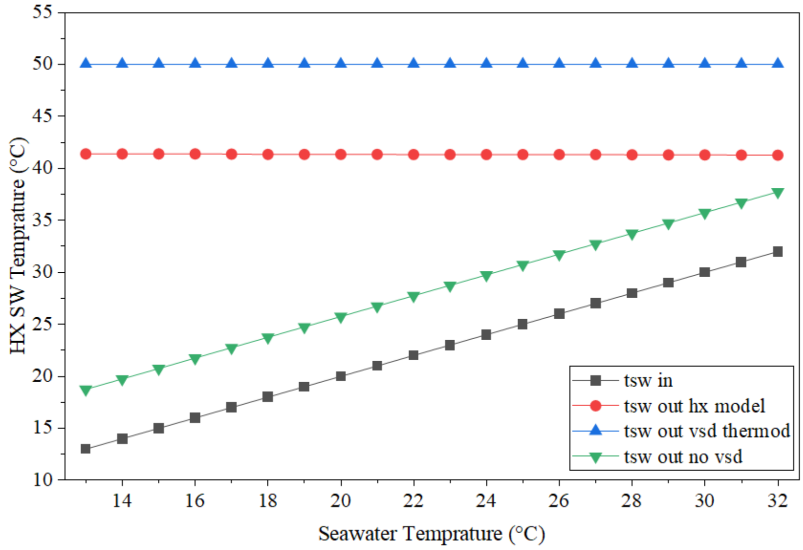

Figure 2. Variation of Seawater inlet and outlet temperature under 25% engine load.

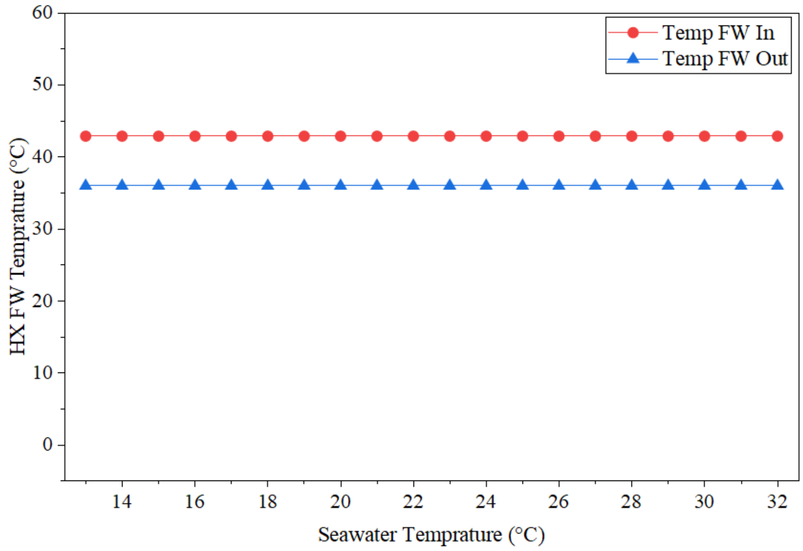

Figure 3. Variation of freshwater inlet and outlet temperatures under 25% engine load

This indicates that at 25% engine load, the heat exchanger is still capable of transferring heat effectively despite the increase in seawater temperature. The difference between the modeled Tsw-out and the thermodynamic Tsw-out is relatively small, indicating that the simulation method remains consistent with the heat transfer theory presented in the reference study. The increase in seawater temperature reduces the driving temperature difference, causing the outlet temperature to rise in order to maintain energy balance. In the second graph, the freshwater temperatures (Temp fw-in and Temp fw-out) remain relatively constant with respect to variations in seawater temperature. This indicates that under low thermal loading conditions, the cooling system is still capable of maintaining stable thermal performance. Even as the seawater temperature increases up to 32°C, the freshwater temperature remains within safe operating limits.

From a thermodynamic perspective, this phenomenon indicates that at low engine load (25%), the heat exchanger does not operate at its maximum capacity and therefore retains sufficient performance margin to compensate for the increase in seawater temperature. This finding corresponds with the design principles reported in previous studies which reported that heat exchangers maintain stable performance under partial load conditions. The results suggest that under 25% engine load the system operates in a stable condition. The freshwater temperature remains well controlled, and the increase in seawater temperature does not lead to cooling failure. The heat exchanger still possesses thermal margin, indicating that its performance remains within safe operational limits.

Seawater vs. Freshwater: Cooling Performance at 50% Load

At 50% engine load the cooling system performance was evaluated under varying seawater temperatures ranging from 14°C to 32°C. This condition represents a moderate operating regime, where the engine generates a higher thermal load compared to lower load conditions.

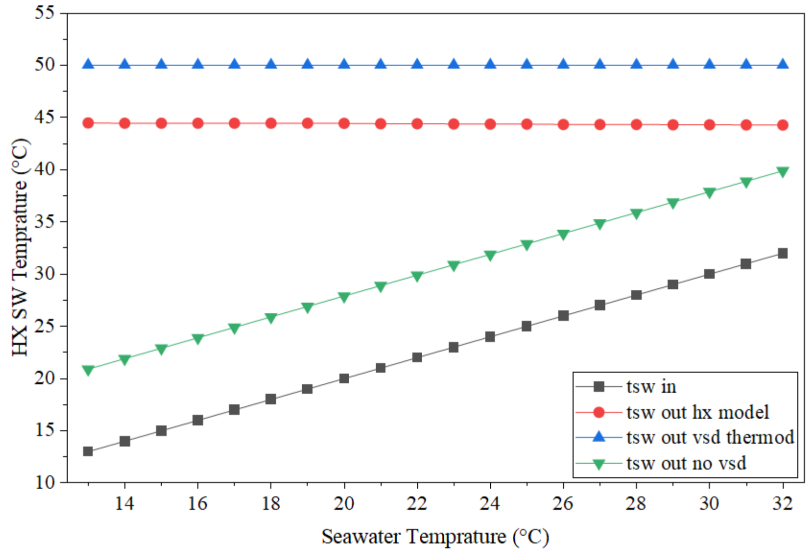

Figure 4. Variation of seawater inlet and outlet temperatures under 50% engine load

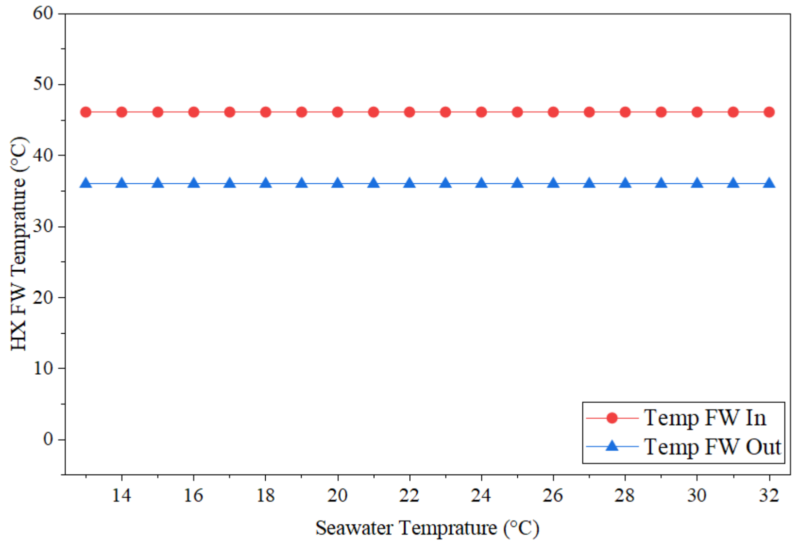

Figure 5. Variation of freshwater inlet and outlet temperatures under 50% engine load

As shown in Figure 4, the inlet seawater temperature (Tsw-in) increases linearly with ambient seawater temperature, while the outlet seawater temperature (Tsw-out) rises more significantly compared to the 25% load condition. This indicates that the seawater absorbs a larger amount of heat from the cooling system at higher engine loads. The increased difference between inlet and outlet seawater temperatures (ΔTsw) suggests that the heat exchanger operates under greater thermal duty, resulting in a higher heat transfer rate. According to thermodynamic principles, higher engine thermal loads require greater heat dissipation to maintain energy balance within the cooling system. Consequently, the heat exchanger transfers more heat to the seawater, causing the outlet seawater temperature to increase more noticeably. Figure 5 shows the variation of freshwater temperatures (Tfw-in and Tfw-out) under the same operating conditions. Unlike the seawater temperatures, the freshwater temperatures remain relatively stable despite changes in seawater temperature. However, the freshwater temperatures at 50% engine load are consistently higher than those observed at 25% load, indicating that the cooling system operates at a higher overall thermal level while still maintaining acceptable thermal stability.

Overall, the results demonstrate that the heat exchanger performs more actively at medium engine loads due to the increased heat transfer demand. Although the system still maintains stable operating conditions at seawater temperatures up to 32°C, the cooling performance becomes increasingly influenced by variations in seawater temperature at higher engine loads. This occurs because higher seawater temperatures reduce the temperature gradient within the heat exchanger, thereby decreasing heat transfer effectiveness and increasing the thermal sensitivity of the cooling system.

Seawater vs. Freshwater: Cooling Performance at 75 % Load

At an operating condition of 75% main engine load the cooling system performance was investigated under seawater temperature variations ranging from approximately 13°C to 32°C. This condition represents a high main engine operating load, where the engine generates a substantially greater thermal load compared to lower engine load conditions. Figure 6 illustrates inlet seawater temperature (Tsw-in) and the ambient seawater temperature, showing a consistent linear increase. As the engine thermal load increases, a larger amount of heat must be transferred from the cooling system to the seawater, resulting in a noticeable increase in the outlet seawater temperature (Tsw-out).

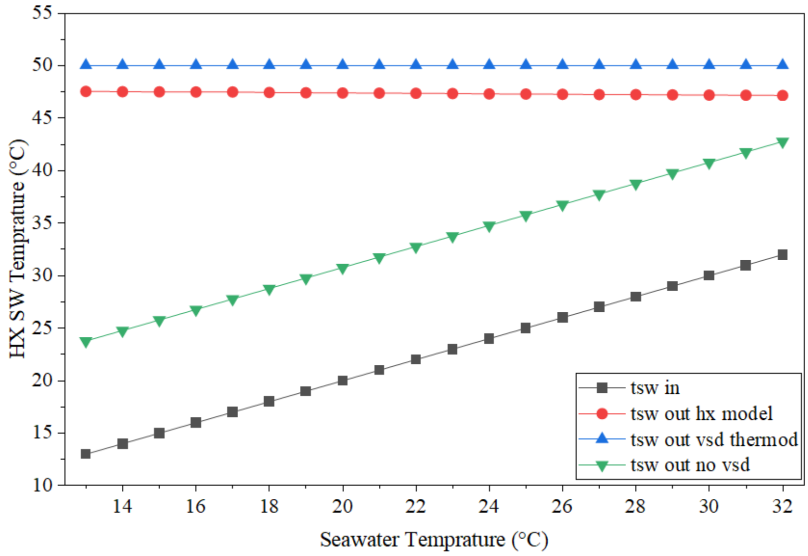

Figure 6. Variation of seawater inlet and outlet temperatures under 75% engine load

The results obtained from both numerical and thermodynamic analyses indicate that the outlet seawater temperature remains relatively stable despite increasing seawater temperatures. However, under constant-speed pump operation without the application of Variable Speed Drive (VSD), the outlet seawater temperature increases more significantly as the inlet seawater temperature rises. This behavior indicates that, at higher main engine loads, the cooling system without speed control becomes more sensitive to variations in seawater temperature.

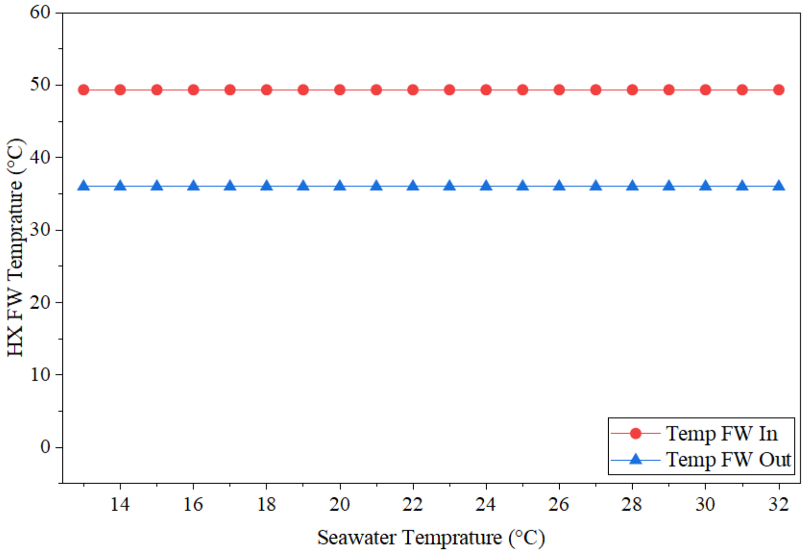

Figure 7. Variation of freshwater inlet and outlet temperatures under 75% engine load

Figure 7 presents the variation of freshwater inlet (Tfw-in) and outlet (Tfw-out) temperatures under the same operating conditions. The freshwater temperatures remain relatively stable, indicating that the cooling system is still capable of maintaining acceptable thermal operating conditions at high engine loads. Nevertheless, the system performance becomes more constrained at higher seawater temperatures because the reduced temperature gradient within the heat exchanger decreases the effectiveness of heat transfer. Consequently, the cooling system becomes more sensitive to environmental temperature variations under high main engine load conditions**.** Similar observations have been reported in previous studies, where marine cooling systems operating at high engine loads maintain stable performance but exhibit lower tolerance to increasing seawater temperatures and thermal load variations.

Seawater vs. Freshwater: Cooling Performance at 100 % Load

At full engine load 100% The influence of variations in seawater temperature on heat exchanger performance was assessed, focusing on the inlet and outlet temperatures on both the seawater and freshwater sides. In Figure 8, the seawater temperature inlet (Tsw-in) varies within the range of 13°C to 32°C. A corresponding increase is observed in the outlet seawater temperature (Tsw-out), which follows a nearly linear trend. This behavior indicates that variations in the cooling medium temperature directly affect the outlet temperature after the heat exchange process.

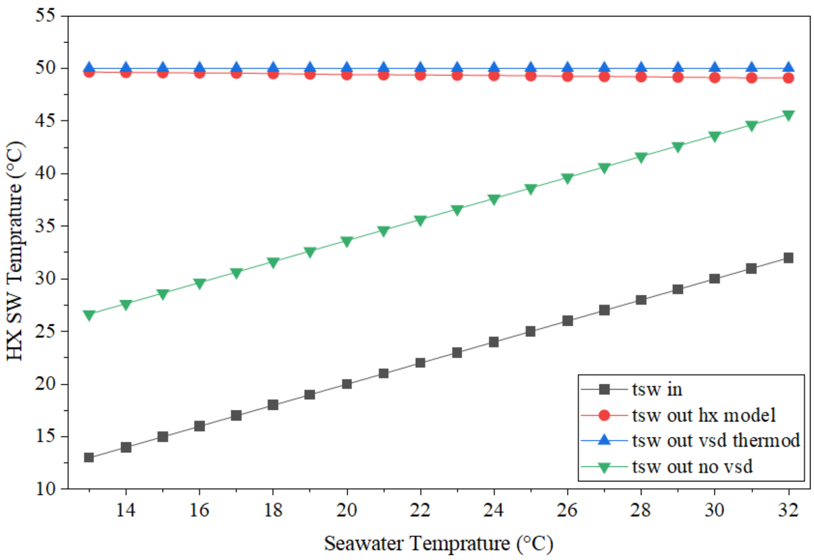

Figure 8. Variation of seawater inlet and outlet temperatures under 100% engine load

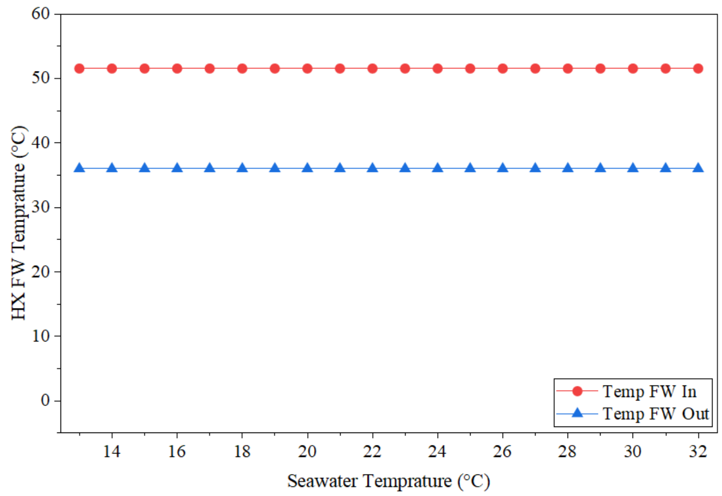

Figure 9. Variation of freshwater inlet and outlet temperatures under 100% engine load

As shown in Figure 9, the freshwater circuit maintains stable thermal conditions despite a 19°C increase in seawater temperature. The inlet (Temp fw-in) and outlet (Temp fw-out) temperatures remain constant at approximately 51°C and 36°C, respectively. This consistent \(\Delta T_{fw}\) of 15°C indicates steady engine thermal load and effective heat exchanger performance, demonstrating that the heat transfer process is largely unaffected by external temperature variations.

Furthermore, the ability of the system to maintain the freshwater outlet temperature (Tfw-out) at approximately 36°C despite increasing seawater temperatures indicates that the cooling system is capable of sustaining stable thermal performance under high engine load conditions. This confirms that the heat exchanger can still provide effective heat removal within the investigated operating range. As the seawater temperature increases, the temperature difference between freshwater and seawater gradually decreases, leading to a decrease in the heat transfer driving force. Consequently, although the cooling system remains thermally stable under the investigated conditions, the available thermal margin becomes more limited at higher seawater temperatures, which may reduce cooling effectiveness under more extreme environmental conditions.

Pump Performance and Energy Consumption

The pump energy consumption versus flow rate clearly differs between systems with and without Variable Speed Drive (VSD). In the fixed-speed system, pump power remained nearly constant at approximately 26 kW across the 80–220 m³/h flow range, indicating operation at full speed regardless of demand and resulting in energy waste at low flow rates. Conversely, the VSD system adjusted pump power according to flow.

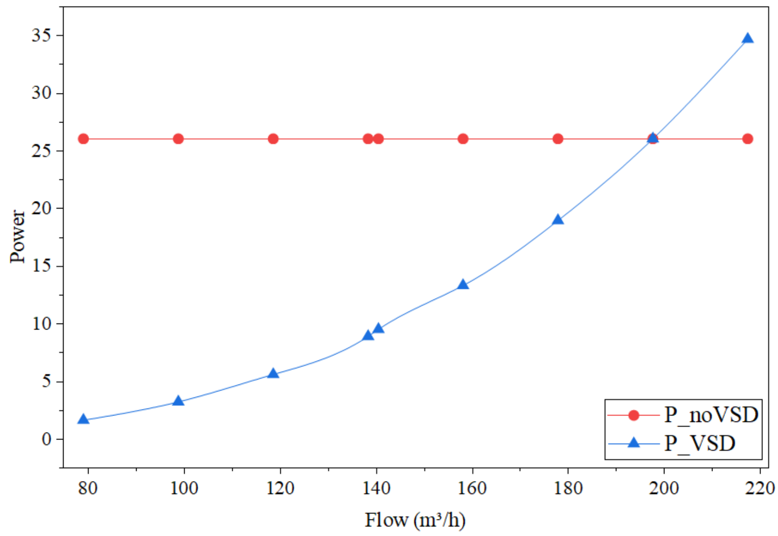

Figure 10. Pump Performance

At low flow rates (80–140 m³/h), power consumption was significantly lower (≈2–10 kW), demonstrating substantial energy savings. At medium flow rates (160–180 m³/h), VSD still maintained lower power than the fixed-speed system, preserving efficiency. Near maximum flow (≈200–220 m³/h), VSD power approached or slightly exceeded fixed-speed power, reducing energy-saving benefits.

This behavior aligns with pump affinity laws, which state that power is proportional to the cube of flow rate ($P \propto Q^3$), explaining the drastic reduction in power when speed is lowered. Therefore, VSD is most effective under partial load conditions. he reduction in pump rotational speed significantly reduced power demand due to the cubic relationship between rotational speed and power consumption, which is consistent with previous studies on variable-speed pumping systems. Overall, VSD provides higher efficiency in the 80–180 m³/h range, with optimal operation at low to medium flows, while its advantage diminishes near maximum flow. For systems with fluctuating loads, such as cooling systems or heat exchangers, implementing VSD is strongly recommended, as it aligns energy consumption with actual demand and improves overall system efficiency [21][22].

Energy Efficiency Analysis

Figures 11 and 12 illustrate the efficiency characteristics of the seawater cooling pump in terms of the relationship between volumetric flow rate, pump head, and pump efficiency. Figure 11 presents the pump head characteristics, while Figure 12 shows the pump efficiency characteristics under varying flow rate conditions.

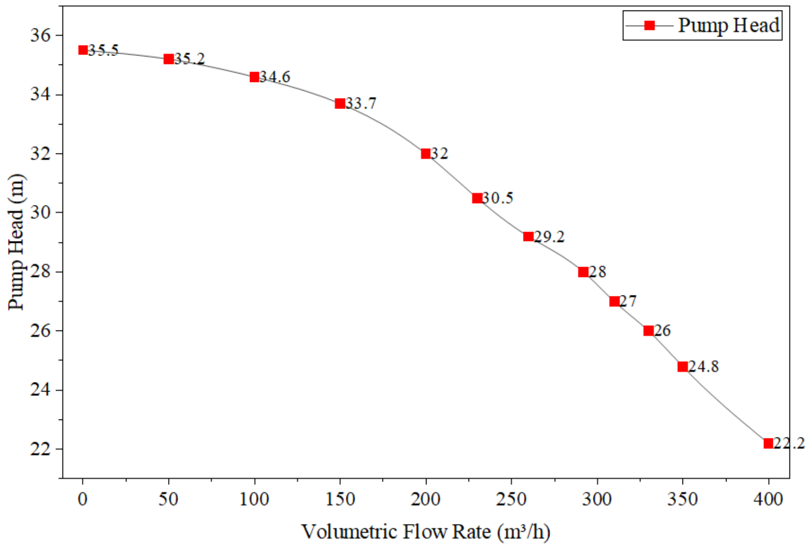

Figure 11. Head pump

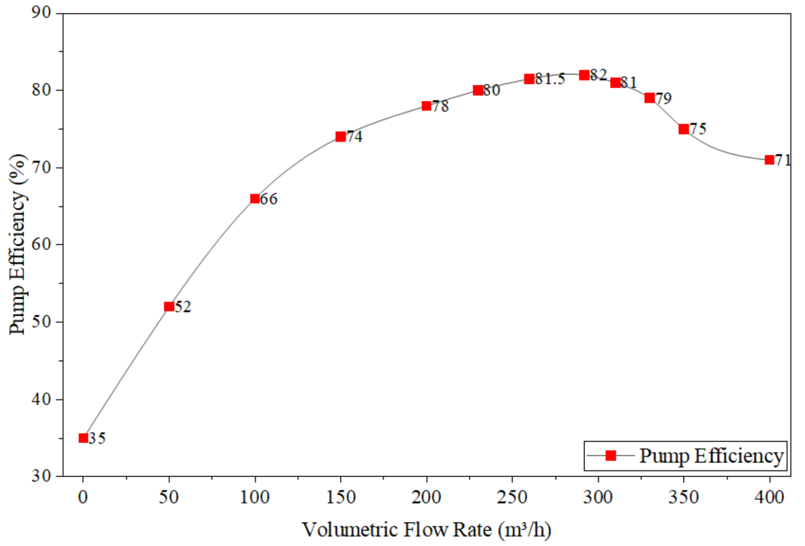

Figure 12. Efficiency Pump

Figure 11 the pump head gradually declines as the volumetric flow rate rises, which is a common characteristic of centrifugal pumps. When the flow rate is low, the pump produces a relatively high head of approximately 35.5 m, while during high-flow operation the head decreases due to increased fluid velocity and hydraulic losses within the pump system.

Meanwhile, Figure 12 indicates that pump efficiency increases with increasing flow rate until achieving a peak value efficiency of approximately 82% at a flow rate of 292 m^3/h. This condition represents the Best Efficiency Point (BEP), where the balance between flow rate, pump head, and internal energy losses is achieved. Beyond this operating point, pump efficiency gradually decreases because of increasing hydraulic losses and deviations from the pump design condition.

The results demonstrate that the optimal operating condition of the cooling system occurs near the BEP, where the pump is able to maintain sufficient head while operating with maximum efficiency and lower energy consumption. This finding highlights the importance of operating the cooling pump near its optimal range to improve overall cooling system energy efficiency. Similar centrifugal pump performance characteristics have also been reported in previous marine cooling system studies [7].

CONCLUSION

This study confirms that the implementation of a ariable Speed Drive (VSD) can enhance energy efficiency of the main cooling pump system in a bulk carrier under varying operating conditions. The application of VSD enables the pump to operate according to actual cooling demand, reducing unnecessary energy consumption while maintaining stable cooling performance and effective heat transfer. The results show that pump power consumption decreased from approximately 26 kW to 2–10 kW under partial-load conditions, with the pump achieving a maximum efficiency of approximately 82% near the Best Efficiency Point (BEP). In addition, the cooling system maintained stable freshwater outlet temperatures around 36°C, while the pump achieved a maximum efficiency of approximately 82% near the Best Efficiency Point (BEP). The main contribution of this research is the integrated evaluation of pump energy consumption, heat transfer performance, and seawater cooling system operation under different engine loads and seawater temperatures. This study contributes to improving maritime energy efficiency by demonstrating the practical potential of VSD technology to support fuel-saving operations and sustainable green shipping practices. However, this study is limited to steady-state simulation and specific operating conditions. Therefore, future research is recommended to investigate transient operating conditions, real onboard implementation, and intelligent control systems for adaptive energy management in marine cooling applications.

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