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Increasing the Economic Efficiency of Marine Power Plants Using Waste Heat Boilers with Controlled Flow Separation

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ABSTRACT

Heat recovery of exhaust gases from main and auxiliary marine diesel engines is an effective way to improve the technical and economic parameters of marine power plants. Improvements in engine efficiency necessitate an increase in the weight-size parameters of the waste heat boilers, which makes it difficult to recover heat. Intensification of the heat transfer process is considered to be an effective way to reduce these indicators. By utilising mathematical modelling, this paper shows the effectiveness of using profiled heating surfaces of waste heat boilers for this purpose. The use of elliptical heating surfaces with a mechanism of controlled flow separation, in the form of a triangular notch, is proposed. This will reduce surface drag and increase the overall thermal-hydraulic efficiency of the heat transfer processes. It is shown that the use of such surfaces in waste heat boilers makes it possible to increase the efficiency of marine power plants in tankers with a deadweight of about 45,500 tons up to 1.5% absolute and container ships with a deadweight of about 122,000 tons up to 2.5% absolute.

Keywords: marine power plant, waste heat boiler, intensification of heat transfer, efficiency, heat transfer surface, flow separation, waste heat recovery

INTRODUCTION

According to analysts, the average annual growth rate of world trade for the period 2019-2023 increased by 3.4% [1]. Maritime transport played an important role in achieving this aim.

As of January 2022, the composition of the main types of transport vessels in the structure of the world merchant fleet was as follows: bulk carriers - about 43%; oil tankers, product tankers and Liquefied natural gas (LNG) or Liquefied petroleum gas (LPG) tankers - about 30%; and container ships - about 14%. The portfolio of new orders for these types of vessels in 2022 was as follows: bulk carriers – about 35%; oil tankers – 22%; container ships – 18%; and gas carriers – 13% [1].

An analysis of the composition of the power plants of the listed vessels, according to the data in [2], showed that diesel power plants, with direct power transmission to the propeller, are mainly used as propulsion plants. A feature of some LNG tankers is the use of diesel-electric plants. Engine types 6S60MC-C Mk7 and 6S70MC-C Mk7 (which are licensed by the MAN B&W Company) were used for tankers and bulk carriers with a deadweight of up to 75,000 tons, according to [2]. Large-capacity container ships, built between 2015 and 2020, used 8-11 cylinder engines of the S90ME-C10.2 type. Engines of the 6G60ME-C9.2 type (built by the MAN B&W Company) or similar (Wärtsilä Company) engines were used in tankers.

At the same time, the analysis of statistical data for the composition of the power plants of these vessels showed that their steam consumption in 'sea mode' reached up to 5000 t/h. However, if the waste heat boilers of the main engines were installed on the vessels built in 2010 to ensure this then, starting in 2015, the preference was given to composite boilers.

In part, this can be explained by the fact that, in order to obtain a certain amount of steam, the required amount of heat is calculated by Eq. (1) [3]:

$$Q_s = D \cdot (i_s - i_w) \quad (1)$$

where D is the required steam capacity, kg/s; and i_{st} and i_w are the enthalpy steam and water respectively, J/kg.

Using the obtained value of Q_s, the required heating surface area of the waste heat boiler can be determined by Eq. (2) [3]:

$$Q_s = k \cdot F \cdot \Delta t_{\log} \quad (2)$$

where k is the overall heat transfer coefficient, W/(m²·K); F is the heat transfer surface area, m²; and Δ_{tlog} is the log mean temperature difference, °C.

On the other hand, the amount of heat extracted from the exhaust gases of the main engine in the waste heat boiler is [3]

$$Q_g = G_g C_{pg} \left(t_g^{in} - t_g^{out} \right) \quad (3)$$

where G_g is the main engine exhaust gas flow rate, kg/s; C_{pg} is the average specific heat capacity of gases in the temperature range $t_g^{n} \ldots t_g^{out}$, J/(kg·K); and t_g^{n}, t_g^{out} is the exhaust gas temperature at the inlet and outlet of the boiler respectively, °C.

Then, assuming equal performance conditions of a pair of the same parameters, and under equal conditions with the same values k, $\Delta t_{\log}$, C_{pg}, t_g^{n}, and t_g^{out}, increasing the gas flow rate G_g will lead to the possibility of decreasing the heat transfer surface F and decreasing the flow rate - to the necessity of increasing F.

A comparison of the parameters for the two MAN B&W engines is shown in Table 1 [4].

Tab. 1. Engine characteristics of MAN B&W Company models

	6S60MC-C Mk7 [4]	5G60ME-C9.5 [4]
Nominal power N_e, kW	13530	13400
Gas flow rate G_g, kg/s	32.9	27.8
Exhaust gases temperature t_g, °C	255	255

Under such conditions, the increase in the surface area of heat transfer will be up to 32.9/27.8≈1.18 (18%) and, if it is necessary to take into account the work at partial capacities, this increase can reach 33%, which will complicate the location of boilers in the exhaust gas ducts of vessels.

Therefore, the development of compact heat transfer surfaces for marine waste heat boilers is an urgent problem. The solution of this problem will allow for a bigger use of waste heat boilers as part of marine power plants, which will increase their technical and economic efficiency by reducing the total fuel consumption of the plant, as well as reducing harmful emissions into the environment.

LITERATURE ANALYSIS OF EXISTING BASIC TECHNICAL SOLUTIONS, HIGHLIGHTING THE UNRESOLVED PART OF THE PROBLEM

It is known that reducing the waste heat boiler surface area is possible through the intensification of heat transfer processes.

The most commonly used method of heat transfer intensification is the finning of heating surfaces. Many different types of ribs are currently used [5]. Their advantages include the resulting reduction in weight-size parameters and manufacturability, while their disadvantages include an increase in aerodynamic drag of the surface and being more susceptible to dirt and fire.

Kuznetsov V showed in [6] that pipes with a non-circular cross-section can be used as an alternative method for creating the heating surface (flat, oval or elliptical). The later separation of the flow on such surfaces contributes to the reduction of their aerodynamic drag, which improves their overall thermal-hydraulic characteristics.

A further development of such surfaces may be the use of the "controlled flow separation" mechanism in them. According to [7], the dimples used for this purpose generate volumetric vortex fluctuations in the flow. These pulsations introduce additional kinetic energy into the boundary layer, contributing to its stability by providing a positive pressure gradient.

The beneficial effect of using dimple systems to intensify heat transfer processes was shown in [8]. However, it presented the results of the research on the efficiency of using dimples on the plate ribs of flat-oval and elliptical tubes but did not investigate the direct effect of depressions on the pipes.

A detailed overview of the mechanism of controlled flow separation was presented in [7] and [9]. However, these papers presented the results of research relating to gas turbine blades and the flat surfaces of plate heat exchangers. This makes it difficult to use the results obtained for multi-row tubular bundles, which are typical for marine waste heat recovery boilers.

Numerical results from flow separation research on the wing profile were presented in [10]. The results presented were limited to a single wing profile. This does not allow them to be used for tubular bundles, even if we assume that the wing profile is a well-streamlined body.

Similar results, aimed at increasing lift and drag, were presented in [11]. The results did not take into account the peculiarities of the hydrodynamic bundles of such profiles.

A promising method of controlling flow separation was presented in [12] and [13], where a plasma actuator was proposed for this purpose. This makes it possible to suppress the Kármán vortex track. The presented results were limited to data for only one circular cylinder and the possibilities of implementing this technology for the pipe bundles were not presented.

Research results of the flow separation mechanism at the compressor working stage were presented in [14] and [15]. The presented results were limited because only one compressor stage was researched.

The analysis showed that there is a lack of data on the efficiency of using round and profiled pipe-bundles with a controlled flow separation mechanism as the heat exchange surfaces of waste heat boilers of marine power plants.

Spherical dimples were used to generate volumetric vortex structures and, at the same time, the vortex structures which formed were similar to natural vortex structures of the 'tornado' type [16], having a triangular shape with the top down in cross-section.

Therefore, to assess the effectiveness of the use of round and profiled pipes with a mechanism of controlled flow separation in waste heat boilers in ship power plants, it is necessary to: justify the investigation method; justify the criterion and perform a comparative assessment of the thermal-hydraulic efficiency of using dimple systems and a triangular notch made along the entire length of the pipe at the point of flow separation (on a single pipe and in pipe bundles); and carry out an assessment of the effectiveness of using the proposed surfaces as part of the waste heat boilers of marine power plants.

INVESTIGATION METHOD AND COMPARATIVE EFFECTIVENESS CRITERION

It is known that the methods of studying thermal-hydraulic characteristics are mathematical and physical modelling. The modern development of mathematical modelling tools in the direction of CFD (Computer Fluid Dynamic) modelling makes it possible to justify the most effective implementation options out of a variety of options, which significantly reduces the cost of developing heat exchange surfaces and the experimental research required.

Mathematical modelling methods, using software packages with a free license (Code Saturne [17] and the cloud service Sim Scale [18]), were used to study the heat transfer processes under controlled flow separation.

The mathematical model describing the thermal-hydraulic processes in the external flow around the pipe bundle comprises a system of equations, including the equations of continuity, of quantity of motion, and conservation of energy. Semi-empirical equations for the pressure tensor, the heat flux, the equation of state for ideal gases, and the differential equations of the turbulence model are used to close this system [19].

On the basis of the recommendations given in [19, 20], the *RSM* turbulence model was used to close the resulting system of equations. To solve the resulting system, the *RANS* approach was implemented.

The mathematical model was verified by comparing the results of numerical modelling with the experimental data obtained during the testing of a prototype heat exchange surface consisting of flat-oval pipes [8].

The efficiency of heat transfer processes was evaluated using the Reynolds analogy factor [16] as

$$FAR = \frac{\left(Nu/Nu_0\right)}{\left(f/f_0\right)} \tag{4}$$

where Nu and f are the Nusselt number and coefficient of drag, respectively, and index 0 defines the base surface with which the comparison is made.

Such an assessment not only makes it possible to assess the change in heat transfer but, also, to take into account the change in resistance required to achieve such heat transfer.

EFFICIENCY DETERMINATION OF PROFILED HEAT EXCHANGE SURFACES WITH CONTROLLED FLOW SEPARATION

The capabilities of modern post-processing of the obtained CFD results make it possible to widely analyse the obtained results.

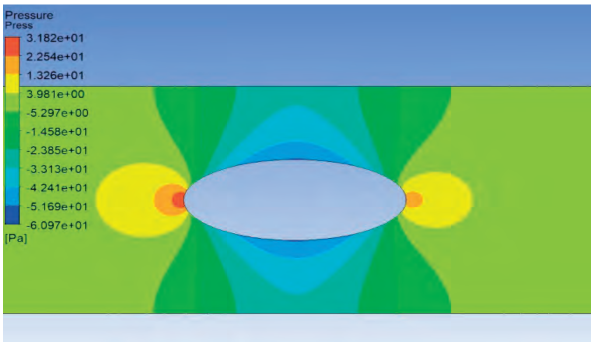
Fig. 1 (*a-d*) presents the results of flow simulation around a single smooth elliptical pipe (*a*), and then with one triangular notch at the place of the expected flow separation for the studied parameters (*b*), with two symmetrical triangular notches (*c*), and with plotted dimples (*d*). The presented results were obtained for the number Re=10000 and the temperature of the flow that flowed around the surface, 300 °C.

The results show the redistribution of pressure during the flow around the surface in all four cases and allow us to achieve the following results for the *FAR* indicator. For comparison, Table 2 presents the results of flow simulations around a single smooth cylinder and those with dimples.

Tab 2. Results of comparative simulation of flow around single round and elliptical pipes

Heat transfer surface	Value of *FAR* indicator
Smooth round pipe	1.0
Smooth elliptical pipe	2.2
Round pipe with dimples	1.2
Elliptical pipe with single notch	3.2
Elliptical pipe with two notches	3.9
Elliptical pipe with dimples	2.1

Fig. 2 (*a-c*) show the results of modelling the flow around the elliptical pipe bundles. In this case, a slightly different flow pattern was observed. As a result of the superposition of the rarefaction regions in the bundle row from the upper



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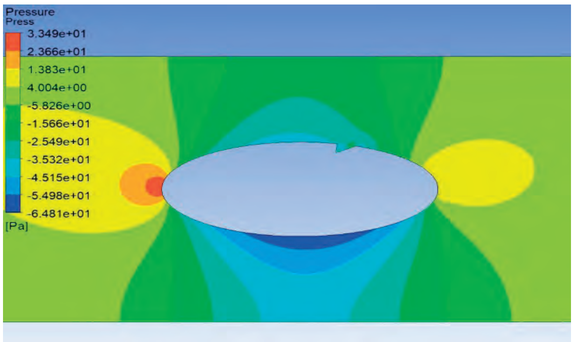

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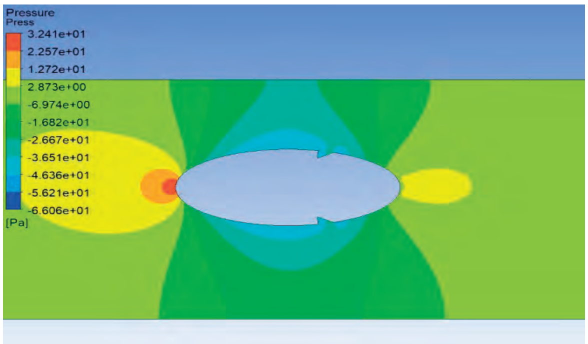

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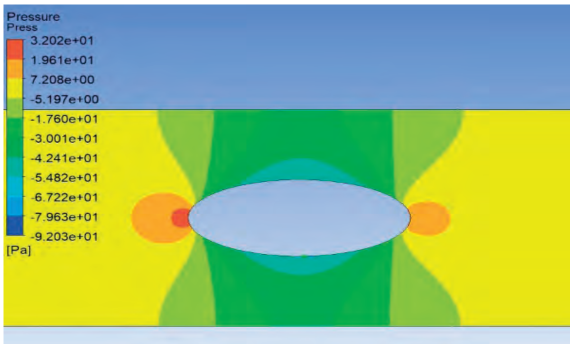
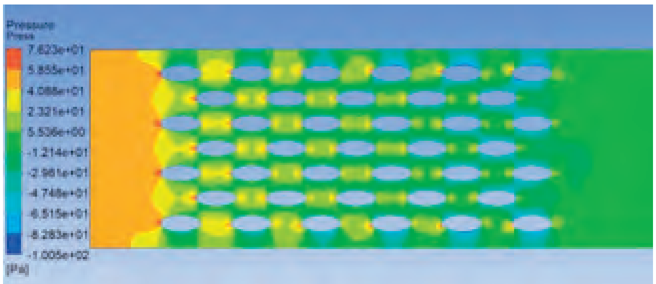


d

Fig. 1. Simulation results of the flow around a single elliptical pipe

and lower notches in a pipe with two notches (Fig. 2c), the total bundle drag is greater than in a bundle of pipes with one notch (Fig. 2b). Thus, the thermal-hydraulic efficiency of the single-notch bundle is higher (Tab. 3).



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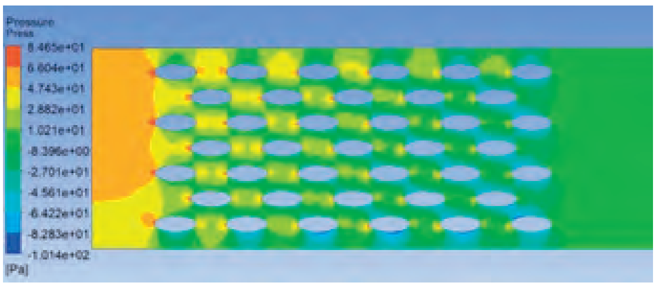

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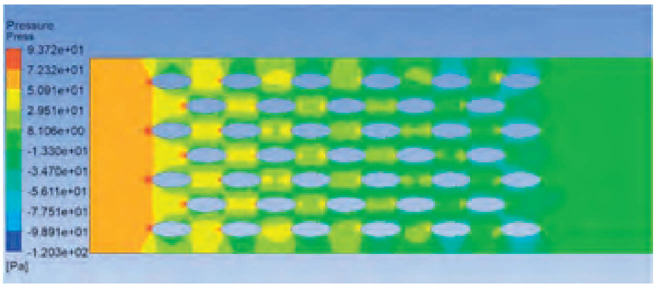


c

Fig. 2. Results of comparative modelling of flow around profiled pipe bundles: a) bundle of smooth elliptical pipes; b) bundle of pipes with a single notch; c) bundle of pipes with two notches

Tab. 3. Results of comparative modelling of flow around a bundle of round and elliptical pipes

Heat transfer surface	Value of *FAR* indicator
Bundle of smooth round pipes	1.000
Bundle of round pipes with dimples	1.303
Bundle of elliptical smooth pipes	1.465
Bundle of elliptical pipes with single notch	2.450
Bundle of elliptical pipes with two notches	1.686
Bundle of elliptical pipes with dimples	1.363

The results show that the most efficient heating surface, in terms of the “change in heat transfer/change in resistance” ratio, is the surface of elliptical pipes with a single notch. The installation of such pipes in bundles should not cause difficulties. In such boilers, the pipes are usually fixed by rolling. Therefore, it is advisable to make the ends of elliptical pipes round, which will be fixed in the pipe plate (Fig. 3).

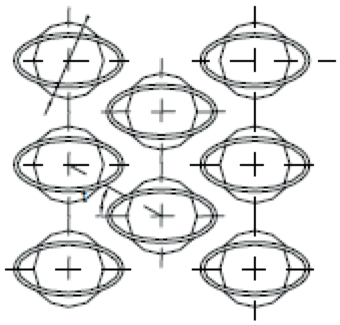


Fig. 3. Features of elliptical pipe mounting

Therefore, a surface of elliptical pipes with a single triangular notch was accepted for further analysis.

The results obtained made it possible to assess the efficiency of waste heat recovery boilers with a suitable heat transfer surface as part of marine power plants.

Thermal efficiency is accepted as being an efficiency indicator. The increase in efficiency should be due to a decrease in the total fuel consumption of the plant due to an increase in the efficiency of the utilisation of secondary energy resources.

Improving the efficiency of marine power plants is considered for tankers and bulk carriers of the PANAMAX type and container ships, with a deadweight of more than 100,000 tons.

TANKERS AND BULK CARRIERS OF PANAMAX TYPE

According to the data in [2], during the period from 2014 to 2022, about 150 vessels (with a deadweight of 45,000-45,700 tons) were built with a similar composition of power plant (Fig. 4).

Fig. 4.Tanker with deadweight of 45,500 t with a MAN 6S50ME-B9.3 main engine

A diesel power plant with direct power transmission to the propeller was used. Low-speed «B» series MAN B&W main engines and Aalborg XW waste heat boilers were installed. The steam capacity of the auxiliary boiler was 16,000-18,000 kg/h, depending on the transported cargo.

For the purposes of the analysis, the total steam discharge for such a tanker was taken to be in accordance with the data in [21, 22] which, in typical modes, were:
- ballast crossing – 2,100 kg /h;
- passage with maintenance of cargo temperature – 5,800 kg/h;
- passage with heating of cargo – 13,400 kg /h;
- passage with mopping up of tanks – 11,950 kg /h.

The schematic diagram of the system for the deep heat recovery of high-potential waste energy resources of the tanker power plant's main engine, with a deadweight of 45,500 tons, is shown in Fig. 5.

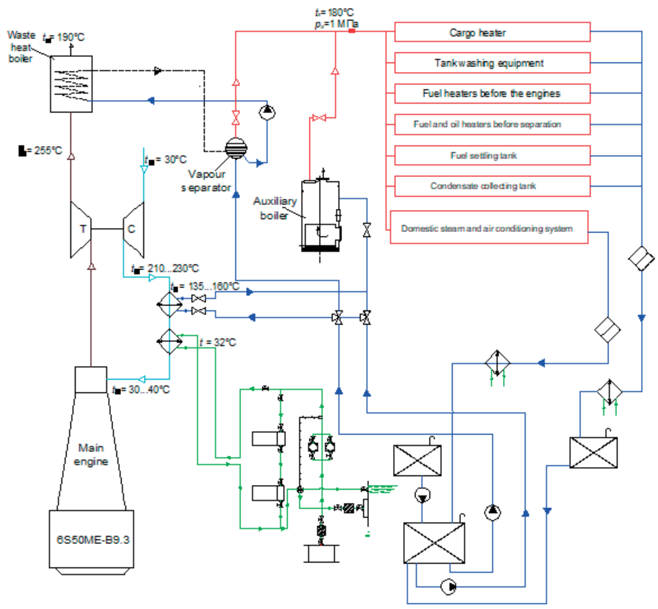


Fig. 5. Schematic diagram of the system for deep heat recovery of high-potential secondary energy resources of the tanker power plant main engine with deadweight of 45,500 tons

The diagram shows a two-section charge air cooler of the main engine. Both this and the waste heat boiler used an elliptical surface with controlled flow separation. This made it possible to provide heating of feed water in the first section of the charge air cooler, with its specified weight-size parameters, from 60 to 135°C…160 °C, depending on the main engine power. Next, the water was supplied to the waste heat boiler and, if necessary, to the auxiliary boiler. The steam generating plant produced saturated steam at a pressure of 1 MPa.

The calculated steam capacity values, taking into account the intensification of heat transfer when using elliptical pipes with controlled flow separation, are presented in Table 4.

Tab. 4. Generalised table of steam consumption of tankers with deadweight 45,500 t

	Transition mode with maintaining the temperature of the cargo		Transition mode with warm-up of the cargo		Transition mode with Tank Clearing	
	[21, 22]	Calculation	[21, 22]	Calculation	[21, 22]	Calculation
Steam capacity of the waste heat boiler, kg/h	1000	3630	1000	3630	1000	3630
Necessary steam capacity of the auxiliary boiler, kg/h	4800	2170	13400	10770	10950	8320

The results of the calculations show that the use of heat transfer intensification in waste heat boilers increases their steam capacity and, in the ballast transition mode, excludes the auxiliary boiler from operations (not indicated in the table), significantly reducing its load in other modes.

The expected results of introducing heat transfer intensification, to improve the efficiency of the tanker's power plant, are presented in Table 5.

Tab. 5. Expected results of implementation of heat transfer intensification to improve the efficiency of the tanker's marine power plant

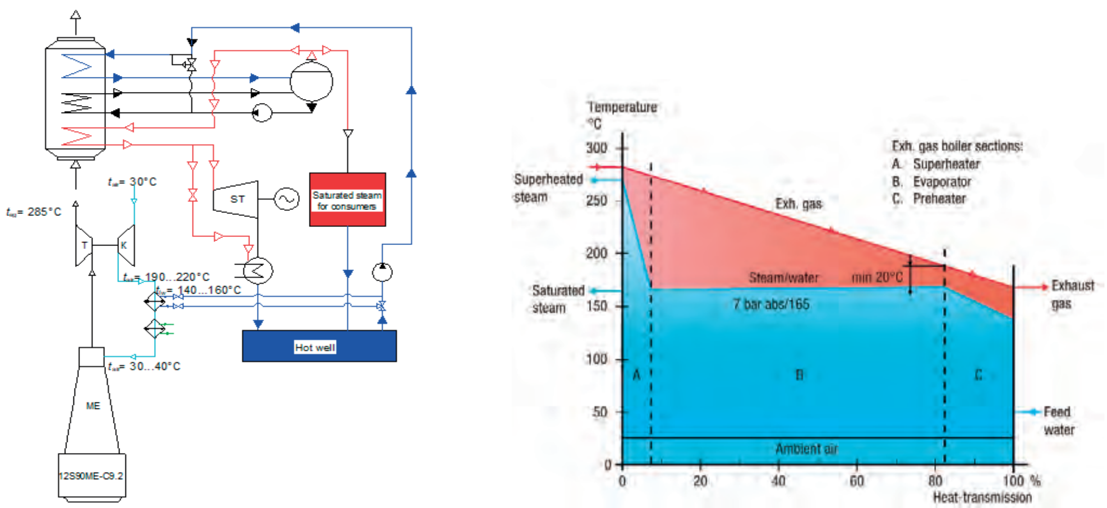
No.	Indicators, units of measurement	Values	
		Basic [2]	Calculated
1	Marine power plant efficiency, %	50.8	52.1

Analysis of the composition of bulk carrier power plants [2] has shown that the steam capacity of the waste heat boiler components does not exceed 1000-1500 kg/h, which makes it possible to provide consumers with power plants in running modes. In this case, the intensification of heat transfer in the waste heat boiler can be used to reduce its weight-size parameters, which should facilitate the placement of equipment in the engine room to neutralise harmful emissions from the power plant.

CONTAINER VESSELS

According to [2], for container vessels with a deadweight of more than 100,000 tons (Fig. 6), the capacity of a marine electric power plant can reach 33-41% of the main engine's power. This is due to the fact that such vessels can carry up to 10% refrigerated containers in the total capacity of the vessel. This makes it possible to recover the heat of both the main and auxiliary engines [4], which makes the issues of energy saving through the recovery of heat from secondary energy resources relevant.

Fig. 6. Container ship with deadweight of 122,000 t and a MAN 12S90ME-C9.2 main engine



a *b*

Fig. 7. Schematic diagram of the high-potential secondary energy resources heat recovery system of the container ship's power plant main engine [4, 23]

The schematic diagram of the heat recovery system of high-potential secondary energy resources of the main engine of the container ship's marine power plant is shown in Fig. 7a [4]. To ensure the functioning of the recovery system, the main engine is rebalanced to raise the temperature of its exhaust gases (Fig. 7b) [23]. The feed water of the boiler plant is heated up to 160-180 °C in the first section of the inflatable air cooler of the main engine, the heat exchange surface of which is made of elliptical tubes with one triangular notch. The water enters the recovery boiler, which produces saturated steam at a pressure of 0.7 MPa and superheated steam at a temperature of 280 °C.

Changes in the structure of the heat balance of the main engine with a waste heat boiler, with and without intensification of the heat transfer processes, are shown in Fig. 8.

The results presented for improving marine power plants' efficiency are obtained for the rated load mode of engines. The expected increase in power plant efficiency with a waste heat recovery boiler with controlled flow separation, obtained based on the mathematical model [24], is up to 2.5%.

The results were obtained at 80% engine load. Since the engine load is a probabilistic value and depends on many factors (weather conditions, vessel load, technical conditions of the propulsion complex, etc.), it is advisable to continue researching the efficiency of the heat exchange surface at partial load modes (e.g. 60%, 40%, etc.), as well as various geometric dimensions of the element providing controlled flow separation.

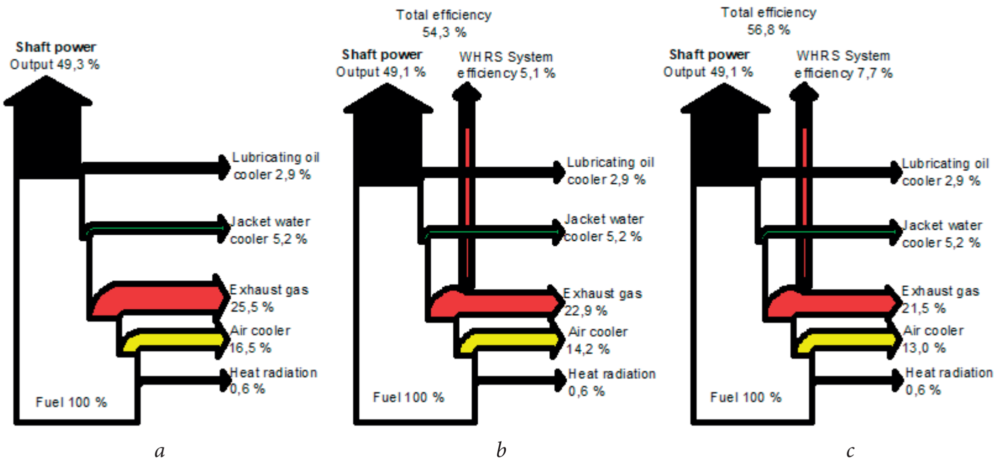


Fig. 8. The heat balance of the 12S90ME-C9.2 engine: a – no heat recovery, b – WHRS MAN B&W system [4], c – WHRS MAN B&W system with proposed heat transfer intensification

It was found that the use of the proposed technical solutions for heat transfer intensification in the charge air cooler and the main engine waste heat boiler reduced emissions in the running mode, due to a decrease in total fuel consumption, to 2.0% absolute (Table 6).

Tab. 6. Expected results of heat transfer intensification implementation to improve the efficiency of the container marine power plant

№	Indicators, units of measurement	Values	
		Basic [4]	Calculated
1	Power of the system WHRS, MW	2.48	3.24
2	Thermal efficiency of marine power plant, %	54.3	56.8

DISCUSSION OF RESULTS

Increasing the efficiency of using exhaust gas waste heat from the main and auxiliary engines of marine power plants makes it possible to increase their economic and environmental efficiency. The results obtained show that waste heat boilers with controlled flow separation can be effectively used for this purpose.

CONCLUSIONS

1. It was found that, when using the mechanism of controlled flow separation for flow around single pipes, the most effective "heat transfer increase/drag increase" ratio is obtained for a pipe with two triangular notches at the flow separation point at a given flow mode.

2. In bundles of pipes, the most effective, in terms of the specified ratio, are bundles of elliptical pipes with one triangular notch at the point of flow separation at a given flow mode.

3. It has been shown that the use of such bundles as part of marine waste heat boilers makes it possible to increase the efficiency of power plants by up to 2.5%, by reducing the total fuel consumption of the plant.

4. It is advisable that further studies are undertaken into the efficiency of the proposed heat exchange surface in partial modes of operation, as well as the impact of the notch size on the service life.

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