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The effect of selected methods of waste heat utilization on waste heat boiler steam production

Wpływ wybranych sposobów wykorzystania ciepła odpadowego na ilość pary wytwarzanej w kotle utylizacyjnym

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Key words: marine power plants, waste heat utilization, waste heat boilers

Abstract

Growing costs of ship operation and actions taken to reduce the emission of harmful components in exhaust gases make designers seek more effective methods of utilizing substantial amounts of waste energy in marine power plants. One such method leads to the steam turbogenerator. This machine to run, however, requires substantially greater amount of steam generated in the waste heat boiler (compared to steam demand for heating purposes). It is possible to supply a sufficient amount of steam if the waste heat contained in exhausts and charge air of the main engine is fully utilized. This article analyzes the influence of some methods of using waste heat from exhaust gases and charge air on the amount of steam produced in the waste heat boiler. The analysis takes account of boundary conditions, such as steam pressure in the boiler and the minimum value of outlet gas after the boiler. The analysis is illustrated with examples of basic calculations for the waste heat boiler co-operating with a specific slow speed engine. Two variants of waste heat recovery installation solutions are considered.

Słowa kluczowe: siłownie okrętowe, utylizacja ciepła odpadowego, kotły utylizacyjne

Abstrakt

Rosnące koszty eksploatacji statków oraz działania związane z ograniczeniem emisji szkodliwych składników spalin skłaniają konstruktorów do wnikliwych analiz możliwości skuteczniejszego wykorzystania zasobów energii odpadowej w siłowniach okrętowych. Jedną z nich jest zastosowanie turboprądnicy parowej. W tym celu należy znacząco (w porównaniu z zapotrzebowaniem pary na cele grzewcze) zwiększyć ilość pary wytworzonej w kotle utylizacyjnym. Jest to możliwe przy pełnym wykorzystaniu ciepła odpadowego zawartego w spalinach i w powietrzu doładowania silnika napędu głównego. W artykule przedstawiono analizę wpływu wybranych sposobów wykorzystania ciepła spalin i powietrza doładowania na ilość pary wytworzonej w kotle utylizacyjnym z uwzględnieniem warunków brzegowych, takich jak ciśnienie pary w kotle oraz minimalna wartość temperatury spalin za kotłem. Analizę zobrazowano przykładami podstawowych obliczeń dla kotła utylizacyjnego współpracującego z wybranym typem silnika wolnoobrotowego w dwóch wariantach rozwiązań instalacji utylizacji ciepła odpadowego.

Introduction

In modern marine Diesel engines substantial part of chemical energy of fuel is lost along with exhaust gases escaping to the atmosphere while part is transferred to the water cooling charge air and the engine.

In reference to chemical energy contained in fuel, the largest quantities of waste heat are those in exhaust gases and charge air. The respective values are shown in table 1.

Also, in terms of their temperature, both media have the highest energy level, which increases possibilities of recovering the heat contained in them.

Table 1. Percentage of waste heat in selected media [1]
Tabela 1. Udział ciepła odpadowego w wybranych nośnikach [1]

	Medium	Percentage of waste heat	
		Slow speed engines	Medium speed engines
1	Exhaust gases	25.8 ÷ 28.8%	26.6 ÷ 33.7%
2	Charge air	12.1 ÷ 14.4%	9.4 ÷ 11.7%

The temperatures of exhaust gases and charge air in ISO reference conditions defined for marine engines are presented in table 2.

Table 2. Temperatures of exhaust gases and charge air of modern marine engines [1, 2]
Tabela 2. Temperatura spalin i powietrza doładowującego współczesnych silników okrętowych [1, 2]

	Medium	Temperature	
		Slow speed engines	Medium speed engines
1	Exhaust gases	235 ÷ 275°C	320 ÷ 415°C
2	Charge air	170 ÷ 180°C	190 ÷ 200°C

In order to increase the degree of utilizing the chemical energy supplied in fuel to a marine Diesel engine as a prime mover, thus enhancing the energy efficiency of the marine power plant, a waste heat recovery turbogenerator can be used as an alternative technical solution.

Water steam produced in a waste heat boiler is then used for heating purposes in the power plant and other shipboard installations and for feeding the turbogenerator. If a constant steam demand for heating will be assumed, the turbogenerator power will depend on the amount of steam delivered to it.

This article deals with heat recovery systems in which the steam generated in a waste heat boiler is used for heating purposes and feeding the turbogenerator, where the waste heat contained in exhaust gases and charge air is utilized for increasing the quantity of steam produced by the boiler. It has been assumed that the steam feeding the turbine will be saturated steam.

Methods of using the waste heat from exhaust gas and charge air

Waste heat contained in exhaust gases is used for the production of steam in waste heat boilers. Attempts to increase the amount of steam produced in the boiler mean that the heat contained in exhaust gas should be used for the evaporation process only, not for heating the boiler feed water. Higher temperature of feed water can be obtained from other, available sources of waste heat, first of all from charge air cooler.

One restriction here is the temperature of outlet gas after the boiler evaporating section that should be higher by at least 10 K [2, 3] than the saturated steam temperature for a given steam pressure. This requirement results from the fact that heat exchange should be sufficiently intensive, which affects the size of evaporation section and the values of exhaust gas flow resistance.

The acceptable minimum temperature of exhaust gas leaving the heat exchanger depends on the content of sulphur in fuel. Sulphur compounds created during fuel combustion combined with water condense in temperatures higher than those in which clean water does. The condensation temperature, known as the dew point, is a function of sulphur content of fuel, i.e. the higher sulphur level is, the higher SO_x concentration and the dew point are (Fig. 1). The risk that acidic products of combustion will condense decreases along with lower sulphur content. The market of marine fuels tends to constantly enforce sulphur reduction in fuels. According to current regulations (MARPOL), the maximum sulphur content of marine fuels used in international shipping, except for ECA (Emission Controlled Area), should not exceed 3.5 mass %, with an envisaged reduction below the 0.5% S level starting from the year 2020. Even lower values (1%) are compulsory in SECA, where from 2015 they will be reduced to the 0.1% level [4]. Such low sulphur contents of fuel make it feasible to decrease temperatures of exhaust gases without a threat that low temperature sulphur corrosion will occur.

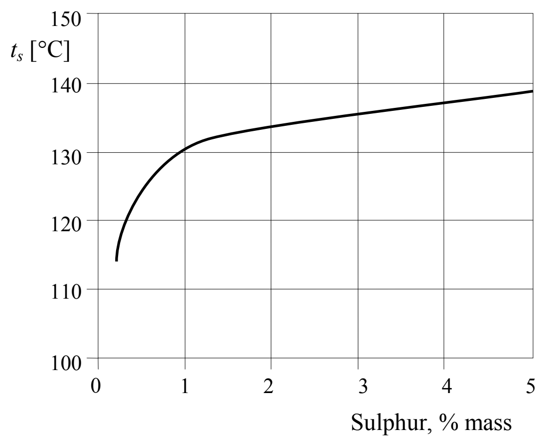

Fig. 1 Relation between the dew point and sulphur content of marine fuel by mass [5]
Rys. 1. Zależność punktu rosy od masowej zawartości siarki w paliwie [5]

The restriction determining the temperature after the evaporation section equal to the saturation temperature plus 10 K may lead to a situation where the temperature of outlet gas after the boiler will be much higher than the temperature acceptable from the viewpoint of low temperature corrosion. Consequently, heat contained in exhaust gas will not be fully utilized.

A solution tackling this problem is an exhaust gas water preheater operating as the last section of the waste heat boiler. The restriction in its use is the temperature of exhaust gas after the water preheater that should be higher by 10 K [2, 3] than the temperature of heated water, also dependent on steam pressure.

Another solution is the use of waste heat recovery in the process of charge air cooling. The use of two-segment air cooler and high air temperature after the air compressor enables heating boiler feed water to the saturation temperature for presently applied pressures 0.5 MPa to 0.9 MPa of steam generated in waste heat boilers for heating purposes and auxiliary machines. The following analysis of the influence of the method of heating boiler feed water on the amount of steam produced by the boiler takes the above restrictions into account. The examined boiler co-operates with a selected marine slow speed engine working as a prime mover.

Proposed waste heat recovery systems, assumptions and calculations methodology

Two systems presented in figure 2 have been taken for considerations on the recovery of waste heat contained in exhaust gas and charge air.

In the system presented in figure 2a there is no exhausts gas feed water preheater in the boiler. Feed water is heated to the saturation temperature for a given steam pressure in the first section of the charge air cooler. Figure 2b shows the heat recovery system in which water attains the saturation temperature heated by exhaust gas in the water preheater installed in the boiler.

For an analysis of the operation of the proposed heat recovery systems a MAN type 6K98-MC engine was chosen, with the following operating parameters:

– operating power P_e = 29 200 kW,
– exhaust gas mass flow rate m_{sp} = 245 320 kg/h,
– exhaust gas temperature t_{sp} = 228°C.

The above data were taken from the MAN documentation [6] and are based on the methodology of determining exhaust gas parameters presented in [2].

Taking into account low temperature of exhaust gas t_{s1} at the boiler inlet, the working medium was assumed to be saturated steam. Manufacturers as well offer a variety of marine steam turbines that can be fed with saturated steam.

Steam parameters for the assumed range of pressures 0.5 to 0.9 MPa are given in table 3.

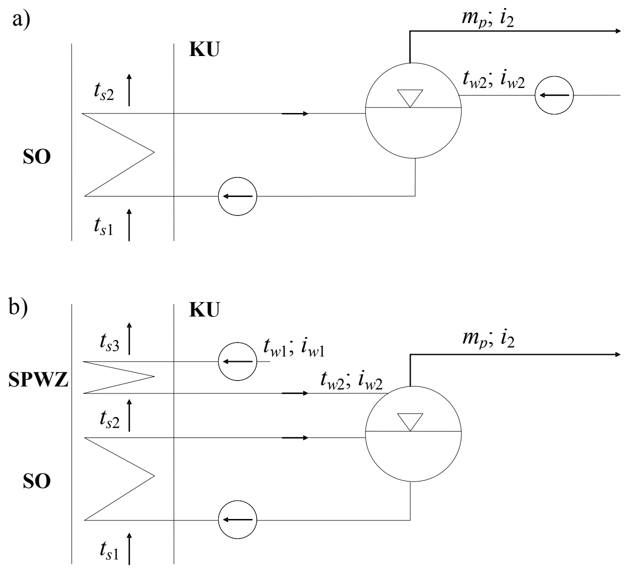

Fig. 2. Proposed systems of waste heat recovery, a) without SPWZ, b) with SPWZ, KU – exhaust gas boiler, SO – evaporator section, SPWZ – exhausts gas feed water preheater, t_s – exhausts gas temperature, 1 before KU, 2 after SO, 3 after KU; t_w – water temperature, 1 before preheater, 2 after preheater; m_p –steam production

Rys. 2. Proponowane układy utylizacji ciepła odpadowego, a) bez SPWZ, b) z SPWZ, KU – kocioł utylizacyjny, SO – sekcja odparowania, SPWZ – spalinowy podgrzewacz wody zasilającej, t_s – temperatura spalin, 1 przed KU, 2 za SO, 3 za KU; t_w – temperatura wody, 1 zasilającej, 2 za podgrzewaczem; m_p – masowe natężenie przepływu pary

Table 3. Parameters determining the state of water and steam on the saturated vapour line [7]

Tabela 3. Parametry określające stan wody i pary na linii granicznej [7]

	Steam pressure	Steam temperature	Specific enthalpy		Enthalpy of evaporation
			Water	Steam	
	p_p	t_p	i_1	i_2	i_p
	MPa	°C	kJ/kg	kJ/kg	kJ/kg
1	0.5	151.9	640.1	2748.5	2108.4
2	0.6	158.8	670.4	2756.4	2086.0
3	0.7	165.0	697.1	2762.9	2065.8
4	0.8	170.4	720.9	2768.4	2047.5
5	0.9	175.3	742.6	2773.0	2030.4

Balance equations were used to determine the steam mass m_p of steam generated in the waste heat boiler and temperatures after each boiler section.

The following assumptions were made:

– temperature of boiler feed water t_{w1} = 85°C,
– efficiency of KU as a heat exchanger η_{KU} = 100%,
– temperature t_{w2} of water after the heater is equal to saturation temperature t_p for a given steam pressure,
– temperature of exhaust gas after SO $t_{sp2} = t_p$ + 10 K [2, 3],

Table 4. Parameters of exhaust gas and boiler feed water
Tabela 4. Parametry spalin oraz wody zasilającej kocioł

	Steam pressure in KU	Temperature of exhaust gas		Boiler feed water after heater		Boiler feed water before heater	
		Before KU	After SO	Temperature	Enthalpy	Temperature	Enthalpy
	p_p	t_{s1}	t_{s2}	t_{w2}	i_{w2}	t_{w1}	i_{w1}
	MPa	°C	°C	°C	kJ/kg	°C	kJ/kg
1	0.5	228	161.9	151.9	640.1	85.0	782.9
2	0.6	228	168.8	158.8	670.4	85.0	782.9
3	0.7	228	175.0	165.0	697.1	85.0	782.9
4	0.8	228	180.4	170.4	720.9	85.0	782.9
5	0.9	228	185.3	175.3	742.6	85.0	782.9

– specific heat of exhaust gas

c_{ws} = 1,061 kJ/kg [7],

– engine power is equal to its operating power P_e.

Taking the above assumptions into account, the parameters of exhaust gas and feed water are presented in table 4.

For calculations, the balance equation known in literature [3, 8, 9, 10] has been used for each boiler section.

The evaporation section (SO):

$$m_p(i_2 - i_{w2}) = m_{sp}c_{ws}(t_{s1} - t_{s2}) \quad (1)$$

The above equation was transformed to determine the stream of generated steam mass:

$$m_p = \frac{m_{sp}c_{ws}(t_{s1} - t_{s2})}{i_2 - i_{w2}} \left[\frac{kg}{h}\right] \quad (2)$$

The feed water preheater section SPWZ:

$$m_{sp}c_{ws}(t_{s2} - t_{s3}) = m_p(t_{w2} - t_{w1}) \quad (3)$$

From the above relation the temperature t_{s3} of exhaust gas after SPWZ was obtained:

$$t_{s3} = \frac{m_{sp}c_{ws}t_{s2} - m_p c_w (t_{w2} - t_{w1})}{m_{sp}c_{ws}} \quad (4)$$

Then the data from tables 3 and 4 and those specified in the assumptions were put in the equations defining m_p and t_{s3}.

The calculation results for assumed steam pressures are given in table 5.

The results in table 5 were used for making graphic illustrations of the relations $m_p = f(p)$ and $t_s = f(p)$ shown in figure 3. Additionally, figure 3

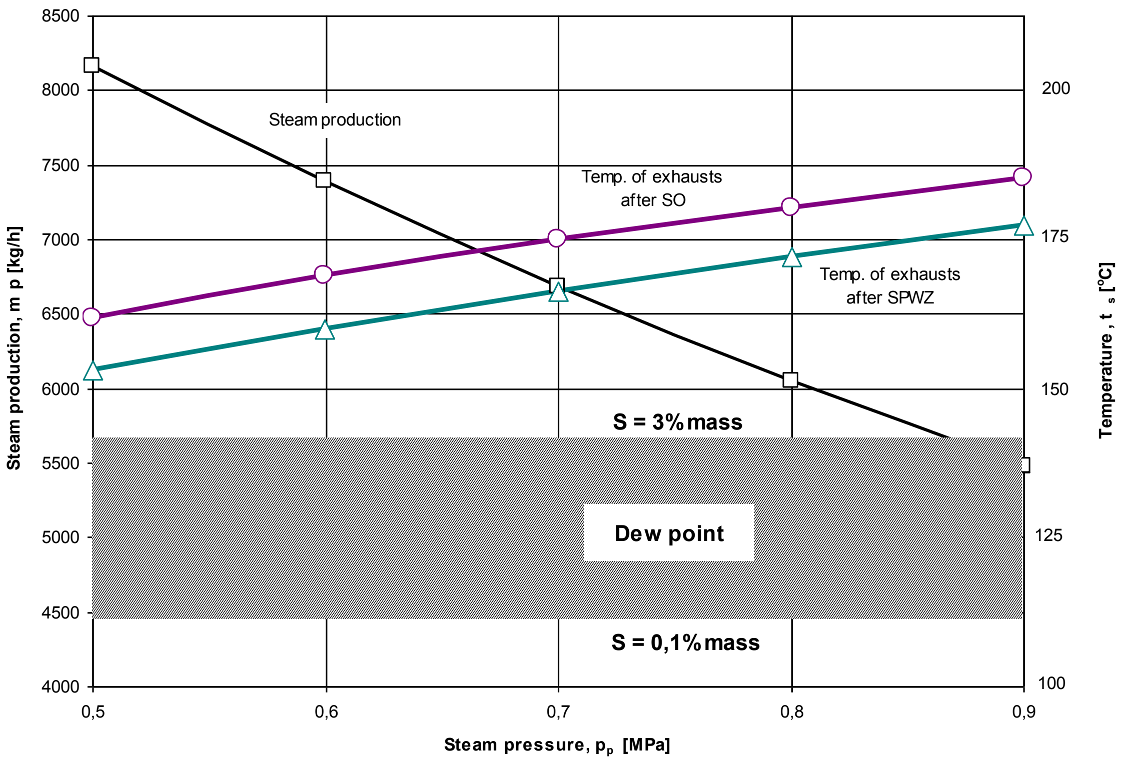

Fig. 3. Amount of generated steam and the temperature of exhaust gas after the boiler depending on the steam pressure
Rys. 3. Ilość wytwarzanej pary oraz temperatura spalin za kotłem w zależności od ciśnienia pary

includes the range of dew point for sulphur content of fuel from 0.1 to 3%.

Table 5. Calculation results
Tabela 5. Wyniki obliczeń

	Steam pressure in KU	Generated steam mass	Temperature of exhaust gas after	
			SO	SPWZ
	p_p	m_p	t_{s2}	t_{s3}
	MPa	kg/h	°C	°C
1	0.5	8160	161.9	153.1
2	0.6	7387	168.8	160.0
3	0.7	6678	175.0	166.4
4	0.8	6051	180.4	172.1
5	0.9	5474	185.3	177.3

Conclusions

- It has been indicated that, while meeting the steam demand for power plant and general shipboard heating, ranging on modern ships from 1.5 to 2.5 t/h, in the examined cases of waste heat recovery systems there is surplus steam for feeding a turbogenerator;
- Absence of an exhaust gas feed water preheater in the waste heat boiler leads to incomplete utilization of waste heat contained in exhaust gases. That loss will be higher in proportion to steam pressure, due to an increasing temperature of outlet gases of the boiler;
- When an exhaust gas feed water preheater is used, the temperature of exhaust gas going out of the boiler drops, but there is no risk of low temperature corrosion at the examined ranges of steam pressure;
- In either of the examined waste heat recovery system part of the waste heat contained in exhaust gases is not utilized, and its amount is proportional to the steam pressure;
- Extra waste heat in exhaust gas can be utilized by employing two-pressure systems, and generated saturated steam of lower pressure also can be used for feeding a turbogenerator;
- In two-pressure systems the ability to fully utilize waste heat contained in exhaust gas will depend on the dew point value.

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