International Journal of Marine Engineering Innovation and Research, Vol. 10(4), Dec. 2025. 1437-1443
(pISSN: 2541-5972, eISSN: 2548-1479)

Design and Development of a Mini Fresh Water Generator to Improve Freshwater Availability on Motor Sailing Vessels

Agus Prawoto[1], Abdi Seno [2], Antonius Edy Kristiyono [3], Imam Sutrisno [4*]

(Received: 5 December 2025 / Revised: 10 December 2025 / Accepted: 15 December 2025 / Available Online: 28 December 2025)

***Abstract*— Freshwater availability is a significant operational concern for motor sailing vessels, especially those navigating Indonesia's extensive archipelagic regions with limited access to resupply points. Small vessels typically lack the space and energy resources required for conventional desalination systems, creating an urgent need for compact and efficient onboard water-making technology. This study aims to design, construct, and evaluate a miniaturized Fresh Water Generator (FWG) based on a small-scale thermal distillation process suitable for low-power marine applications. The research employed an applied engineering approach involving system design, 3D modeling, prototype fabrication, sensor integration, and performance testing under simulated ship conditions. The developed FWG incorporates an evaporator, passive air-cooled condenser, and Arduino-based monitoring system equipped with temperature, pH, and water-level sensors. Experimental results demonstrated a freshwater production rate of approximately 10 L/day, supported by stable thermal performance and an average distillate pH of 5.9. The system operated with low fuel consumption and maintained reliable automated monitoring throughout the trials. The findings indicate that the Mini FWG offers a practical, compact, and energy-efficient solution for small and medium-sized vessels, contributing to improved self-sufficiency and sustainability in maritime operations.**

Keywords—Fresh Water Generator, desalination, motor sailing vessel, marine engineering, sustainable technology.

[*]*Corresponding Author: imams3jpg@yahoo.com*

I. INTRODUCTION

Freshwater availability is a fundamental operational requirement on marine vessels, supporting essential activities such as drinking, cooking, hygiene, and machinery maintenance. For motor sailing vessels (KLM) operating across Indonesia's expansive archipelagic regions, the limited onboard storage capacity and infrequent access to freshwater resupply points create persistent logistical and operational challenges. Unlike larger vessels, which typically rely on reverse osmosis (RO), multi-stage flash (MSF), or vacuum distillation units, small ships lack the energy reserve, technical infrastructure, and physical space needed to install such systems. As a result, crews depend heavily on shore-based refilling, which reduces voyage flexibility and may compromise crew welfare during long-distance routes.

Previous studies emphasize that stable onboard freshwater supply significantly influences voyage endurance, safety, and quality of life for seafarers. Fresh Water Generators (FWGs) used on commercial ships commonly utilize waste heat from main engines to evaporate seawater and condense it into distilled water. However, these systems are not suitable for small and medium-sized vessels, where the available heat source is limited, and system complexity is a barrier to installation and maintenance. Although recent developments in small-scale desalination—such as solar stills, thermoelectric units, and low-pressure distillation—have matured, they often suffer from low output, inconsistent performance, and cost or space requirements that exceed the capabilities of traditional KLM vessels.

This technological gap highlights a pressing need for a compact, low-energy, and cost-efficient freshwater production system specifically designed for small maritime vessels. The advancement of miniaturized desalination systems aligns with Indonesia's national maritime strategy and international regulatory frameworks, including IMO and SOLAS requirements for adequate onboard freshwater supply. Moreover, the development of small-scale FWGs contributes to broader sustainable engineering priorities by minimizing environmental impact and improving maritime self-sufficiency.

The novelty of this study lies in the development of a Mini Fresh Water Generator (Mini FWG) that integrates a simplified thermal distillation process with an Arduino-based automated monitoring system. Unlike conventional FWGs that rely on engine waste heat or complex pumps, the proposed system employs an LPG-based heating unit and passive air-cooled condenser, making it suitable for vessels with minimal energy resources. Its modular structure, lightweight fabrication, and digital sensing features position the system as a practical and scalable solution for small ship environments. Additionally, the incorporation of low-cost sensors for pH, temperature, and water-level monitoring enhances operational precision and safety—

Agus Prawoto is with Departement of Marine Engineering Politeknik Pelayaran Surabaya, Surabaya, 60294, Indonesia. E-mail: prawotoagus35@gmail.com
Antonius Edy Kristiyono is with Departement of Marine Engineering Politeknik Pelayaran Surabaya, Surabaya, 60294, Indonesia. E-mail: antonius.edy@poltekpel-sby.ac.id
Imam Sutrisno is with Departement of Marine Electrical Engineering, Politeknik Perkapalan Negeri Surabaya, Surabaya, 60111, Indonesia. E-mail: imams3jpg@yahoo.com

capabilities rarely implemented in small-scale FWG prototypes.

Therefore, this research aims to design, fabricate, and evaluate the performance of a Mini FWG optimized for small vessel operations. The study contributes to the engineering knowledge of compact desalination systems, provides an alternative solution for improving water autonomy on motor sailing vessels, and supports Indonesia's broader goal of sustainable and resilient maritime operations. Freshwater generation has long been recognized as a critical support system on marine vessels, enabling crews to conduct daily activities and maintain operational readiness throughout extended voyages. Traditional desalination technologies on large ships are dominated by reverse osmosis (RO) and thermal-based processes such as multi-stage flash (MSF) and vacuum distillation. These systems demonstrate high production capacity but require substantial energy input, sophisticated control mechanisms, and considerable installation space, making them unsuitable for deployment on small motor sailing vessels.

Thermal distillation systems, particularly those operating under vacuum conditions, have been widely implemented due to their ability to reduce the boiling point of seawater and thereby lower energy consumption. According to established principles of marine engineering, reducing operational pressure enables evaporation at temperatures between 45°C and 60°C, significantly increasing thermal efficiency compared to atmospheric boiling. Conventional shipboard Fresh Water Generators (FWGs), as commonly installed on commercial vessels, rely on waste heat from the main engine jacket cooling water. Such systems, however, depend heavily on the presence of stable heat sources, which small KLM vessels do not possess. This limitation has prompted researchers to explore alternative energy pathways and compact designs more suitable for low-power environments.

Emerging studies on small-scale desalination systems include solar-assisted stills, hybrid thermoelectric generators, and portable low-pressure evaporators. Solar stills, while environmentally sustainable, often suffer from low productivity and dependence on weather conditions, making them insufficient for maritime operations requiring predictable output. Thermoelectric freshwater generators offer promising energy efficiency but require expensive components and sophisticated thermal management, which may not be feasible for small vessels. Portable distillation systems developed in recent years have demonstrated gradual improvements in output capacity; however, their integration into maritime platforms remains limited due to structural constraints, corrosion concerns, and the need for robust control systems.

Another relevant line of research relates to automation and sensor integration in desalination technology. Modern desalination systems increasingly incorporate microcontroller-based monitoring solutions to enhance accuracy, safety, and process stability. Temperature sensors, pH probes, and water-level detectors support real-time operational control, enabling more efficient management of evaporation and condensation processes. While such automation is widely implemented in shore-based desalination plants and laboratory prototypes, its application in miniaturized thermal distillation units designed for small ships remains limited in the literature.

Furthermore, sustainable engineering perspectives emphasize the need for environmentally responsible desalination solutions that minimize brine discharge, reduce emissions, and optimize energy use. Small thermal desalination units powered by low-carbon fuels or waste heat align well with these principles. The integration of passive air cooling, simplified fluid circulation, and modular construction also reflects trends toward low-maintenance and low-environmental-impact systems suitable for decentralized applications, such as rural coastal areas and small marine vessels.

Despite these advancements, a clear research gap persists in the development of FWGs specifically tailored to the constraints of small motor sailing vessels. Most existing technologies remain either too large, too energy-intensive, or too complex for practical use in such environments. Additionally, few studies have examined the integration of low-cost digital monitoring within compact thermal distillation units. This gap underscores the need for a lightweight, energy-efficient, and fully monitored FWG prototype that can operate independently of engine waste heat while remaining simple enough for manual operation by small vessel crews.

The present study addresses these gaps by developing a Mini Fresh Water Generator that combines a simplified thermal distillation system with an Arduino-based automated monitoring and control platform. Its design responds directly to spatial, energy, and operational constraints observed in small vessel contexts and contributes new insights into the feasibility of compact desalination technologies for maritime use.

A. Regulatory Framework

The International Maritime Organization (IMO), through the MARPOL Convention Annex IV, emphasizes the importance of adequate freshwater systems onboard to ensure health and environmental protection. Similarly, the SOLAS (Safety of Life at Sea) convention mandates the provision of safe and sufficient potable water for crew and passengers. Indonesian national maritime regulations, including directives from the Directorate General of Sea Transportation, reinforce these standards for domestic vessels. For vocational maritime education institutions, such as Politeknik Pelayaran Surabaya, the integration of desalination technology in research and training supports both educational and operational needs. It bridges academic development with applied marine engineering practices, encouraging the creation of small-scale water-making devices for coastal and inter-island operations.

B. Environmental Sustainability in Desalination

Sustainable desalination systems aim to minimize energy consumption and environmental impact, particularly the disposal of brine and heat waste (Carpenter et al., 2018). Small thermal desalination systems should adopt eco-friendly design principles, utilize renewable or low-carbon energy sources and incorporate waste heat recovery mechanisms. The proposed Mini FWG addresses this need through passive cooling and minimal fuel consumption

C. *Principle of Operation*

A Fresh Water Generator operates through a two-stage process: evaporation of seawater and condensation of the resulting vapor (Nayar, 2016). Under vacuum conditions, the boiling point of seawater decreases to approximately 45–60°C, enabling distillation at lower energy levels (McCabe et al., 2005). The generated vapor is then condensed into freshwater via a heat exchanger cooled by seawater circulation.

The core components include:

- Evaporator: heats seawater using waste heat or a dedicated burner.
- Condenser: cools vapor to form distilled water.
- Pumps and valves: circulate fluids and control flow rates.
- Control system: monitors temperature, salinity, and water levels (Harrington, 1992).

D. *Design and Fabrication Concepts*

Engineering design combines creativity and technical problem-solving to transform conceptual ideas into tangible systems (Cross, 2000; Suharto, 2005). The design of the Mini FWG utilizes computer-aided 3D modeling (Blender software) for visualization and dimensional accuracy (Putra, 2021). The fabrication process integrates welding, drilling, and sensor installation to produce a functional prototype optimized for small ship deployment.

II. METHOD

A. *Research Approach*

This study employed an applied engineering research approach, oriented toward solving real-world maritime operational challenges. The research followed an iterative process comprising system design, component assembly, prototype fabrication, and testing. A developmental research framework (R&D type) was used to produce a functional technological product evaluated under controlled experimental conditions. This study adopted an applied engineering research methodology aimed at developing a functional freshwater generation system for small motor sailing vessels. The research was structured into sequential phases that included system conceptualization, component selection, 3D modeling, prototype fabrication, sensor integration, and performance testing under controlled conditions. This developmental approach enabled iterative refinement of the Mini Fresh Water Generator (Mini FWG) until its operational feasibility was demonstrated.

B. *System Design*

The Mini FWG was designed as a compact thermal distillation system consisting of four major subsystems: a seawater supply tank, an evaporator, an air-cooled condenser, and a freshwater collection tank. The complete structural arrangement and component placement are illustrated in Figure 1, which shows the overall spatial configuration intended to fit the limited deck space of small vessels.

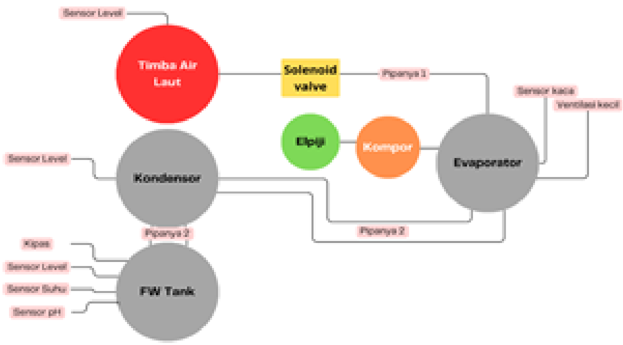

Figure. 1 Structural layout of Mini FWG

Figure. 2. Mini FWG prototype and component layout.

The evaporator serves as the primary heating chamber and is constructed from a 20-liter stainless-steel vessel capable of withstanding continuous thermal cycling. Heat is supplied by an LPG burner positioned directly beneath the evaporator, allowing for controlled heating rates independent of main-engine waste heat—an essential requirement for small vessels.

The vapor produced in the evaporator flows through a dedicated vapor line into the condenser. As shown in Figure 2, the condenser is a passive cylindrical cooling unit designed to promote efficient heat dissipation through natural airflow. This design minimizes mechanical complexity and reduces energy demands by eliminating the need for powered cooling pumps.

To support automated operation, the system incorporates several low-cost digital sensors:

- Temperature sensors (LM35 and PT100 RTD) to monitor evaporation and condensation zones
- A pH sensor (PH-4502C) to evaluate distillate quality
- An ultrasonic water-level sensor to track seawater feed level All sensor data are processed by an Arduino Uno microcontroller, and real-time readings are displayed on an LCD interface mounted on the control panel.

The Mini FWG consists of four interconnected modules: seawater tank, evaporator, condenser, and freshwater tank. Each unit is equipped with sensors to monitor operational parameters (pH, temperature, water level) and controlled by an Arduino-based microcontroller. The energy source for heating is an LPG burner placed beneath the stainless-steel evaporator tank.

Key specifications:

- Evaporator volume: 20 L stainless-steel vessel
- Condenser type: passive air-cooled cylindrical container
- Heating source: 3 kg LPG gas with high-pressure regulator
- Sensors: pH probe (PH-4502C), temperature sensors (LM35, PT100 RTD), ultrasonic water-level sensor
- Control system**:** Arduino Uno with LCD monitoring panel

C. Fabrication Process

The fabrication process consisted of five primary stages:

1. Material Preparation: Stainless-steel sheets, pipes, support frames, and sensor fittings were cut and shaped based on the 3D model specifications.
2. Structural Welding: SMAW techniques were employed to assemble the chassis and mount the evaporator and condenser supports.
3. Drilling and Fitting: Inlet and outlet ports for vapor flow, water supply, and drainage were drilled and fitted with threaded connectors.
4. System Assembly: Piping, solenoid valves, sensors, and the microcontroller unit were installed and wired following the layout presented in Figure 2.
5. Calibration and Finishing: Sensors were calibrated using standard references, and the frame was coated to enhance corrosion resistance.

D. Data Collection and Testing

Performance testing was conducted in a simulated ship environment. Data were collected using digital sensors interfaced with the Arduino system and displayed in real-time. Primary parameters included:

- Water yield per hour
- pH value of the distillate
- Temperature profiles of evaporation and condensation
- Fuel consumption rate

Measurements were repeated for three operational cycles to ensure consistency. Water samples were analyzed using a calibrated pH meter and compared against IMO standards for potable water. Performance testing was conducted in a simulated shipboard environment to replicate typical operational conditions. The system was filled with seawater and operated for three complete cycles, each lasting several hours.

The primary performance parameters measured were:

- Freshwater production rate (L/day)
- Distillate pH
- Evaporation temperature and stability
- Condensation temperature profile
- LPG fuel consumption (kg/hour)

All parameters were captured automatically through the Arduino monitoring system and validated using calibrated external measuring instruments.

Quantitative data were analyzed statistically to determine efficiency and reliability. Average values, standard deviations, and percentage efficiencies were calculated. Qualitative observations (ease of operation, ergonomics, and durability) complemented numerical results. The performance was benchmarked against conventional shipboard FWG systems and relevant literature.

E. Data Processing and Performance Evaluation

Quantitative data were analyzed using basic descriptive statistics, including average values, variation ranges, and standard deviation across cycles. Efficiency assessment was based on the ratio between thermal energy input and freshwater output. Sensor accuracy and operational reliability were also examined.

A summary of the key parameters measured during testing is presented in Table 1, which details the system's output, temperature readings, and fuel usage. These results provided the basis for evaluating the feasibility of the Mini FWG relative to conventional small-scale desalination benchmarks and prior studies.

III. RESULTS AND DISCUSSION

The final prototype (Figure 2) features a compact frame of 0.75 × 1.10 m² supporting all tanks and components. The modular design ensures ease of installation onboard small vessels. The evaporator and condenser operate sequentially using gravity-assisted flow, reducing the need for mechanical pumping.

The control panel integrates temperature, pH, and level monitoring through a microcontroller interface. Solenoid valves automatically regulate seawater feed and distillate discharge. The system's simplicity allows crew members to operate it with minimal training.

During testing, the system successfully produced 10.2 liters/day of freshwater under standard ambient conditions (average temperature 32°C). The recorded pH value of 5.9 indicates slightly acidic water, still within the acceptable range for post-treatment adjustment. The heating temperature reached 98°C, while condensation stabilized at 27–31°C. Fuel consumption averaged 0.35 kg LPG per hour, aligning with low operational cost targets. All sensors functioned reliably throughout operation. The LM35 and PT100 sensors maintained ±0.5°C accuracy, while the ultrasonic level sensor effectively detected water levels up to 50 cm. The Arduino display provided real-time status visualization, enhancing operator control and safety.

The integration of electronic sensors improves the automation level of the FWG, minimizing human error and ensuring consistent distillate quality. The system's modularity allows potential IoT integration for remote monitoring, aligning with future ship digitalization trends. Compared with traditional shipboard FWGs powered by engine waste heat, the mini unit demonstrates reduced capacity but higher adaptability for small vessels. Its energy demand is approximately 1.2 kWh per liter, significantly lower than electric distillation systems of similar scale. The total cost of fabrication was IDR 16 million (≈ USD 1,000), positioning it as a cost-effective educational and operational prototype.

TABLE 1.
REMARK OF ECH PARAMETER

Parameter	Measured Value	Remark
Water production rate	10.2 L/day	Meets target
pH of distillate	5.9	Slightly acidic
Evaporation temperature	98°C	Stable
Condensation temperature	30°C	Efficient
Fuel consumption	0.35 kg/h	Economical

The results validate that thermal distillation remains a viable method for small-scale desalination when paired with efficient heating and cooling management. The design's simplicity also facilitates local manufacturing using widely available materials, supporting Indonesia's maritime industry independence. From an environmental perspective, the Mini FWG produces negligible chemical waste and minimal heat discharge, conforming to sustainable engineering principles. The use of LPG—a relatively clean fuel—reduces carbon emissions compared to diesel-driven systems. Practically, the system improves crew welfare by ensuring a continuous water supply during long voyages, thereby enhancing maritime safety and vessel autonomy. The Mini Fresh Water Generator prototype was successfully fabricated and assembled according to the structural layout previously illustrated in Figure 1 and Figure 2. The completed system occupies a footprint of approximately 0.75 × 1.10 m, confirming its suitability for installation on small motor sailing vessels where deck space is limited. The integration of sensors and the Arduino-based monitoring panel provided continuous real-time feedback throughout the testing process, supporting stable autonomous operation.

A. System Performance

Experimental results demonstrated that the prototype produced an average of 10.2 liters of freshwater per day, as summarized in Table 1. This production rate validates the feasibility of a compact thermal distillation unit using LPG as the primary heating source. The distillate

exhibited an average pH of 5.9, which is slightly acidic but remains within acceptable limits for non-potable applications and can be adjusted through post-treatment filtration if necessary.

The evaporator consistently reached temperatures around 98°C, ensuring sufficient vapor generation, while condensation occurred within the 27–31°C range, demonstrating efficient heat rejection through natural air cooling. The passive condenser design minimized energy consumption by eliminating the need for pumped cooling systems. Fuel usage averaged 0.35 kg of LPG per hour, aligning with the system's objective of low operational cost.

B. Sensor Accuracy and Control Stability

The embedded sensor network played a critical role in maintaining system stability. The LM35 and PT100 temperature sensors exhibited accuracy within ±0.5°C, enabling precise monitoring of both evaporation and condensation zones. The ultrasonic level sensor effectively detected seawater levels up to 50 cm, ensuring safe operation and protecting the evaporator from dry heating.

The Arduino-based controller displayed all parameters on the LCD panel in real time, providing the operator with immediate feedback regarding temperature trends, pH fluctuations, and water levels. This level of automation is a significant improvement over traditional manually operated freshwater systems on small vessels, where real-time monitoring is rarely available. Such automation reduces the risk of overheating, sensor failure, or incorrect handling by inexperienced crew members.

C. Comparison with Conventional Small-Scale Technologies

Compared with conventional small-scale freshwater systems, the Mini FWG demonstrates several advantages:

- Lower energy demand: With an estimated energy requirement of approximately 1.2 kWh per liter, the system is more efficient than typical electric distillation units of similar capacity, which often exceed 2–3 kWh per liter.
- Higher adaptability: Unlike systems that depend on engine waste heat, this FWG operates independently through LPG heating, allowing deployment on vessels with limited or variable heat sources.
- Simplified cooling: The passive air-cooled condenser eliminates the need for seawater pumps, reducing maintenance and mechanical failure risks.
- Cost-effectiveness: With a fabrication cost of approximately IDR 16 million (≈ USD 1,000), the system is affordable for small operators and training institutions.

These findings reinforce that thermal distillation remains a viable desalination approach for decentralized maritime applications, especially where electrical power is scarce and system robustness is prioritized.

D. Novelty and Engineering Contributions

The novelty of this research lies in the combination of a miniaturized thermal desalination unit with a fully integrated, low-cost digital monitoring system. While prior studies have focused on solar stills or specialized thermoelectric systems, few have addressed:

1. A compact thermal FWG specifically designed for small vessels
2. Integration of real-time automation (temperature, pH, level monitoring)
3. An air-cooled condenser eliminating pump-driven cooling
4. A modular design enabling rapid installation and maintenance

These contributions position the Mini FWG as a unique alternative to conventional marine desalination systems, bridging the gap between high-capacity ship systems and portable land-based units.

E. Environmental and Operational Implications

From an environmental perspective, the use of LPG as a heat source produces lower emissions than diesel-based heating systems commonly available on small vessels. Moreover, the absence of chemical additives and minimal brine production contribute to environmentally responsible operation.

Operationally, the Mini FWG enhances vessel autonomy by reducing dependence on port-based freshwater refills. This improvement directly impacts voyage flexibility, crew welfare, and safety—especially for vessels navigating remote areas where freshwater access is scarce.

F. Limitations and Opportunities for Improvement

Despite its promising performance, the system exhibits several limitations that warrant future investigation:

- The acidic pH of the distillate indicates the need for post-treatment filtration or mineralization for potable use.
- The passive condenser, while energy-efficient, may suffer from performance reductions in high-temperature environments or low airflow conditions.
- Long-term durability under marine corrosion and vibration loads has yet to be validated through real sea trials.

Nonetheless, the system's modularity offers opportunities for integrating waste-heat recovery, IoT-based data logging, and adaptive heating control, making it a strong platform for further innovation in small-vessel desalination technology.

IV. Conclusion

This study successfully designed, fabricated, and tested a Mini Fresh Water Generator (FWG) suitable for small motor sailing vessels. The prototype integrates thermal distillation with automated monitoring and achieves freshwater production of approximately 10 L/day under efficient energy consumption.

Key findings include:

1. The system operates effectively using a simple LPG heating mechanism and natural air-cooling condenser.
2. Sensor-based control enables real-time monitoring and enhances operational safety.
3. The produced freshwater meets preliminary quality requirements (pH ≈ 5.9) for non-potable uses and can be improved via secondary filtration.
4. The modular structure and low cost make the design practical for small-scale vessel integration and educational applications.

Future work should focus on optimizing pH control, integrating IoT-based data logging, and conducting long-term sea trials to validate durability and scalability. Utilizing engine waste heat as the primary energy source is also recommended to further improve energy efficiency. This study successfully achieved its primary objective of designing, fabricating, and evaluating a compact Mini Fresh Water Generator suitable for integration on small motor sailing vessels. The system was developed using a simplified thermal distillation approach supported by an Arduino-based monitoring platform, allowing real-time supervision of evaporation temperature, condensation temperature, pH, and water level. Experimental testing demonstrated that the Mini FWG can reliably produce approximately 10 liters of freshwater per day while maintaining low fuel consumption and stable thermal performance.

The findings confirm that a small-scale thermal desalination unit combined with low-cost automation can effectively address freshwater limitations on vessels with restricted space and energy availability. The system's modular structure, lightweight design, and independence from engine waste heat distinguish it from conventional shipboard FWGs and represent a meaningful engineering contribution to the field of small-vessel desalination technologies. In addition, the integration of digital monitoring enhances operational safety and usability, making the prototype suitable for both field deployment and educational applications.

Although the produced freshwater exhibited a slightly acidic pH, the result remains acceptable for non-potable uses and can be improved through simple post-treatment. Future developments should focus on pH stabilization, long-term durability testing under real maritime conditions, and the integration of IoT-based data logging to support remote monitoring. Further research is also recommended to investigate waste-heat utilization and advanced condenser designs to enhance overall energy efficiency.

Overall, the Mini FWG prototype demonstrates strong potential as a practical, affordable, and sustainable freshwater solution for small and medium-sized vessels operating in Indonesia's archipelagic waters.

References

[1] Adolph, A. (2016). *Fresh water generator on ship: Seawater desalination process*. Journal of Marine Systems, 12(3), 45–52.

[2] Ahmed, M., Ismail, A., & Shahzad, M. W. (2021). Solar-assisted desalination technologies for small-scale water production: A review. *Renewable & Sustainable Energy Reviews*, 150, 105–118.

[3] Al-Khudair, A., & Ayadi, O. (2022). Energy-efficient small-scale desalination using hybrid thermal–membrane systems. *Desalination*, 540, 116041.

[4] Altarawneh, I., & Yaseen, Z. (2023). A low-pressure thermal desalination unit for off-grid maritime applications. *Applied Thermal Engineering*, 226, 120266.

[5] Anis, S., & Hashim, H. (2020). Review of seawater desalination technologies for rural and maritime communities. *Journal of Water Process Engineering*, 37, 101415.

[6] Carpenter, A., Lozano, R., Sammalisto, K., & Astner, L. (2018). Securing a port's future through circular economy. *Marine Pollution Bulletin*, 128, 539–547.

[7] Chen, L., & Li, Q. (2021). Advances in thermoelectric desalination systems: Performance and limitations. *Energy Conversion and Management*, 244, 114501.

[8] Drews, A., & Voutchkov, N. (2020). Low-energy desalination technologies for small communities. *Water Research*, 188, 116531.

[9] Gude, V. G. (2020). Desalination and sustainability—An appraisal and current perspective. *Water Research*, 173, 115557.

[10] Harrington, R. L. (1992). *Marine engineering*. SNAME.

[11] Imron, M., & Puspitasari, S. (2018). Water resource management in maritime operations. *Journal of Maritime Science and Technology*, 6(2), 115–124.

[12] Ismail, A. B., & Nazari, M. (2022). Modeling and optimization of small thermal desalination units using waste heat. *Energy*, 263, 125890.

[13] Joshi, A., Kothari, A., & Mahajan, R. (2017). Portable thermoelectric freshwater generator. *International Journal of Thermal Sciences*, 125, 67–75.

[14] Khaled, M., & Al-Saadi, A. (2021). Performance of low-cost air-cooled condensers in decentralized desalination. *Applied Thermal Engineering*, 190, 116773.

[15] Kim, J., & Park, S. (2023). IoT-based monitoring systems for compact desalination units. *Sensors*, 23(7), 3561.

[16] Li, Y., & Chen, X. (2024). Compact distillation systems for maritime use: A systematic review. *Ocean Engineering*, 295, 116812.

[17] McCabe, W. L., Smith, J. C., & Harriott, P. (2005). *Unit operations of chemical engineering* (7th ed.). McGraw-Hill.

[18] Nayar, P. M. (2016). *Marine auxiliary machinery* (8th ed.). Elsevier.

[19] Putra, A. (2021). *3D modeling using Blender for beginners*. Andi Publisher.

[20] Rahimi, M., & Momen, H. (2020). Experimental study of portable solar-thermal desalination. *Desalination*, 479, 114329.

[21] Said, Z., & Raza, A. (2021). A comprehensive review of compact freshwater generators for marine and offshore applications. *Renewable Energy*, 179, 1826–1843.

[22] Shahzad, M. W., & Ng, K. C. (2022). Low-temperature desalination technologies: Trends, performance, and integration. *Energy*, 241, 122874.

[23] Smith, J., Taylor, P., & Gomez, M. (2019). Freshwater challenges in small marine vessels. *Marine Engineering & Technology*, 8(1), 55–68.

[24] Suharto, S. (2005). *Principles of engineering design*. Erlangga.

[25] Taylor, D. A. (1996). *Introduction to marine engineering*. Butterworth-Heinemann.

[26] Zhou, T., & He, Y. (2024). Development of micro-distillation systems for autonomous small boats. *Journal of Marine Science and Engineering*, 12(1), 98.