

BALLAST WATER HEAT TREATMENT OPTIONS AND POSSIBILITIES

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Abstract: Heat has been proved to be a very attractive method of minimizing the risk of introducing exotic marine organisms into the ports where ballast is discharged. It does not necessitate the use of chemicals or biocides that could be harmful to the environment. Waste heat from a ship's main engine can potentially provide a cost-effective source of heat. An analysis of available heat and methods to obtain required ballast water temperature with maximum efficiency is the main concern of this paper.

Heating of the ballast tanks is inconvenient for vessels operating in cold regions since thermal stress may impact ship's structural safety. Therefore, proposed engine cooling system modifications could be used for further development of heat treatment. Combination of heating with other methods of ballast water treatment would be more effective. Heating could significantly improve ozone or UV treatment. There are some indications that heat transfer from water to marine organisms could be improved by ultrasound.

Key words: ballast water, heat treatment, waste heat

NAËINI I MOGUÆENOSTI OBRADÉ BALASTNIH VODA TOPLINSKOM METODOM

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Sažetak: Toplinska metoda pokazala se vrlo zanimljivom za smanjivanje rizika unosa egzotičnih morskih organizama balastnom vodom; ona ne zahtijeva upotrebu kemikalija odnosno biocida koji bi mogli biti opasni po okoliš. Otpadna toplina glavnog brodskog dizelskog motora može se efikasno iskoristiti za zagrijavanje balasta. U radu su prikazani rezultati analize u svrhu postizanja zahtijevane temperature zagrijavanja balasta s maksimalnom efikasnošću.

Zagrijavanje tankova nepovoljno je za brodove koji plove kroz hladna područja s obzirom da temperaturna naprezanja mogu umanjiti sigurnost konstrukcije. Zbog toga, predložene opcije mogu se iskoristiti u daljnjem razvoju toplinske metode. Kombinacijom toplinske metode s nekim drugim metodama obrade balasta značajno se može povisiti učinkovitost i brzina obrade. Zagrijavanjem balasta moguće je poboljšati učinkovitost obrade ozonom ili UV. Postoje naznake da se prijelaz topline s vode na organizme može poboljšati primjenom ultrazvuka.

Ključne riječi: balastne vode, toplinska obrada, otpadna toplina

I. INTRODUCTION

Heat is one of the options for ballast water treatment that is receiving considerable research attention. Many methods of ballast water heat treatment could be realised according to biological heat strategies, which are shown in tables 1 and 2. It is very hard to determine the duration of exposure at temperature sufficient for complete organism inactivation because of the huge amount of marine species contained in ballast water. Therefore, only the most resistant organisms have been tested.

Table 1. Near complete kill of dinoflagellate hypnocyts, Hallegraeff et al., 1997 [5]

Exposure	duration	temperature
Short	0.5 to 3 minutes	approx. 45 °C
Medium	up to 7 hours	35 to 40 °C
Long	3 or more days	32 °C

Table 2. Near complete kill of the most resistant organism, Mountfort et al., 1999 [6]

Exposure	duration	temperature
Short	≤ 10 minutes	≥ 46 °C
Medium	10 min. to 16 hours	36 to 45 °C
Long	≥ 16 hours	≤ 36 °C

Strategies shown in tables are derived from results of laboratory studies but some of them have been confirmed by shipboard trial [4]. Assuming high reliability of these experiments, several methods of diesel engine waste heat utilisation have been proposed. These methods are based on the medium heat treatment strategies and can be obtained depending on time voyage limitations, open ocean depth, and seawater temperature.

2. POSSIBILITIES OF DIESEL ENGINE WASTE HEAT UTILISATION

2.1. Diesel Engine Heat Dissipation

Actual available diesel engine waste heat is determined from engine data supplied by manufacturer, which are essential during propulsion plant design stages. Differences of engine data for various engine types and manufacturers should not blur the insight of waste heat utilisation for ballast water heat treatment. Available diesel engine waste heat can be approximately determined for various diesel engine types using statistic analysis. Therefore, conclusions regarding ballast water heat treatment could be derived generally.

Necessary capacities of auxiliary machinery for main engine are stated in table below. Capacities are average approximate for almost all MAN B&W MC engine programme and are stated at the nominal MCR power - L1 (P_{nom}) for power range from 4800 to 51840 kW, [1]. These data can not be used for engine selection or installation but could be a base for approximate evaluation of ballast heating possibilities. Heat dissipation values increase from S over L to K series where S means super long stroke, L - long stroke and K is short stroke. Therefore engine efficiency generally increases with higher engine stroke. Also, higher rated engines may have higher efficiency. Similar table is written for New Sulzer Diesel engines. Only data for Sulzer 52U, 62U and 72U diesel engines [2] have been analysed.

As could be seen from tables, these values are similar for various engine types and manufacturers. For central cooling system capacities are very close to those for conventional seawater cooling system.

Diagrams on fig. 01. reflect heat dissipation percentages for scavenge air, jacket cooling water and lubricating oil. Heat dissipation is dependent on percentages of nominal values for engine load ($P\%$) and revolutions ($n\%$), where $q_{air80}(P\%)$ is heat dissipation for scavenge air cooling water at 70-100% engine nominal power and 80% engine nominal revolutions. These diagrams are derived using equations determined by regression analysis [1]:

$$q_{air} = e^{-0.8548 \ln(n\%) + 1.832 \ln(P\%) + 0.1045} \quad (1)$$

$$q_{jw} = e^{-0.081 \ln(n\%) + 0.8072 \ln(P\%) + 1.2614} \quad (2)$$

$$q_{lub} = 67.3009 \cdot \ln(n\%) + 7.6304 \cdot \ln(P\%) - 245.0714 \quad (3)$$

$$Q_{dm} = q_{air} + q_{jw} + q_{lub} \quad (4)$$

Diagram on Fig. 01.d. regards diesel engine waste heat calculated for various part load conditions. It can be used for determining available cooling water waste heat Q_{dm} for various conditions of engine's part load and speed. Available cooling water waste heat Q_{dm} is shown in relation with nominal engine power - P_{L1} .

Table 3. Marine diesel engines, conventional seawater cooling

		Scavenge air	Lubricating oil	Jacket water	Sum
heat dissipation / engine power, Q / P_{nom}	MAN B&W MC	0.338 - 0.35	0.071 - 0.082	0.140 - 0.150	0.55 - 0.582
	Sulzer	0.337 - 0.340	0.092 - 0.105	0.162 - 0.184	0.587 - 0.626
Seawater cooling pump capacity/ engine power, M_{sw} / P_{nom} , m^3 / kWh	MAN B&W MC	0.0175 - 0.019	0.0102 - 0.0112	0.0102 - 0.0112	0.028 - 0.03
	Sulzer	0.0128 **	0.0111 - 0.0126	0.0111 - 0.0126	0.024 - 0.025 **
Water flow / seawater pump capacity, M / M_{sw}	MAN B&W MC	0.625 - 0.635 aver. 63% P_{sw}	0.365 - 0.375 aver. 37% P_{sw}	0.365 - 0.375 aver. 37% P_{sw}	100%
	Sulzer	0.51 - 0.54** aver. 53% P_{sw}	0.46 - 0.49** aver. 47% P_{sw}	0.46 - 0.49** aver. 47% P_{sw}	100%

** These values can vary because scavenge air seawater flow depends on turbocharger selection
New Sulzer Diesel Engines, conventional seawater cooling without efficiency booster system (EBS)

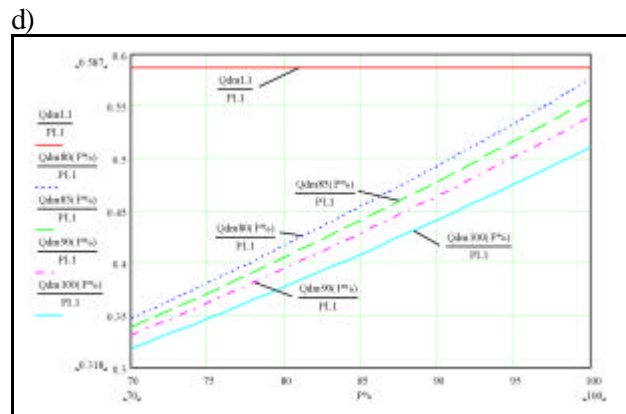
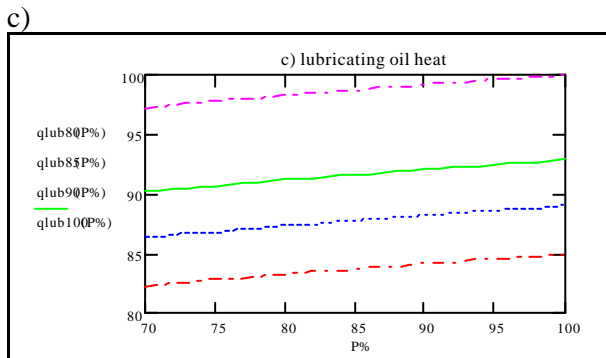
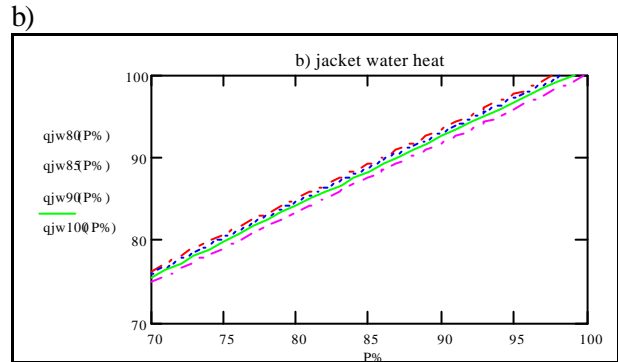
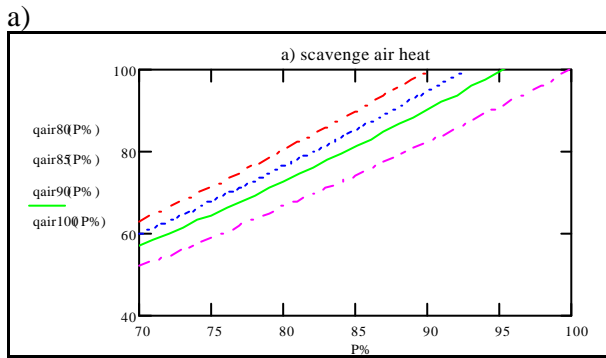


Fig. 01. Diagrams for heat dissipation in percentage of engine power(P%) for MAN B&W MC Diesel Engine

2.2. Exhaust Gas Heat Utilisation

Diesel engine exhaust gas heat is utilised by waste heat boiler. Steam generated in waste heat boiler is usually used for heating – mostly heavy fuel oil heating or cargo heating on tankers. Also, steam produced in waste heat boiler is often used for electrical energy production by means of steam turbine generator. Therefore, exhaust gas heat should not be regarded as available energy for ballast water heat treatment.

2.3. Estimated Diesel Engine Installed Power

For proper estimation of diesel engine cooling water waste heat it is very important to determine relations of ship's dead-weight tonnage (dwt) and diesel engine installed power. Fig. 3.0 shows relations between installed power (BHP) and dead weight tonnage which are approximated from data of a large number of ships in service [1]. It reflects the installed power for bulk carriers, tankers and general cargo ships and are only valid for a service speed from 13 to 16 knots. Common service speed for these ships can be used to determine the voyage time, which has to be sufficient for ballast water heat treatment.

For better insight of waste heat utilisation possibilities other relations also may be very important. It is very important to determine quantity of ballast water for various ship types, which is shown in table 05 [3]. An average value of ratio between ballast water quantity and dead-weight tonnage for bulk carriers and tankers is about 40%. More detailed values should be obtained from statistical analysis of ships in service.

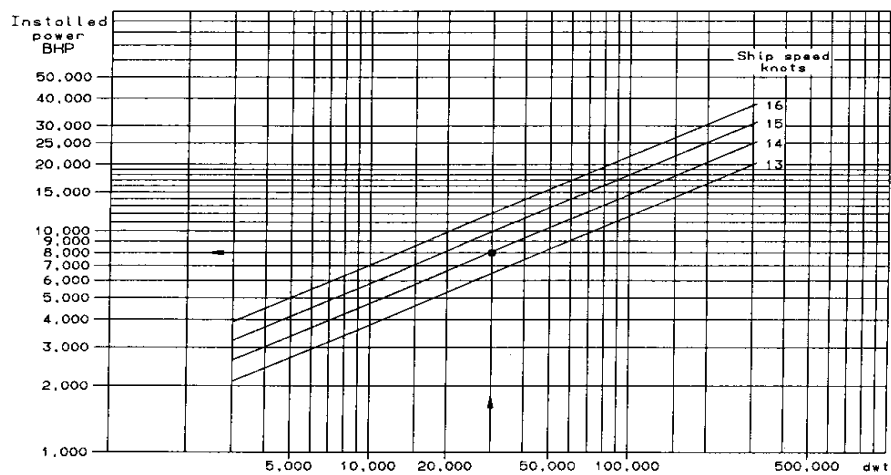


Fig. 03. Installed power for bulk carriers, tankers and general cargo ships

Table 5. Ratio of ballast water to dead weight for various ship types

SHIP TYPE	DESCRIPTION	YEAR	TOTAL BALLAST CAPACITY m ³	DEAD WEIGHT tonnes	BLST/DWT RATIO %
OIL TANKER	Single skin (two long. bulkheads)	1990	40397	62485	64,65
	Single skin (two long. bulkheads)	1990	59168	106679	55,46
	Single skin (two long. bulkheads)	1995	122308	258076	47,39
	Double side	1988	19636	39988	49,10
	Duble hull with a centreline bulkhead	1996	21865	47252	46,27
	Double hull	1992	73097	154970	47,17
	Double hull with two long. bulkheads	1993	119878	298900	40,11
	Double hull with two long. bulkheads	1998	132631	311189	42,62
BULK CARRIER	Handysize, single side skin	1996	26575	45654	58,21
	Panamax, single side skin	1994	35151	73236	48,00
	Capesize, single size skin	1996	55171	122301	45,11
	Capesize, single size skin	1994	85592	151301	56,57
CONTAINER SHIP	1725 TEU	1998	9677	24554	39,41
	2668 TEU	1993	19199	47120	40,74
	3429 TEU	1996	13830	46350	29,84
	3842 TEU	1998	11991	48224	24,87
	4477 TEU	1995	19933	61428	32,45
LNG CARRIER	Membrane type	1997	46538	62500	74,46
	Moss type	1990	53751	78988	68,05
SELF-DISCHARGING BULK CARRIER	Double hull	1998	18576	36634	50,71
	Double hull	1993	33473	50587	66,17
OBO-CARRIER	Double hull	1984	32851	54500	60,28
	Double hull	1991	61311	95000	64,54
	Double hull	1992	61436	169416	36,26
GENERAL CARGO	Multipurpose cargo ship	1999	6300	22948	27,45
	General cargo/container carrier	1984	11865	41600	28,52

4. MAXIMUM OBTAINABLE TEMPERATURES OF BALLAST WATER WHEN HEATED BY EXISTING DIESEL ENGINE COOLING WATER SYSTEMS

4.1. Conventional Seawater Cooling System

For ballast water heating there are two major constraints regarded cost of coolers and fuel consumption of the diesel engine. That is why the inter-related positioning of the coolers in the system (Fig. 04) serves to achieve:

- The lowest possible cooling water inlet temperature to the lubricating oil cooler(s) in order to obtain the cheapest cooler. Contrary, to prevent the lubricating oil from stiffening in cold services, the inlet cooling water temperature should not be lower than 10 °C.
- The lowest possible cooling water inlet temperature to the scavenge air cooler, in order to keep the fuel oil consumption as low as possible [1].

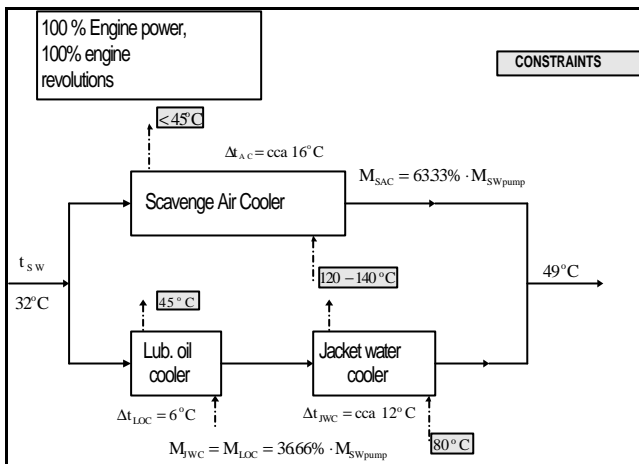


Fig. 04. Diagram for conventional seawater cooling system - 100% Engine nominal power - project values (MAN B&W MC)

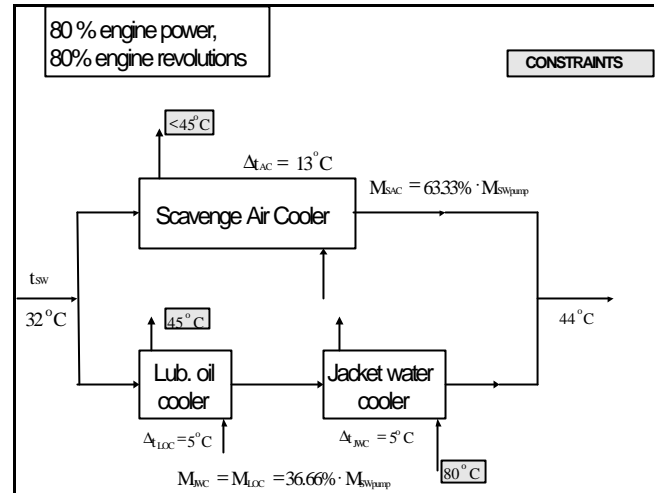


Fig. 05. Diagram for conventional seawater cooling system - 80% Engine nominal power, 80% nominal speed (MAN B&W MC)

Fig. 04. shows simplified diagram for conventional seawater cooling system. If the seawater inlet temperature is 32°C (tropical conditions) then the maximum obtainable outlet temperature from the system is 49°C , or 44°C for 80% of nominal power and 80% of engine revolutions. The main limitation of this option is inlet seawater temperature to the system, which has to be as low as possible but still above 10°C .

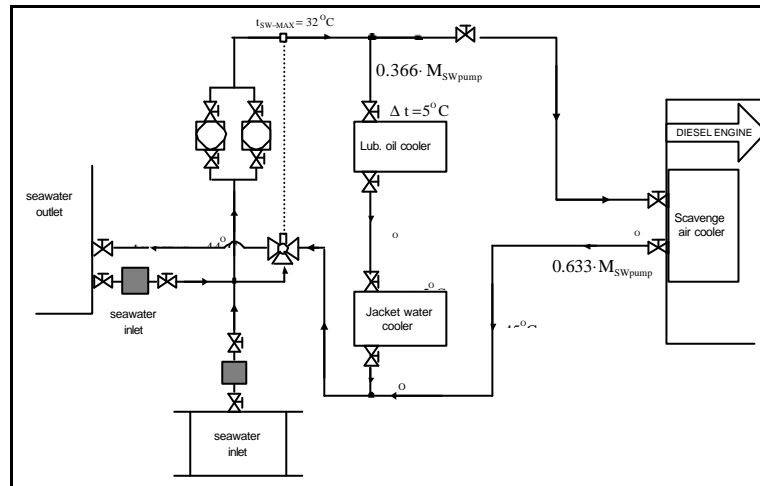


Fig. 06. Conventional seawater cooling system – 80% Engine nominal power, 80% nominal speed (MAN B&W MC)

4.2. Central Cooling Water System

In order to prevent too high scavenge air temperature, the cooling water design temperature in the Fresh Water-Low Temp. (FW-LT) system is normally 36°C , corresponding to a maximum seawater temperature of 32°C for tropical conditions (fig. 07). MAN B&W recommendation for keeping the cooling water inlet temperature to the main engine scavenge air cooler as low as possible also applies to the central cooling system. Outlet seawater temperature in central cooling water system is 50°C for 100% of nominal power and 100% of nominal speed. Outlet seawater temperature in central cooling water system is 45°C for 80% of nominal power and 80% of nominal speed (fig. 08).

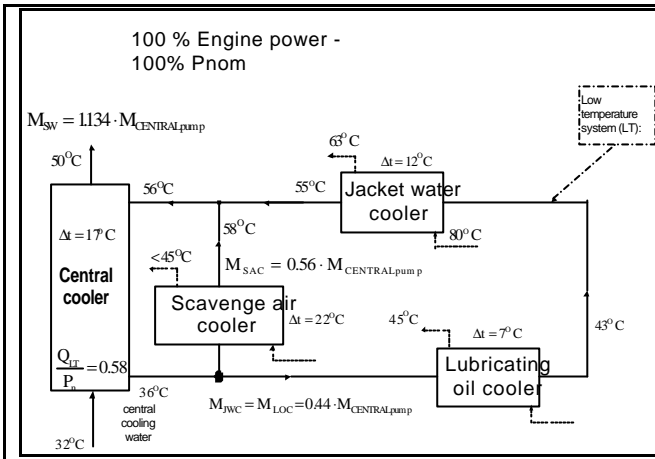


Fig. 07. Diagram for central cooling system for MAN B&W MC diesel engines - 100% Engine nominal power

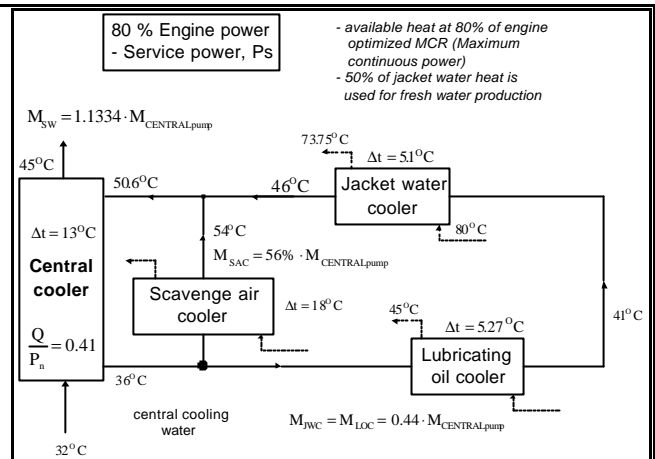


Fig. 08. Diagram for central cooling system for MAN B&W MC - 80% Engine nominal power, 80% nominal speed

4.3. Estimation Of Maximum Obtainable Cooling Water Temperatures For Various Engine Conditions

Temperatures shown on figs. 04-06 for conventional seawater cooling system are valid only for specified part load conditions. Diagrams shown on fig. 09. are derived from B&W MC engines data analysis and can be used to determine temperatures in conventional seawater cooling system for various engine part load conditions. $\Delta tacw80(\%P)$ is temperature difference for scavenge air cooler for 80% of nominal engine speed, and 70 to 100% of nominal power.

For central cooling system and various engine conditions for B&W MC programme these temperatures can be calculated using diagram on fig. 01, data in table 05 and equations 1 to 3.

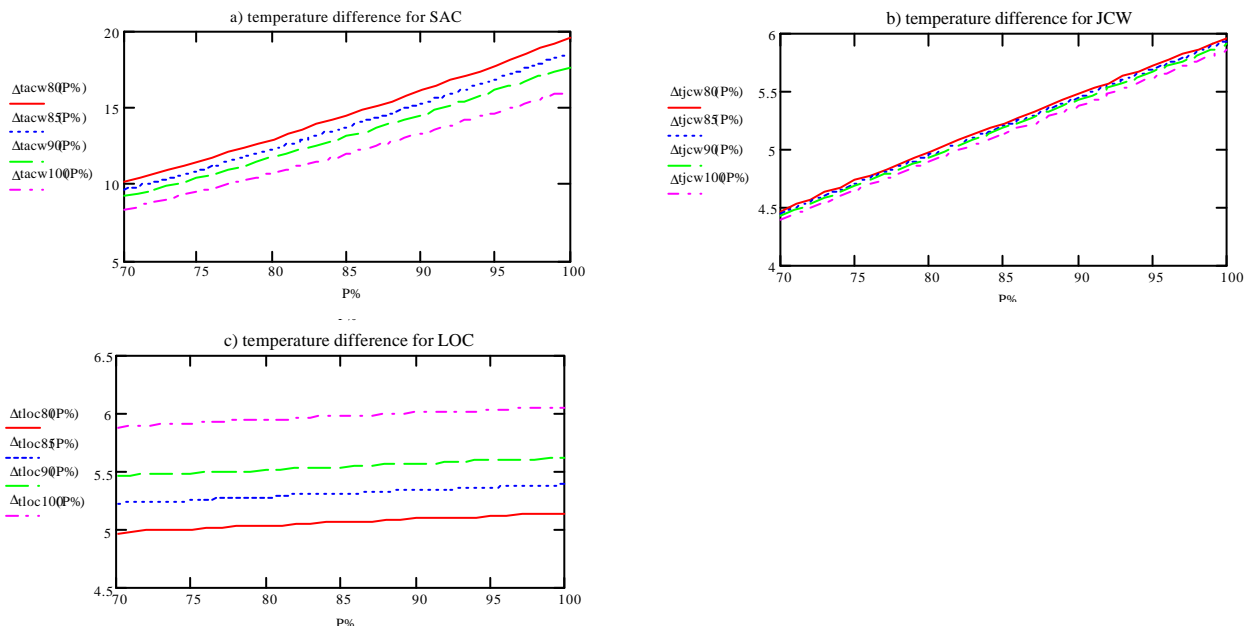


Fig. 09. Temperature difference for scavenge air cooler (SAC), jacket water cooler (JCW), and lubricating oil cooler (LOC) in conventional seawater cooling system for part load and speed (MAN B&W MC Diesel Engine)

5. CIRCULATION OF BALLAST WATER

5.1. Open Circuit Ballast Water Heat Treatment

In the open circuit the seawater outlet from the seawater cooling system or seawater outlet from the central cooler in central cooling system can be connected to ballast piping and the ballast water in the tank can be flushed by heated seawater sucked from the ship's chest [4]. On that way, the combination of two methods can be achieved:

ballast dilution - replacing port water from the ballast tank by oceanic sea water by dilution process

heating of ballast water

Ballast dilution At the moment, the only satisfactory method of ballast water treatment is ballast dilution. Ballast dilution is replacement of ballast water by constant flushing with oceanic seawater, which contains low proportion of marine organisms. Because of structural and stability ship's limitations tanks can not be emptied at open ocean. Ballast dilution has proved to be the best method for ballast water replacement because the tanks are kept full filled with water and the flushed water continuously released through tank's vent.

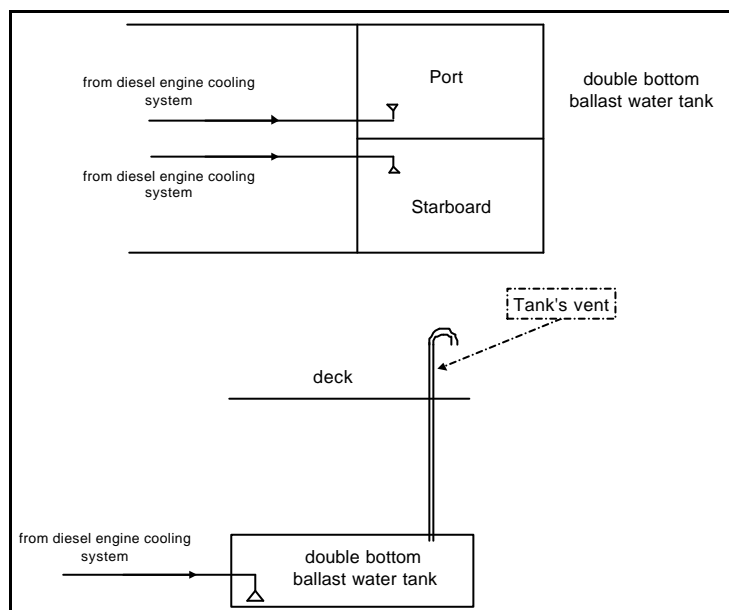


Fig. 10. Open circulation of engine cooling water for ballast water heating

Disadvantages of ballast dilution

To obtain 90% replacement of ballast water by oceanic seawater 3 tank exchanges are necessary. If the tank capacity is 5 000 tons of ballast water, 15 000 tons of oceanic seawater have to pass through that tank. The result of flushing is 10% of original water, which remains in tank, mixed with oceanic seawater.

An assumption that removing a proportion of the ballast water will remove a similar proportion of organisms present has been proved to be incorrect. Some part of organisms migrates to sediments and another crannies within ballast tanks. Another part of organisms migrates away from flowing water or migrates into zones of low flow during the dilution process.

The open ocean was initially defined as water deeper than 2000 m, but it is not defined in the current IMO draft regulations where 500 m depth and at least 200 nautical miles from shore are under discussion. Some vessels are unable to get to these depths, such as coastal shipping vessels.

Ballast water heating If the ballast water is heated, there is no need for 3 tank exchanges. Ballast water have to be flushed by heated oceanic seawater until temperature in the tank is satisfactory raised.

Disadvantages of ballast dilution and heating

Part of the heated water is continuously flushed through the tank’s vent. That will significantly increase unrecoverable heat loss, resulting in larger required time for ballast water heating. Since open ocean area is not defined satisfactorily, there is concern that disposed ballast water may be drawn by sea currents into the coastal area where marine organisms can survive.

5.2. Closed Circle Ballast Water Heat Treatment

In closed circle heat treatment, waste heat from diesel engine cooling systems can also be used for ballast water heat treatment. Conventional seawater cooling system and central cooling system could be converted as proposed bellow.

An additional heat exchanger and circulation pump should be installed, according to fig. 11. Tanks should be heated one by one while port and starboard ballast tanks can be heated together. For proper mixing of ballast water, interconnection between port and starboard tanks could be introduced. To avoid problems with ship’s stability, ballast tanks should be kept full filled with water.

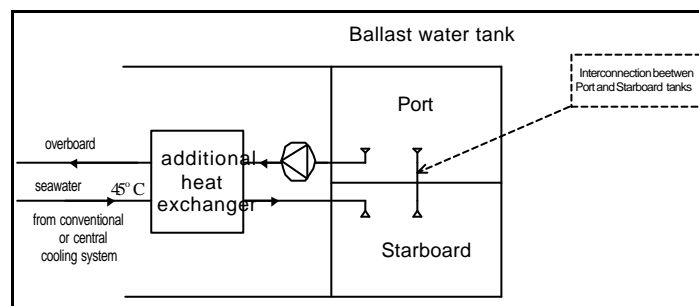


Fig 11. Diagram for closed circle ballast water circulation heating

If the ballast water temperature is lower then 32 °C there is possibility of ballast water direct heating within the ballast tank. Added heat exchanger can be bypassed and the water from the ballast tank can circulate through the cooling system. When the temperature in ballast water tank is raised to 32 °C problems with scavenge air cooling may occur. In that case, valves could be manipulated automatically and ballast water can be heated by means of heat exchanger, as proposed on figure 11.

6. IMPROVED HEAT UTILISATION

Required time for ballast water heating mostly depends on seawater temperature and for temperatures lower than about 20 °C heat method may not be applicable. If the ballast water temperature is 20 °C, time required for rising ballast water temperature within the tank up to 44 °C will be more than twice longer then for ballast water heated to 32 °C. Higher temperature difference between ballast water and seawater, results in higher heat loss. Assumptions concerning heating plan should be confirmed by computer simulation results and shipboard trial.

Improved heat utilisation consists of:

- Preheating of ballast water by transfer of accumulated heat in ballast tank using 1st stage of heat exchanger
- Additional heating of ballast water by diesel engine cooling water waste heat in 2nd stage of heat exchanger

6.1. Preheating of ballast water – by transfer of heat from heated tank to non-heated tank

During heating, temperatures of the water in the tank are not uniform. Assuming that the temperature of the ballast water within the tank is 40 °C, 7 hours is enough time to kill almost all marine organisms. For medium heat strategy, the inactivation process of marine organisms begins at 35 °C and is finished at approx. 45 °C. In certain circumstances, required time for rising the temperature within the ballast tank from 35 to 45 °C may be more than 7 hours. According to tables 1 and 2, that may be sufficient time of organism exposure. Therefore, there is no need to keep that temperature constant or to wait until ballast water being naturally cooled by means of heat transfer to ship's surrounding seawater. Regarding fig. 13, the heat accumulated in treated ballast tank can be used in the first stage of additional heat exchanger for pre-heating the next ballast tank.

This proposition may not be possible to obtain for all journey conditions unless the time of exposure at temperatures between 35 to 45 °C is 7 hours or more. It may be better to heat port and starboard tanks simultaneously to lower the thermal stress and prolong the time of exposure of marine organism. Therefore, two or more ballast tanks can be heated together. According to diesel engine cooling system seawater temperature design limit seawater inlet temperature to central cooler can not be higher than 32 °C.

6.2. Additional heating of pre-heated tank

Additional heating would require rising the ballast water tank temperature to 45 °C by diesel engine cooling water waste heat. An example of improved heat utilisation and maximum heat recovery is shown on fig. 12. Seawater inlet for diesel engine cooling can be connected to ballast water tank until temperature of ballast water in tank no. 3 is raised to 32 °C.

Proposed method could improve heat utilisation and required time for ballast heating may be shortened significantly. Proposed method may not be applicable for heating of top ballast tanks. Therefore, this system could be required for newbuilds, rather than for in-service vessels where ballast piping retrofitting may be hard to accomplish.

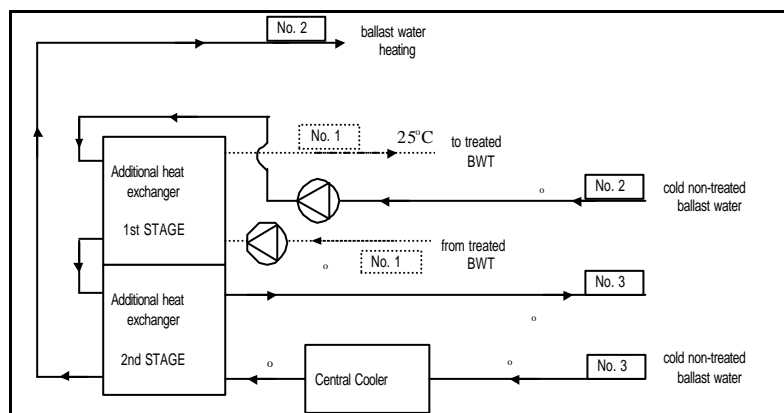


Fig. 12. Improved heat utilisation for diesel engine central cooling system

7. SPECIAL ADAPTATION OPTIONS TO ACHIEVE MAXIMUM BALLAST WATER TEMPERATURE

7.1. Adaptation Of Conventional Seawater Cooling System

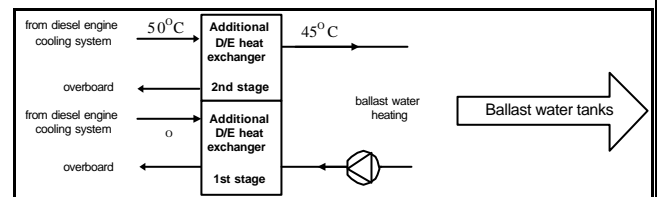
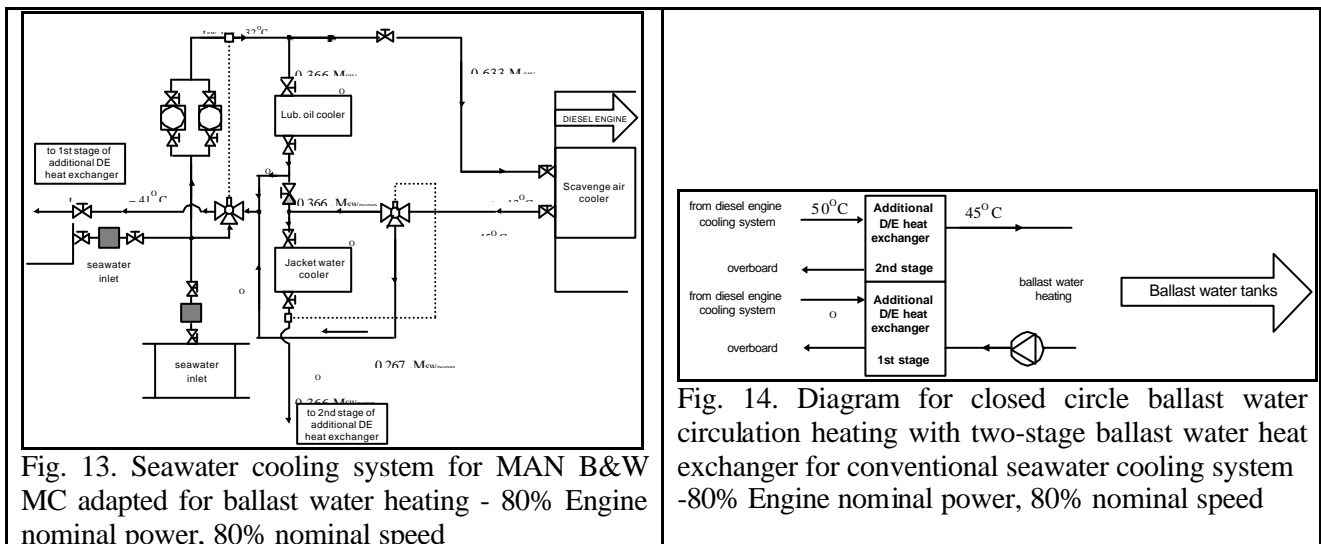
Regarding previous figures it is evident that maximum seawater cooling system temperature can not be higher than 45 °C. Therefore, the maximum ballast water temperature could not probably be higher than 40 °C. On outlet from 2nd stage additional heat exchanger, there would be hard to achieve required ballast water temperature for closed circle circulation ballast heating. Proposed improvements for conventional seawater cooling system will comply with medium and short duration exposure strategy.

Adaptation of conventional seawater cooling system shown on fig. 13 serves to achieve maximum seawater cooling outlet temperature. These examples are derived for B&W MC diesel engines at 80% of engine nominal power and 80% of nominal speed. Better results will be achieved for more realistic sea conditions. So, for 90% of engine nominal power and 95% of nominal speed, cooling system outlet temperatures will be higher.

By connecting scavenge air cooler outlet to jacket water cooler inlet, the seawater cooling system outlet temperature can be raised to 50 °C or more. Additional heat exchanger, proposed on fig. 14, should be two stages. 63.4% cooling seawater pump flow capacity with approx. maximum temperature of 40 °C will pass through the first stage of heat exchanger while the other 36.6% with approx. temperature of 50 °C will be used for heat transfer in the second stage.

Added 3-way valve serves to protect the engine from overheating by keeping the jacket water cooler minimum temperature difference between cooling seawater outlet and cooling fresh water (HT) inlet to jacket water cooler. Obviously, minimum temperature difference mostly depends on installed heat transfer area of the jacket water cooler and some other characteristics such as heat transfer coefficient of the heat exchanger. Therefore, jacket water cooler area should be increased.

So, the jacket water cooler has to be large enough to compensate the cooling seawater inlet temperature rise, according to fig. 14. Since, 50% of jacket water heat is used for water production in fresh water generator during ship's voyage this proposition would not be hard to accomplish. In case of fresh water generator failure there is always possibility to convert cooling system by automatic control of 3-way valve.



7.2. Adaptation Of Central Cooling Water System

As shown on fig. 13. for the seawater cooling system, the central cooling system could also be adapted for ballast water heating on similar way. For central cooling system the application of proposed idea is some more complicated than for conventional cooling system. Regarding fig. 15. fresh water passes through jacket water cooler after being heated in scavenge air cooler. On this way more than half of the engine cooling

water waste heat is utilised in central cooler no. 2 which can be noted from inlet and outlet seawater temperature difference of central cooler.

If the seawater mass flow remains unchanged, connecting scavenge air cooler outlet to jacket water cooler inlet will result with the same seawater outlet temperature (45 °C) as it was the case for classic central cooling water system, shown on figure 08. Therefore, mass flow through the central cooler second stage should be lowered as proposed on figure 16.

To obtain higher temperature difference, seawater flow through the central cooler no. 2 can be lowered. Seawater outlet from the central cooler should not be higher than 55 °C for proper heat transfer through the cooler. To achieve temperature difference of 14.3 °C in central cooler second stage, seawater flow should be approx. $M_{SW}=0.78 M_C$ instead of $M_{SW}=1.334 M_C$.

Additional two-stage heat exchanger can be used on similar way as for conventional seawater cooling system. Here, seawater is used for heat transfer from central cooler to ballast water heat exchanger. Using ballast water for engine cooling would not be practical since maximum inlet temperature to central cooler should not be higher than 32 °C. Fresh water temperatures have to be low enough to ensure proper cooling of scavenge air and lubricating oil.

System design proposed on fig. 16 seems to be effective for proper ballast heating and comply with engine cooling limitations. Outlet from the central cooler no. 2 can be connected directly to ballast piping.

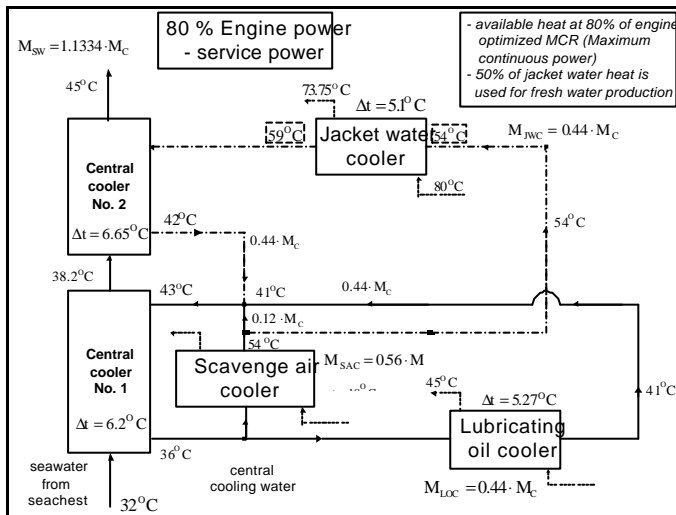


Fig. 15. Diagram for adapted central cooling water system for ballast heating (MAN B&W MC)

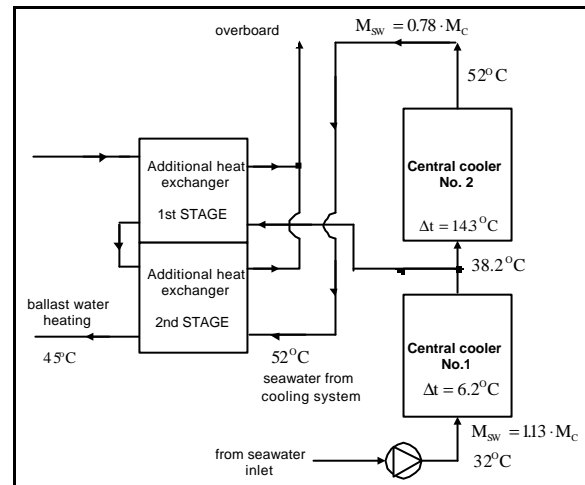


Fig. 16. Diagram for closed circuit ballast water circulation heating with two-stage ballast water heat exchanger for central cooling system

8. CONCLUSION

To obtain required ballast water temperature without (or minimum) affecting an engine performance and fuel consumption appropriate modifications of ballast piping and diesel engine conventional and central cooling systems have been proposed. Waste heat and cooling water system temperatures were calculated at part load and nominal engine's load. Ballast water can be treated in an open or closed circuit. In the open circuit some part of water in the ballast tank will be continuously flushed through the tank's vent. In proposed closed heating circuit such loss will be prevented. There will be no any discharge or dilution of ballast water. That would be much more convenient for ships operating in non-open ocean waters since organisms will be held in ballast tanks until all treated and discharged inactivated at final port destination.

Closed circuit heat treatment can be obtained either by conventional seawater or central cooling system modifications. Also, other ballast tanks can be heated by heat accumulated in treated ballast tank. Therefore, ballast water flow through the heat exchanger can be increased without lowering the outlet ballast water temperature and required time of the treatment will be much more shortened.

The journey time and seawater environment temperature are the most important constraints for ballast water heat treatment. If the seawater is lower than 15 to 20 °C heat method will be less effective and the time

required for treatment may be longer than the journey. Heating of the ballast tanks is inconvenient for vessels operating in cold regions since thermal stress may impact ship's structural safety. Therefore, proposed engine cooling system modifications could be used for further development of heat treatment - short time exposure strategy. Heating predictions should be confirmed by shipboard trial.

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