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THE ANALYSIS OF THE DESIGN LIMITATIONS OF THE SELECTED THERMODYNAMIC PARAMETERS OF THE WORKING MEDIA IN THE MARINE WASTE ENERGY RECOVERY SYSTEMS

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Abstract

The waste energy utilisation degree in the marine Diesel power plants grows as the exhaust gas boiler exhaust gas temperature decreases. The limitation in this case is not only a likelihood of sulphur corrosion occurrence in the boiler and exhaust gas ducts, but also the obtainment of too little, or altogether negative values of so called pinch point.

The article presents the analysis of the limitations related with the pinch point and minimum boiler exhaust gas temperature which are possible for the acceptance at the stage of the preliminary design in terms of the system correct operation and its energetic effectiveness. The possible negative results of the exhaust gas boiler exhaust gas temperature reduction and the methods to prevent the results have been presented. In the effect of conducting the calculations for the selected thermodynamic parameters of a model waste energy recovery system there has been presented the graphic course of the changes in the achieved power of the steam turbine generator and the pinch point in exhaust gas boiler in relation to the boiler exhaust gas temperature, the generated steam pressure, recovery system feedwater temperature and the main engine exhaust gas temperature. The data presented in the article are but of general nature and reflect the relations between the selected thermodynamic parameters that characterise the model of the waste energy recovery system in the marine Diesel power plant.

Keywords: *marine power plants, waste energy recovery systems, design limitations*

1. Introduction

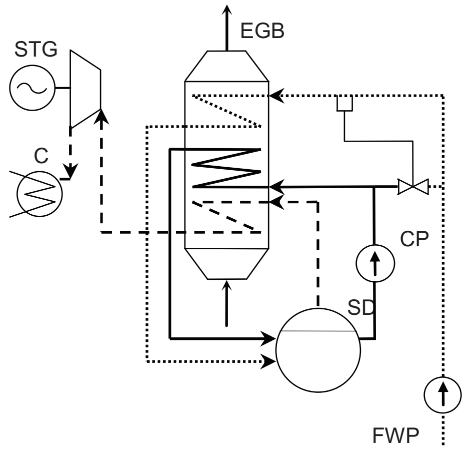
The obtainment of the high energetic effectiveness ratios on the Diesel powered ships [also referred to as the 'motor ships'] is possible owing, inter alia, to the application of the complex waste energy recovery systems. One of the methods to make it possible to improve the effectiveness of the use of this energy is the application of the possibly low temperature of the exhaust gas boiler outlet exhaust gas that characterises the waste energy deep recovery systems. It is universally assumed that the limit values of this temperature result chiefly from the level of water dew point temperature of the exhaust gas directed to the exhaust gas boiler and the heat transfer surface in the boiler possible to be accepted from the economic point of view. However it should also be noticed that there are some other limitations resulting from the physical phenomena occurring in the exhaust gas boilers which are present during the operation of the waste heat recovery systems. The tendency of the boiler heating surface to get contaminated is, among others, of significant importance. This phenomenon in the exhaust gas boilers is related with the adherence of the soot particles contained in the exhaust gas to the heating surface. The dominating mechanisms during this process are the inertial collision of those particles with the heat transfer surface and their tearing away as well as thermoforesis (Soret effect), resulting from the difference in the temperatures between the heating surface and the exhaust gas [9]. The inertial collisions of the solid particles form the prevailing mechanism for the particles exceeding 10 μm [9]. The presence of the asphaltenes in fuel significantly increases the contents of those particles in the exhaust gas. It should be noted that the effect of the thermoforesis decreases as the heat transfer surface in the boiler grows [2, 3]. The other unfavourable phenomenon is the generation of the sulphur trioxide in the exhaust gas in the effect of the reaction occurring both in high and low temperatures.

The sulphur oxide and water content in the exhaust gas significantly influences the value of the dew point temperature for the water in exhaust gas. This temperature is related with the water dew point temperature decreased by the value related with partial pressure values of acid and water. The adequate formulae to allow to determine this temperature have already been elaborated within the 1950's of XX century [7]. On account of relatively high general air excess factor in Diesel engines the water dew point temperature in the exhaust gas is relatively low. For the air temperature of 45°C and RH 100% the water dew point temperature amounts to approximately 48°C [3, 4]. The higher the fuel sulphur content, the higher exhaust gas water dew point temperature [8, 11, 12]. The presence of the sulphur oxides in the exhaust gas causes the generation of the sulphuric acid and thus the sulphur corrosion of the boiler elements and exhaust gas ducts. The remaining acid becomes isolated by condensation on the boiler heat transfer surface, if this has the lower temperature than the exhaust gas water dew point temperature. In case of the majority of the exhaust gas boilers the temperature of the heat transfer surface external walls is slightly higher than he temperature of the medium flowing inside the piping due to the high heat transfer coefficient at the side of this medium. Thus the temperature of the heat transfer surface in the boiler – instead of the temperature of the exhaust gas itself – is the decisive factor for the acid condensation and the corrosion intensity. The high-concentration acid gets deposited on cool surface just below the exhaust gas dew point temperature [7] and is not as aggressive to the steel as a diluted acid which occurs at the water dew point temperature [2, 7]. Therefore the exhaust gas boiler is supplied with water of adequately high temperature, exceeding the temperature of the condensate supplied by the recovery system feedwater pump.

It is worth emphasising that the exclusive application of the natural and forced LNG evaporation product as the fuel is characterised by low emission of the harmful engine exhaust gas (according to Wärtsilä the reduction is as big as the tenfold in relation to the emission of the harmful exhaust gas emitted by slow-speed Diesel engines supplied with liquid fuel [5]). It should be noted that the application of the natural gas as the fuel, particularly in the marine Diesel and gas turbine power plants, provides large potential for the heat recovery from the engine exhaust gas [4]. However, a limitation in this case might be the significantly large heat transfer surface in the boiler and the value of the minimum difference in the temperature of the exhaust gas and saturated steam (ΔT_{min}) in the exhaust gas boiler referred to as the "pinch point". The need to maintain the positive value of this parameter may influence significantly the limitations in relation to the apparently big possibilities of the usage of the exhaust gas heat by way of lowering its temperature at the outlet from the exhaust gas boiler.

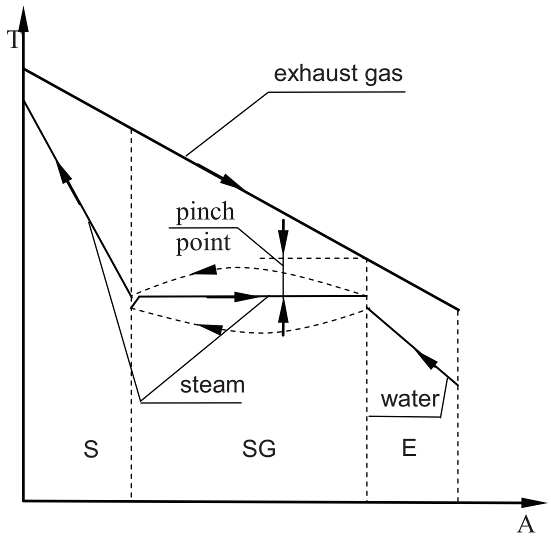
2. The Specification of the Object of the Analysis

The object of the analysis are the selected working parameters of a model recovery system of the heat contained in the ship's main engine exhaust gas. The schematic diagram of the system is presented in figure 1. The figure 2 shows the course of the changes in the working media temperatures – exhaust gas and water as well as steam in the exhaust gas boiler. The table 1 shows, on the other hand, the basic input data for the calculations of the thermodynamic parameters of the analysed system. The calculations have been conducted, inter alia, basing on the method determined in [6].



C – condenser, CP – circulating pump, EGB – exhaust gas boiler, FWP – feedwater pump, SD – steam drum, STG – steam turbine generator

Fig 1. The simplified schematic diagram of the outlet exhaust gas heat recovery system



E – economizer, S – superheater, SG – steam generator

Fig 2. The courses of the changes of the thermodynamic parameters in exhaust gas boiler

Tab. 1. Calculation Input Data

Main engine exhaust gas stream	20,28	kg/s
The specific heat capacity of exhaust gas	1,069	kJ/kgK
Exhaust gas temperature after main engine	275	°C
Exhaust gas temperature after exhaust gas boiler	180	°C
Exhaust gas temperature drop after main engine	5	°C
Exhaust gas boiler efficiency	0,98	-
Steam turbine generator efficiency	0,675	-
Steam consumption coefficient for the needs of steam turbine generator	0,07	-
Recovery system feedwater temperature	60	°C

Generated steam pressure	0,7	MPa
Steam pressure drop before steam turbine generator	0,015	MPa
Steam temperature drop before steam turbine generator	2	°C
Steam pressure in condenser	0,005	MPa
Heat flux for heating purposes	600	kW

The research covered the influence of the changes of the exhaust gas temperature after exhaust gas boiler, the pressure of the generated steam in the exhaust gas boiler, the temperature of the recovery system feedwater and the temperature of the main engine exhaust gas on the value of the power output of the steam turbine generator and the value of pinch point in the boiler. The values of the remaining parameters shown in table 1 have been meanwhile maintained.

The analysis did not include, inter alia, the change of the steam turbine generator efficiency ensuing from the change of its power output and the steam parameters at the turbine inlet and outlet. The inclusion of this value does in fact influence the value of the turbine generator power output whereas it does not have any influence on the value of the pinch point in boiler which has been the basic object of the conducted analysis. The research has not covered either the influence of the thermodynamic parameters on the size of the heat transfer surface in the boiler and condenser and operation parameters of the other auxiliary equipment of the waste energy recovery system.

3. The Analysis Results Specification

The graphic results of the analysis conducted are shown in figures No 3 to 10. The increase of the temperature of the exhaust gas leaving the exhaust gas boiler leads to decrease in the power output of the steam turbine generator which is the evident effect of the reduced amount of the heat recovered in the exhaust gas boiler. This is shown in figure 3. The assumption of the low value of this temperature allows to achieve the bigger power output of the steam turbine generator, but it is also likely to cause that the pinch point value shall become negative. As shown in figure 4, for the set of the data determined in table 1, the zero value of the pinch point has been reached at the exhaust gas temperature of approximately 143°C. Below this value ΔT_{min} shall be already negative. Thus the excessive reduction of the temperature of the exhaust gas at the exhaust gas boiler outlet, even if the exhaust gas water dew point temperature is not exceeded, may turn unacceptable from the technical point of view.

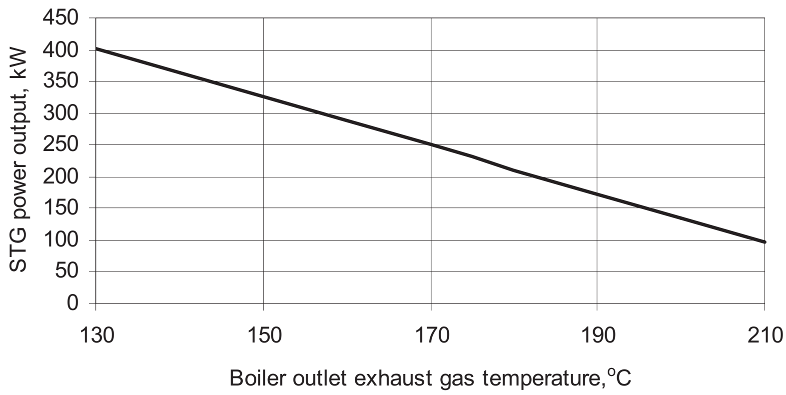


Fig 3. The relation of the STG power output and the temperature of the of the exhaust gas at the boiler outlet

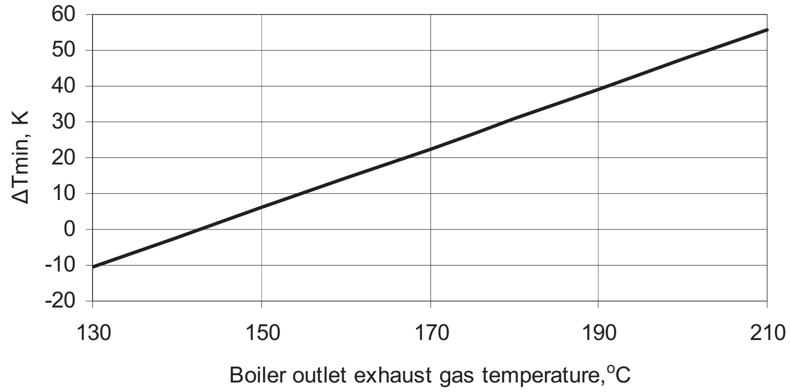


Fig 4. The relation of the boiler minimum temperature and the boiler outlet exhaust gas temperature

The course of the value ΔT_{min} is also influenced by the pressure of the steam generated in the boiler. The increase of the steam pressure favourably influences the steam turbine generator power output (provided that the constant *effective efficiency* is assumed), because this increases the efficiency of Clausius-Rankine cycle. This is shown in figure 5. However, with the steam high pressure values the value of ΔT_{min} decreases, which is shown in figure 6. Thus the assumption of the high steam pressures with the simultaneous reduction of the exhaust gas at the exhaust gas boiler outlet is likely to accelerate significantly the moment of reaching too low values of pinch point.

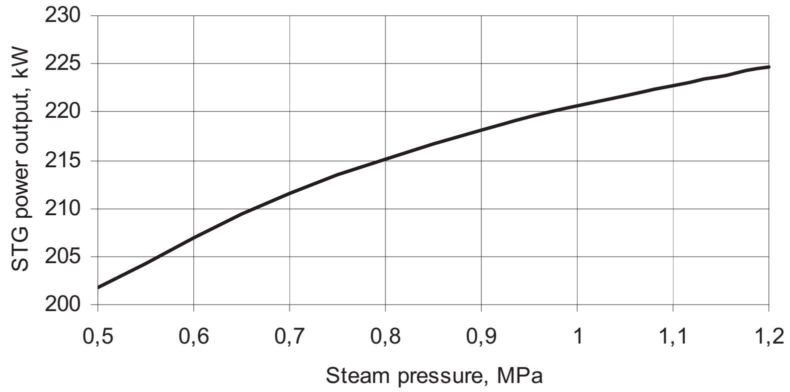


Fig 5. The relation of the steam turbine generator power output and the steam pressure

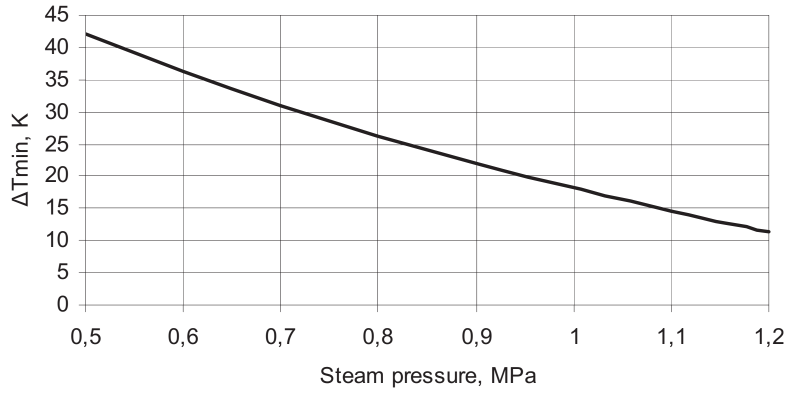


Fig 6. The relation of the minimum temperature in the boiler and steam pressure

A significant parameter influencing both the reached power output of the steam turbine generator and the pinch point value is the temperature of the feedwater supplied by pump to the recovery system. Its value results from the balance of the condensate mass stream and the heat of the heating steam condensate returning from the heaters and the condensate mass and the heat of the turbine outlet steam condensate. The bigger steam turbine generator power output corresponds to the higher temperature of this water (figure 7).

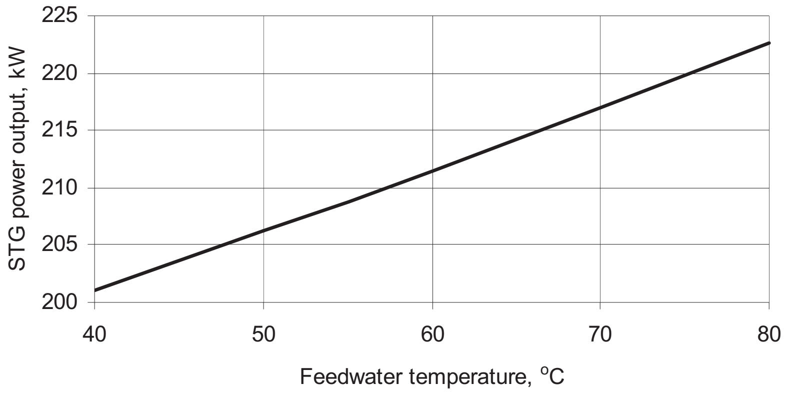


Fig 7. The relation of steam turbine generator power output and the recovery system feedwater temperature

As shown in figure 8 the pinch point value decreases however as the recovery system feedwater temperature grows. From this point of view it becomes favourable to reduce the steam pressure in condenser owing to which the steam condensation temperature in the condenser is reduced which in turn leads to reduction of the recovery system feedwater temperature. While striving to maintain the possibly high energetic effectiveness of the recovery system, this temperature might be increased within certain limits by the application, inter alia, of the complex recovery of the engine waste energy where the heat contained in engine charging air or the remaining waste heat of low energetic potential are used [1].

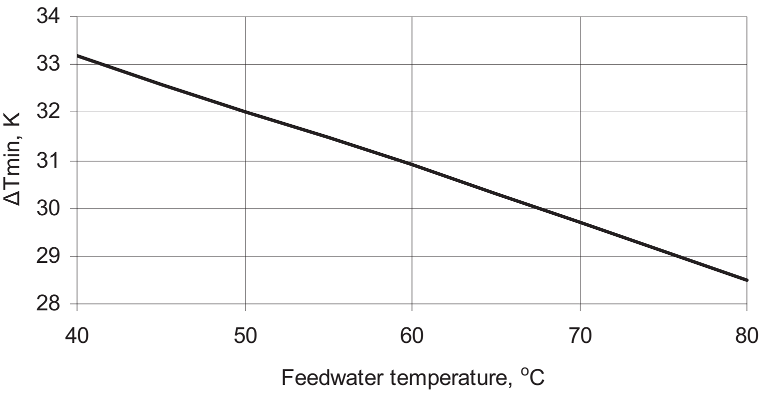


Fig 8. The relation of the boiler minimum temperature and the recovery system feedwater temperature

The exhaust gas temperature after main engine, thus the temperature of the exhaust gas at the inlet to the exhaust gas boiler, has the similar influence on both the steam turbine generator power output and the value of the pinch point. The courses of the changes of these parameters are shown in figures 9 and 10, respectively. They reflect the increase of their value accompanying the increase of the temperature of the exhaust gas after main engine. The outlet exhaust gas temperature of the engine assumed as the main propulsion, however, depends on its characteristics/specification data and may only constitute a constant input value for the calculations.

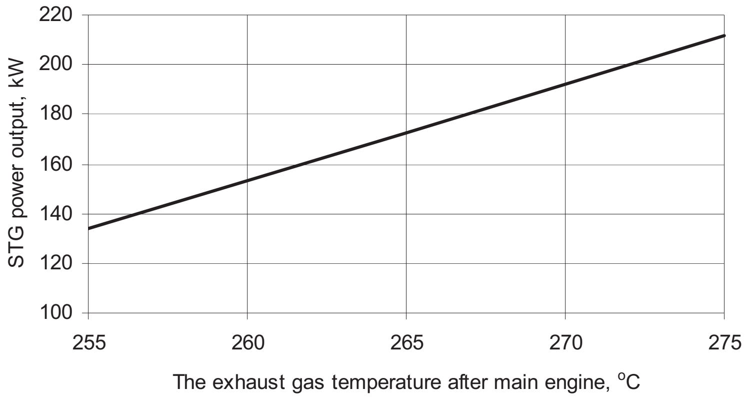


Fig 9. The relation of the steam turbine generator power output and the main engine exhaust gas temperature

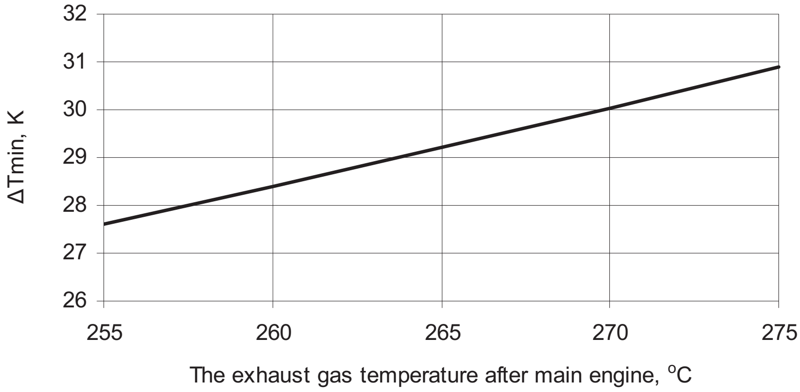


Fig 10. The relation of the boiler minimum temperature and the temperature of the main engine exhaust gas

4. Conclusions

While striving to improve the ship's energetic effectiveness one should tend to adopt the marine power plant arrangements characterised, inter alia, by the high degree of the utilisation of the chemical energy contained in the fuel burnt. This can be achieved, apart from the improvement of the primary engine efficiency, by way of the complex and deep recovery of the waste energy.

The waste energy utilisation degree grows as the exhaust gas boiler outlet exhaust gas temperature decreases. The limitation in this case is not only the likelihood of the occurrence of the sulphur corrosion in the boiler and exhaust gas ducts, but also the obtainment of too low or just altogether negative values of so called pinch point value.

Several other parameters also influence the pinch point value. They include, among others, the generated steam pressure or the recovery system feedwater temperature whose higher values allow to increase the theoretical efficiency of the steam cycle, however, at the same time causing the reduction of the pinch point value.

The data presented in the article are but of general nature and reflect the relations between the selected thermodynamic parameters that characterise the model of the waste energy recovery system in the marine Diesel power plant.

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