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TECHNICAL NOTE

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Thermal desalination of ballast water using onboard waste heat in marine industry

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Summary
Ballast water management is a national and international issue in the shipping industry because of potential ecological hazards caused by the release of ballast water into the marine environment. Although many international standards have been implemented in recent years, technological and practical considerations make the ballast water treatment a major challenge for many shipping companies. In this paper, a novel concept of utilizing ballast water as source water for a multieffect desalination process driven by onboard waste heat to meet the freshwater supply needs is proposed with theoretical analysis and practical considerations. A main engine with a capacity of 7500 kW in a cruise ship can serve as a potential waste heat source for water desalination of 1000 m^3/d, which can provide for freshwater needs of 2000 to 4000 ship occupants. This scenario presents an attractive alternative to ballast water management and treatment as well as reducing the nonrenewable energy footprint of onboard water supplies in marine industry.

KEYWORDS
ballast water, cruise ship, desalination, freshwater, main engine, waste heat

1 | INTRODUCTION

Ballast water is required to maintain loading and unloading operations in cruise ships and other marine vessels such as ferries, chemical and ore transporters, container ships, fishing vessels, barge carrying cargo vessels, and military assault vessels.[1] The main uses of ballast water are to replace cargo, vessel control, and loading and unloading operations. Ballast water is usually drawn from the seawater sources in the ports. The quality of ballast water is impaired in ship operations because of its contact with the container walls and other surfaces. Moreover, ballast water discharged by ships can have a negative impact on the marine environment.[2,3] Ballast water also poses serious ecological, economic, and health problems.[4]

The majority of ballast water is usually disposed without proper treatment, especially, in marine industrial and tourism sectors across the world.[5] As a result, the International Maritime Organization (IMO) has established the Ballast Water Exchange Standards. Many technologies are available for treating ballast water.[6] These include physical separation of suspended and colloidal materials (filtration, hydrocyclone, and coagulation), chemical disinfection using oxidizing biocides (chlorination, electrochlorination, ozonation, chlorine dioxide, and hydrogen peroxide), and physical disinfection (ultraviolet [UV] irradiation, deoxygenation, cavitation, and high/low pressure stress). Other hybrid processes such as UV-hydrogen peroxide, filtration-UV, and UV-ultrasound were also evaluated.[7] Among these, physical separation is ineffective in removing the microbiological contamination of ballast water. Chemical disinfection results in disinfection byproducts and other undesired chemical formation while physical disinfection methods are not totally effective and could be more costly. Considering the aforementioned concerns, heat treatment would be an ideal option for ballast water treatment.

Waste heat utilization has become an important concept in shipping industry similar to other industrial applications in recent years.[8-12] The shipping industry contributes significant environmental emissions by consuming large quantities of fossil fuels for marine transportation.[13] Waste heat generated from shipping operations (marine engine and exhaust gas) and service cooling can be used for treating ballast water because waste heat from ship propulsion and onboard equipment may be used to raise the temperature of the water without the formation of chemical byproducts or residuals.[14] To destroy biological components, ballast water should be heated to 35°C to 45°C and held there for a set period of time. Recent research efforts have focused on the effect of treatment temperature and time required for inactivation of certain organisms. Heat exposures between 60°C and 70°C for 60 seconds resulted in 80% to 100% mortalities of phytoplankton, zooplankton, and bacteria.[15] Heat treatment technique under different operational conditions was also studied to treat the organisms smaller than 50 μm (phytoplankton and bacteria) in the ballast water.[4] Many studies have focused on developing thermal treatment systems for ballast water management.[16-21] Some other studies have developed microwave heating systems for *artemia* cysts and other microbial contaminant removal.[19,20] Waste heat from the main engine was extracted to treat the ballast water. A treatment time between 10 minutes and 16 hours is required for temperatures between 35°C and 40°C. About 20 hours of heating time was reported as effective at a temperature of 35°C.[15,21] However, a higher temperature range such as 55°C to 75°C would require only 15 to 60 seconds, which is ideal in desalination process operations. A recent study reported almost complete mortalities of phytoplankton, zooplankton, and bacteria at these temperatures.[15]

On the other hand, the use of process waste heat and renewable or nuclear energy sources has been widely advocated for desalination industry because of the large quantities of thermal energy required by desalination processes.[22-32] High-temperature desalination processes are usually constructed in cogeneration schemes to enable combined water-power production to improve overall economics and reduce environmental impacts. Low-temperature desalination processes can be supported by waste heat extracted from various waste heat sources from process industry including domestic air-conditioning and other ambient heat sources.[29-32]

An evaluation of recent efforts on heat treatment shows that longer treatment periods are required for inactivation of microorganisms in ballast water and under some conditions, these cannot be removed effectively at low temperatures.[33,34] Alternative and beneficial uses for ballast water are more desirable on the basis of these considerations. Here, we propose to capture the waste heat released from the exhaust gas after the economizer for further use in desalination of ballast water with the aim of achieving two major goals: (1) to produce freshwater for onboard potable water needs of passengers and (2) to eliminate the microbial and biological contaminants and minimize the ballast water residual volume for further management. The following sections will describe the process analysis and integration of ballast water desalination scheme powered by onboard ship waste heat. This concept is applicable across a wide range of shipping operations from small to very large size cruisers, tankers, transporters, military vessels, fishing, and other barge cargo carrying vessels. A general schematic of ballast water operations and the proposed alternative for desalination of ballast water are shown in Figure 1. The specific objectives of this research are (i) to study the potential of ballast water as a water supply source for water desalination in a thermal desalination process, (ii) to evaluate the feasibility of utilizing waste heat from the main engine in shipping industry for desalination application in a multieffect distillation (MED) desalination process, and (iii) to discuss the potential costs and water quality of ballast water desalination in comparison with other ballast water management and treatment methods.

2 | MATERIALS AND METHODS

This section presents an overview of the waste heat source availability on the ships, desalination processes driven by process waste heat, case study of a MED

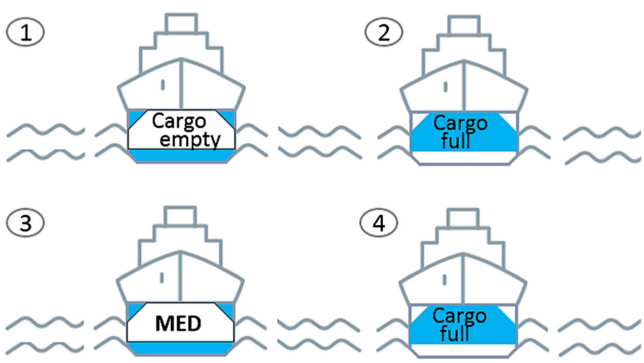

FIGURE 1 Ballast water needs and potential desalination plant incorporation to its management (ballast water is discharged during cargo loading operations in normal operations. However, this water can be used as source water for desalination during voyage to meet the freshwater needs as well as to minimize ballast water residual and improve the discharge water quality) [Colour figure can be viewed at wileyonlinelibrary.com]

desalination plant in a passenger ship, waste heat recovery analysis, and MED process design analysis.

2.1 | Waste heat on cruise ships

Waste heat recovery has significant potential for use in marine propulsion systems. Approximately 50% of the energy content of the fuel is lost through heat rejected to the environment, and the remaining is transformed into mechanical work.[35,36] Waste heat that would otherwise be rejected to the environment can be captured for increasing the fuel efficiency in shipping operations. The recovered waste heat can be used for beneficial applications such as desalination (see Figure 2A). Typically, waste heat is recovered by using exhaust gas boiler to generate additional power from exhaust gas power turbine and for scavenging air and/or jacket water.

2.2 | Desalination using waste heat

Desalination technologies demand large quantities of energy for producing freshwater through both thermal- or membrane-based separation processes. Thermal technologies require heat energy to evaporate water while membrane technologies require high-quality electrical energy to separate salts from saline water. As a result, waste heat and renewable energy (such as solar and wind technologies) sources have been widely studied for their integration into desalination plant operations.

2.3 | Case study of a passenger ship

Various characteristic details of the ship under study are provided in Table 1 (parts of data were taken from Baldi et al[37]), while Figure 2B conceptually represents the ship energy systems. The ship is propelled by two 4-stroke diesel engines (ME) rated at 3.84 MW each. The two engine shafts are connected to a common gearbox (GB) while another shaft from the GB connects it to the electric generator, which provides 60-Hz current to the ship.[37] Additionally, two auxiliary engines (AEs) rated at 0.682 MW each can provide electric power when the MEs are not in operation or whenever there is a failure in the electric generator.

2.4 | Waste heat analysis for the ship

For a diesel engine, the heat input comes from the fuel supplied and the heat balance could be shown as follows:

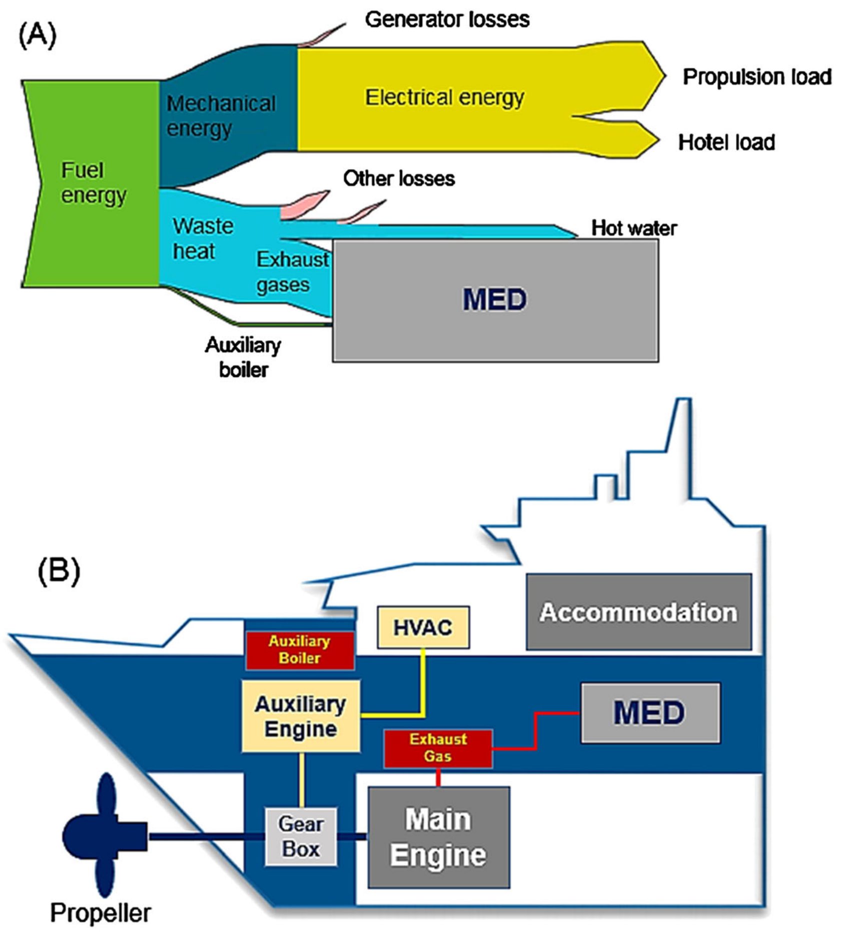

FIGURE 2 A, Energy conversion and losses from fuel consumption in a typical marine vessel (mechanical power—48%; exhaust gas—25.5%; high thermal water cooling—15%; low thermal water cooling—11%; and heat radiation—0.5%).[35,36] B, Potential incorporation of multieffect distillation (MED) process powered by exhaust gases of a main engine or a power turbine [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Ship features and passenger water needs considered for the simulation study

Dimension	Value	Cruise	Value
Deadweight	47 000 tons	No. of passengers	1500
Installed power (main engines)	7700 kW	No. of crew members	1000
Installed power (auxiliary engines)	1400 kW	Total no. of people	2500
Shaft generator design power	3200 kW	Daily potable water needs	400 L/d
Exhaust boilers design steam gen.	1400 kg/h	Total water demand	1000×10^3 L
Auxiliary boilers design steam gen.	28 000 kg/h		

$$Q_{\text{in}} = Q_{\text{exhaust}} + Q_{\text{water}} + Q_{\text{odd losses}} + W_{\text{engine power}} \quad (1)$$

The three major energy losses would include the heat lost through exhaust gas, cooling water, and other losses comprising friction, radiation, and convection. The exhaust waste heat input for a known main engine power can be expressed as follows:

$$Q_{\text{e-g}} = m_{\text{e-g}} c_{\text{p,e-g}} \left(T_{\text{e-g,Turbine}} - T_{\text{o}} \right) \quad (2)$$

Q_{in}	input energy, kW
Q_{exhaust}	energy lost through exhaust gases, kW
Q_{water}	energy lost through cooling water, kW
$Q_{\text{odd losses}}$	energy lost in radiation and convection, kW
$W_{\text{engine power}}$	productive output power of the engine, kW
m_{f}	mass flow rate of fuel, kg/s
$Q_{\text{e-g}}$	energy available in exhaust gas, kW
$m_{\text{e-g}}$	mass rate of gas flow, kg/s mw; mass rate of water flow, kg/s
$C_{\text{p,e-g}}$	specific heat capacity of exhaust gas, kJ/kg K

2.5 | Analysis of MED

A conventional MED system (6-10 effects) using steam generated from the waste heat derived from exhaust gases of a main engine or a power turbine on ships is shown in Figure 3. The MED system was simulated at different heat source temperatures. Waste heat from the main engine is an ideal source for a high-temperature MED (HT-MED) plant operation at a rate of 3 MW. Several influencing parameters such as number of stages, evaporation and brine temperatures, cooling and heating surface areas, cooling water flow rates for the final condenser, and other factors such as the desalination plant capacity were evaluated through the simulation study. Design calculations were performed using Equations 3 and 16.[38,39] The pertinent design parameters and process performance profiles for the MED system from the analysis are shown in Tables 2 and 3. An appendix is also included for notations.

The following design equations were used for the evaluation and optimization of both HT-MED and low-temperature MED (LT-MED) systems.

Temperature drop across all effects is calculated using Equation 3:

$$\Delta T_{\text{t}} = T_{\text{s}} - (n-1)\Delta T_1 - T_{\text{b}_n} \quad (3)$$

Temperature drop in first effect is obtained by

$$\Delta T_1 = \frac{\Delta T_{\text{t}}}{U_1 \sum_{i=1}^{n} \frac{1}{U_i}} \quad (4)$$

Similarly, the temperature drop in effects 2 to n is obtained by

$$\Delta T_i = \Delta T_1 \frac{U_1}{U_i} \quad (5)$$

Brine temperature in first effect is obtained from the relation

$$T_{b_1} = T_{\text{s}} - \Delta T_1 \quad (6)$$

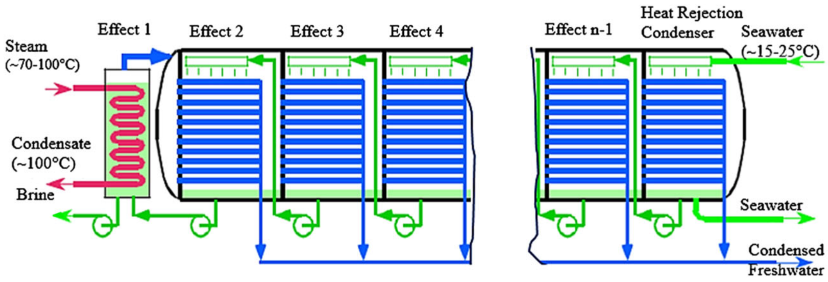

FIGURE 3 Schematic of a conventional multieffect distillation (MED) system (6-10 effects) using steam generated from the waste heat derived from exhaust gases of a main engine or a power turbine on ships [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Design parameters of the multieffect distillation (MED) system[38,39]

Parameter	Value	Parameter	Value
n_e	6-10	T_f, °C	15-25
M_d, m^3/d	500-1000	T_{cw}, °C	15-25
X_f, ppm	35 000	C_p, kJ/kg	4.2
T_{ev}, °C	2	U_c, kW/m^2-K	2
T_s, °C	70-100	d_t (diameter of tube)	0.03
T_{bn}, °C	>30	L_t (length of tube)	10

Brine temperature in effects 2 to n

$$T_{b_i} = T_{b_i-1} - \Delta T_1 \frac{U_1}{U_i} - \Delta T_1 \tag{7}$$

Distillate flow rate in the first is given by

$$D_1 = \frac{M_d}{\lambda_{v_1}\left(\frac{1}{\lambda_{v_1}} + \frac{1}{\lambda_{v_2}} + \cdots + \frac{1}{\lambda_{v_{n-1}}} + \frac{1}{\lambda_{v_n}}\right)} \tag{8}$$

Distillate flow rate in effects 2 to n

$$D_i = D_1 \frac{\lambda_{v_1}}{\lambda_{v_i}} \tag{9}$$

Brine flow rate in effects 1 to n

$$B_i = \frac{X_{cw} D_i}{(X_{bi} - X_{cw})} \tag{10}$$

Feed flow rate in effects 1 to n

$$F_i = D_i + B_i \tag{11}$$

Heat transfer area in the first effect

$$A_1 = \frac{D_1 \lambda_{v_1}}{U_1 (T_s - T_{b_1})} \tag{12}$$

Heat transfer area in effects 2 to n

$$A_i = \frac{D_i \lambda_{v_i}}{U_i (T_{v_i-1} - T_{b_i})} \tag{13}$$

Heat steam flow rate, M_s, required for the first effect

$$M_s = \frac{D_1 \lambda_{v_1}}{\lambda_s} \tag{14}$$

Heat transfer area of the condenser can be expressed as

$$A_c = \frac{D_n \lambda_{v_n}}{U_c (\text{LMTD})_c} \tag{15}$$

Flow rate of cooling water (M_{cw})

$$D_n \lambda_{v_n} = (M_{cw}) C_p (T_f - T_{cw}) \tag{16}$$

The performance ratio (PR) of MED is defined as the kg of distillate produced by 2300 kJ heat input.[40]

3 | RESULTS AND DISCUSSION

3.1 | Evaluation of MED system powered by waste heat

The effect of heat source temperature on thermal energy needs is shown in Figure 4A. An HT-MED process with heat source temperatures between 70°C and 100°C was considered with the number of effects varying between 6 and 10. The energy requirements increased as the heat

TABLE 3 Profiles of the multieffect distillation (MED) system (heat source temperature = 80°C and n = 8)

Effect	1	2	3	4	5	6	7	8
U, kW/m^2-K	2.75	2.67	2.59	2.51	2.43	2.36	2.29	2.22
T, °C	3.59	3.70	3.81	3.93	4.05	4.18	4.31	4.44
T_b, °C	76.4	70.7	64.9	59.0	52.9	46.7	40.4	34.0
T_v, °C	74.4	68.7	62.9	57.0	50.9	44.7	38.4	32.0
λ_v, kJ/kg	2325	2339	2353	2367	2382	2396	2411	2427
D, kg/s	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4
A, m^2	348.3	348.3	348.3	348.3	348.3	348.3	348.3	348.3
B, kg/s	40.7	39.3	37.8	36.4	34.9	33.5	32.1	30.6
F, kg/s	42.2	40.7	39.3	37.8	36.4	34.9	33.5	32.1
X_b, ppm	36 266	37 619	39 068	40 624	42 298	44 105	46 062	48 186

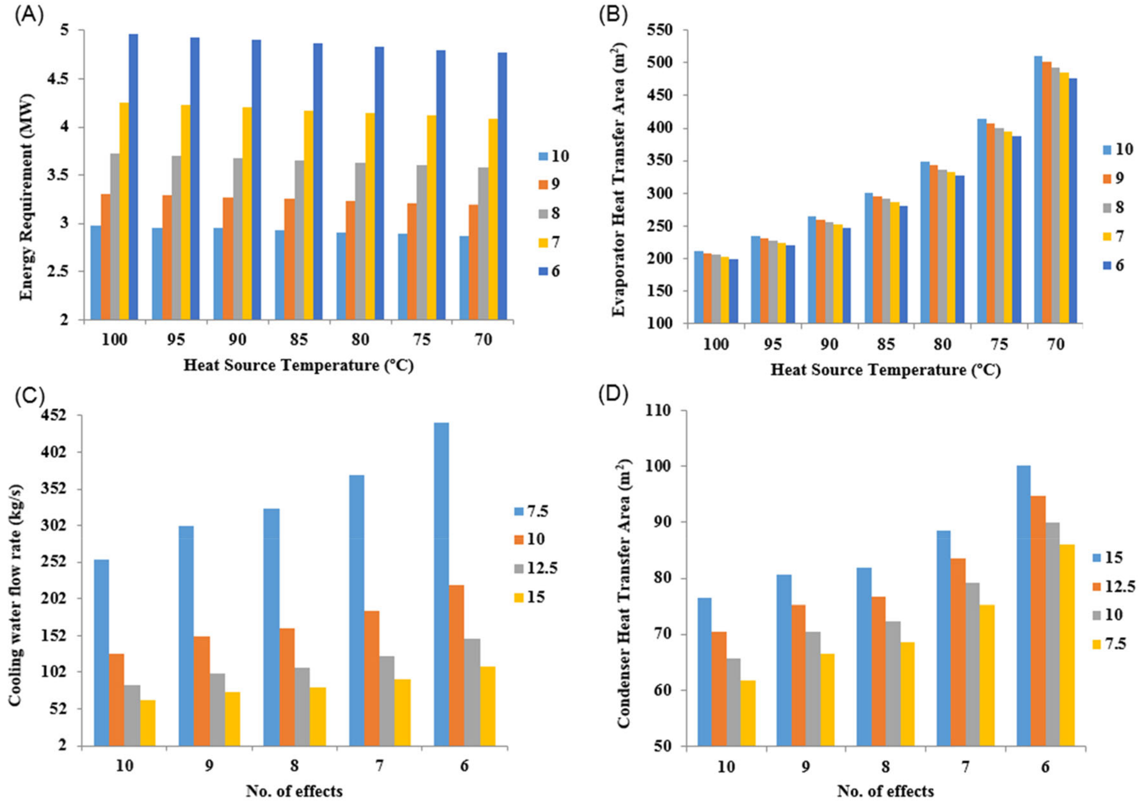

FIGURE 4 A, Effect of heat source temperature on the energy requirements by the multieffect distillation (MED) system with number of stages between 6 and 10 effects for a defined volume of freshwater production (1000 m^3/d). B, Effect of heat source temperature on evaporator heat transfer area (m^2). C, Effect of heat source temperature on cooling water flow rate (kg/s). D, Effect of heat source temperature on evaporator heat transfer area (m^2) [Colour figure can be viewed at wileyonlinelibrary.com]

source temperature increased because of increased heat losses and the heat rejected in the final brine stream. Thermal energy demand decreases with increasing number of effects and decreasing heat source temperature; ie, low heat source temperature results in lower heat losses and lower heat rejection. For instance, a process configuration with 10 effects at a heat source temperature of 70°C is more energy-efficient than other combinations. Thermal energy demand for the MED process can be extracted from the waste heat released by the main engine, which can vary between 2.75 and 5 MW (Figure 2). The required final heat source temperature determines the actual amount of heat that can be extracted from the waste heat source.

The effect of heat source temperature on the evaporator heat transfer area is shown in Figure 4B. It can be noted that higher temperature operation with low number of effects required smaller evaporator heat transfer areas whereas the heat transfer areas for low-temperature operations were significantly higher regardless the number of effects. Figure 4C shows the relationship between the cooling water flow rate and the number of effects. The cooling water flow rate significantly decreases with increase in number of effects. This is due to lower evaporating temperatures in the final condenser with more number of effects. Figure 4C also shows the required cooling water flow rates with respect to the available temperature differential, ie, between 2.5°C and 10°C. The cooling water flow rates vary in proportion with the exit temperatures. Assuming the cooling water inlet temperature to be 5°C, the temperature differentials between 2.5°C and 10°C increase the flow rates as seen in Figure 4C. Cooling water flow rates are significantly lower at higher available temperature differential and vice versa. Figure 4D shows the condenser heat transfer areas required for number of effects between $n = 6$ and $n = 10$. Similar to other observations, with higher temperature differentials between the cooling water stream and the condenser, the heat transfer areas vary with the number of effects. The higher is the temperature differential, the smaller will be the condenser heat transfer area and vice versa. Cooling water flow rates are inversely proportional to the number of effects. It is influenced by the final evaporator temperature because with lower number of effects, the final evaporator will be higher requiring a higher flow rate of cooling water.

3.2 | Number of effects vs performance (PR)

The PR decreased with increasing heat source temperature as shown in Figure 5A. This trend is in line with increasing top brine temperature with increasing heat source temperature as shown in Figure 5B.

For example, the PR for the number of effects at 6 decreases from 5.95 to 5.8 with increase in heat source temperature between 70°C and 100°C. The top brine temperatures at these heat source temperatures were 66.6°C and 92°C, respectively. Similarly, for n = 7-10, the PR varies between 6.9 and 6.7, 7.87 and 7.7, 8.87 and 8.7, and 9.8 and 9.6, for heat source temperatures between 70°C and 100°C, respectively, high end PR representing low temperature operation. This relationship is expected because low-temperature operation with a higher number of effects ensures a higher PR (i.e., higher thermodynamic efficiency) because of lower ambient losses (see Figure 5C).

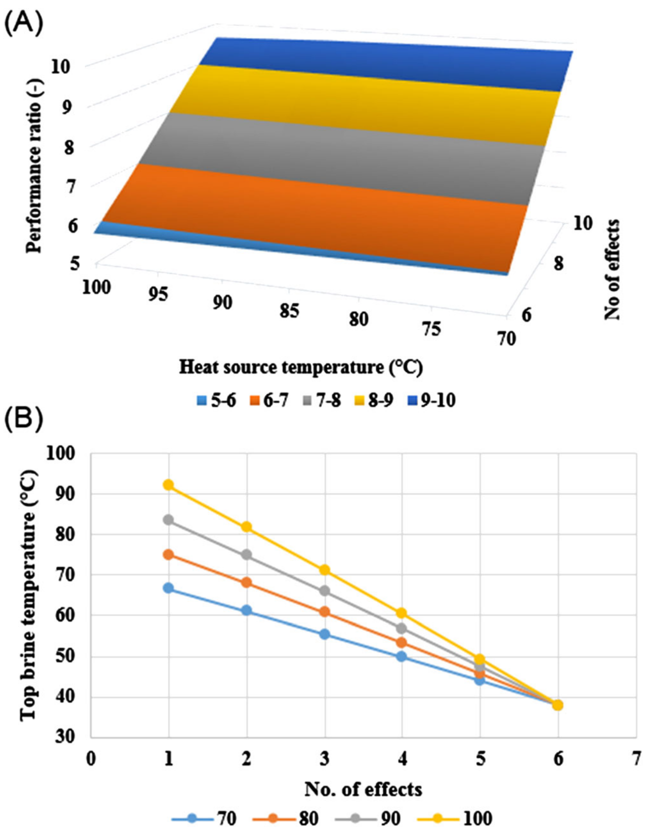

FIGURE 5 A, Relationship between the number of effects and performance ratio in a multieffect distillation (MED) process affected by heat source temperature between 70°C and 100°C. B, Variations in top brine temperatures in the first effect with the number of effects at different heat source temperatures

3.3 | Heat source temperature and energy-desalination relationships

A desalination capacity of 1000 m^3/d was considered to study the relationship between the number of effects and the energy demands (Figure 6A). The energy demand was the lowest for the lowest first-effect heat source temperature and the highest number of stages, ie, T = 70°C and n = 10. Thermal energy needs increased as the number of effects decreased and as the heat source temperature increased. For example, thermal energy needs increased by 4% when the heat source temperature is 100°C and the number of effects is 10. At the same heat source temperature, thermal energy needs increase by 15%, 30%, 48%, and 73% for effects 9, 8, 7, and 6, respectively. Following a similar trend, if the MED system was to be operated at a low heat source temperature, say 70°C, then the freshwater production rate will increase by 4%, 15%, 30%, 48%, and 73% respectively when compared with a high heat source temperature of 100°C

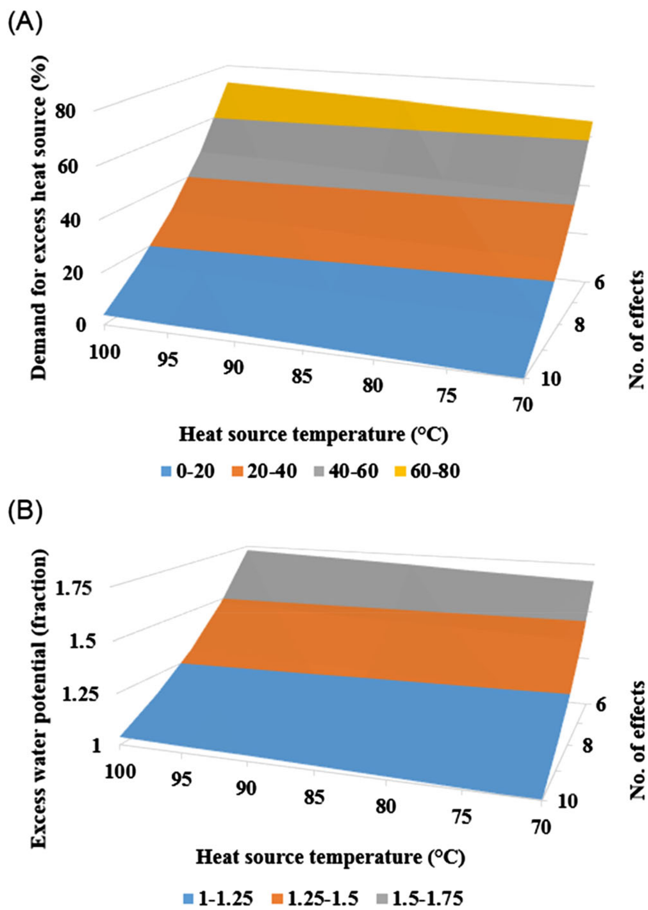

FIGURE 6 A, The relationship between the heat source temperature, the number of effects, and the demand for excess heat for the same desalination capacity. B, Water production potential in a multieffect distillation (MED) process affected by heat source temperature between 70°C and 100°C with different number of effects [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 6B). This clearly demonstrates that the freshwater production rate from the LT-MED operation could benefit significantly from the excess waste heat that would otherwise be derived from the main engine exhaust gas at HT-MED operation. However, it should be noted that higher desalination rates at low-temperature operation come with the need for higher heat transfer areas due to low-temperature differentials between the effects. Although larger heat transfer areas are required, these can be provided using low-cost, low-scaling heat transfer materials improving desalination costs.

3.4 | Desalination potential with onboard waste heat sources

Table 4 shows the waste heat characteristics of main engines of different capacities. This range may represent small to very large size cruisers, tankers, transporters, military vessels, fishing, and other barge cargo carrying vessels as mentioned before. As shown in Table 4, the exhaust gas temperatures are available between 273°C and 342°C depending on the engine power capacities and models. This heat source is ideal for meeting the thermal energy needs in MED process at a first-effect heat source temperature between 70°C and 100°C.

Waste heat recovery potentials and corresponding desalination capacities are shown in Figure 7. Ballast water tank capacity depends on the tonnage of the vessel. As shown in Figure 7A, the ballast water quantities are adequate for onboard water desalination. The relationship between the engine capacity and waste heat recovery potential is shown in Figure 7B. The waste heat recovery rates were calculated on the basis of the exhaust air flow rates and temperatures for different main engine capacities. The waste heat recovery rate was between 31 and 45 percentage of the main engine capacity.

Assuming a heat source temperature of 110°C and using the waste heat, freshwater production rates corresponding to the main engine capacities are shown in Figure 7C. The specific thermal energy requirements for this calculation were taken from the MED model at heat source temperature of 70°C and $n = 10$. Assuming a per capita per day demand between 200 and 400 L, the relationship between the numbers of passengers that could be served with freshwater is shown in Figure 7D. These results show that the onboard freshwater needs can be easily met with the desalinated water on cruise ships while on other vessels were there is a small need for water consumption such transport vessels and container vessels, the desalinated water can be stored and transported back to the port for local water supplies.

4 | SPECIAL CONSIDERATIONS AND FUTURE PERSPECTIVES

A number of critical factors need to be considered for ballast water treatment through the thermal desalination process. The freshwater requirements, the tonnage capacity of the marine vessel, and the passenger capacity should be considered. Length of voyage can play a significant role. Longer voyages will help treat and consume large quantity of ballast water leaving less quantity of waste to be managed at the end of the voyage. The amount of available waste heat is the critical factor for the design of the desalination plant. Therefore, waste heat from other sources should be considered to increase desalination capacity, if necessary or a thermal energy storage unit can be incorporated for better management of waste

TABLE 4 Calculated engine temperatures and flows for different total main engines power[37]

Power, kW	1500	2500	3500	4500	5500	6500	7500
No. of engines running	1	1	2	2	2	2	2
Engine load	0.39	0.65	0.46	0.59	0.72	0.85	0.98
Engine bsfc, g/kWh	224	206	218	209	204	203	207
m_s, kg/s	2.8	4.6	6.5	8.3	10.2	12.1	13.9
T_{air} comp in, K	308	308	308	308	308	308	308
T_{air} comp out, K	376	441	397	429	452	473	494
T_{air} CAC out, K	328	328	328	328	328	328	328
m_s, kg/s	2.9	4.8	6.7	8.6	10.5	12.4	14.3
T_{eg} turb in, K	749	736	745	738	737	747	770
T_{eg} turb out, K	687	614	664	627	605	595	600
T_{eg} out EGE, K	573	546	615	590	574	569	577

Note. Air flow rates, engine brake-specific fuel consumption (bsfc), and compressor and turbine temperatures are measured values taken from Baldi et al[37]

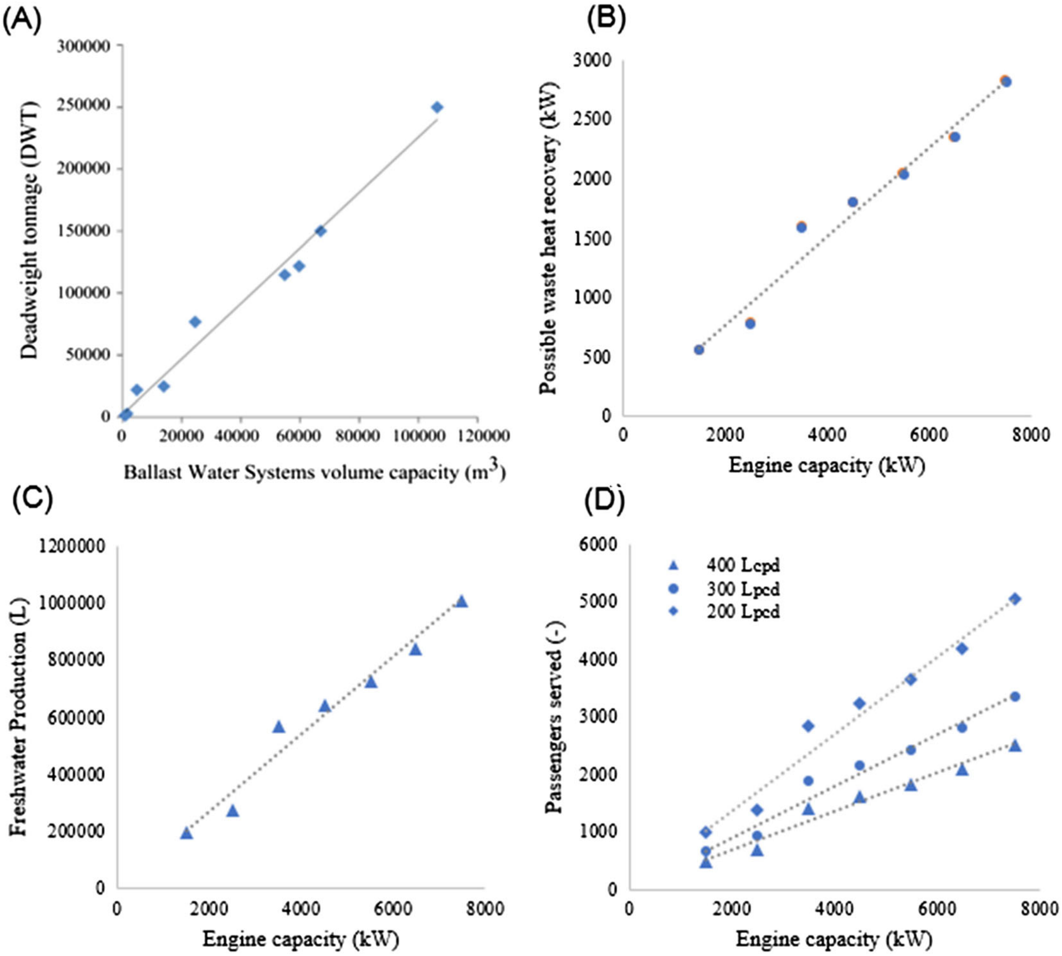

FIGURE 7 Relationships between freshwater production and waste heat recovery potential in ship operations: A, the relationship between deadweight tonnage and ballast water volume (m^3); B, waste heat recovery potential (kW) vs engine capacity (kW); C, freshwater production potential vs engine capacity (kW); and D, number of passengers served vs engine capacity (kW) corresponding to different ship capacities [Colour figure can be viewed at wileyonlinelibrary.com]

heat source.[27,39,40] Final condenser requires cold water to condense water vapor in the last effect, the performance of which depends on the seawater temperatures.

By using onboard waste heat for desalination, the amount of CO_2 emissions in relation to the engine's mechanical power output will be lower.[37] Through the waste heat recovery system, the recovered energy could be used for various beneficial uses. For instance, energy recovered from the main engine exhaust can be converted to mechanical work and added back to the propeller shaft as well. Ballast water treatment could also shave 1.6% to 4% of the annual operational cost of a ship.[41] Overall, this study helps address the ongoing issues faced by growing tourism and cruise ship operations from a technical, environmental, and economic point of view.[42]

Regarding the desalinated water costs, thermal energy requirements for multieffect desalination system can be provided by the waste heat available from the main engine; however, electricity is needed for pumping and other process flows. Excluding the heat requirements in this process scheme, the freshwater costs could be around $0.67/$m^3$. In addition, the LT-MED operation allows for use of low-cost heat transfer materials with low scaling rates and numerous process waste heat sources.[43-48] This process is more environmentally friendly when compared with a MSF desalination process powered by conventional energy sources in which large quantities of pollutants such as CO_2, NO_X, and SO_X are discharged along with concentrated brines at higher temperatures causing more severe environmental and ecological issues in the marine environment.[48]

A comparison of ballast water treatment costs with desalinated water costs is important to determine the potential advantages of the proposed configuration. A 25-year life-cycle costs analysis study of different types of marine vessels (Bulker cape sized; Bulker Panamax; Container 2500 TEU; Container 8000 TEU; General Cargo Breakbulk; General Cargo RO-RO; Tanker T APS Trade; and Tanker VLCC) has reported average low and high costs for different treatment options as

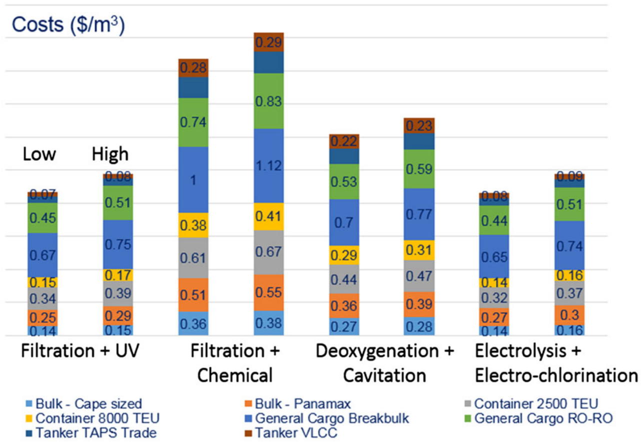

FIGURE 8 Ballast water treatment costs for different methods in different marine vessels—low and high treatment costs are represented in different columns for comparison (data taken from King et al[50]). Costs vary depending on the treatment method and capacity [Colour figure can be viewed at wileyonlinelibrary.com]

shown in Figure 8. Filtration + UV light treatment costs between \$0.07 and \$0.75 per m^3 of the ballast water treated in these vessels. The lowest costs represent Tanker VLCC vessel, and the highest costs represent General Cargo Breakbulk vessel. Similarly, ballast water treatment costs for filtration + chemical treatment, deoxygenation + cavitation, and electrolysis + electrochlorination options vary as follows: \$0.28 to \$1.12 per m^3, \$0.22 to \$0.77 per m^3, and \$0.08 to \$0.74 per m^3. This means that the ballast water treatment by the above methods renders it suitable for reuse or disposal into the marine environment. If the ballast water can be used as a water supply source for desalination process that would in turn provide for freshwater needs, then it is a considered a high-value added benefit at the same treatment costs. This configuration is especially suitable for cruise and passenger ships where onboard freshwater supply needs can be replenished by using ballast water. In other applications, ballast water converted into freshwater can be traded for revenue generation at the port for use in coastal communities.

Considering the environmental emissions of the marine industry activities at the global level, it is estimated that the shipping industry greenhouse gas emissions are expected to increase by 250% by the year 2050. This means that the current global share (2%) of CO_2 emissions by the shipping industry will represent a 17% of the global emissions in 2050. Waste heat generated from the shipping operations is the main cause for these greenhouse gas emissions. By tapping the waste heat for its beneficial use in desalination process, additional energy needs for water treatment and storage on the ship can be eliminated.

Water quality of the desalinated ballast water will be superior to other treatment schemes because pretreatment (physical separation and disinfection) and posttreatment including final disinfection processes will remove the biological contaminants regulated by ballast water treatment standards. These include less than 10 viable organisms per m^3 greater than or equal to 50 μm in minimum dimension and less than 10 viable organisms per mL less than 50 μm in minimum dimension and greater than or equal to 10 μm in minimum dimension; and discharge of the indicator microbes shall not exceed the specified concentrations.[51-54]

5 | CONCLUSIONS

Ballast water management in ship operations is a major concern at regional and global levels. The use of waste heat released from the main engine exhaust gas was considered as a potential source for the treatment of ballast water desalination in marine vessels. Results from this study suggest that the freshwater needs can be addressed conveniently using main engine waste heat and ballast water in passenger and cruise ships. The desalination costs compare well with other ballast water management and treatment schemes. This approach eliminates the need for water storage in passenger vessels while saving costs and eliminating environmental damages that would otherwise occur because of nonrenewable energy consumption for providing freshwater for passengers onboard. In addition, the environmental and ecological impacts associated with both desalination and ballast water management can be reduced through this approach. Further studies should focus on addressing the design and retrofitting aspects of the proposed configuration. Inclusion of a thermal energy storage unit may also enhance the performance of the combined waste heat recovery and ballast water management system. Further, innovative low-cost heat transfer materials should be developed for compact design and operations to address the space limitations in marine vessels.

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APPENDIX

NOTATION FOR MED

A	Area, m^2
B	Brine flow rate from each evaporation effect, kg/s
C_p	Specific heat at constant pressure, kJ/kg EC
D	Amount of vapor formed in each flashing stage or evaporation effect, kg/s
F	Feed flow rate to each evaporation effect, kg/s
LMTD	Logarithmic mean temperature difference
M	Mass flow rate, kg/s
n	Number of tubes, flashing stages, or evaporation effects
P	Pressure, kPa
PR	Performance ratio, PR = M_d/M_s, dimensionless
T	Temperature, °C
ΔT	Temperature drop, °C
ΔT_l	Temperature losses in each evaporation effect, °C
U	Overall heat transfer coefficient, kW/m^2°C
V	Specific volume, m^3/kg
X	Salinity, ppm

Subscripts

λ	Latent heat for evaporation, kJ/kg
b	Brine
bh	Brine/feed preheater
c	Condenser or condensate
cw	Intake seawater or cooling water
d	Distillate
e	Evaporator
f	Feed
h	Brine heater
j	Heat rejection section in MSF
o	Outer diameter or outlet temperature
n	Last flashing stage or last evaporation effect
r	Heat recovery section in MSF
v	Vapor