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The methods of the evaluation of the waste energy recovery systems in the marine Diesel power plants

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Abstract
The article presents the general description of the waste energy recovery systems in the marine Diesel power plants. Both, the simple as well as the complex recovery systems have been discussed. The substantial part of the article concerns the overview of the evaluation methods of the recovery systems arrangements. There have been presented the rudiments of the thermodynamic evaluation which in the effect provides the material for the determination of the energetic and exergetic efficiency of the recovery systems. The significant issue is also the description of the method of the arrangements economic evaluation, including the method of the determination of the annual profit ensuing from the operation of the waste energy recovery system and the dynamic methods of the economic analysis with the particular emphasis on the investment outlay payback period index. There have been presented the examples of the dependence of the waste heat turbo-generators on the main engine power output, the estimated payback times of the investment outlays incurred in connection with the discussed systems and the payback time of the outlays with reference to the main engine power output in the function of its power output.

Introduction

The energetic transformations occurring in the marine waste energy recovery systems form the typical associated processes. The effective products of those processes may consist in general: electric energy, mechanical energy used to supplement the ship's main propulsion, heat for the heating purposes, sometimes cold temperatures and fresh water produced out of the sea water. The recovery systems are driven in the most general case by the waste energy of the fuel burning equipment. There is a large variety of the waste energy recovery system arrangements possible for the application and implementation. Making the decision about the choice of the appropriate arrangement is connected with its evaluation, both in terms of the technical implementation possibilities on the ship, as well as provision of the most favourable thermodynamic parameters and the acceptable costs. In order to make the decision concerning the method of the energy recovery it becomes necessary also to make the right choice between the utilisation of the conventional energy sources and the waste energy recovery. The analysis of the functional types of the waste energy recovery systems and their relations with the conventional energy sources provides the view of the possibility of substituting the classic manner of energy generation (thermal, electric or mechanical energy) by a system utilising the waste energy of the main propulsion engine or engines, or the joint operation of this machinery.

The final evaluation of the waste energy recovery system arrangements possible for the application on the specific ship should include the forecasted / planned operation conditions and may be made upon the completion of the technical-economic analysis.

General description of the recovery system arrangements

The diagram of the generalised recovery system is presented in figure 1, where the energy balance boundary has been marked for the recovery system, as well as the energy balance boundary for the entire energy system of the marine Diesel power plant.

In the majority of the existing marine power plants the effective products of the recovery system are the heat whose carrier is steam, more rarely the special heating oils and electric energy and the fresh water produced in the evaporators. The simplest waste energy recovery systems are the single--pressure systems producing in the waste-heat boilers exclusively the saturated steam for the heating purposes. The driving energy in these systems is the heat contained in the main engine exhaust gases. The complex recovery systems cover the systems for so called complex recovery of the waste energy where not only the heat contained in the exhaust gas is utilised, but also the heat contained in the engine charging air, engine cooling water and lubricating oil, as well as the increased exhaust gas pressure behind the engine [1]. In these systems not only different sources of waste energy are utilised, but also the different form of the waste energy.

The application of the recovery system arrangement depends chiefly on the type of the ship (inter alia the heat and electric energy demand), main engine power output and type. However, the most frequently used source of the driving energy for the recovery system are the main engine exhaust gases owing to their relatively high specific exergy and large amount of the heat carried. The application of this source is, however, related with the problems resulting mainly from the physical--chemical properties of the exhaust gas itself, as the gas contains among others the significant amounts of the sulphur oxides limiting the possibility of any substantial reduction of the exhaust gas temperature behind the waste-heat boiler. On the other hand, the utilisation of the auxiliary engines exhaust gas heat can be considered only in a limited extent.

The systems with the waste-heat boilers applied in the power plants of the ships with engines of small power output are generally very simple since the steam demand in this case is usually small and the ships are characteristically for the short time periods at sea and remain for a rather long time in ports. The amount of the saved fuel owing to the application of the complex recovery system is in this case relatively minor, while the time of payback of the investment outlays on the complex system is long. The additional problem is also the availability of the bigger space in the engine room as necessary to accommodate the extensive recovery system. Such problems do not occur or are much less significant on the big ships with spacious engine rooms fitted with the propulsion engines of large power output.

The simplest set-up of the waste-heat boiler is the single-pressure system producing exclusively the saturated steam. The single-pressure system with the steam superheater can produce the superheated steam needed to supply the steam turbines driving the generators or supplementing the ship's main propulsion, as well as driving the other auxiliary equipment, e.g. cargo pumps on some tankers. The application of the waste-heat turbogenerators allows not only to improve the power plant energetic efficiency, because it reduces the fuel consumption by the independent Diesel generating sets while en route at sea, but also in certain cases allows to reduce the number of these generating sets.

If the waste-heat boiler is extended by the additional economizer, then there is a possibility of increasing the boiler capacity in relation to the system with the shallow exhaust gas heat recovery owing to the possibility of decreasing the exhaust gas temperature after the boiler. Such system is referred to as the deep exhaust gas heat recovery system.

On the ships with the Diesel engine or gas turbine propulsion system, where the steam produced in the waste-heat boilers is used for the propulsion of the generating set turbines, the changes in the ship's heating steam receivers load are a problem, which is translated into the available amount of the turbine supply steam. In such case, there would be a justified solution to adopt the double-pressure waste-heat boilers. In such systems most frequently the low pressure steam is used to supply the heat receivers, whereas the superheated steam from the high-pressure circulation is used exclusively to supply the turbine. Various arrangements of the systems are possible in such circumstances. The acceptance of a specific concept is subject mostly to the required steam heating installation capacity, the required steam pressure values, as well as the acceptable installation cost. The additional benefits related with the application of the double-pressure systems result from the power increase of the applied turbo-steam power generating sets.

There is also a large variety of the recovery systems resulting from the manner of boiler feed water supply. The results of the investigations presented in [2] indicate that with the existing various arrangements of the waste-heat boiler systems it is necessary to perform the analysis for the choice of both, the thermodynamic parameters as well as the diagram of the supply system in order to obtain the possibly cheapest and effective solution on a given ship.

The relatively high efficiency of the modern turbochargers provides the possibility to use a part of the exhaust gas in the separate exhaust gas turbine supplementing the ship's propulsion, thus creating the hybrid propulsion system or in the exhaust gas turbine driving the generator. In these arrangements the temperature part and the pressure part of the waste energy from the engine exhaust gas are utilised. The saturated steam generated in the waste-heat boiler supplies the receivers on the ship while at sea.

Also the combined arrangements are proposed where the exhaust gas from waste-heat turbine is directed to the waste-heat boiler producing, besides the saturated steam, also the superheated steam that supplies the additional steam turbine. Various methods of the steam generating can be applied in such cases, as well as various manners of the steam turbine steam supply. The advanced solutions of the waste energy recovery systems where shaft generator has been additionally applied with the possibility of the operation as the electric motor of the auxiliary function for the ship's propulsion are referred to inter alia in [3].

The thermodynamic evaluation of the arrangements of the marine waste energy recovery systems

The low exergy of the waste energy carriers in the Diesel power plants has such an effect that the degree of the utilisation of the waste energy is small, and the commonly applied recovery system arrangements are usually limited to the utilisation of the main engine exhaust gas heat and generation of the steam to satisfy either wholly or partially the heating needs on the ship. Only in a few instances the available amount of the waste energy allows additionally to generate the mechanical energy in the gas or steam turbine, or both turbines at a time and use it to drive the generator or the propeller [1]. However, in each case it is significant to make the appropriate choice of the parameter values in the individual points characterising the working media thermodynamic transformations. In order to make the right choice, it is necessary to conduct the adequate analyses which will enable the evaluation of the quality of the individual process courses and indicate the places where the major losses occur and the methods to minimise them.

The basis for the calculations of the waste energy recovery systems in the Diesel power plants are the systems of mass and energy balance equations. While designing the discussed systems, the enthalpy analysis has become commonly applied. To make the correct evaluation, particularly of the waste energy sources, the exergetic analysis is used [4, 5], whereas to evaluate the quality of the processes occurring during the system operation, the entropy analysis may be applied. The general methods of minimising the entropy increases occurring in the heat transfer processes and in the power plants have been described in [4, 6, 7].

The energetic efficiency of the waste energy recovery systems

The energetic efficiency of the energetic system presented in figure 1 is determined by the ratio of the effective energy ΣE_e to the energy supplied to the system ΣE_S:

$$\eta_E = \frac{\sum E_e}{\sum E_S} \tag{1}$$

The energetic system effective energy consists of the mechanical energy used for the ship's propulsion. The electric energy and the heat transferred by the heating media to the various receivers on the ship. The energetic efficiency of the power plant is determined in general case by the relation:

$$\eta_E = \frac{N_S + \Delta N_S + N_{elDG} + N_{elWHTG} + \dot{Q}_{AB} + \sum_i \dot{Q}_i}{B_{ME} W_{dME} + B_{DG} W_{dDG} + B_{AB} W_{dAB}} \tag{2}$$

where:

- N_S – main propulsion engine shaft power;
- ΔN_S – power of the equipment supplementing the ship's main propulsion obtained in the recovery system;
- N_{elDG} – electric power measured at the Diesel generating set generator terminals;
- N_{elWHTG} – electric power measured at the waste-heat turbo-generator terminals;
- $\dot{Q}_{AB}$ – thermal power of the auxiliary oil-fired boiler;
- $\sum_i \dot{Q}_i$ – thermal power of the waste-heat heating system;
- B_{ME} – main engine fuel consumption;
- B_{DG} – Diesel generating set fuel consumption;
- B_{AB} – auxiliary oil-fired boiler fuel consumption;
- W_{dME} – lower calorific value of the fuel burnt in main engine;
- W_{dDG} – lower calorific value of the fuel burnt in the Diesel engines of the generating sets;
- W_{dAB} – lower calorific value of the fuel burnt in the auxiliary boiler.

The efficiency determined according to the relation (2) includes as the effective energy also own needs of the energetic system itself. It is regarded

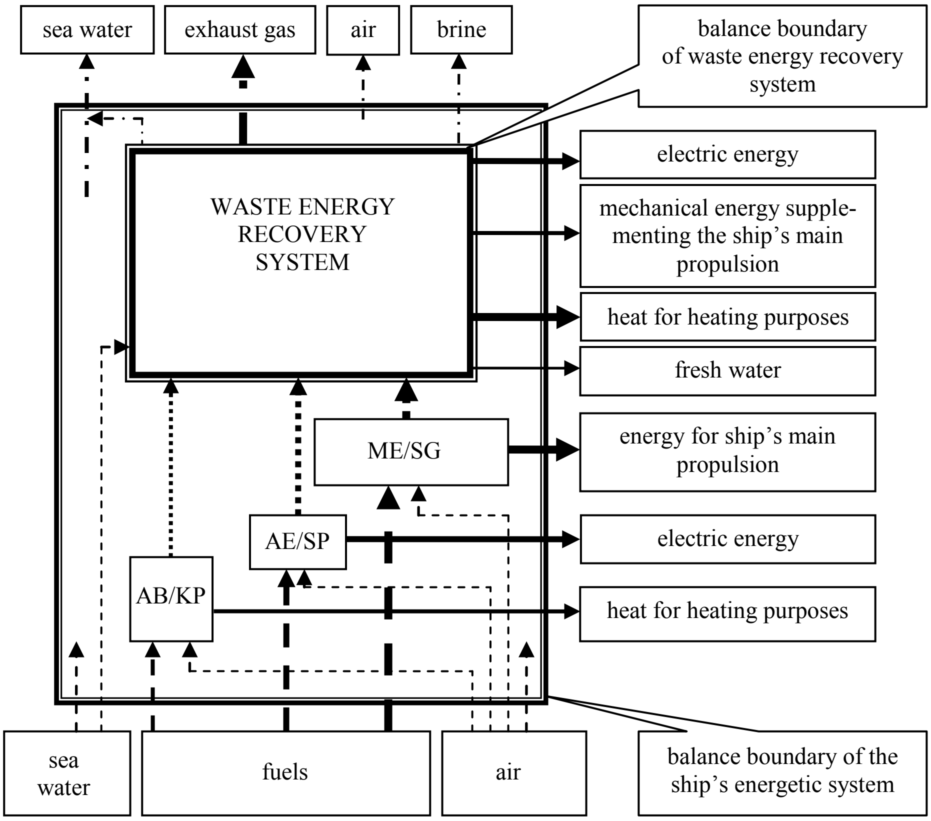

Fig. 1. The diagram of the energy distribution for the generalised recovery system: ME – main engine, AE – auxiliary engines, AB – auxiliary fuel-fired boiler; – – ▶ input products for the ship's energetic system, ········▶ waste products at the recovery system inlet, ——▶ effective products, – · –▶ waste products at the ship's energetic system outlet

as the gross efficiency of the ship's energetic system and treated as the symbolic [conventional] value.

A part of the waste energy on the ship is also used to produce the fresh water out of the sea water in the evaporator. The energetic outlays incurred for its production are subject to its amount and the technology applied. The fresh water producing installation is regarded as the integral part of the energetic system, located within the balance boundary. This means that the energy needed to drive the evaporator installation pumps is not included as the effective energy, also the energy difference occurring between the sea water carried to the recovery system and the produced fresh water is omitted. The fresh water obtained from the evaporator is not regarded as the effective energy carrier.

Generally, the waste energy utilisation degree can be characterised by the ratio of the effective energy, obtainable in the result of the recovery system application, to the sum of the waste energy of the fuel burning machinery [8]. This index, considered as the energetic degree of the utilisation of the waste energy in the marine power plant, can be presented in such case by means of the following relation:

$$\eta_E = \left(\Delta NS + N_{elWHTG} + \sum_i \dot{Q}_i \right) \Big/ \left[(1-\eta_{oME}) B_{ME} W_{dME} + (1-\eta_{oDG}) B_{DG} W_{dDG} + (1-\eta_{AB}) B_{AB} W_{dAB} \right] \quad (3)$$

where:

η_{oME} – overall efficiency of main engine;
η_{oDG} – overall efficiency of the Diesel generators;
η_{AB} – efficiency of the auxiliary oil–fired boiler.

The reduction of the effective energy value by the energetic demands related with the fresh water production is included in case when the fresh water producing installation is placed within the balance boundary of the recovery system. In case of the partial evaluation of the waste energy recovery degree in the recovery system only such energy fluxes are included which are subject to recovery. Thus defined index does not differentiate the values of the individual kinds of the effective energy, and neither includes the quality of the waste energy in the marine power plant as the source of the practical possibilities of its recovery.

The exergetic efficiency of the waste energy recovery systems

In order to evaluate the degree of the perfection of the thermodynamic processes carried out in the marine recovery systems it is possible to apply the exergetic efficiency of the recovery system.

It can be assumed that:

- Generally, the propulsion exergy consists the sum of the physical exergies of the media acting as the Diesel engine waste energy carriers, such as: exhaust gas. charging air, cooling water and lubricating oil, and in the auxiliary oil-fired boiler – exhaust gas and the propulsion work carried from outside the system.
- The value of the propulsion exergy is subject to reduction by its such part which is used for the fresh water production in the recovery system.
- The effective exergy flux consists the power output of the turbine supplementing the main propulsion ΔN_S, electric power N_{elWHTG} and the decrease of the heating media exergy flux used outside the recovery system reduced by the values of the exergy fluxes related with own demands of the recovery system.
- The differences of the physical exergies of the sea water and the fresh water produced out of it will be omitted as irrelevant.

In such case the exergetic recovery degree, as the criterion of the comparative evaluation of the thermodynamic perfection of the recovery systems, can be determined as:

$$\eta_B = \frac{\Delta N_S + N_{elWHTG} - \delta \dot{B}_{OD} + \sum_i \dot{m}_i^g \Delta b_i^g}{\sum_i \dot{m}_i^n b_i^n + N_n - \delta \dot{B}_{FWG}} \tag{4}$$

where:

$\dot{m}_i^g$ – heating media mass fluxes leaving the recovery system;

Δb_i^g – the increase of the specific physical exergies of the heating media;

$\dot{m}_i^n$ – the mass fluxes of the media consisting the sources of the propulsion exergy for the recovery system;

b_i^n – specific physical exergies of the media acting as the sources of the propulsion exergy;

$\delta \dot{B}_{OD}$ – the exergy flux used for recovery system own demands and the fresh water production;

$\delta \dot{B}_{FWG}$ – the decrease of the exergy flux of the media acting as the source of the propulsion exergy related with the fresh water production within the recovery system;

N_n – power carried to the recovery system from the outside.

The economic evaluation of the arrangements of the waste energy recovery systems

In consideration of the large variety of the arrangements of the waste energy recovery systems applicable on the ships with Diesel propulsion the decision making as to the set-up of such a system on a specific ship should result not only from the conducted technical analysis, including inter alia the thermodynamic, reliability or construction analysis, but should also be preceded by the analysis of the economic nature. The implementation of the energy-saving arrangement is usually accompanied by the increase of the investment outlays. This decision should be made jointly by the ship designer and her future owner, on the basis of the design assumptions taken for the specific ship and its operation conditions and the established technical and economic criteria [9, 10].

The well proven tool enabling to conduct the complex technical-economic analysis is among others the multi-criterion method of the solution evaluation. The practical mode of its application has been presented in [11].

The annual profit resulting from the operation of the waste energy recovery systems

One of the methods of the evaluation of the arrangements of the waste energy recovery system can be the determination of the annual profit resulting from the operation of the waste energy recovery system. Generally, the annual profit AP resulting from the application / operation of the waste energy recovery system on the ship, similar as it is done in case of the effectiveness evaluation of e.g. waste-heat boilers in the shore applications [12], can be determined from the general equation (5):

$$\begin{aligned} AP = {} & M_{pR}k_{sp} + \Delta E_S k_{sS} + E_{elWHTG}k_{sel} + \\ & + M_{fwR}k_{sfw} - P_{WHG}I_{WHG} - P_{PT}I_{PT} + \\ & - P_{WHTG}I_{WHTG} - P_{FWG}I_{FWG} - K_{WHG} + \\ & - K_{PT} - K_{WHTG} - K_{FWG} + \delta K_E + \\ & + P_{ME}\delta I_{ME} + P_{DG}\delta I_{DG} \end{aligned} \tag{5}$$

where:

M_{pR} – the annual amount of the heating medium used from the waste-heat boiler;

k_{sp} – the cost per unit of the heating medium produced in the independent oil-fired boiler, as the machinery replaced by the waste-heat boiler;

ΔE_S – the annual amount of energy transmitted onto main shaft by the turbine supplementing the main propulsion;

k_{sS} – the cost per unit of the mechanical energy produced by main engine, as the machinery replaced [supplemented] by the turbine supplementing the main propulsion;

E_{elWHTG} – the annual amount of the electric energy generated by the system with the waste-heat turbo-generators;

k_{sel} – the cost per unit of the electric energy generated by the independent Diesel generating sets, as the machinery replaced by the waste-heat turbo-generators;

M_{fwR} – the annual amount of the consumed fresh water produced in the vacuum evaporator;

k_{sfw} – the cost per unit of the fresh water taken from the shore, as the medium replaced by the water produced in the evaporator;

I_{WHG}, I_{PT}, I_{WHTG}, I_{FWG} – the investment outlays on the waste-heat boiler, main propulsion supplementing turbine, waste-heat turbo-generators and vacuum evaporator;

δI_{ME}, δI_{DG} – the corresponding reduction in the investment outlays on the purchase of the main engine and the generating sets owing to the application of the turbine supplementing the main propulsion and the waste-heat turbo-generators;

P_{WHG}, P_{ME}, P_{PT}, P_{WHTG}, P_{FWG}, P_{DG} – the annual rate of the service of the investment capital related with the waste-heat boiler, main engine, turbine supplementing main propulsion, waste-heat – turbo-generators, vacuum evaporator and Diesel generating sets;

K_{WHG}, K_{PT}, K_{WHTG}, K_{FWG} – the annual operation costs of the waste-heat boiler, turbine supplementing main propulsion, waste-heat turbo-generators, vacuum evaporator;

δK_E – the annual reduction of ecological charges, if any, owing to the utilisation of the waste energy.

The evaluation of the economic effectiveness of the waste energy recovery systems

The major indication as to the quality of the arrangement of the analysed energetic systems can be the evaluation of their economic effectiveness [13]. In case of the marine waste energy recovery systems the purpose is to apply such solutions which would lead to minimising of the generation costs of the necessary amounts of the appropriate energy forms on the ship against economically justified price. The economic effectiveness in such terms joins the adequate technical and economic criteria. In many cases, when the obtained energy generation level is constant (results from the adopted design assumptions), the analysis of the solutions is limited to conducting the economic evaluation exclusively [14].

A significant issue while making the economic evaluation of the arrangement solutions is including the time factor in the form of the adequately determined discount rate. While striving to properly consider the proecological aspects of the adopted solutions, the attention should be paid to accept the lower values of the discount rates.

In the models describing the investment outlays and the operation costs incurred, not only the costs associated with the execution and operation of the waste energy recovery system itself should be included, but the costs of the entire energetic system of the ship.

The result of the economic analysis of the solutions of the waste energy recovery system on the ship should be the determination which of them (with the assumed / target technical parameters) together with the remaining elements of the ship's energetic system (the propulsion system, independent generating sets, oil-fired boiler) meets the condition of the minimum costs incurred for the purchase and operation. It could be assumed that the sufficient criterion of the economic evaluation is the comparison of the purchase costs of the ship's energetic system and the costs of the fuels and luboils consumed throughout the entire operation period of the vessel. In the more profound and detailed analyses one should also take into account among others the comprehensive costs of the system service. The economic analysis consists in the further stages of the evaluations of the design solutions as the basis for the performance of the risk and economic effectiveness analysis [15].

On the basis of the analysis of the dynamic methods of the economic analysis conducted in [14], the most frequently applied effectiveness indices of the shipping investments could be divided into three categories:

AAC – Average Annual Cost;
NPV – Net Present Value;
RPT – Real Payback Time.

Considering the fact that the energetic system, including the waste energy recovery system, consists only a component of the whole investment which a ship is, as the sufficient comparative criterion allowing to evaluate the solutions of the systems may be the average annual cost AAC, whereas the RPT index is the significant parameter playing a major role in the decision-making process concerning the possible application of the optimum recovery system on a specific ship.

This is calculated from the relation:

for $q \neq 1$

$$\mathrm{RPT} = \frac{\log\left(1 + \frac{q-1}{q} \cdot \frac{\Delta I_{SE}}{\Delta K_{fo}}\right)}{\log q} \tag{6}$$

for $q = 1$

$$\mathrm{RPT} = \frac{\Delta I_{SE}}{\Delta K_{fo}} \tag{7}$$

where:

$$q = \left(1 + \frac{S_i}{100}\right) \Big/ \left(1 + \frac{r}{100}\right)$$

ΔI_{SE} – the difference between the investment outlays concerning the energetic system arrangement solution under consideration and the investment outlays concerning the cheapest system assumed as the reference basis:

$$\Delta I_{SE} = \left(I_{ME} + I_{DG} + I_{SG} + I_{WERS} + I_{AB}\right)_i + -\left(I_{ME} + I_{DG} + I_{SG} + I_{WERS} + I_{AB}\right)_{\text{basis}} \tag{8}$$

ΔK_{po} – the difference between the annual cost of the fuel and luboils for the energetic system assumed as the reference basis and the annual cost of the fuel and luboils for the system under consideration:

$$\Delta K_{fo} = \left(K_f + K_o\right)_{\text{basis}} - \left(K_f + K_o\right)_i \tag{9}$$

I_{ME} – investment outlays related with the main engine purchase;

I_{DG} – investment outlays related with the purchase of the independent generating sets;

I_{SG} – investment outlays related with the purchase of the shaft generator;

I_{WERS} – investment outlays related with the purchase of the waste energy recovery system;

I_{AB} – investment outlays related with the purchase of the auxiliary boiler;

K_f – annual cost of fuels burnt in the engines;

K_o – annual cost of the luboils;

S_i – inflation rate (annual price increase of fuel and oil in percent);

R – annual discount rate.

In case of the analysis of several variants, the higher appreciated is that where the payback time is shorter. The assumption of the high discount rates extends the investment payback time. The index analysed does not account for the expected benefits of the application of the complex recovery systems in the form of inter alia gaining the additional freight or possible reduction of the ecological charges owing to the status of the "green ship".

The payback time of the waste energy recovery systems proposed by MAN B&W Diesel A/S has been the object of the analysis presented in [16]. The single-pressure and double-pressure systems have been considered. Four power plants variants have been considered: with 6S90 ME-C engines of 29,340 kW output, 7K98 ME-C engines of 39,970 kW output, 12K90 ME engines of 54,840 kW and with 12K98 ME engines of 68,640 kW output. The obtained electric power values, as the result of the operation of the waste-heat gas turbines and steam turbines, consisted from 5.4 to 9.8% of the service power output of the main engines (85% maximum continuous power). This is shown in figure 2.

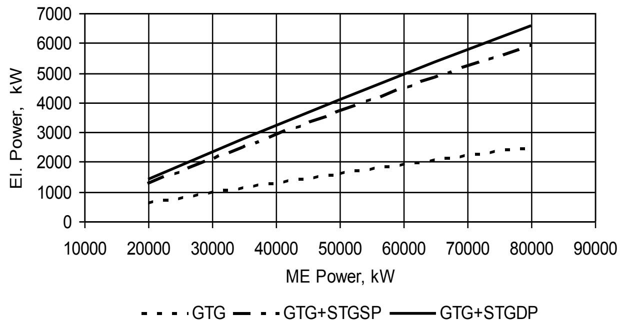

Fig. 2. The waste-heat turbo-generator power as the function of the main engine power output [16]: GTG – Gas turbo--generator; GTG+STGSP – Gas turbo-generator and steam turbo-generator in the single-pressure system; GTG+STGDP – Gas turbo-generator and steam turbo-generator in the double--pressure system

The payback time of the systems under consideration does not depend on the degree of their complexity (the single- or double-pressure system), but on the main engine power output. This time oscillates between 5 years for the biggest of the engines considered and the period of 9 years for the smallest engines. This relation between the recovery system investment outlays payback time and the main engine power output is shown in figure 3. The possible reduction of the fuel consumption

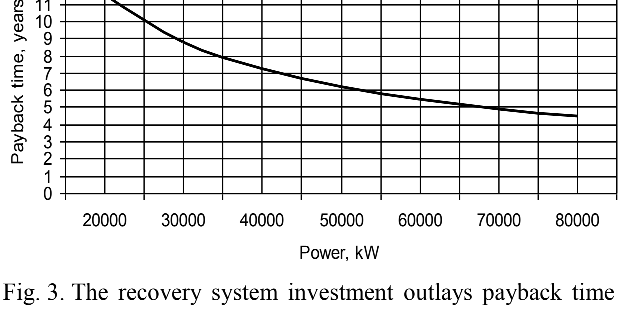

Fig. 3. The recovery system investment outlays payback time as the function of the main engine power output [16]

oscillates between 8–10% owing to the application of the single-pressure systems with the engine normal load and between 9–11% for the more complex double-pressure systems.

The figure 4 shows the index of the investment outlays payback time as the payback time of the outlays in reference to the main engine power output in the function of the main engine power output. This index is more favourable for the ships equipped with main engines of high power outputs, therefore, in case of building of the big ships the consideration of the application of the advanced waste energy recovery systems becomes of special significance.

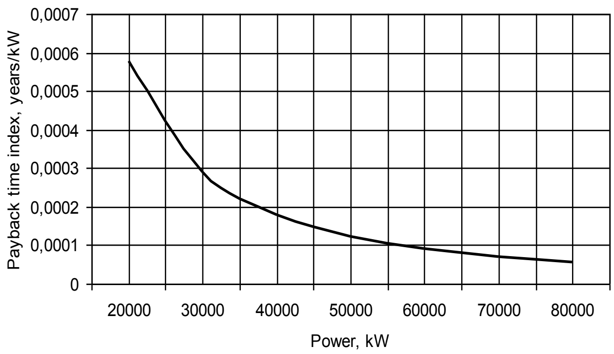

Fig. 4. The recovery system investment outlays payback time index as the function of the main engine power output

Conclusions

The way to improve the marine power plant energetic effectiveness is inter alia the application of recovery systems of the waste energy whose basic source on the ships with Diesel propulsion, presently dominating in the worldwide fleet, are the piston Diesel engines, which consist their main propulsion. There is a large variety of the possible arrangements of such systems. Besides the most simple and commonly applied systems that satisfy exclusively the heating demands on the ship, a growing interest can be observed in respect to the more complex systems where mechanical and electric energy is additionally generated. The acceptance of the specific system for the application is subject to the type and size of the ship, the power ratings and the type of her main engine, as well as the acceptable installation cost. The comparative analysis of the waste energy recovery systems at the stage of the execution of the preliminary design of the ship's power plant makes their choice possible, when reasonably simple and complex methods of their evaluation are available.

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