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Innovative Closed-Loop Self-Sustaining Freshwater Cooling Technologies for AC CWP Condenser in The Maritime Industry: A Feasibility Study

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Abstract

This study investigates the feasibility of transitioning from a seawater-based cooling system to a closed-loop freshwater cooling system in chilled water plants of Naval ships. Seawater systems, while historically efficient, face significant challenges such as biofouling, corrosion, and inefficiencies due to high seawater temperatures, especially in middle east climate. These challenges increase maintenance demands, operational downtime, and lifecycle costs, compromising long-term system sustainability and environmental concerns. Three system modification options were analyzed: downsizing the condenser and integrating a chilled water line, adding a heat exchanger and storage tank, and adding a heat exchanger and accumulator. Among these, the option featuring a heat exchanger and thermal buffer tank (Option 2) emerged as the most feasible for a complete system replacement. It offers enhanced operational stability, reduced maintenance demands, and significant long-term cost savings despite a higher initial investment. The findings underscore the strategic advantages of Option 2, highlighting its adaptability to existing infrastructure, long-term cost savings, and alignment with sustainability goals. The study demonstrates that a closed-loop freshwater cooling system provides substantial improvements in energy efficiency and environmental sustainability. By eliminating seawater dependency, the proposed system reduces maintenance requirements, improves lifecycle performance, supporting clean water usage, energy efficiency, and reduced emissions. While the initial investment is higher, the projected return on investment within 4-6 years and significant lifecycle cost reductions establish it as a viable and future-proof solution.

Keywords
Closed-loop, Cooling, Naval, Seawater, Systems

1. Introduction
Chilled water plants are vital components of naval ships, playing a central role in maintaining optimal cooling for critical equipment, machinery, and crew comfort. These systems form the backbone of the HVAC operations onboard, ensuring that temperature-sensitive areas remain within operational limits, even in the harsh maritime environments faced by naval vessels. By circulating chilled water through various cooling units such as air handling units (AHUs) and fan coil units (FCUs), these plants ensure effective heat transfer, supporting the overall efficiency and reliability of ship operations (Figure 1).

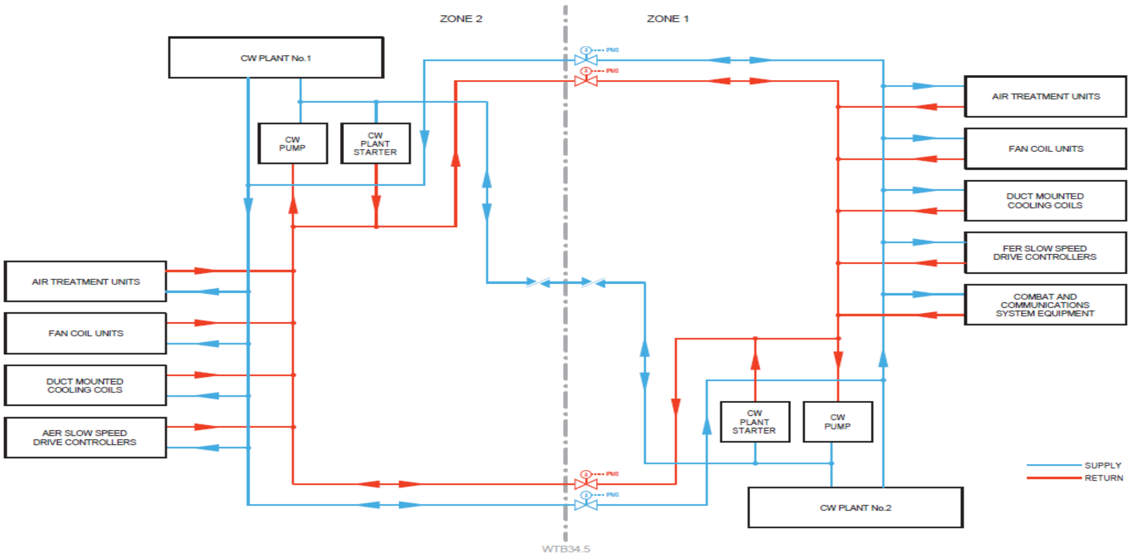

Figure 1. Diagram for AC chiller System for Naval Ship **(BAE, 2013)**.

In naval ships, the current chilled water systems rely on open-loop seawater cooling to manage condenser temperatures. While effective in principle, this approach poses significant challenges, including biofouling, corrosion, and inefficiencies due to Middle East's elevated seawater temperatures. These factors increase maintenance demands, operational downtime, and lifecycle costs, making the system less sustainable in the long term.

To address these issues, this study investigates the feasibility of transitioning from an open-loop seawater cooling system to a closed-loop freshwater cooling system tailored for naval ships. This innovative approach seeks to enhance operational stability, reduce maintenance demands, and eliminate seawater dependency. The Vision prioritizes sustainability, technological innovation, and efficient resource management, making this study a vital contribution toward achieving these goals. Furthermore, the project supports global SDGs, including Goal 13 (Climate Action) and Goal 14 (Life Below Water), The proposed solution is designed to minimize environmental impacts while improving system efficiency and reducing lifecycle costs.

2. Functionality and Challenges of Seawater Cooling Systems in Naval Ships

Under standard operating conditions, the Chilled Water (CW) Plant condenser within the HVAC system of naval ships relies on the Sea Water Cooling System for efficient cooling. This system comprises a series of critical components, including a sea chest, strainer, seawater (SW) pump, condenser (configured as a shell-and-tube exchanger), and an integrated antifouling system, as illustrated in Figure below. Together, these elements facilitate a continuous flow of seawater, ensuring the condenser maintains optimal operating temperatures and thereby supports the overall efficiency of the HVAC system (Figure 2).

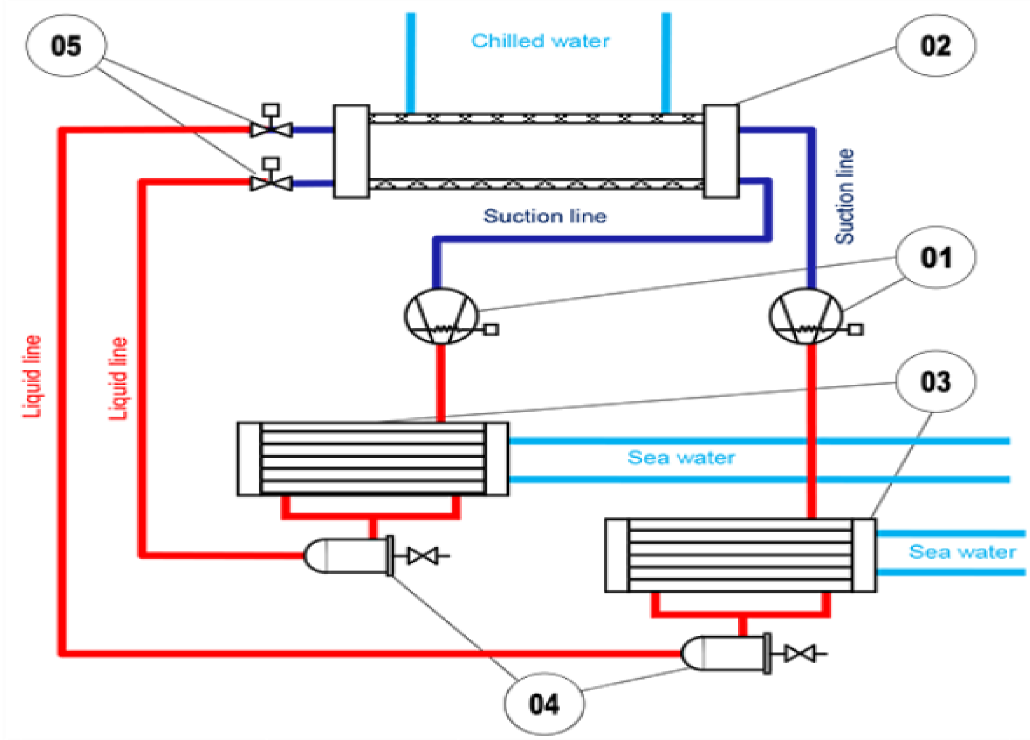

Figure 2. Chilled Water Unit Schematic **(Support, 2014)**.

The reliance on seawater (SW) for cooling the condenser in chiller systems presents significant challenges. High seawater temperatures, especially during the summer months, and marine growth contribute to fouling condensers and strainers, reducing system efficiency, increasing maintenance requirements, and leading to potential equipment failures (Figure 3).

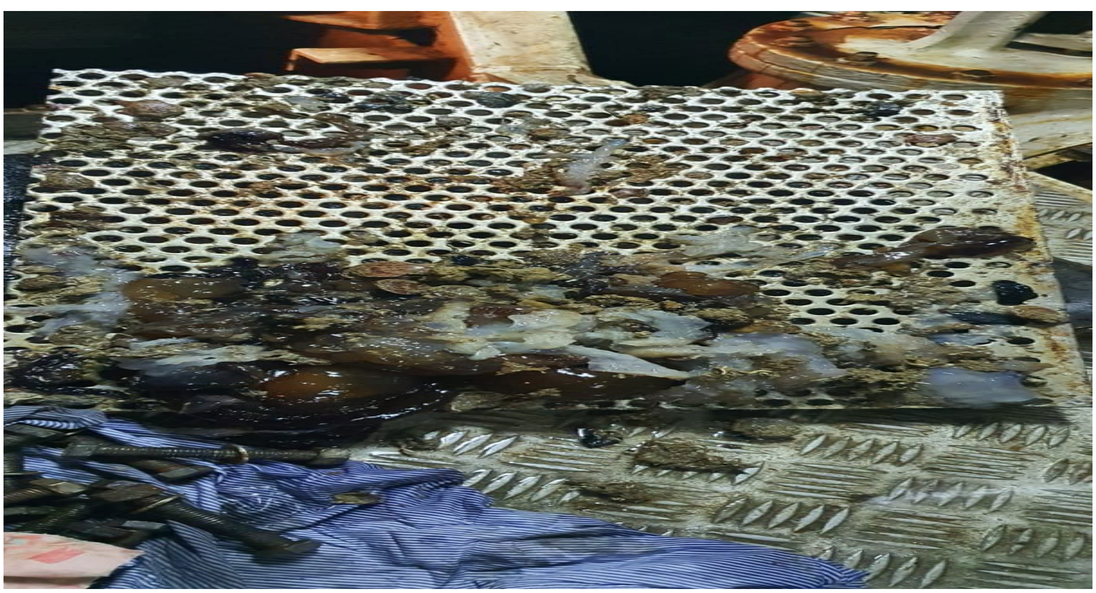

Figure 3. Effect of Sea Growth in Condenser Inlet Sea Chest Strainer.

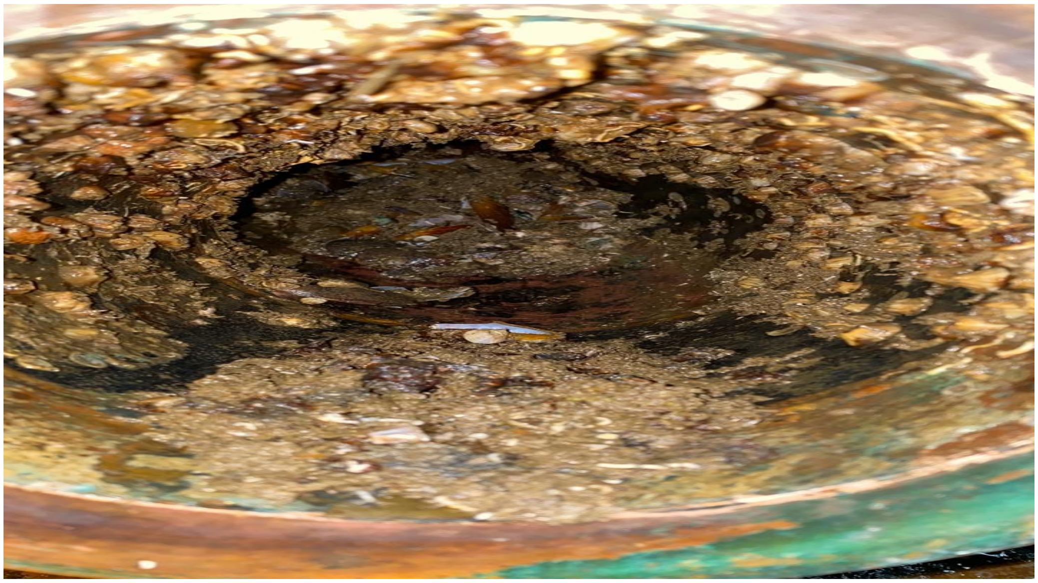

Figure 4. Effect of Sea Growth on the Condenser Pipeline.

Biofouling and corrosion are primary challenges affecting seawater cooling systems (Figure 4), particularly in marine environments (Izadi, 2011). Biofouling occurs when marine organisms, such as algae, barnacles, and bacteria, accumulate on surfaces within the cooling system, such as condenser tubes and strainers. This buildup impedes water flow, reduces heat transfer efficiency, and increases energy consumption. Corrosion, accelerated by the saline nature of seawater, weakens metal surfaces and can lead to leaks, cracks, or structural failures. Together, biofouling and corrosion result in frequent maintenance needs, reduced equipment lifespan, and increased operating costs.

Figure 5. Effect of Corrosion in Condenser Cover.

Figure 6. Effect of Biofouling in SW Cooling Line.

Due to biofouling, corrosion (Figure 5-Figure 7), and temperature-related inefficiencies, seawater cooling systems require extensive and frequent maintenance. The buildup of marine organisms and corrosion damage means that system components, particularly strainers and condenser tubes, must be regularly cleaned and inspected which increased maintenance needs beyond OEM recommendations. These maintenance routines are labor-intensive and result in considerable downtime, adding to operational costs and resource demands. The associated repair and replacement costs, as well as the operational delays from downtime, further stress the need for a more efficient, low-maintenance alternative.

One of the most frequent issues in seawater cooling systems is the blockage of strainers and condenser tubes caused by marine growth specially during Ships availability at harbor with lower sea depth. Sea growth, including algae, silt, and other organic matter, accumulates on the inner surfaces of strainers and condenser tubes, obstructing the flow of seawater and diminishing heat transfer efficiency. These blockages increase pressure drops within the system, elevate pump energy demands, and lead to frequent system outages for cleaning and unblocking and/or using of the HPSW as a support to normal SW pump, which is mainly designed for firefighting onboard ships. These leading to degrade the pressure of the HPSW for fire a fire affecting ships safety. The accumulation can also exacerbate corrosion within the tubes, compounding the issue and reducing system reliability.

Figure 7. Condenser Pipe Blockage Due to Sea Growth.

There are many research gaps in this field. Existing research and industry practices focus predominantly on open freshwater cooling systems that rely on seawater as a secondary cooling medium. While freshwater systems reduce biofouling and corrosion compared to direct seawater cooling (Ezgi, 2014) (Pugh, 2010), they are still subject to issues associated with seawater exposure, such as contamination and the need for additional antifouling measures. These open systems also lack the closed-loop functionality necessary to ensure independence from environmental variations, meaning that they remain dependent on seawater for secondary cooling and are susceptible to similar operational inefficiencies and maintenance demands.

There is a notable gap in research concerning a closed-loop, self-sustaining freshwater cooling system that eliminates seawater dependency entirely. A fully closed-loop configuration could offer stability in operational performance, minimized biofouling, and reduced corrosion, making it a potentially viable alternative for naval HVAC applications where consistent cooling, reliability, and low maintenance are critical. This study investigated the feasibility of such a closed-loop freshwater system, presenting a novel solution that could enhance naval cooling system efficiency and sustainability.

3. Current Methods and Limitations

To mitigate the challenges posed by seawater cooling in naval ships, several solutions have been implemented. These include antifouling systems, the use of an emergency High-Pressure Sea Water (HPSW) system to maintain adequate flow, zinc anodes in condensers and strainers to reduce corrosion, and frequent cleaning routines, especially during summer. However, these solutions still face significant limitations in ensuring long-term reliability and efficiency.

3.1 Antifouling Systems

Antifouling systems Figure below are employed to prevent the buildup of marine organisms within the seawater cooling circuit. While these systems reduce some biofouling, they do not fully eliminate it. Over time, organisms still accumulate within the condenser and strainers, leading to partial blockages, reduced heat transfer efficiency, and increased energy demands.

3.2 Zinc Anodes for Corrosion Control

Zinc anodes are installed in condenser covers and strainers to combat corrosion. While they help reduce some corrosion, the saline and harsh marine environment continues to degrade metal components. Corrosion remains prevalent, contributing to equipment wear, potential leaks, and structural weaknesses. Frequent opening and closing of system components exacerbate this issue, with signs of advanced corrosion and wear often observed around seals and fittings.

Despite various measures to address the limitations of seawater cooling systems, several challenges remain unresolved. Biofouling and corrosion continue to degrade system efficiency, leading to frequent maintenance, increased operational costs, and reduced equipment lifespan. Temperature-related inefficiencies, driven by Middel East’s high seawater temperatures, place additional strain on the HVAC system, causing increased energy consumption and reducing cooling capacity, especially in summer. Existing solutions, including antifouling systems, emergency use of the HPSW system, zinc anodes, and frequent cleaning, only offer partial relief and come with significant limitations. These persistent challenges underscore the need for a more effective cooling approach. A closed-loop freshwater cooling system offers the potential to reduce biofouling, corrosion, and temperature-related inefficiencies, providing a stable and reliable solution for naval HVAC needs. Implementing such a system could improve HVAC performance, reduce maintenance demands, and extend equipment lifespan, ensuring a more sustainable and efficient cooling solution for naval ships.

4. Feasibility Study

The primary objective of this Article is to conduct a comprehensive feasibility study to evaluate potential modifications to the existing seawater-based cooling system onboard naval ships. The study aims to assess whether transitioning to a closed-loop freshwater cooling system, or modifying the existing system with specific enhancements, can improve overall efficiency, reduce maintenance, and extend the operational lifespan of HVAC components.

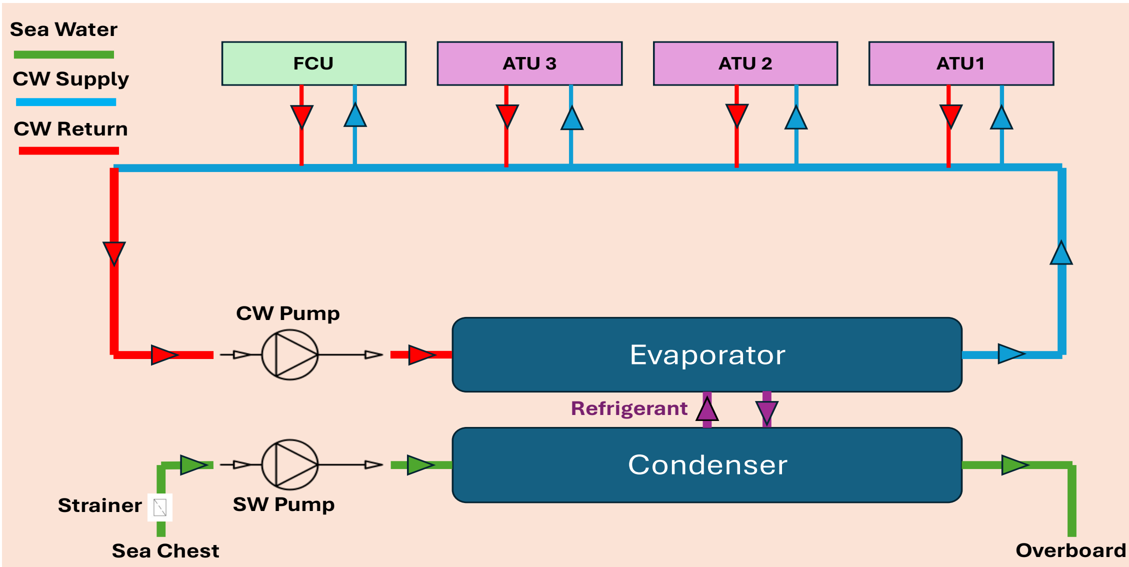

Figure 8. Current CWP System with SW Cooling.

This feasibility study is structured to provide a detailed analysis of three proposed options, each designed to address the limitations of the current system (Figure 8- Figure 9):
Option 1: Downsizing the condenser and integrating a new chilled water (CW) line to optimize cooling efficiency.

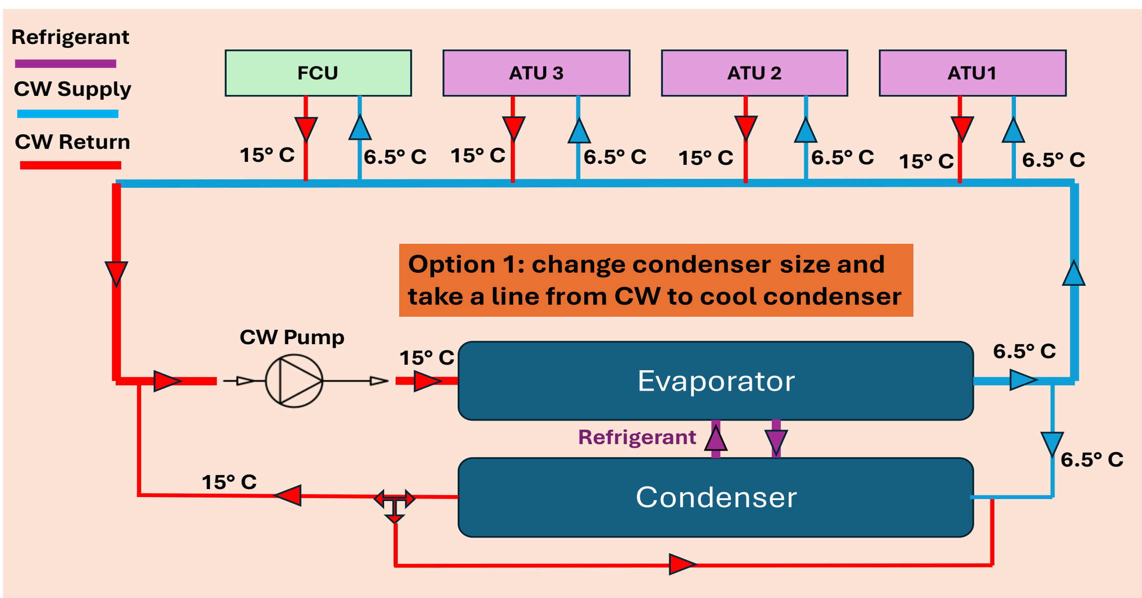

Figure 9. Proposed Option 1.

Option 2: Adding a heat exchanger and storage tank to enhance system stability and reduce the reliance on seawater (Figure 10-Figure 11).

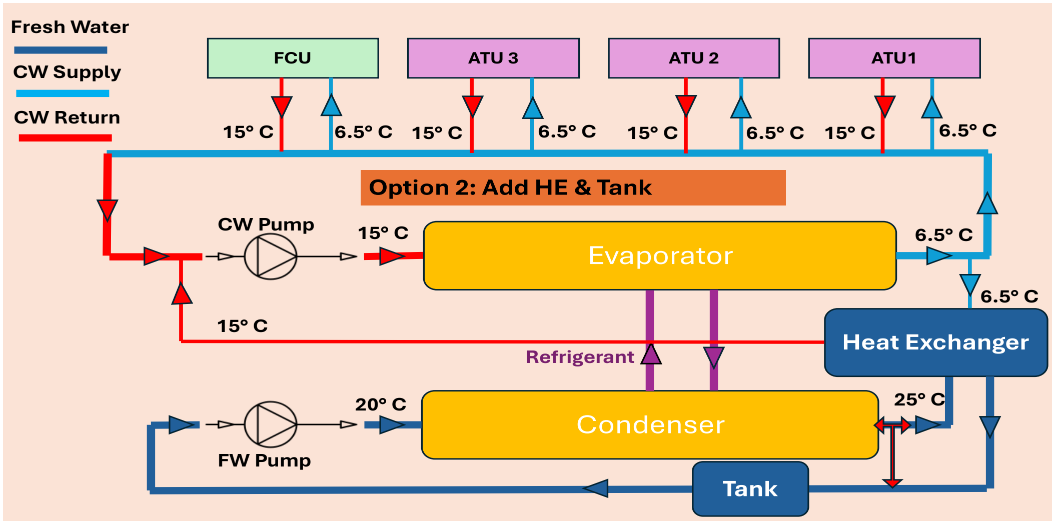

Figure 10. Proposed Option 2.

Option 3: Introducing a heat exchanger and an accumulator to stabilize flow rates and pressure within the cooling loop.

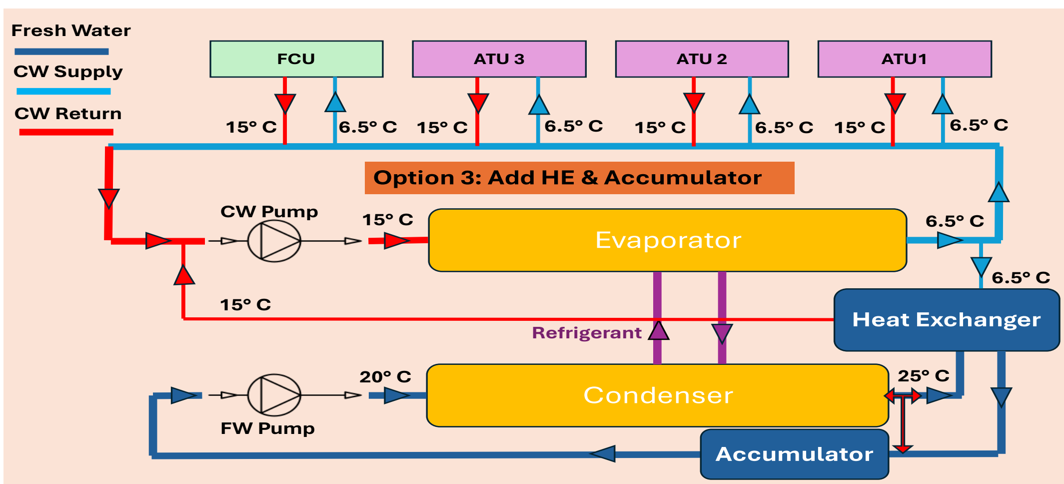

Figure 11. Proposed Option 3.

The technical feasibility analysis aimed to determine whether the proposed modifications to the cooling system can be effectively implemented on naval ships without compromising existing operations. This assessment focuses on the practicality, integration challenges, and expected performance improvements of each solution.

To determine the feasibility of the three proposed options (Option 1, Option 2, and Option 3), two scenarios were used to best evaluate these options:

1. **Modifying the Current System** (least disruptive, minimal changes)
2. **Changing the Entire Current System** (significant overhaul)

5. Results and Discussion

Option 1 is the most feasible for modifying the current system because it requires the least number of changes while still improving efficiency. It leverages the existing CW infrastructure, making it a cost-effective and less invasive upgrade. However, still making these changes will put the system under high risk. But for a smaller system with smaller condenser (like Refrigerant plants) this option will be more applicable (Table 1).

On the other hand, **Option 2** is the most feasible for a complete system change because it offers a comprehensive solution that significantly improves efficiency and reduces maintenance. While it requires a higher upfront investment and more modifications, it provides greater long-term benefits and sustainability compared to Options 1 and 3.

Table 1. A Comparison Summary of Technical Analysis

Scenario	Most Feasible Option	Key Benefits	Key Challenges
Modifying the Current System	Option 1 (Change Condenser Size & Use CW Line)	Minimal changes, cost-effective, utilizes existing infrastructure	Potential increased load on CW loop
Changing the Entire System	Option 2 (Add Heat Exchanger & Tank)	Comprehensive solution, isolates CW loop, reduces maintenance	Higher initial cost, increased complexity, space constraints

Option 2 is the most feasible choice for a complete system change because it offers a comprehensive and balanced solution that significantly enhances operational efficiency, reduces maintenance demands, and aligns with long-term sustainability goals. Unlike Option 1, which involves minimal modifications but retains limitations in thermal stability and system efficiency, and Option 3, which adds complexity without proportional benefits, Option 2 delivers measurable improvements across key metrics. The inclusion of a heat exchanger and thermal buffer tank in Option 2 ensures a stable cooling process by isolating the chilled water (CW) and freshwater (FW) loops. This design minimizes thermal fluctuations, reduces compressor load during startup, and prevents strain on the overall system. By eliminating seawater entirely, it effectively addresses persistent issues of biofouling and corrosion, leading to a 66% reduction in maintenance frequency and significant cost savings over the system's lifecycle.

The implementation of Option 2 requires precise system design to ensure technical feasibility and optimized performance. This chapter outlines the design specifications, critical calculations, and integration strategies for incorporating a heat exchanger and thermal buffer tank into the cooling system. The proposed design aims to stabilize the cooling performance while eliminating seawater dependency, reducing biofouling, and enhancing energy efficiency. This chapter serves as the foundation for validating the feasibility of the system through simulations and real-world applications (Table 2).

Table 2. System Parameters

Parameter	**Value**
Heat Load	283 kW
Inlet Temperature (CW)	6.5°C
Outlet Temperature (CW)	15°C
Inlet Temperature (FW)	25°C
Outlet Temperature (FW)	20°C
Log Mean Temperature Difference (LMTD)	8.75°C
Estimated Heat Transfer Area	12 m² (calculated based on heat load and LMTD)
Type of Heat Exchanger	Plate Type Heat Exchanger
Material	Stainless Steel (316L)

Below is a table summarizing the **Tank Sizing Calculations** for the thermal buffer tank (Table 3).

Table 3. Tank Sizing Calculations

Parameter	Value
Stabilization Time	30 minutes (0.5 hours)
Heat Storage Capacity	283 kW (from system heat load)
Temperature Difference (ΔT)	5°C (25°C to 20°C in FW loop)
Tank Volume (V)	8.1 m³ (calculated using heat storage formula)
Material Selection	Stainless Steel (316L) for corrosion resistance

Table 4. Flow Rate and Pressure Comparison

Parameter	Existing Seawater System	Proposed Freshwater System
Flow Rate (m³/hr)	196	196
Pressure (bar)	2.5	2.5
Piping Diameter (mm)	100	100
Piping Material	Carbon Steel (CS)	Stainless Steel (316L)

Table 5. Component Specifications

Component	Specification	Details
Pump (Freshwater)	**Flow Rate:** 196 m³/hr **Pressure:** 2.5 bar	Matches existing seawater pump specifications for compatibility.
Heat Exchanger	**Type:** Plate-type **Material:** Stainless Steel (316L) **Heat Load:** 283 kW **LMTD:** 8.75°C	Efficient for compact designs with high heat transfer rates.
Thermal Buffer Tank	**Volume:** 8.1 m³ **Material:** Stainless Steel (316L) **Pressure Rating:** 3 bar	Stabilizes flow and absorbs temperature fluctuations in the FW loop.
Condenser	**Type:** Shell-and-Tube **Material:** Stainless Steel (316L) **Capacity:** 283 kW	Retains current design but optimized for FW loop.
Valves	**Type:** Flow Control **Material:** Stainless Steel (316L) **Pressure Rating:** 3 bar	Installed to regulate flow between CW and FW loops.
Sensors	**Type:** Temperature and Pressure **Range:** 0-100°C, 0-10 bar **Material:** Stainless Steel	Ensures real-time monitoring for flow and temperature stability.
CW Pump	**Flow Rate:** 163.5 m³/hr **Pressure:** 5 bar	Supports ATUs, FCUs, and heat exchanger with adequate capacity.

The startup phase of a closed-loop freshwater cooling system presents unique challenges compared to the current seawater-based system (Table 4- Table 5). Unlike seawater, which is immediately available at ambient temperature, chilled water requires time to stabilize to its operational temperature of 6.5°C. This delay can lead to increased condenser temperatures and compressor loads, especially during system restarts after maintenance or shutdowns. A refined approach is necessary to address these challenges while maintaining system efficiency and reliability.

Key Challenges:

1. Delayed Temperature Stabilization: The chilled water loop requires time to cool to 6.5°C after a system restart, leaving the condenser temporarily under-cooled.
2. Compressor Overload: High condenser temperatures during startup result in elevated refrigerant pressures, increasing the load on the compressor.
3. Impact on System Components: Immediate operation of ATUs and FCUs can overload the chilled water loop before it stabilizes, reducing overall cooling efficiency.

Proposed Solution: Refined Startup Strategy:
To mitigate these challenges and ensure a smooth startup process, the following steps are recommended:
Step 1: Circulate Chilled Water Through Heat Exchanger and Condenser Only
Start the CW pump and restrict flow to the heat exchanger and condenser. This limits the initial cooling demand, allowing the CW loop to focus on stabilizing the condenser.
Step 2: Stabilize CW Temperature
Utilize the buffer tank to supply pre-cooled water to the condenser during the stabilization phase. Allow the CW loop to reach its operational temperature of 6.5°C before introducing additional loads.
Step 3: Gradual Activation of ATUs and FCUs
Once the CW loop stabilizes, gradually bring the ATUs and FCUs online. This ensures controlled load management and prevents a sudden drop in CW temperature.
Advantages of the Proposed Solution

1. Immediate Cooling: The buffer tank provides pre-cooled water, reducing the risk of condenser overheating during startup.
2. Controlled Load Management: Sequential activation of system components prevents overloading the CW loop.
3. Efficient System Stabilization: Ensures smooth operation without sudden disruptions or high refrigerant pressures

The design of Option 2 introduces a robust and efficient cooling system that eliminates the challenges associated with seawater dependency. By leveraging advanced calculations and precise component selection, this system enhances thermal stability, reduces maintenance demands, and supports long-term operational efficiency.

To validate the simulation results, theoretical calculations from heat transfer equations will be compared against simulated performance metrics. The results will be further benchmarked against industry standards and similar case studies where closed-loop cooling systems have been successfully implemented. Additionally, sensitivity analysis will be performed to assess how key parameters such as flow rate, temperature differential, and cooling capacity influence the system's efficiency. By integrating these simulation and validation methods, this study ensures a data-driven approach to optimizing the design and performance of the closed-loop freshwater cooling system, enhancing its credibility and practical applicability.

6. Conclusion

The transition from a seawater to a freshwater cooling system is a significant undertaking, requiring careful planning, robust design, and strong risk management. This study reinforces the value of adopting innovative solutions to address longstanding maintenance and efficiency challenges in maritime applications. It also highlights the importance of balancing immediate operational needs with long-term sustainability. The study concludes that a closed-loop freshwater cooling system, particularly the proposed design featuring a heat exchanger and thermal buffer tank, is a viable and effective solution for naval ships. This approach addresses critical maintenance and efficiency issues, offering a sustainable alternative to seawater cooling systems. With proper implementation and management, the transition will ensure enhanced operational efficiency, reduced environmental impact, and long-term cost savings.

References

Azienda Chimica Genovese s.r.l. *'Anti Fouling System'*2020
Chambers, L.D., Stokes, K.R., Walsh, F.C. and Wood, R.J.K., *Modern approaches to marine antifouling coatings*. Surface & Coatings Technology, 201, pp.3642–3652. 2006.
Chatterjee, A, *Design and Modeling of Shipwide Navy Integrated Power and Energy Corridor Cooling System.* Master's Thesis. Massachusetts Institute of Technology, Department of Mechanical Engineering. 2023.
Cui, X., Chua, K.J., Islam, M.R., & Yang, W.M, *Fundamental formulation of a modified LMTD method to study indirect evaporative heat exchangers.* Energy Conversion and Management, 88, pp.372–381. 2014.
Danjuma, D.M., Damack, D.A., Sylvester, S.K. and Manji, L, *Energy savings in HVAC systems on board ships. Arab Academy for Science,* Technology and Maritime Transport, College of Maritime Transport and Technology, Marine Engineering Technology Department. 2019.
Davidson, I., Cahill, P., Hinz, A., Kluza, D., Scianni, C. & Georgiades, E, *A review of biofouling of ships' internal seawater systems.* Frontiers in Marine Science, 8, p.761531. 2021

Ezgi, C., Özbalta, N. and Girgin, I, *Thermohydraulic and thermoeconomic performance of a marine heat exchanger on a naval surface ship.* Applied Thermal Engineering, 64, pp.413-421. 2014.

Izadi, M., Aidun, D.K., Marzocca, P. and Lee, H., *Integrated experimental investigation of seawater composite fouling effect on the 90/10 Cu/Ni tube.* Applied Thermal Engineering, 31(14-15), pp.2464-2473. 2011.

Jeter, S.M. *Effectiveness and LMTD correction factor of the cross flow exchanger:* A simplified and unified treatment. 2006.

Jhonson Control, *Heating, Ventilation and Air Conditioning System: Installation, Operation and Maintenance Manual.* 2009.

Markowski, M., Trafczynski, M. and Urbaniec, K., *Validation of the method for determination of the thermal resistance of fouling in shell and tube heat exchangers*. Energy Conversion and Management, 76, pp.307-313. 2013.

Melo, L.F. and Bott, T.R., *Biofouling in water systems. Experimental Thermal and Fluid Science*, 14(4), pp.375-381. 1997.

Nebot, E., Casanueva, J.F., Pendón, C., Solera, R., Taracido, L.J., Casanueva-Robles, T. & López-Galindo, C., *Marine biofouling in heat exchangers*. In: J. Chan & S. Wong, eds. Biofouling: Types, Impact and Anti-fouling. New York: Nova Science Publishers, pp. 1-30. 2010.

Pugh, S.J., Hewitt, G.F. & Müller-Steinhagen, H., *Fouling during the use of seawater as coolant—the development of a user guide*. Heat Transfer Engineering, 26(1), pp.35-43. 2005.

Pugh, S.J., Hewitt, G.F. & Müller-Steinhagen, H., *Fouling during the use of "fresh" water as coolant—the development of a user guide.* Heat Transfer Engineering, 30(10-11), pp.851-858. 2009.

Sheikh, A.K., Zubair, S.M., Younas, M. and Budair, M.O., *A risk based heat exchanger analysis subject to fouling Part II:* Economics of heat exchangers cleaning. Energy, 25(5), pp.445-461. 2000.

Wang, Z., Han, F., Ji, Y. & Li, W., *Performance and exergy transfer analysis of heat exchangers with graphene nanofluids in seawater source marine heat pump system.* Energies, 13(7), p.1762. 2020.

Biographies

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