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# CONDITIONS OF WASTE HEAT RECOVERY IN MARINE WASTE HEAT RECOVERY SYSTEMS

**Key words**: marine power systems, waste heat recovery, waste heat recovery, turbogenerator.

**Abstract:** The paper is a discussion on the problems regarding the determination of possible methods to recover waste heat from marine diesel engines in an engine room. Waste heat resources of low-speed and medium-speed marine diesel engines are specified herein. The paper also includes a classification of the marine waste heat recovery systems taking into account the degree of their technical complexity and the use of steam generated by the boiler for the purpose of heating and to drive turbogenerators. Factors affecting the possible amount of heat recovery are also discussed in this paper. Among them, one may distinguish the temperature of water feeding the boiler, the sulphur content in fuel, and the pressure of generated steam. The analyses consist of the waste heat resources of the highest energy level included in exhaust gas, charge air, and engine cooling water. The waste heat resources are specified for a nominal engine power load. A selected, double-pressure waste heat recovery system is a subject of an assessment. The analysis presented in the paper, as well as the recommendations, may be applied to develop a concept of a marine waste heat recovery system that would be optimal in terms of maximizing the recovered heat that meets the demand for heat and electricity on a ship.

### Uwarunkowania odzysku ciepła odpadowego w okrętowych systemach utylizacji

**Słowa kluczowe:** okrętowe systemy energetyczne, utylizacja ciepła odpadowego, turboprądnice utylizacyjne.

**Streszczenie:** W artykule przedstawiono problemy związane z określeniem możliwości odzysku ciepła odpadowego silników spalinowych napędu głównego stosowanych w siłowniach okrętowych. Określono zasoby ciepła odpadowego wolno- i średnioobrotowych silników okrętowych. Zaproponowano podział okrętowych systemów utylizacji ciepła odpadowego uwzględniający stopień ich komplikacji technicznej i wykorzystanie uzyskanej w kotle utylizacyjnym pary na cele grzewcze i do napędu turboprądnic. Omówiono czynniki wpływające na ilość możliwego do odzyskania ciepła takie jak: temperatura wody zasilającej kocioł, zawartość siarki w paliwie, ciśnienie wytwarzanej pary. Przy analizach uwzględniono zasoby ciepła odpadowego o najwyższym poziomie energetycznym zawarte w spalinach odlotowych, powietrzu doładowania i wodzie chłodzącej silnik. Zasoby ciepła odpadowego określono dla nominalnego obciążenia silników mocą. Przedstawiona w artykule analiza i zalecenia mogą być wykorzystane do opracowania koncepcji okrętowego systemu utylizacji optymalnego z punktu widzenia maksymalizacji odzyskanego ciepła spełniającego wymogi okrętowego zapotrzebowania na cele grzewcze i energię elektryczną.

## Introduction

During the operation of the marine power system, the greatest losses are in waste heat generated by the diesel main engine. Due to the implementation of combined heat and power economics and by seeking to meet increasingly rigorous requirements for environment protection in terms of the emission of harmful exhaust gas components, waste heat recovery systems have been developed. Employing waste heat in the re-use process results in the reduction of fuel consumption by the ship's power system. As the effect of these systems, the following may be considered: a lower cost of purchased fuel, a lower amount of emitted exhaust gas components, and and extended operational period of machines and devices on a ship.

When making a decision on employing the systems, one should know data regarding the amount of waste heat contained in particular medium and the methods of its application. The possible recovery systems' levels related with the degree of their development and use of the waste heat and generated steam are presented in Table 1.

The largest resources of waste heat in diesel engines are in exhaust gases, charge air, and engine cooling water. The heat in the exhaust gas is used to generate steam in exhaust gas boilers. The steam is a heat medium used for heating purposes and for driving the auxiliary steam turbine interfaced with power generators and pumps.

**Table 1. Waste heat recovery levels and methods of waste heat use in power systems at ships**

| Recovery level | Waste heat source | | | Steam purpose | |
|---|---|---|---|---|---|
| | Exhaust gas | Charge air | Cooling water | Heat medium | Conversion of energy to kinetic energy of rotational motion |
| I | Waste heat recovery boiler | – | Vacuum evaporator | Heating | – |
| II | Waste heat recovery boiler | – | Vacuum evaporator | Heating | Turbogenerator drive, pump drive |
| III | Single, double or even triple-pressure waste heat recovery boiler, gas power turbine | Water heater feeding the boiler, sanitary water heater | Vacuum evaporator, water heater feeding the boiler, sanitary water heater | Heating | Turbogenerator drive, pump drive |

The heat in charge air is transferred in the multi-section air cooler to heat the water feeding the boilers in order to reduce the amount of heat necessary to reach the saturation temperature for a particular steam working pressure. This should result in an increased amount of steam generated in both the waste heat recovery boiler and the oil-fired boiler. In the following cooler sections, the water may be heated and then used in the ship's heating and sanitary systems, which should reduce the demand for heating steam generated by the ship's boilers. The waste heat in the water cooling the engine is used in evaporators to produce potable water, preheat the water, and to heat sanitary water.

The analysis regarding the amount of steam generated by the waste heat recovery boilers and used to meet the demand for heating and supplying power to turbogenerators [2–5] showed that the demand for electricity and heating purposes will occur in marine power systems where the main power does not exceed 25 MW. Such power of a propulsion system is applied on ships that have to develop high operational speeds (container ships, LNG tankers) and ships of high capacity, e.g., VLCC tankers.

Particular decisions on using the waste heat energy and the employed waste heat recovery level on the ship in question may be made upon detailed technical and economic analysis regarding waste heat resources, the demand for electricity, and heat for heating purposes. Further analysis is related to the selection of waste heat recovery boiler dimensions and type, the type of steam turbine driving the power generator and pump, gas turbines cooperating with the main propulsion system, and investment costs.

The paper includes the focus on preliminary analysis regarding using the waste heat in order to increase the amount of steam generated in the waste heat recovery boiler to meet the demand for heating and to supply the waste heat recovery turbogenerator.

## 1. Waste heat resources in main engines

The main function of waste heat recovery systems employed in ship power systems is to generate saturated steam in the amount that is sufficient for heating purposes. This solution, applied since the mid-twentieth century, contributes to the reduction of fuel consumption in the marine power systems due to the option to resign from the oil-fired boilers. Such an approach to the function of the waste heat recovery boiler may mean that one has not used the available waste heat resources included in the exhaust gas generated by the main engine.

When analysing the potentials to increase the amount of steam generated in the waste heat recovery boiler, in order to provide the steam stream directed to the turbogenerator, a number of factors should be considered, e.g., the need to extend the heat exchange surface of the boiler. The rise may be reached by lengthening the boiler tubes or by ribbing or studding them on the surface whre the heat is exchanged. The constraint is the resistance limit value for exhaust gas flow through the boiler, which equals 15 hPa [1, 5, 6, 10].

The dimension and weight of the waste heat recovery boiler should also be taken into consideration. Using only the waste heat in the exhaust gas to generate steam for heating purposes is characteristic for the first waste heat recovery level (Table 1).

Using waste heat recovery systems (Level III in Table 1) requires that the waste heat amount in other sources should be a subject of an analysis.

Table 2 presents the waste heat resources generated in marine main engines and included in the particular medium. The data gathered and analysed in the table refers to the technical data for engines manufactured by the top producers such as MAN, Wartsila, MAK, and ABC.

**Table 2. Waste heat resources of marine main engines in particular [7, 8, 9]**

| Engine type | Waste heat medium | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Exhaust gas | | | Charge air | | | Engine cooling water | |
| | Share in supplied heat | Temperature | Flow | Share in supplied heat | Temperature | Flow | Share in supplied heat | Temperature |
| | % | °C | kg/kWh | % | °C | kg/kWh | % | °C |
| Low-speed | 26.0–31.5 | 240–300 | 8.0–9.3 | 11.2–14.5 | 160–190 | 7.8–9.1 | 6.3–7.9 | 80–115 |
| Medium-speed | 24.8–33.9 | 380–450 | 6.5–7.7 | 9.4–13.0 | 160–210 | 6.3–7.5 | 7.0–8.4 | 80–115 |

The value of $Q_{sp}$ for the probable heat to be recovered from exhaust gas in the waste heat recovery boiler and the amount of steam generated in the boiler may be determined under the following formula (1):

$$Q_{sp} = \dot{m}_{sp} \; c_{spt_{sp2}}^{t_{sp1}} \left(t_{sp1} - t_{sp2}\right) = \eta \, \dot{m}_p \, c_{t_{wz}}^{t_n} \left(i_p - i_{wz}\right) [kW] \tag{1}$$

where

$\dot{m}_{sp}$ – exhaust gas flow [kg/kWh],

$c_{spt_{sp2}}^{t_{sp1}}$ – exhaust gas specific heat in relation to its temperature [kJ/kgK],

$t_{sp1}$ – exhaust gas temperature before the waste heat recovery boiler [°C],

$t_{sp2}$ – exhaust gas temperature after the waste heat recovery boiler [°C],

$\dot{m}_p$ – steam flow [kg/s],

$c_{t_{wz}}^{t_n}$ – water specific heat in relation to its temperature [kJ/kgK],

$i_p$ – generated steam enthalpy [kJ/kg],

$i_{wz}$ – enthalpy water feeding the boiler [kJ/kg],

$\eta$ – boiler efficiency.

## 2. Impact of steam parameters and the use of waste heat resources on the amount of steam generated in waste heat recovery boiler

When analysing the data in Table 2 and the Formula 1 components, it is difficult to state clearly in cooperation with which type of engine the waste heat recovery boiler will generate a larger amount of steam. Medium-speed engines are characterized by higher exhaust gas temperature, while low-speed engines by larger exhaust gas flux. That means that, when multiplying these values in Formula 1, each case must be considered separately. Whereas, due to a high temperature of exhaust gas in medium-speed engines, higher steam superheat temperature may be reached in the waste heat recovery boiler.

An increase of the temperature of water feeding the boiler to the saturated temperature for the working pressure of the steam results in the increased amount of steam generated in the boiler. For currently applied working pressures of the waste heat recovery boilers, being in the range from 0.6 to 1.0 MPa, the saturated temperature varies from 165°C to 185°C. The only source of waste heat available for reaching the temperatures is charge air at the nominal power load of the engine (Table 2).

Applying the formula (1), at the assumed temperature of water at the inlet to the heat exchanger (charge air cooler) equal to $t_{wz}$ = 60°C and at the constant amount of the heat received from the exhaust gas in the waste heat recovery boiler, the saturated steam amount increments were determined for the pressures from the range 0.6–1.0 MPa, depending on the temperature of the feeding water. The results of the calculations were applied to prepare Figure 1.

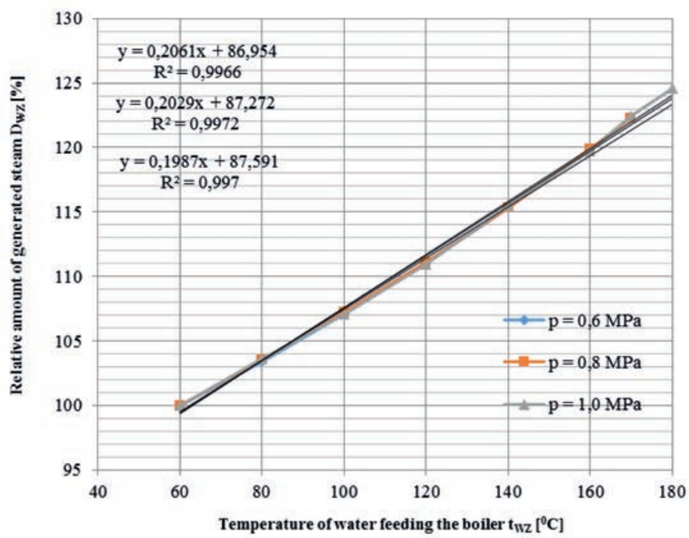


**Fig. 1. Impact of temperature of feeding water and working pressure on the amount of steam generated in the waste heat recovery boiler**

Source: Author.

By the application of the obtained relations, included in Figure1, it has been proved that, regardless of the steam pressure value in the assumed range of its variations (0.6–1.0 MPa), each feeding water temperature increment of 10 K results in the increased amount of generated steam by around 3%.

A significant factor limiting the use of waste heat contained in exhaust gas is low-temperature corrosion. It is a result of the presence of sulphur oxides as oxidation products of sulphur contained in the fuel. Sulphur is oxidized to sulphur dioxide $SO_2$ and, in the presence of catalysts, to sulphur trioxide $SO_3$. Sulphur trioxide sequentially combines with water to form sulphuric acid (VI) $H_2SO_4$ [4]. Sulphuric acid is in a gas state at the high temperature and does not create a risk of corrosion of elements with which it has contact. The sulphuric acid condensation occurs when the temperature in the space filled with exhaust gas decreases below the dew point. Then, the acid condensates and reacts directly with metal elements. Figure 2 presents how the sulphur content in fuel affects the temperature of exhaust gas dew point.

The temperature values of the dew point are within the marked area in Figure 2 due to the variable composition of sulphur oxides, which is dependent on the conditions in the exhaust gas pipe and local distribution of catalysts [6]. In order to prevent this phenomenon occurring during the combustion process of fuel containing more than 1% of sulphur, the temperature of the exhaust gas down the waste heat recovery boiler should not be lower than 160°C.

The applicable requirements for the environment protection state that the sulphur oxides emission should be limited and reduced. In enclosed areas, such as the Baltic Sea, it is required to use fuels with sulphur contents less than 0.1%, alternative fuels, e.g., LNG, or it is permitted to install a device in exhaust gas pipes which would reduce sulphur oxides in the exhaust gas.

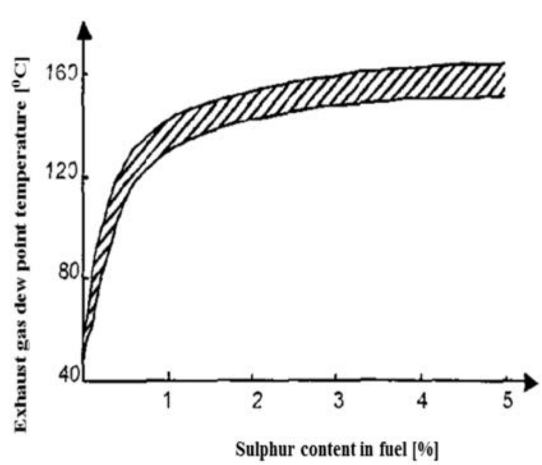


**Fig. 2. Impact of sulphur content in fuel on exhaust gas dew point temperature**

Source: Author, based on [1, 4, 6].

Considering the amount of heat recovered from the exhaust gas, the most efficient solution is to use low-sulphur fuel or alternative fuel due to the possibility to cool exhaust gas to low temperatures in the range from 110 to 120°C.

Another, very important, and significant factor is the pressure of steam generated in the waste heat recovery boiler. Along with the increase of the pressure steam, the saturation temperature increases. This results in the increase in the temperature of the exhaust gas exiting the boiler. According to [1] the allowable difference between the saturation temperature for the particular pressure and the exhaust gas temperature down the evaporation section should equal to minimum of $\Delta t_{min}$ = 10 K. For example, for the steam pressure equal to 1.0 MPa, the temperature of the exhaust gas temperature down the evaporation section should be around 200°C. This means, when compared with the minimum temperature in terms of low-temperature corrosion, that the amount of heat that may be recovered from the exhaust gas cooled to 200°C is reduced. The solution to this problem may be the installation of an additional combustion heater for feeding water in the last section in the waste heat recovery boiler.

In the case of waste heat recovery systems (Level III – Table 1), due to heating the water feeding the boiler in the charge air cooler, a low-pressure evaporation section is installed as the last section of the waste heat recovery boiler. The generated saturated steam is directed to drive the steam turbine. An additional stream of steam of low pressure causes that the power of the turbine increases.

## 3. Selected waste heat recovery system – assessment

The concepts of waste heat recovery systems have been developed by the top producers of marine main engines taking into consideration the exhaust gas parameters and the resources of waste heat in the offered engines [6–10].

An example of a double-pressure waste heat recovery system produced by MAN [7, 8] is presented in Figure 3.

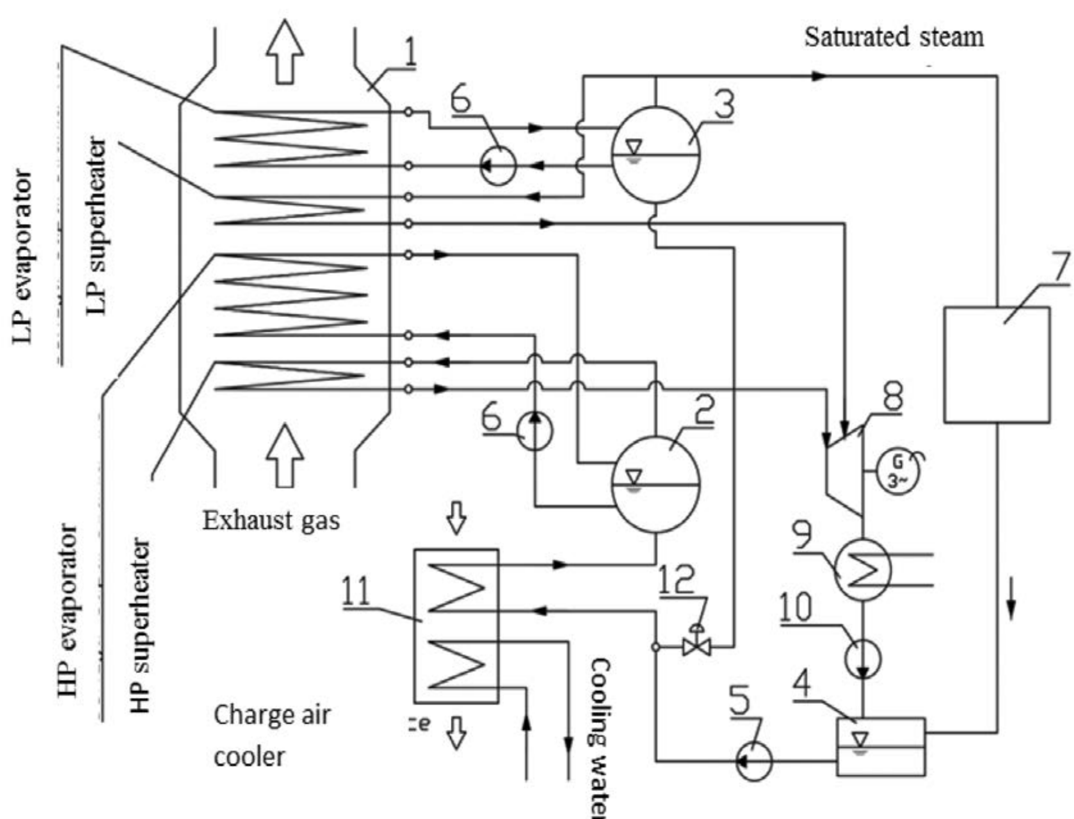


**Fig. 3. Waste heat recovery system based on the solution of MAN-B&W: 1 – waste heat recovery boiler, 2 – HP steam--water boiler drum WC, 3 – LP steam-water boiler drum, 4 – hot well, 5 – pump feeding boiler, 6 – circulation pump, 7 – heating steam receivers, 8 – turbogenerator, 9 – condenser, 10 – condensate pump, 11 – charge air cooler, 12 – pressure reducing valve, HP – high pressure, LP – low pressure**

Source: Author, based on [8].

Having the scheme presented in Figure 3 analysed, it may be stated that the degree of technical sophistication of the system is very high, which results in the maximization of the amount of recovered waste heat. Superheated steam, generated in the HP cycle, is designed for driving the turbogenerator. The aim of the LP cycle is to generate started steam to feed heat receivers and superheated steam directed to the turbogenerator.

For the purpose of heating water feeding the boiler, waste heat in the charge air has been used.

The distribution of exhaust gas and steam temperatures in the double-pressure waste heat system is shown in Fig. 4.

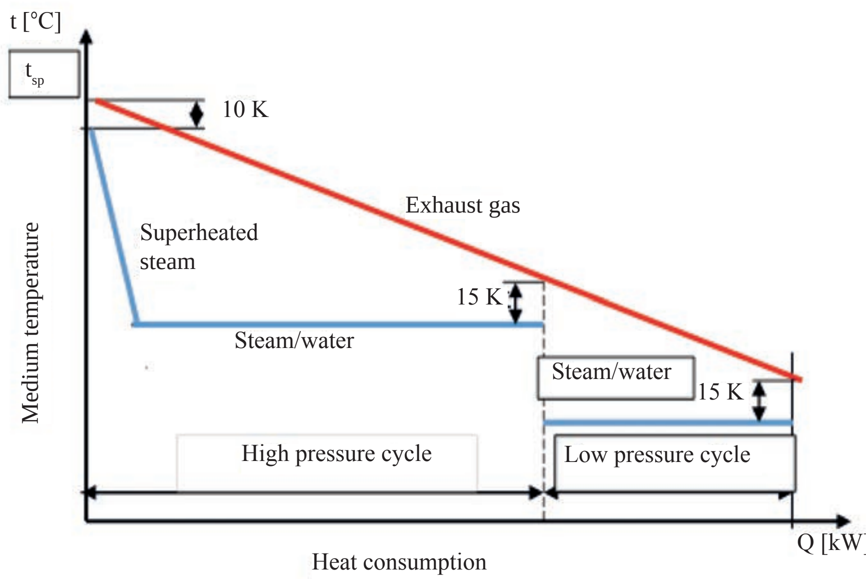


**Fig. 4. Distribution of temperatures in the double-pressure waste heat system**
Source: Author.

The basic line presented in Fig. 4 is the line indicating the decrease of the exhaust gas temperature, which has been drawn by taking into consideration the actual exhaust temperature at the boiler inlet and the temperature down the boiler (depending on the sulphur content in the fuel).

Including the minimum temperatures values between the exhaust gas and the steam down particular boiler sections (marked in Fig. 4) allows for adjusting the steam pressure in the LP and HP cycles.

## Conclusion

An increase in the amount of steam generated in waste heat recovery boilers to meet the demand for heating and to feed turbocharges is one of the methods to reduce the fuel consumption on ships and to mitigate the threat to pollute the environment with toxic exhaust gas.

The analysis provided in the paper enables the following conclusions to be drawn:

- By using waste heat contained in the charge air to heat the water feeding the boiler to the saturation temperature, it is possible to increase the amount of saturated steam generated in the boiler by around 3% per each 10 K of water temperature increment.
- The amount of generated steam depends mainly on the amount of waste heat available in the exhaust gas. The values of heat flux in exhaust gas are affected by the engine type, its power load, and engine environmental and operational conditions.
- Along with increased content of sulphur, the exhaust gas temperature increases at the boiler exit due to the risk of low-temperature corrosion. This results in the reduced amount of waste heat received by the receiver.
- The greatest amount of steam will be generated in double-pressure waste heat recovery systems using waste heat contained in the exhaust gas and charge air.
- A waste heat recovery system should be selected individually for each ship. The following should be taken into consideration: engine type, engine power, demand for electricity, and steam turbine power (unit demand for steam by the turbine decreases along with an increase of its power, e.g., for a turbine of 200 kW power, the unit demand for steam equals 13.5 kg/kWh, while for 2000 kW only 8.5 kg/kWh [1.2]).

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