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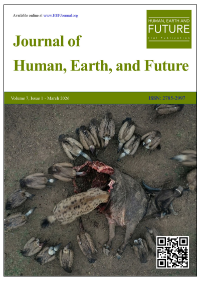

Development of an Incinerator-Based Waste Management Model for Marine Pollution Mitigation

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Abstract

Marine pollution caused by ship-generated waste remains a critical environmental challenge, particularly on training vessels that operate continuously with high waste variability. This study aims to develop and validate an incinerator-based onboard waste management model that enhances waste processing efficiency while ensuring compliance with MARPOL 73/78 regulations. A mixed-method approach was applied, integrating quantitative waste characterization and regression-based estimation of waste generation with qualitative operational analysis across six Indonesian training ships. The regression outputs were used to parameterize incinerator capacity and combustion load, while system integration, thermal simulation, and operational validation were conducted to evaluate performance under representative shipboard conditions. The findings demonstrate that the engineered incinerator significantly improves feeding capacity, combustion efficiency, and energy utilization, while reducing residual ash and carbon monoxide emissions by approximately 15–20 ppm compared to standard systems. Thermal simulations confirmed stable combustion at 950–1050°C and effective exhaust gas treatment through water spray cooling and activated carbon filtration. The proposed model offers a system-level improvement over existing studies by explicitly integrating regulatory requirements, engineering design, emission control, and crew-operational workflows within the spatial and functional constraints of training vessels. This integrated and vessel-specific approach constitutes the main novelty of the study, providing a practical, compliant, and environmentally sustainable solution for shipboard waste management and marine pollution mitigation.

Keywords: Waste Management; Marine Pollution; Training Ship; Combustion Efficiency; Marpol Compliance; Energy Recovery.

1. Introduction

Marine pollution remains a critical global environmental challenge, with shipping activities recognized as a persistent and complex source of marine-based pollution . Ship-generated waste including solid waste, oily residues (sludge), domestic refuse, and combustion-related emissions is continuously produced during vessel operation and, if inadequately

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managed, poses serious risks to marine ecosystems and coastal environments [1, 2]. This issue is particularly pronounced on vessels with high operational intensity, such as training ships, where extended voyages and high onboard occupancy rates result in substantial and heterogeneous waste generation.

To address these risks, the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) provides the primary international regulatory framework governing shipboard waste management. Annex I regulates oily waste, Annex V governs solid waste disposal, and Annex VI sets limits on air pollutant emissions, including those arising from onboard incineration processes [3, 4]. Compliance with these annexes requires ships to adopt waste treatment systems that ensure controlled combustion temperatures, effective emission reduction, and safe operational procedures. Recent regulatory analyses emphasise that the effectiveness of such conventions depends not only on legal adoption but also on the availability of technically implementable systems that can be realistically operated onboard ships [5].

From a technical perspective, shipboard incinerators are widely recognised as a key solution for reducing waste volume and destroying hazardous compounds at sea. Studies report that incineration can reduce waste volume by up to 90% while supporting onboard waste-to-energy (WtE) applications and reducing dependence on shore-based disposal facilities [1, 3]. Recent research has explored the integration of incinerators with waste heat recovery systems, such as Organic Rankine Cycles and thermoelectric generators, to enhance overall vessel energy efficiency and reduce carbon emissions [2, 6, 7]. Innovative concepts, including the utilisation of incinerator waste heat for absorption-based cooling systems, further demonstrate the potential of incineration as part of broader energy and environmental strategies in maritime operations [3].

However, effective incinerator performance depends heavily on engineering design and operational control. Imbalances in fuel supply, airflow, or combustion temperature can result in incomplete combustion, elevated carbon monoxide emissions, and excessive ash residue [8]. In addition, occupational safety concerns related to shipboard waste incineration have been highlighted, particularly with respect to crew exposure, maintenance procedures, and emergency handling [9]. Complementary technologies such as hydrocarbon water purification systems [10] and anaerobic co-digestion of organic waste streams [11] have been proposed to support integrated waste management, yet these systems are rarely assessed as part of a unified onboard operational model.

Several studies emphasise the need for sustainable onboard waste management. Cruise ship waste reviews highlight the pressures from increasing maritime tourism and the necessity for integrated systems encompassing social, economic, and regulatory aspects [4, 12]. Innovative approaches, including oil recycling [13] and microplastic source control [14], further underline the importance of both technical and policy measures in protecting marine environments. Despite significant progress in understanding ship-generated waste and its environmental impacts, the existing literature reveals several critical gaps that this study addresses. First, most recent research on onboard waste incineration focuses on broad feasibility and energy potential rather than providing a practical model tailored to specific vessel types and operational contexts. For instance, recent studies on shipboard waste-to-energy (WtE) systems largely emphasise energy feasibility and logistics for large container ships rather than vessel-specific system design and operational integration (e.g., numerical modelling of waste logistics for 8,500 TEU container vessels) [1]. Similarly, investigations into incineration on cruise ships concentrate on energy recovery from flue gases rather than holistic waste management system design that incorporates regulatory compliance, system layout, and operational protocols on board real vessels [3].

Second, the literature lacks models that systematically integrate regulatory requirements, such as MARPOL Annex V and VI, with engineering design, emission control, and crew operational processes within the confined spatial and functional constraints of training ships. Although regulations specify allowable incineration practices and emission limits, limited research has translated these standards into implementable waste management models for real ship classes [15]. Existing studies also frequently overlook safety considerations and workflow implications for ship crews during incinerator operation, which are particularly relevant for non-commercial vessels such as training ships, where cadets are directly involved in daily operations.

To address these gaps, this study proposes an incinerator-based waste management model specifically developed for training vessels, using the KL Laksamana Malahayati and its sister ships as case studies. Unlike previous studies that emphasise isolated technical performance or energy recovery potential, this research adopts a system-level design synthesis that integrates combustion efficiency, emission mitigation, piping and process visualisation, and operational procedures in accordance with MARPOL 73/78 technical principles and relevant environmental standards. This approach not only contributes to marine pollution mitigation but also supports the operational requirements of training ships, thereby ensuring both practical relevance and academic novelty.

Based on this background, this study aims to design and establish a model incinerator system for controlling solid waste pollution on training vessels. The design adheres to MARPOL 73/78 technical principles while addressing the operational needs of the KL Laksamana Malahayati and its sister ships. The research further incorporates system visualisation, combustion efficiency analysis, emission control strategies, and the integration of piping and operational processes within the context of training ship operations.

The remainder of this article is structured as follows. Section 2 describes the materials and methods, including the mixed-method research design, waste characterisation approach, and system development procedures. Section 3 presents the results and discussion, covering system performance, waste reduction efficiency, emission characteristics, and thermal simulations. Section 4 concludes the study by summarising the key findings, highlighting regulatory and operational implications, and outlining directions for future research on sustainable shipboard waste management.

2. Material and Methods

This study employed an integrative mixed-methods design, in which quantitative modelling and qualitative inquiry were deliberately combined at the design and decision-making level rather than treated as independent analytical strands. Quantitative analysis was used to estimate shipboard waste generation rates and operational loads, which provided the numerical basis for determining incinerator capacity, feeding rates, and thermal requirements. In parallel, qualitative findings derived from interviews, onboard observations, and document analysis were systematically translated into engineering design constraints, including system layout, operational sequencing, crew interaction points, safety mitigation measures, and compliance mechanisms. The integration of both data types occurred during the system design phase, where statistical outputs defined what the system must accommodate, while qualitative insights determined how the system should be configured and operated under real shipboard conditions.

The research was conducted between 2024 and 2026 on six Indonesian training ships, namely KL *Laksamana Malahayati* (Aceh), KL *Mohammad Husni Thamrin* (Jakarta), KL *Bung Tomo* (Surabaya), KL *Sultan Hasanuddin* (Makassar), KL *Laksamana Muda John Lee* (North Sulawesi), and KL *Frans Kaisiepo* (Sorong). These vessels were selected to represent diverse operational regions and training profiles. Data collection was carried out over 11 operational days per vessel, resulting in a total of 66 observation units covering a wide range of sailing routes and operational conditions from western to eastern Indonesia.

2.1. Quantitative Data Collection and Analysis

Quantitative data collection focused on characterising solid waste generation onboard training ships as a basis for incinerator system design and capacity determination. Ship-generated waste was classified into plastic waste, food waste, and galley-related waste. Daily waste quantities were measured together with occupancy variables, namely the number of crew members and cadets, as occupancy level constitutes a primary determinant of waste generation on training vessels.

Statistical modelling was conducted using multiple linear regression analysis to estimate waste generation rates under varying occupancy conditions. Classical assumption tests, including normality, multicollinearity, and heteroskedasticity, were performed to ensure statistical reliability. To account for variability across vessels and operational days, panel data regression approaches, namely Pooled Ordinary Least Squares (OLS), Fixed Effects (FE), and Random Effects (RE), were examined. A Hausman specification test was applied to compare FE and RE models. Although the Random Effects model was statistically appropriate, model selection was guided primarily by goodness-of-fit indicators, particularly the coefficient of determination (R^2), and practical suitability for engineering design purposes. Accordingly, Pooled OLS was retained as the baseline reference model, while FE and RE models were used to assess robustness and ship-specific heterogeneity. Regression outputs were used directly to parameterise incinerator capacity, waste feed rates, combustion load, and baseline emission estimates.

2.2. Qualitative Data Collection and Waste Characterization

Qualitative methods were applied to capture operational, technical, and safety-related aspects of onboard waste management that could not be sufficiently explained through quantitative data alone. Qualitative data collection comprised three main techniques:

a. Semi-structured interviews with ship officers, engineers, and waste-handling personnel to explore existing waste management practices, operational constraints, safety concerns, and challenges related to MARPOL compliance.

b. Non-participant observations of daily waste handling activities, including waste segregation, temporary storage, transfer, and disposal processes onboard the vessels.

c. Document analysis of ship operational manuals, safety procedures, and waste management logs to understand formal protocols and regulatory implementation.

Qualitative data were analysed thematically to identify key constraints and operational patterns, which were then translated into design-relevant parameters directly informing system layout, incinerator placement, operational sequencing, crew interaction points, and safety mitigation measures.

Waste characterisation adopted an engineering-oriented and operational approach, emphasising waste composition, handling characteristics, and combustion behaviour rather than laboratory-based fuel analysis. Ship-generated waste was classified into plastic, food waste, paper, cardboard, styrofoam, and limited medical waste based on onboard observations and operational records, with medical waste strictly limited to non-cytotoxic first-aid and infirmary residues and excluding hazardous or regulated medical waste. Waste segregation followed MARPOL 73/78 Annex V to minimise hazardous fractions. Moisture content and calorific value were not measured directly; their effects were addressed implicitly through system design features, including a multi-zone combustion chamber, auxiliary burners using sludge oil and Marine Diesel Oil (MDO), forced-draft air supply, and automatic temperature control within the range of 850–1100 °C. Limited medical waste was treated by high-temperature incineration at or above 850 °C, combined with activated carbon filtration and water-spray flue gas cooling to comply with MARPOL 73/78 Annex VI. The adequacy of waste characterisation was evaluated indirectly through system performance indicators, including waste volume reduction efficiency, ash residue generation, combustion temperature stability, and carbon monoxide (CO) emissions.

The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 1.

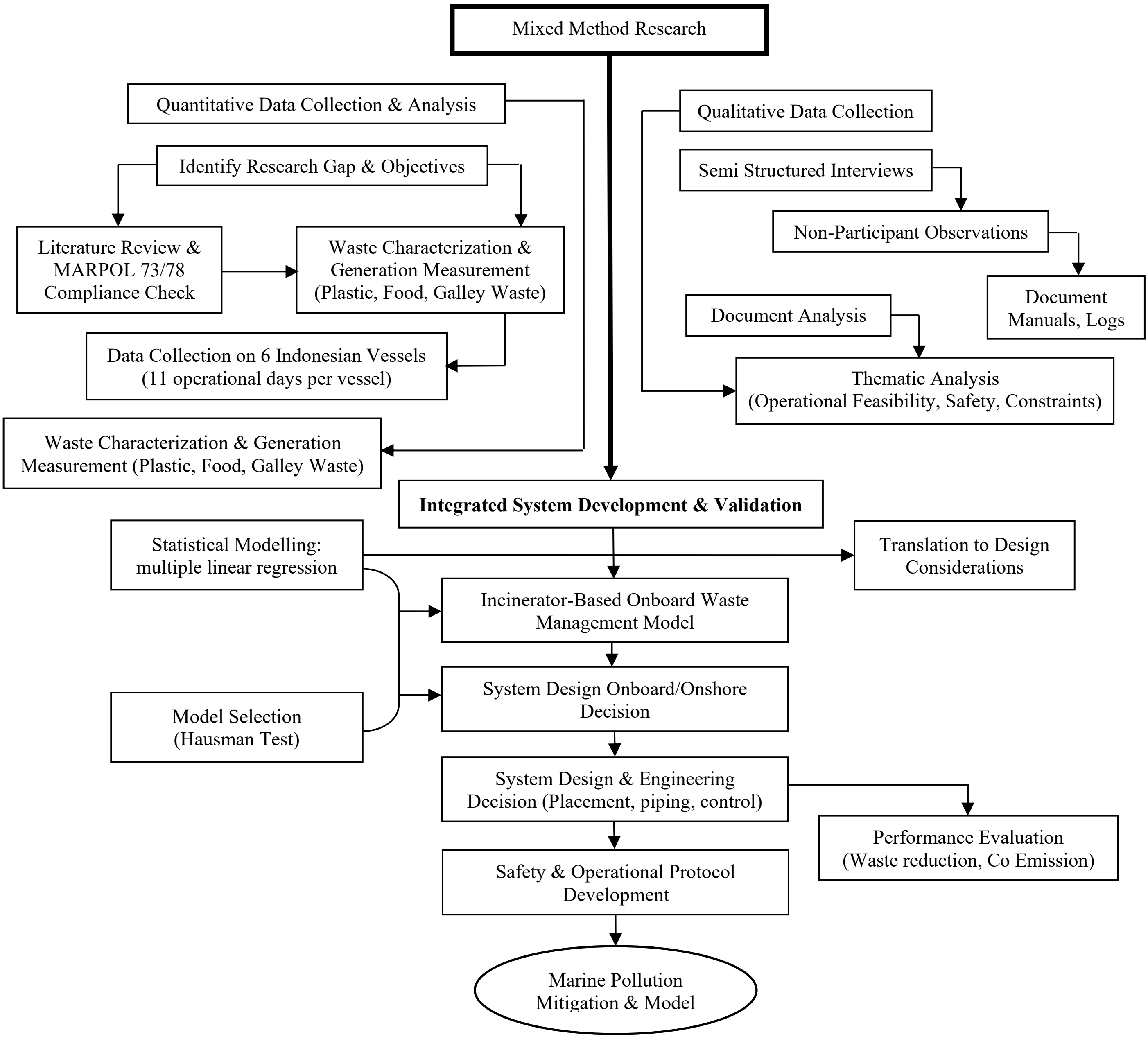


Figure 1. Schematic Representation of the Research Design and Procedures

3. Results and Discussion

3.1. System

A comprehensive evaluation using ten performance dimensions, as illustrated in Figure 2, demonstrates that the locally engineered incinerator system consistently outperforms the standard design across nearly all key indicators. Engineered units achieve higher scores in feeding capacity, thermal capacity, sludge capacity, storage volume, and overall combustion efficiency, with values approaching the maximum ratings on the radar plot.

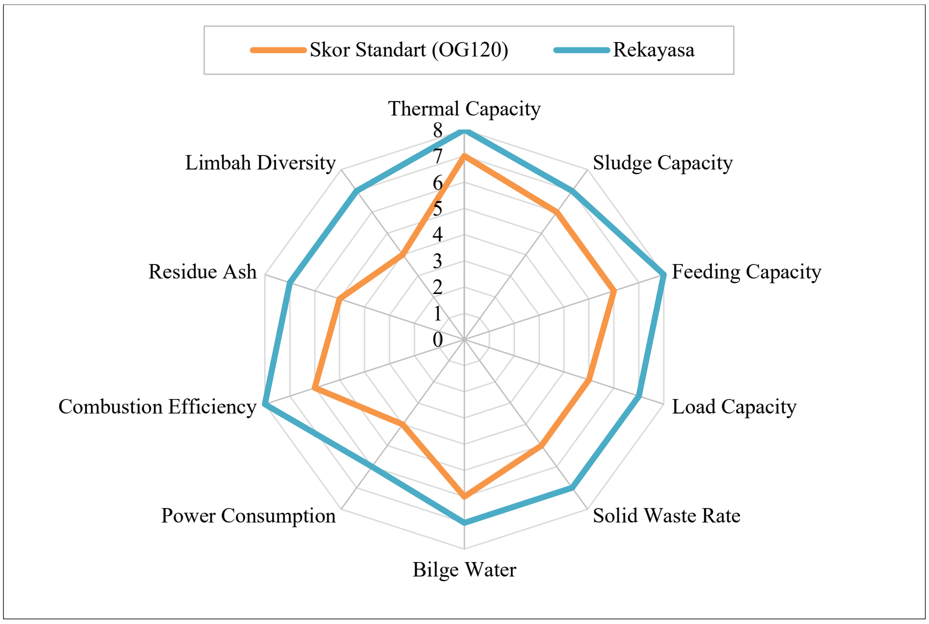


Figure 2. Performance of standard and engineered incinerators

The engineered incinerator also exhibits superior performance in terms of flexibility to process diverse waste types, lower residual ash generation, and reduced solid waste output. Notably, the engineered system requires lower electrical power consumption for blower operation, combustion, and fuel pumping, indicating improved energy efficiency. Enhanced performance in parameters such as thermal efficiency and power consumption not only optimises onboard resource utilisation but also supports compliance with environmental regulations. In addition, the ability to handle variable waste loads, process multiple waste categories, including domestic waste, galley waste, plastics, sludge, and used oil, and achieve higher burn rates is evident from the expanded area of the engineered system on the radar chart. Collectively, these improvements contribute to reduced environmental impact, more complete combustion, and robust compliance with MARPOL 73/78 standards for clean disposal at sea.

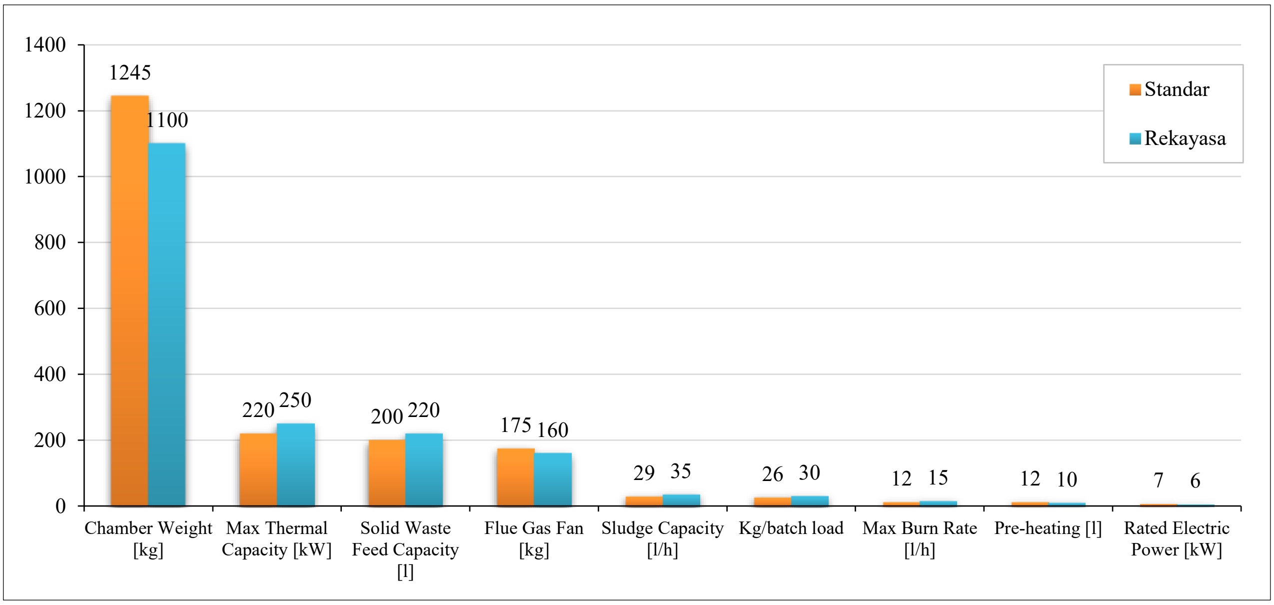


Figure 3. Specifications of engineered vs. standard incinerators

Figure 3 further illustrates quantifiable improvements achieved by the engineered incinerator compared with the standard model. Thermal capacity increased from 400 to 450 kW, while solid waste and sludge processing capacities increased to 250 L and 220 L/h, respectively. The system is capable of handling up to 35 kg per batch, with a burn rate of 15 L/h. Structural weight was reduced to 1,245 kg without compromising durability, and electrical power consumption decreased from 7 to 6 kW through the implementation of efficient preheating mechanisms and automatic control systems. These enhancements collectively improve energy efficiency, waste processing capacity, and structural optimisation, thereby ensuring compliance with MARPOL 73/78 requirements and supporting the system's potential applicability across a broader range of maritime vessels.

3.2. Waste and Residues

Figure 4 illustrates the progressive reduction in waste volume from total input to gas emissions, comparing the standard and engineered incinerators. With equivalent waste inputs of 290–300 kg of mixed waste, the engineered system achieved higher pre-sorting efficiency through an optimised feeding chamber and internal compaction, thereby reducing the effective thermal load. Post-combustion, solid residue levels were substantially lower, indicating more complete thermal decomposition. Stable combustion temperatures, optimised air distribution, and precise automatic fuel control further enhanced system performance. Moreover, lower gas emissions were achieved through effective flue gas cooling and activated carbon filtration. These results confirm that the engineered system not only improves technical efficiency but also meets the requirements of MARPOL 73/78 Annex V, thereby supporting environmentally sustainable shipboard waste management.

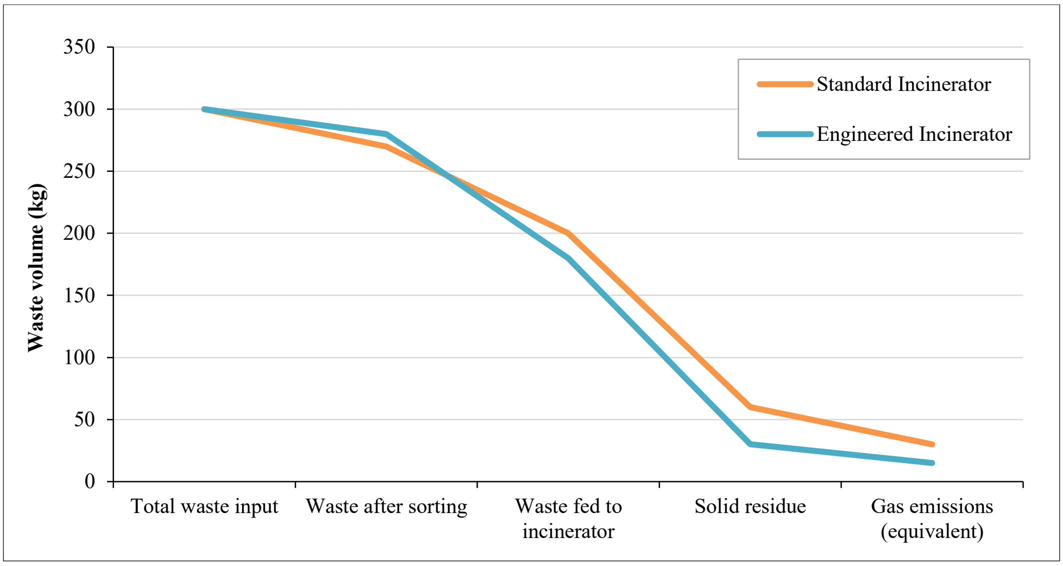


Figure 4. Stages of waste reduction: engineered vs. standard incinerator

Figures 5 and 6 show the composition of waste streams processed by the standard and engineered incinerators. In the standard system, the largest proportions consisted of plastic waste (28%), food waste (23%), paper (19%), cardboard (19%), styrofoam (9%), and medical waste (2%), indicating limited capability in handling more complex waste fractions, particularly styrofoam and medical waste. In contrast, the engineered incinerator exhibited a more balanced waste composition, comprising plastic (32%), food waste (21%), paper (18%), cardboard (14%), styrofoam (11%), and medical waste (4%). This distribution reflects enhanced tolerance to variations in waste density, moisture content, and calorific value. The improved performance is attributable to more precise temperature regulation, a responsive forced-draft air system, and a multi-zone combustion chamber, which together enable efficient combustion of heterogeneous waste. This operational flexibility supports integrated waste management principles and ensures compliance with MARPOL 73/78 Annex V, thereby promoting adaptive and sustainable shipboard waste management practices.

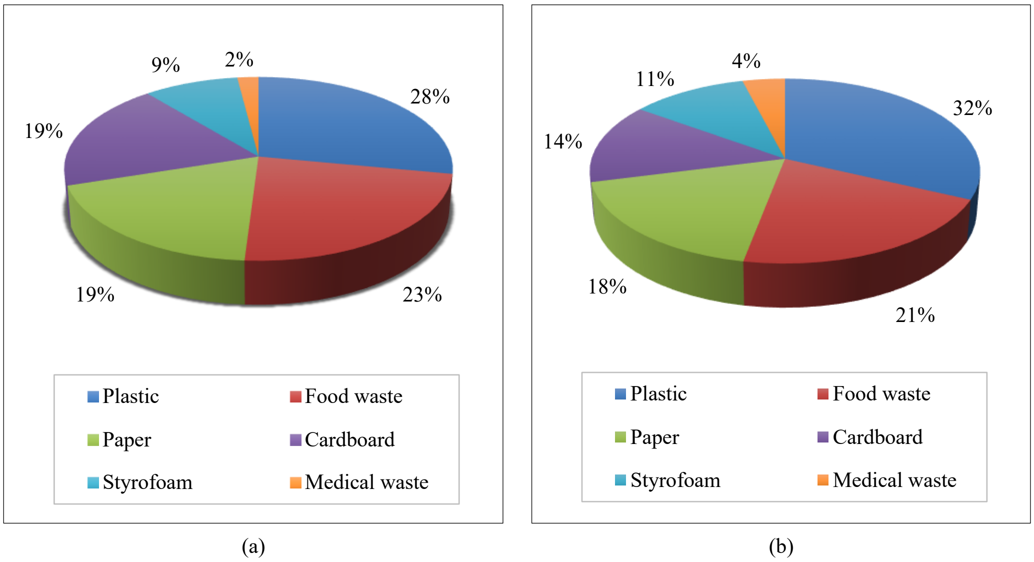


Figure 5. (a) Percentage of waste types in the standard incinerator, (b) Percentage of waste types in the engineered incinerator

Comparative results show that the engineered incinerator achieves higher combustion efficiency and lower CO emissions across six training ships. For example, on KL MH Thamrin, capacity increased from 38 kg to 49 kg/day, while CO dropped from 94 ppm to 78 ppm. Similar improvements occurred on other vessels, with average CO reduction of 15–20 ppm. These results confirm that the engineered system enhances combustion performance without increasing fuel use, supporting cleaner and more sustainable shipboard waste management (Figure 6).

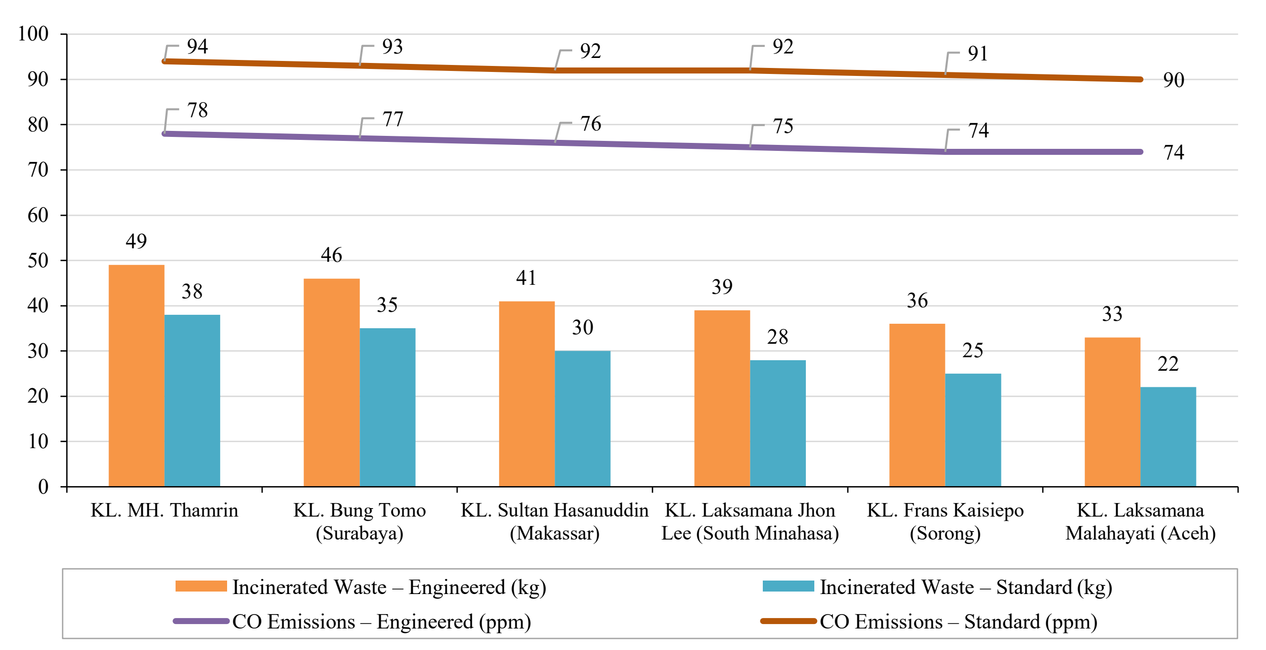


Figure 6. Volume of waste combusted and co emissions: engineered vs. standard incinerator

3.3. Model

The incinerator system on *KL Laksamana Malahayati* demonstrates enhanced efficiency, operational reliability, and compliance with MARPOL 73/78 Annex V. The system comprises two principal stages, namely a waste combustion chamber and an automatic flushing mechanism designed to prevent residue accumulation. The integration of a blower vacuum, back-pressure valve, and bypass line improves overall operational efficiency, while simultaneously reducing harmful emissions and maintaining safe and hygienic operating conditions in accordance with MARPOL standards (Figure 7).

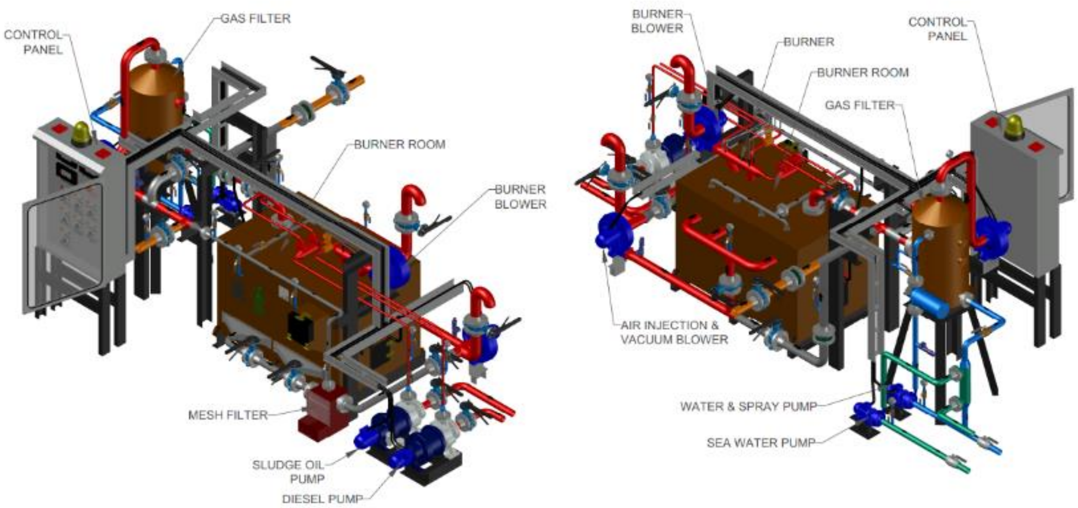


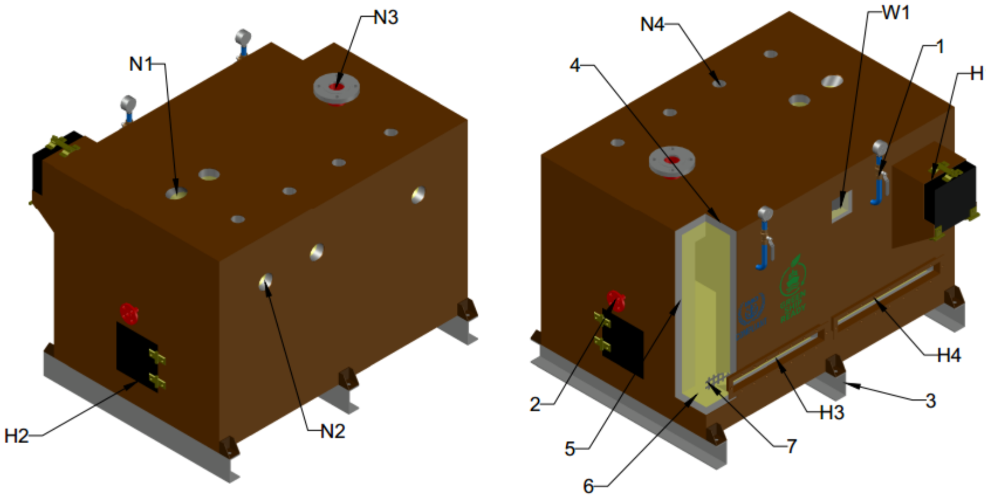
Figure 7. Incinerator design

The combustion chamber operates within a temperature range of 850–1100 °C, ensuring complete thermal decomposition of waste materials. Lined with heat-resistant refractory materials, the chamber maintains both thermal efficiency and structural durability during prolonged operation. The *KL Laksamana Malahayati* incinerator system incorporates a Trash Inlet (H1), an inspection port (H2), ash outlets (H3–H4), and continuous monitoring through pressure and temperature sensors equipped with a quartz glass viewing window. Combustion air is supplied through the Blower Hole (N2), ignition is initiated at the Burner Hole (N1), and exhaust gases are discharged via the Gas Outlet

(N3). The chamber is constructed from SS 304 stainless steel, with Glass Wool insulation and Fire Brick layers, ensuring thermal stability, structural integrity, and efficient combustion performance.

3.4. System

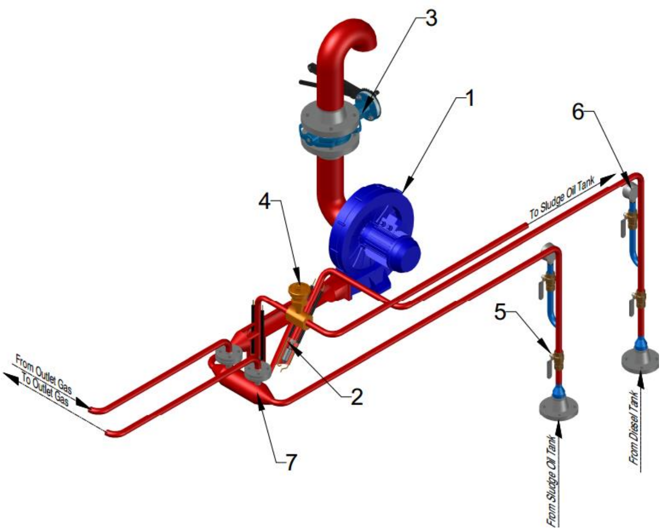
The combustion chamber operates within a temperature range of 850–1100 °C to ensure complete thermal decomposition of waste. Lined with heat-resistant refractory materials, the chamber maintains high thermal efficiency and structural durability. *The KL Laksamana Malahayati* system features a Trash Inlet (H1), inspection port (H2), ash outlets (H3–H4), and continuous monitoring through pressure and temperature sensors equipped with a quartz glass window. Combustion air enters through the Blower Hole (N2), ignition is initiated at the Burner Hole (N1), and exhaust gases are discharged via the Gas Outlet (N3). Constructed from SS 304 stainless steel with Glass Wool insulation and Fire Brick layers, the chamber ensures thermal stability and efficient combustion performance (Figure 8).



H1 = trash inlet	N2 = blower hole	3 = UNP base
H2 = hand hloe	N3 = gas outlet	4 = body SS 304
H3&H4 = residu outlet	N4 = air injection	5 = glass wool
W1 = quarts glass	1 = pressure indicator	6 = morta refractory & fire brick
N1 = bruner hole	2 = thermal sensors	7 = mesh 5 SS 304

Figure 8. Burner room

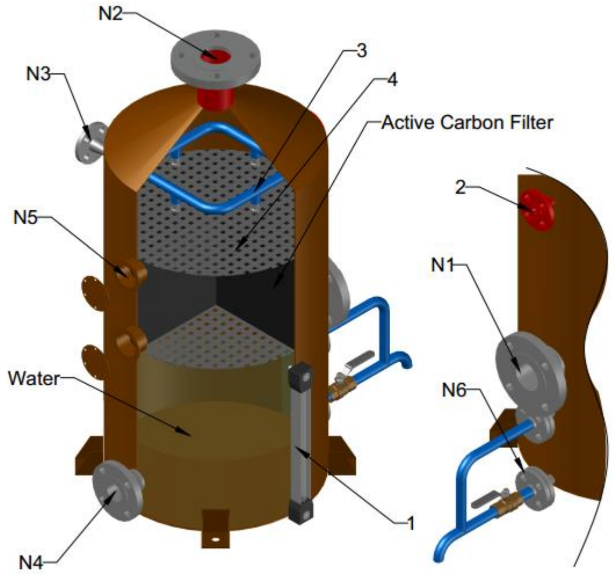
The burner injects a controlled mixture of sludge oil and Marine Diesel Oil (MDO) into the combustion chamber through an automatic high-pressure delivery system with integrated temperature regulation. Fuel is supplied from the sludge tank and purifier, ensuring stable and continuous flow (Figure 9). The system includes a blower for oxygen supply, a pilot burner for ignition, and several valves, namely a butterfly valve for air volume regulation, a needle valve for precise flow control, and a ball valve for rapid shut-off. Pressure conditions are monitored via a pressure indicator, while a heater tube preheats the fuel, thereby enhancing combustion efficiency and reducing pollutant formation.



1 = blower	4 = need valve	6 = pressure indicator
2 = pilot burner	5 = ball valve	7 = heater tube
3 = butterfly valve		

Figure 9. Burner

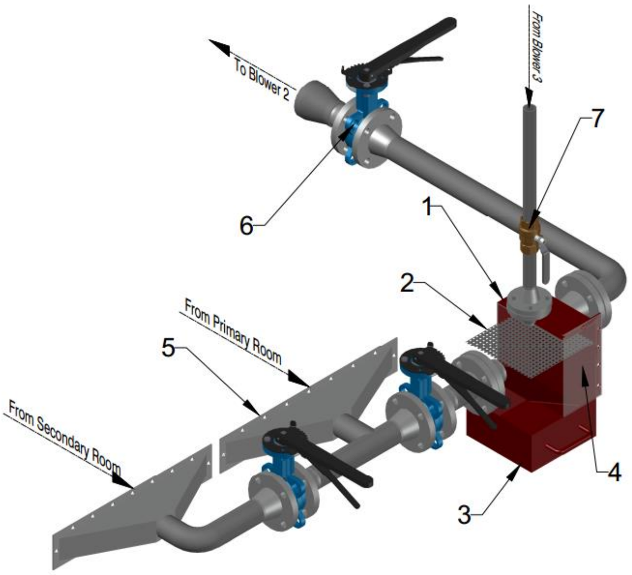
Combustion gases are directed through the outlet channel to a dedicated filtration system designed to reduce harmful emissions, including SOx, volatile organic compounds (VOCs), and particulate matter. The system employs a high-adsorption activated carbon filter combined with a high-pressure water spray to cool exhaust gases, capture dust particles, and ensure that emissions remain within applicable environmental limits (Figure 10). The combined action of water spray cooling and activated carbon adsorption forms a two-stage gas purification process that safely treats exhaust gases. This design enhances both waste destruction efficiency and air pollution control, ensuring compliance with MARPOL 73/78 Annex VI emission standards.



N1 = Gas Inlet	N5 = Carbon Acces	2 = Thermal Sensor
N2 = Gas Outlet	N6 = Offer Flow	3 = Nozze Spray Water
N3 = Water Spray	1 = Level Indicator	4 = Mesh 20 SS 304
N4 = Water Outlet		

Figure 10. Gas Filter

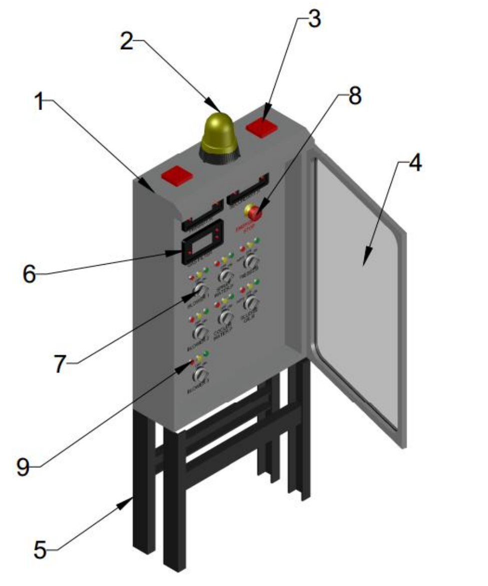
Combustion ash and solid residues are extracted through a suction line into a residue filtration unit for initial separation. The system, which can operate in automatic or semi-manual modes, utilises mesh and Filter Mesh 10 to trap coarse particles, with collected residues stored in a dedicated residue box for periodic removal (Figure 11). An internal air-spray line periodically cleans the filter surface, thereby preventing clogging and extending service life. Visual inspection is enabled through mica glass, while a vacuum intake equipped with butterfly and ball valves maintains stable internal pressure. This configuration ensures efficient residue filtration and safe disposal, in accordance with international shipboard waste management regulations.



1 = mesh filter body	4 = mica glass	6 = butterfly valve
2 = filter mesh 10	5 = vacuum intake	7 = ball valve
3 = residu box		

Figure 11. Suction residu filter

The incinerator operates via an integrated electronic control panel that ensures safe, efficient, and regulation-compliant operation. The panel controls combustion temperature, operating duration, and fuel supply, with automatic shutdown mechanisms activated in cases of overheating or abnormal pressure. On *KL Laksamana Malahayati*, the corrosion-resistant control panel incorporates warning lights, an audible siren, and thermal indicators for real-time monitoring. Waterproof access, clearly labelled switch buttons, and an emergency stop function further enhance operational safety, while indicator lamps display system status. This configuration supports reliable system operation and compliance with MARPOL and IMO emission and safety requirements (Figure 12).



1 = body panel	4 = door panel	7 = switch button
2 = warning lamp	5 = UNP steel	8 = emergency stop
3 = siren speaker	6 = thermal indicator	9 = indicator lamp

Figure 12. Control panel

The ship's incinerator piping system is designed to deliver fuel accurately to the combustion chamber using two fuel types, namely sludge oil as the primary fuel and diesel oil for ignition at approximately 850 °C. Separate pumps supply sludge oil and diesel through independent pipelines to the burner nozzle, supported by dual blowers that maintain an optimal air-to-fuel ratio and reduce carbon monoxide and VOC emissions. Bypass, outlet, and return pipelines regulate pressure, temperature, and fuel circulation (Figure 13). Constructed from heat-resistant and corrosion-resistant materials, the system incorporates valves, pressure gauges, and temperature sensors. This design ensures thermal efficiency, operational safety, and compliance with MARPOL 73/78 Annex I.

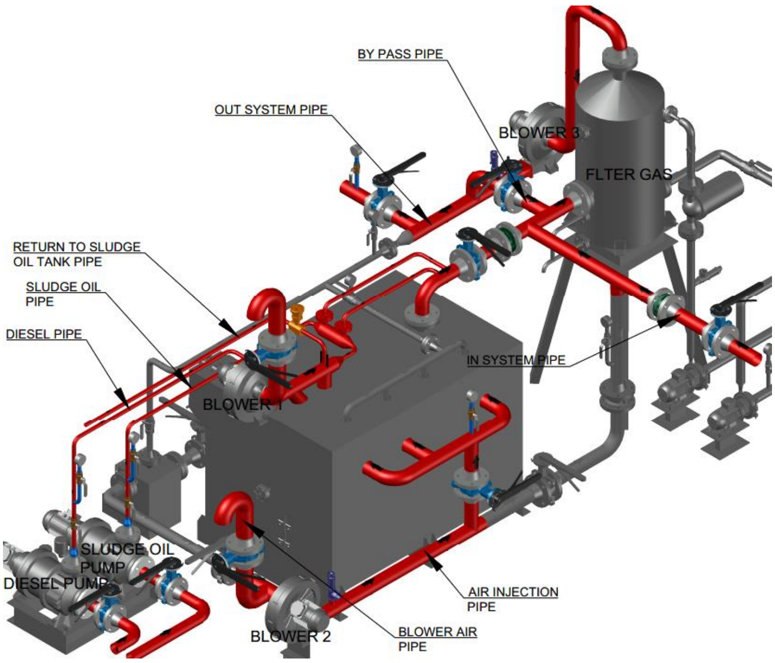


Figure 13. Burn system pipeline

The cooling and exhaust gas backwash system functions to reduce exhaust gas temperature and remove residual contaminants prior to final filtration. Water supplied by the pump flows through pipes and preliminary filters, then is discharged through spray nozzles to cool the gas stream and capture particulate matter. A seawater-cooled pipeline maintains stable operating temperatures, while an overflow line prevents excessive pressure accumulation. This system protects downstream filtration components, maintains consistent filtration performance, and ensures that exhaust emissions meet MARPOL 73/78 Annex VI requirements. The integration of cooling, filtration, and backwash functions enhances both operational safety and environmental sustainability (Figure 14).

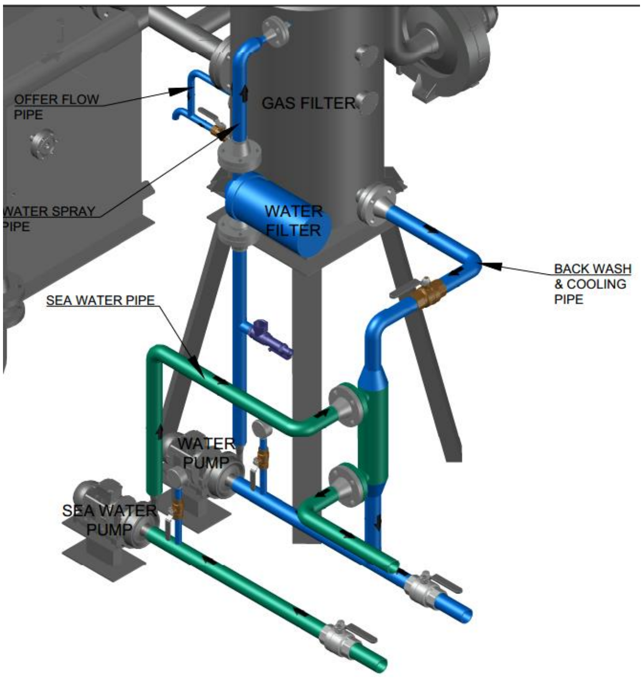


Figure 14. Water system pipeline

The residue management unit is designed to remove combustion ash from the chamber efficiently, thereby maintaining system cleanliness and performance. Through the suction residue pipeline, ash is transferred to a residue collection box and filtered using a stainless-steel mesh to separate larger particles (Figure 15). A backflush air pipeline periodically cleans the filter using reverse air injection, while finer residues are conveyed to the disposal tank via the exhaust residue line. Integrated with the main control panel, the system enables digital monitoring of pressure conditions and residue volume. Its sealed and automated configuration supports safe and hygienic handling of combustion residues, in compliance with MARPOL 73/78 Annex V.

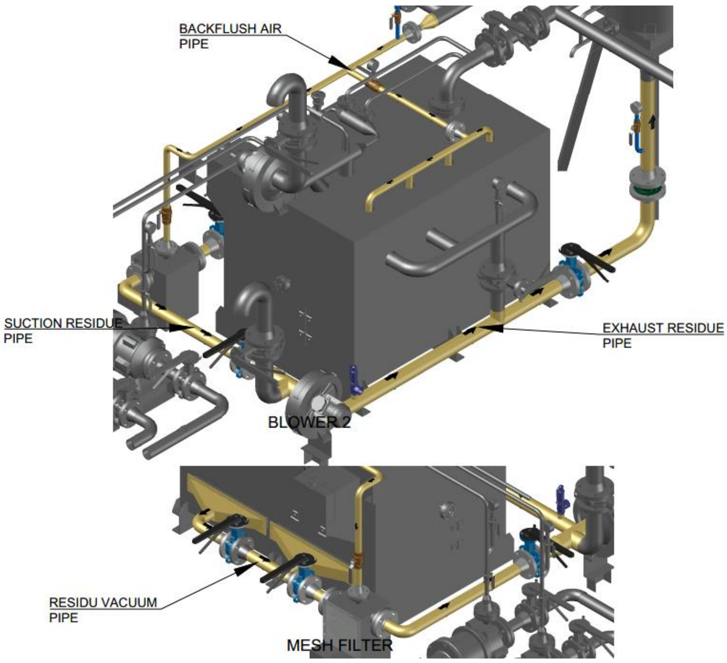


Figure 15. Vacuum system pipeline

3.5. Temperature Simulation

Thermal simulation results indicate that the primary chamber operating at 950 °C and the secondary chamber operating at 1050 °C maintain effective afterburning conditions, ensuring complete destruction of combustion gases and stable heat distribution throughout the system (Figure 16). The refractory lining exhibits high thermal retention, enabling the incinerator to sustain operating temperatures exceeding international minimum requirements of 850 °C. These results confirm the incinerator's thermal reliability, environmental compliance, and suitability for efficient onboard solid waste treatment.

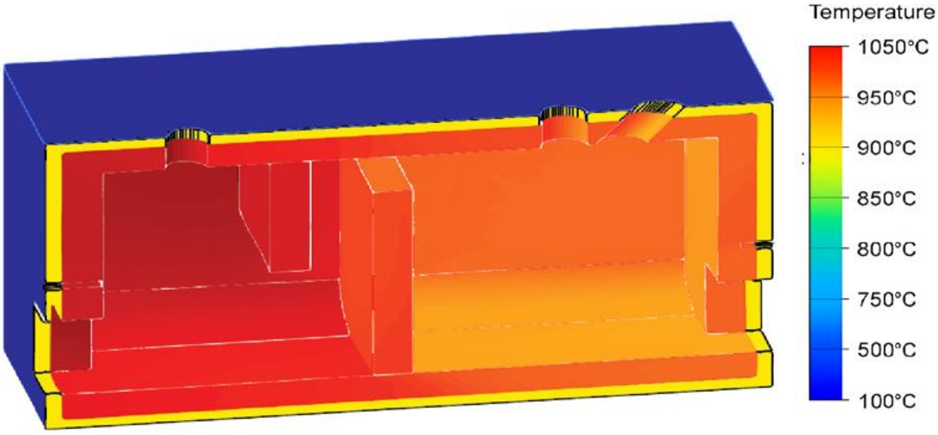


Figure 16. Thermal simulation of the combustion chamber

Thermal simulation of the activated carbon filter indicates peak temperatures of approximately 800 °C in the upper section, primarily due to convective heat transfer from the secondary combustion chamber. The water spray cooling system effectively reduces gas temperature by approximately 30–100 °C, thereby protecting the activated carbon layer and maintaining adsorption efficiency (Figure 17). The resulting stable thermal distribution at or above 600 °C satisfies the requirements of MARPOL 73/78, ensuring safe exhaust gas discharge and confirming the filter's operational reliability and environmental compliance for long-term marine application.

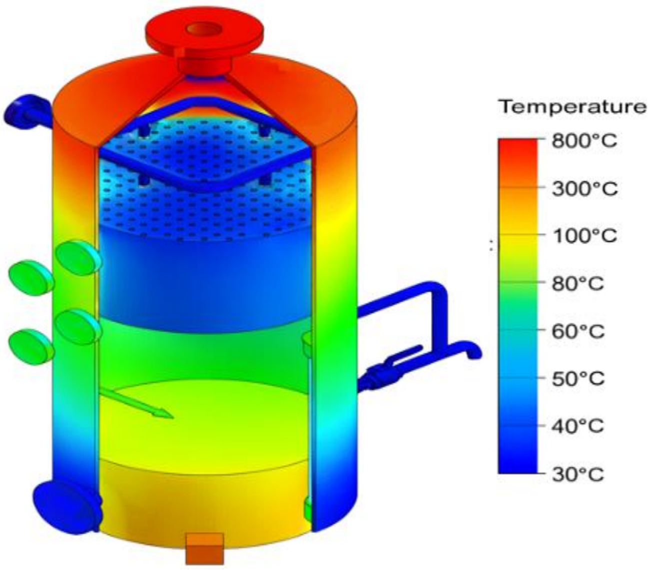


Figure 17. Thermal simulation of the gas filter

3.6. Operating Procedure

The shipboard incinerator operates under strict international regulatory requirements to ensure safe, efficient, and environmentally compliant waste combustion. Operation begins with a comprehensive system inspection, covering the control panel, sensors, blowers, pumps, and cooling units to verify operational readiness. The combustion chamber is preheated to 850–900°C before waste is automatically fed into the system. Temperature and pressure are continuously monitored, while exhaust gases are cooled and filtered through the activated carbon filtration unit. Emissions are required to remain below 200 mg/m³ for particulate matter at gas temperatures of at ≥600°C. Operation concludes with controlled system cooling, data logging in the Garbage Record Book, and verification of compliance with MARPOL and SOLAS requirements.

The engineered shipboard incinerator is fully aligned with MARPOL 73/78 provisions, ensuring safe, efficient, and environmentally responsible waste combustion. Operation within a temperature range of 850-1050°C guarantees complete destruction of hazardous substances, while emission control through activated carbon filtration maintains particulate concentrations below 200mg/m³ and exhaust gas temperatures ≥600°C, in accordance with Annex VI limits. Integrated monitoring systems and automatic shutdown mechanisms enhance operational safety and reliability. The overall system design supports compliance with Annex I, Annex V, and Annex VI, thereby minimising marine pollution risks and reinforcing international commitments to sustainable maritime operations

The performance evaluation of the engineered incinerator installed on the training ship *KL Laksamana Malahayati* demonstrated substantial improvements over the standard system. Feeding capacity, combustion efficiency, and energy consumption were optimised, with the system capable of processing multiple categories of ship-generated waste simultaneously. These findings are consistent with Zhang et al. [16], who reported that emission control technologies such as activated carbon filtration significantly reduce dioxin emissions, and Kwon et al. [17], who emphasised the role of engineering design and operational control in improving energy efficiency and reducing emissions. The system also addresses global shipboard waste management challenges identified by Zhang et al. [18] particularly through efficient waste sorting, heterogeneous waste processing, and emission control, all of which comply with MARPOL 73/78 Annex V.

Regarding chemical pollutants, high combustion temperatures and active filtration effectively reduce hazardous residues, consistent with findings from Tornero & Hanke [19] and Nzihou et al. [20]. The multizone combustion chamber and automatic controls enhance combustion efficiency and minimize residue, supporting the recommendations of Mrakovčić et al. [21] and the National Research Council for MARPOL compliance. The system's flexibility also allows adaptation to port reception facilities, as emphasised by Pérez et al. [22]. Energy savings and a reduction of CO emissions by 15–20 ppm align with energy efficiency principles outlined by Eriksson & Finnveden [23].

Social factors and public acceptance are critical for sustainability, as noted by Suryawan et al. [24]. The system is consistent with integrated waste management principles [25] and technological adaptation requirements [26]. Technically, the dual-stage gas filter reduces SOx, VOCs, and particulate emissions [27]; the residue filter with internal spray maintains filtration efficiency [29]; the integrated control panel ensures safe, reliable operation [28]; the burner pipe maintains ±850°C combustion temperature per Annex I MARPOL 73/78 [29]; and the cooling and backwash water system ensures exhaust emissions meet Annex VI MARPOL 73/78 standards [30]. The vacuum residue system supports clean combustion residue handling [31], while thermal simulations show a combustion chamber temperature of 950–1050°C, demonstrating effective afterburning and thermal efficiency beyond the ≥850°C standard [32]. Simulations on the active carbon filter confirmed that the water spray system reduces gas temperature by 30–100°C, maintaining thermal stability and efficient adsorption of harmful gases [27].

The incinerator operation procedure follows critical stages: initial inspection of the control panel, sensors, blower, The incinerator operating procedure follows clearly defined critical stages, including initial inspection of the control panel, sensors, blowers, lubrication pumps, and cooling systems; preheating to 850–900°C; automated waste feeding; continuous monitoring of temperature and pressure; gas cooling and filtration; and documentation in the Garbage Record Book. These steps ensure particulate emissions <200 mg/m³ and exhaust gas temperatures at or ≥600°C, in compliance with MARPOL and SOLAS requirements [33]. Beyond emission and residue reduction, the system also supports waste-to-energy applications. Studies on plastic waste pyrolysis demonstrate conversion into high-calorific-value plastic oil, with efficiency influenced by temperature, pressure, reactor configuration, and catalyst selection [34]. Co-pyrolysis of biomass and plastic waste enhances biofuel production, reduces oxygenated compounds, and generates valuable aromatic hydrocarbons [35, 36]. This approach aligns with circular economy principles and Life Cycle Assessment (LCA*)* for environmental impact evaluation [37-39].

Moshood et al. highlighted those biodegradable plastics, although beneficial in reducing pollution, may still pose degradation and microplastic challenges [40]. Plastic waste pyrolysis proves effective for producing high-calorie energy, supported by further studies [27, 41–43] showing high conversion efficiency and significant carbon footprint reduction. Moreover, management of liquid and solid waste is critical in modern ship systems. Environmental and economic evaluations of wastewater treatment technologies emphasise adaptation to climate and local waste characteristics [44]. Integrated composting of sludge, green, and food waste also enhances organic waste processing efficiency and reduces marine residual load [45].

4. Conclusion

This study developed and evaluated an engineered, incinerator-based onboard waste management system designed specifically for training vessels operating under diverse maritime conditions. The evaluation conducted on *KL Laksamana Malahayati* demonstrates that the proposed system significantly enhances feeding capacity, combustion stability, and energy efficiency compared with conventional shipboard incinerators. The system successfully processes heterogeneous ship-generated waste streams, including plastics, food waste, and limited medical waste, while achieving substantial reductions in ash residue volume and carbon monoxide (CO) emissions. Stable combustion temperatures were consistently maintained within the optimal range of 950–1050°C, exceeding the minimum international requirement of 850°C and ensuring complete thermal destruction of waste. The integration of activated carbon filtration and water spray cooling systems effectively controlled particulate and gaseous emissions, confirming compliance with MARPOL 73/78 Annexes I, V, and VI, as well as SOLAS safety requirements. Beyond technical performance, the proposed incinerator model offers important operational and sustainability-related advantages. Automated waste feeding, integrated electronic control panels, auxiliary burners, and vacuum-assisted residue handling systems improved operational reliability and reduced crew workload, rendering the system particularly suitable for training vessels with variable occupancy levels and fluctuating waste generation rates. The adaptive system design enables alignment with onboard waste segregation practices and compatibility with port reception facilities, thereby supporting regulatory flexibility and operational resilience. Moreover, the system provides a robust foundation for future integration with waste-to-energy or advanced thermal recovery technologies, contributing to low-carbon maritime operations and circular economy objectives. Overall, this research advances the field of shipboard waste management by integrating engineering optimisation, operational feasibility, and regulatory compliance into a unified and scalable incinerator-based solution. The findings offer practical and policy-relevant insights for ship operators, maritime regulators, and vessel designers seeking environmentally responsible waste treatment systems capable of supporting sustainable maritime transport and marine environmental protection.

5. Declarations

5.1. Author Contributions

Conceptualisation, M.A., H.H., N.A., and A.; methodology, M.A., K.Y., and N.N.; software, M.A., K.Y., A.D.P.R., and A.; validation, M.A., H.H., and N.A.; formal analysis, M.A., H.H., N.A., and A.K.A.; investigation, M.A., H.H., and D.P.W.; resources, A., K.Y., and N.N.; data curation, M.A. and D.P.W.; writing—original draft preparation, M.A., H.H., N.A., and A.; writing—review and editing, I.R.J., A., and A.K.A.; visualization, M.A., A.D.P.R., N.N., and A.K.A.; supervision, H.H., N.A., and A.; project administration, I.R.J., D.P.W., N.N., and A.; funding acquisition, I.R.J., A.D.P.R., and A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.5. Institutional Review Board Statement

Not applicable.

5.6. Informed Consent Statement

Not applicable.

5.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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Appendix I: Summary of Relevant MARPOL 73/78 Annexes

A. Legal Framework of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78)

The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) constitutes the principal international legal instrument regulating the prevention of marine pollution originating from ships. The Convention was adopted in 1973 and subsequently modified by the 1978 Protocol. A further Protocol adopted in 1997 introduced Annex VI concerning air pollution. The Convention entered into force on 2 October 1983.

MARPOL establishes obligations for State Parties to prevent and minimize pollution arising from both operational discharges and accidental releases. The regulatory structure of MARPOL is organized into six technical annexes, each addressing a specific category of ship-generated pollution.

B. Structural Overview of MARPOL Annexes

Annex	Subject Matter	Core Regulatory Focus	Entry Into Force
Annex I	Oil Pollution	Annex I regulates the prevention of marine pollution caused by oil from both operational and accidental discharges. It establishes discharge standards, oil record book requirements, construction requirements for oil tankers (including double-hull standards), and obligations for port reception facilities.	2 October 1983
Annex V	Garbage Pollution	Annex V addresses ship-generated garbage and establishes rules governing its disposal at sea. The Annex imposes a complete prohibition on the discharge of plastics and regulates other types of waste based on distance from land and waste category. It also requires ships to implement garbage management plans and maintain garbage record books.	31 December 1988
Annex VI	Air Pollution	Annex VI sets limits on atmospheric emissions from ships, including sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter, and greenhouse gas emissions. It establishes Emission Control Areas (ECAs) with stricter standards and introduces technical and operational energy efficiency measures aimed at reducing environmental impact.	19 May 2005

Reference

[1] International Maritime Organization (IMO). International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), including the 1978 and 1997 Protocols, as amended.