Рекупераційні системи для утилізації енергії вихлопних газів дизельних двигунів, що існують, призначені для суден великого та середнього розміру. Існує потреба розробки відповідної системи рекуперації енергії відхідних газів для маломірних суден.

Створено технологічну модель рекупераційного пристрою для маломірних суден у вигляді термоелектричного генератора (ТЕГ), який працює на енергії відхідних газів. Проаналізовані технічні умови розташування ТЕГ на судні і визначені складові його конструкції. Запропоновані технічні рішення для удосконалення процесу теплопередачі енергії від газу до ТЕГ, а саме: використання термоелектричних модулів (ТЕМ), що мають робочу температуру вище 1000 °C; застосування квадратної форми перерізу трубопроводу і розміщення спіралеподібного циліндра всередині трубопроводу генератора.

На підставі результатів теоретичних обчислень досліджено теплову модель термоелектричного генератора і розраховані технологічні параметри використання ТЕМ для забезпечення максимального значення ККД ТЕГ. Встановлено необхідність поділу генератора на три складові секції, що працюють як окремі генератори. Показана можливість одержання при використанні ТЕГ до 0,8 кВт електричної енергії, якщо частота обертання валу дизельного двигуна дорівнює 1500 об/хв.

Запропоновано оптимальний спосіб використання електричної енергії генератора, що полягає у застосуванні мотор-колеса. Функцією мотор-колеса обрано перетворення надлишкової електричної енергії ТЕГ в механічну енергію (в допомогу основному двигуну) в межах комплексного підвищення ККД використання палива. Надано відповідну схему під'єднання мотор-колеса до енергосистеми судна.

Вказані шляхи підвищення ККД термоелектричного генератора та розширення можливостей його застосування на маломірних суднах

Ключові слова: рекуперація енергії, дизельний двигун, маломірні судна, термоелектричний генератор, вихлопні гази

BUILDING A TECHNOLOGICAL MODEL OF THE EXHAUST GAS ENERGY RECOVERY DEVICE FOR THE DIESEL ENGINE ON A SMALL-SIZED VESSEL

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1. Introduction

The shortage of energy resources, the desire to use "green technologies" necessitate the improvement of efficiency and environmental indicators of vessel power plants. This need has been documented in the requirements of the International Maritime Organization, Annex VI to the International Convention for the prevention of pollution from ships. Given this, there is a relevant scientific and technical task in the field of energy-saving machine building: to improve the system of energy recovery for vessel engines in order to enhance the efficiency of fuel utilization.

A significant portion (25–30 %) of energy from a ship's diesel engine is released in the form of the thermal energy of exhaust gases, which renders even more relevance to the issue of its recovery. One of the ways to solve such a task is to design and improve the thermoelectric generators (TEG) installed on the exhaust pipe of a ship's engine. As a result, the exhaust gas energy feeds a vessel's electrical circuit, thereby making it possible to remove the electromechanical generator from its electric system.

Analytical calculations indicate [1] that rising fuel prices exert a much larger impact on transportation costs incurred by cargo deliveries by water than by other modes of transportation. At present, there is a steady trend towards price rise for diesel fuel and a corresponding increase in the proportion of its price in the cost of goods transported by waterways. Increasing fuel efficiency by at least several percent owing to the implementation of the engine energy recovery system could significantly affect the decrease in total cost, as well as improve the environmental aspect of transportation by small-sized vessels.

2. Literature review and problem statement

Aboard large specialized vessels, the exhaust gas energy is used in cogeneration plants for the combined production of mechanical and electrical energy. Study [2] considers the appropriate operation principle of vessel thermal machines, whose mechanical energy supplements the energy of the main engine. In a ship's hybrid powerplant, the Stirling engine could be linked to a crankshaft through a hydraulic clutch or work for an electric generator. However, a hybrid plant has significant weight and dimensions and a high cost.

More promising for modern diesel engines is, first, to use the Rankine cycle and, second, to apply the latest developments of turbochargers with an inverse electric machine on the axis. The former was investigated in work [3] as a means to optimize the thermodynamic characteristics of a vessel diesel-electric station with the combined system of exhaust gas heat utilization and the diesel cooling system. The latter, according to study [4], makes it possible to recycle the heat of exhaust gases under the modes at which it is redundant and to add to the turbo compressor rotor rotation under other modes. The disadvantage is the issue of cooling the electric machine. A common drawback of both approaches is the fact that small-sized vessels equipped with stationary motors with a capacity close to 100 kW typically have no space for the examined recovery systems. In addition, servicing them leads to undue additional costs. Therefore, for small-sized vessels, the optimal solution is to use a thermoelectric generator, which directly (without additional coolers) converts thermal energy into electricity. Such a TEG should not include moving parts, not require additional maintenance.

Technical advancements related to the recuperation of energy from exhaust gases of ship engines with the application of TEG are based on appropriate solutions for automobile internal combustion engines. For example, based on data from General Motors, the authors of [5] modeled the heat and electric energy transfer processes in a TEG using the splitting of TEG into sections. Building on such an idea, study [6] proposed the structural division of a thermoelectric generator into three sections that operate as separate thermoelectric generators. The TEG that uses air cooling was estimated. The authors considered the introduction, inside a gas flow, of a hollow cylinder with longitudinal edges on the surface to improve heat transfer by radiation. However, the above advancements primarily concern gasoline engines while ship's engines are diesel. Such engines, at the same capacity as gasoline ones, have a larger volume and a lower exhaust gas temperature. In addition, in order to obtain optimum engine efficiency, the diameter of an exhaust pipe in the diesel engines is increased. That changes the parameters of heat exchange and specifications for the optimal TEG functioning. There is a need to perform separate calculations for the temperature parameters of the diesel engine exhaust system.

The appropriate study was reported in [7] when designing a thermoelectric generator for the diesel engine with a capacity of 330 kW. The disadvantage of the specified project is that preventing the overheating of thermoelectric modules requires that the system should be supplemented with a bypass, which releases the excessive exhaust gas. Thus, the temperature of the modules is maintained at the maximum permissible level, but there is a loss of part of the energy that should be recovered.

Certain modifications of the experimental and industrial designs of TEG for ship diesel engines were examined, respectively, in works [8, 9]. These structures employ thermoelectric modules (TEM) based on Bi_2Te_3 with the maximum upper temperature of 350–550 °C (depending on the module modification). Therefore, the TEG technological circuit includes either the extension of an exhaust system pipeline or a bypass for exhaust gas. These design features warrant the generator performance and reduce the exhaust gas temperature to the specified range. However, there is a reduction in a temperature gradient and a corresponding reduction in TEG efficiency.

Thus, it is expedient to undertake a study to build a technological scheme of the ship TEG for small-sized vessels, which should be devoid of the above drawbacks. The result would also tackle the task of creating a system for converting excessive electrical energy into mechanical energy (to assist the main engine) within the comprehensive increase in the fuel utilization efficiency.

3. The aim and objectives of the study

The aim of this study is to build a technological model of the recuperation device for small-sized vessels in the form of a thermo-electric generator that operates using the energy of exhaust gases. That would make it possible to improve the efficiency of fuel utilization by vessels of this type.

To accomplish the aim, the following tasks have been set:
– to analyze technical conditions for the thermoelectric generator arrangement and determine the components of the TEG design;
– to explore the thermal model of a thermoelectric generator and calculate the technological parameters of the use of thermoelectric modules to ensure the maximum value of TEG efficiency;
– to define the optimal technique for using the generator electrical energy.

4. Analysis of technical conditions for the arrangement of a thermoelectric generator and for defining the components of its design

Modern small-sized vessels employ, in stationary types of diesel, both the "wet" and "dry" gas exhaust from the engine. A "wet" exhaust implies the release of gas through a layer of seawater. To prevent water access to the pipeline and engine, the exhaust system is provided with devices that are located at the beginning and end of the pipeline. These devices would interfere with the arrangement of TEG. A "dry" exhaust applies a silencer that releases gas above the waterline level. Such an exhaust system has no additional devices and provides an opportunity to implement the optimum arrangement of the generator along the pipe (Fig. 1).

To reduce heat losses, the generator should be closer to the source of thermal energy, that is, to the engine (position 1 in Fig. 1). This condition is satisfied by the TEG arrangement on the pipeline (position 4 in Fig. 1) behind a collector (position 2 in Fig. 1).

The spent gas receiver after the generator is also a pipeline. Given such an arrangement, there is a risk of TEG failure at a sharp increase in gas temperature in case there is the absence of water pressure in the cooling system.

Therefore, the first to be arranged along the gas movement are the two-cascade thermoelectric modules (TEM) with an operating temperature above 1,000 °C. For example, ALTEK 1024 or ALTEK 1023 [10]. The proposed technical solution makes it possible, in case the temperature is exceeded, not to use a bypass for separate gas release from the generator. In addition, the specified thermoelectric modules are packed airtight in a steel body; they, therefore, could be installed in a moist environment.
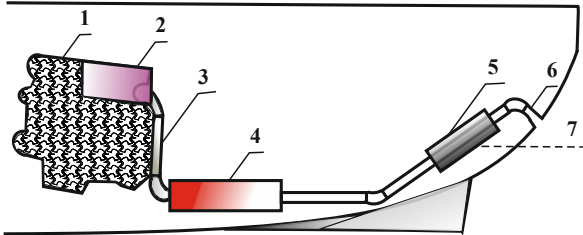

Fig. 1. Principal diagram of TEG arrangement: 1 — engine; 2 — collector; 3 — flexible metallic sleeve with heat insulation; 4 — TEG; 5 — silencer; 6 — exhaust hole; 7 — waterline

Industrial TEMs are flat. The round shape of a pipeline requires additional devices for their arrangement, which reduces the generator efficiency. For the optimum arrangement of thermoelectric modules, the cross-section of the generator should be squared with a corresponding replacement of the pipeline's section (inside the generator). The TEG cross-sectional area is kept constant and equal to the area of the inner cross-section of the engine exhaust pipe. This condition provides for the absence of an increase in the mechanical resistance of gas movement and a pipeline volume. Consequently, on the one hand, there is no reduction in gas temperature, nor a corresponding reduction in the TEG efficiency. On the other hand, there is no influence from the generator on the engine operation.

The respective size of the side of a square cross-section of pipeline d_i equals:

$$d_i = \frac{1}{2} \cdot \sqrt{\pi} \cdot d, \qquad (1)$$

where d is the diameter of the exhaust pipe of the engine.

A material of the pipeline should be stainless steel with a thickness of not less than 2 mm. Hence, the outer size of the pipeline d_0 equals:

$$d_0 = d_i + 0{,}4 \text{ cm.} \qquad (2)$$

If $d_0 < 100$ mm, then it is necessary to place a copper gasket of thickness $d_m = (100 - d_0)$ mm under each TEM of the generator.

When the engine is properly configured, exhaust gas does not contain carbon and is transparent. In a transparent gas, heat transfer could occur only through convection. It is possible to increase the heat transfer via radiation. To this end, it is proposed to put an empty cylinder inside the pipeline, which would be heated by gas and emit additional energy to the wall of the pipeline (Fig. 2).

To stir the gas effectively, the cylinder should be made of stainless steel in the form of a strip of small thickness (1–2 mm), twisted in a spiral (a spiral-type cylinder C in Fig. 2).

The gap between the spiral turns provides efficient gas stirring. The round shape of the cylinder and its flexibility make it possible to easily install a cylinder inside the pipeline of a complex shape. The cylinder diameter is determined by half of the pipe area and equals:
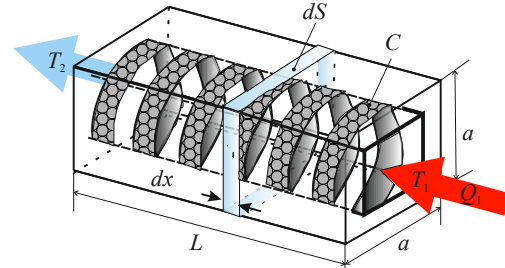
$$d_c = \frac{1}{\sqrt{2}} \cdot d. \qquad (3)$$

Fig. 2. A model of heat transfer along the section of a pipeline inside the TEG: T_1 — gas temperature at the beginning; T_2 — at the end of pipeline; C — spiral-like cylinder

The gap between the spiral turns must be equal to the width of the strip that it is made of. In this case, the inner side of the strip will also take part in radiant energy exchange, similar to the outer side. In this case, given the effective stirring of gas, the area of the active radiant surface of the cylinder will correspond to half the surface area of the pipeline.

5. Studying a thermal model of the thermoelectric generator

5. 1. Determining the heat exchange parameters in the thermoelectric generator pipeline

To calculate the TEG parameters, one needs to determine the parameters of heat transfer in the generator pipeline, namely: the speed of exhaust gas movement depending on the inner diameter of the exhaust pipe, the temperature and heat capacity of gas, the coefficient of transfer of heat from gas to the wall of the pipeline.

Determining exhaust gas velocity depending on the inner diameter of the exhaust pipe. Consider the process of exhaust gas release. In a four-cylinder diesel engine, gas is released through the exhaust pipeline twice per rotation of its shaft. For high-speed motor (with a rotation frequency over 1,000 rpm), the process of gas pressure reduction is approximated by the exponent (the exponent parameters depend on the model and the engine shaft rotation frequency [11]), which is slow enough at the length of the exhaust pipe. To simplify the calculations, such dependence makes it possible to apply the model of gas movement at a constant speed.

The inner diameter of the exhaust pipeline is typically equal to or greater than the internal collector pipe diameter. The latter equals the diameter of the engine cylinder. We analyzed the dependence of the internal diameter of the exhaust pipe d in stationary diesel engines on their capacity P based on the specifications to engines by various manufacturers [12–14]. The results are summarized in Table 1.

Table 1

Dependence of the exhaust pipe diameter on engine power

P, HP	to 40	40–55	55–80	80–130	130–180
d, mm	50	60	80	90	110

As one rotation produces two gas releases to the collector, the volumetric speed of exhaust gas release U is directly proportional to the frequency of shaft rotation n and the half working volume of the engine W:

$$U = \frac{1}{2} \cdot W \cdot n \cdot \frac{10^{-3}}{60} \text{ m}^3/\text{s}. \tag{4}$$

The linear velocity of gas movement through a generator with an inner cross-section S_G is:

$$V = \frac{U}{S_G} = \frac{U}{\frac{\pi \cdot d^2}{4}} = \frac{W \cdot n}{\pi \cdot d^2} \cdot \frac{4 \cdot 10^{-3}}{120}.$$

Hence, we obtain:

$$V = \frac{W \cdot n}{\pi \cdot d^2} \cdot \frac{10^{-3}}{30} \text{ m/s}. \tag{5}$$

Determining exhaust gas temperature. Temperature T_g of the gas released from the diesel engine cylinders depends on the engine load and, according to study [15], is within 700–800 K. The corresponding mean T_g is 750 K. Due to dynamic cooling, the average temperature of the gas coming from the collector to TEG (T_1 in Fig. 2) is

$$T_1 = 0{,}95 \cdot T_g \cong 700 \text{ K}. \tag{6}$$

Determining exhaust gas heat capacity. The composition of exhaust gas and, accordingly, its molar heat capacity C_p, predetermined by the process of combustion of a fuel-air mixture in the cylinder engine. During combustion, part of the oxygen is burned and replaced with gases, which, by the volumetric content, are dominated by nitrogen oxides (76–78 %) and carbon dioxide (1–5 %) [11]. The heat capacity of these gases is higher than that of oxygen, which causes an increase in C_p of the obtained gas mixture relative to the air heat capacity. The degree of an increase is determined by the percentage portion of oxygen combustion based on the coefficient of excess air α (the air and fuel ratio in a combustible mixture) according to the technical parameters of the engine. The thresholds of the coefficient α for different types of engines, according to work [15], are given in Table 2.

Table 2

Threshold of coefficient α for different types of engines

Engine type	α
Low-speed	1.8 .... 2.2
Medium-speed	1.5 .... 2.1
High-speed	1.9 .... 2.3

The average value of those given in Table 2 equals two (α=2). To calculate the specific heat capacity of exhaust gas, we used the average heat capacity of its components. For α=2 and gas temperature in the range from 0 to 700 °C,

Table 3 from work [15] gives the average values of specific heat capacity $\mu \cdot C_p$ (μ – the molar mass of gas).

Dependence $\mu \cdot C_p(t)$, derived according to data from Table 3, is approximated by a linear function

$$\mu \cdot C_P = 30.10 + 0.00327 \cdot t \tag{7}$$

with an error not exceeding ±0.007 kJ/K.

Table 3

Temperature dependence of the average specific heat capacity $\mu \cdot C_p$ of exhaust gas

Temperature t, °C	0	100	200	300	400	500	600	700
μC_p, kJ/(kmol·K)	29.808	30.032	30.285	30.615	30.963	31.338	31.716	32.095

Determining a heat transfer coefficient. When there are no special structural modifications, heat exchange in the generator pipeline occurs only through convection. Heat transfer depends on the velocity of gas flow, the area of contact between the gas and pipeline, the diameter of the pipeline, and the quality of its surface. The latter factors influence the coefficient of convective heat transfer α taking into consideration the regime of gas movement – turbulent, transient, or laminar. Under a turbulent mode (the Reynolds number Re>5·10³), the coefficient α value was determined based on the multifactorial graphic dependences given in [16]. Based on the totality of parameters, these dependences are approximated by the following expression:

$$\alpha = K_t \left(g \cdot V + 2{,}5 \right) \text{ W}/\left(\text{m}^2 \cdot \text{K} \right), \tag{8}$$

where V is the gas velocity, g is the coefficient depending on the inner diameter of the generator pipe d (the values are given in Table 4).

Table 4

Coefficient value

d, mm	40	50	70	100	150
g	2.7	2.4	2.3	2.0	1.8

K_t – a non-isothermal correction [16] when cooling gas, derived from the following formula:

$$K_t = 0.090 \left(T - 273 \right) + 1.4. \tag{9}$$

Thus, for the predefined diameter of the generator pipe, the coefficient α is derived analytically, which is convenient for use in the estimation model of heat transfer.

5. 2. Calculation of the technological parameters for using thermoelectric modules to ensure the maximum TEG efficiency

A procedure to determine the TEG power, taking into consideration the convective and radiative transfer of energy from gas to the pipeline wall, was considered in study [6]. The corresponding system of four equations was obtained.

The first equation defines energy dQ, which is transmitted by gas through the elementary surface of the pipeline wall dS (Fig. 2) per unit time, taking into consideration the radiation by the spiral-type cylinder:

$$dQ = \left[\begin{array}{c} \frac{1}{2}\varepsilon\sigma\left(T_C^4 - T_S^4\right) + \\ + \alpha\left(T_G - T_S\right) \end{array} \right] dS = p(T) \cdot dS, \qquad (10)$$

where ε is the grayness coefficient of the wall's material (for steel, coated with a layer of soot, ε=0.80); σ is the Stefan Boltzmann coefficient; α is the coefficient of exhaust gas heat transfer; p is the thermal power absorbed by unit of wall surface; T_G is the gas temperature; T_S is the pipeline wall temperature, T_C is the cylinder temperature.

The second equation links the gas temperature T_G, cylinder T_C, and pipeline wall T_S:

$$m\alpha \cdot \left(T_G - T_C\right) = \frac{1}{2}\varepsilon\sigma \cdot \left(T_C^4 - T_S^4\right), \qquad (11)$$

where m is the ratio of the total surface area of the spiral-like cylinder to the area from which the transfer of radiating energy to the generator's wall occurs (in calculation, m=3).

The third equation determines the area S, at which the gas temperature would decrease from the initial T_1 to the resulting T_2 (Fig. 2):

$$S = C_p a^2 V \int_{T_2}^{T_1} \frac{dT}{p(T)}, \qquad (12)$$

where a is the side of the square cross-section of the pipeline (Fig. 2).

The fourth equation determines the amount of integral power P, left to the generator by the exhaust gas:

$$P(T_2) = C_p \cdot a^2 \cdot V \cdot \left(T_1 - T_2\right), \qquad (13)$$

where V is the linear velocity of gas movement (derived from expression (5)).

Solving the system of equations (10) to (13) requires the use of computer tools.

We calculated the system of equations on PC employing the software Wolfram Mathematica 10.4 [17]. In addition to heat exchange parameters, examined in chapter 5. 1, the initial data for the calculation are the engine operating volume, the speed of the engine shaft rotation, and the area of the generator pipeline cross-section.

Engine power P_e is derived from expression:

$$P_e = D \cdot K_n, \qquad (14)$$

where D is the ship displacement, K_n is the power consumption factor depending on the speed of movement. Ship displacement equals

$$D = S_T \cdot L \cdot B \cdot \rho, \qquad (15)$$

where S_T is the coefficient of complete ship displacement, L is the length of a vessel, B – its width, ρ is the density of water that depends on its composition.

With a vessel length L=12 m (a yacht or a small fishing vessel) and the corresponding width B=3.5 m, the recommended value S_T=0.5 [18]. For fresh water and a ship speed of 18 knots K_n=6.6. As a result, based on expression (15), D=21 tons, and, based on expression (14), power P_e= =135 HP≈100 kW. The engine volume for the obtained capacity, according to various manufacturers, is W=4.1 l

on average. A diameter of the exhaust pipe, based on Table 1, is 110 mm. The appropriate size of the side of the square cross-section of the pipeline, based on formula (1), is d_i=88.6 mm, and the cross-sectional area S=7,849.96 mm². The engine shaft speed is considered in the range from 1,000 to 2,500 rpm.

To obtain the maximum value of the TEG efficiency, it is necessary to provide for the most effective energy selection from the pipeline inside the generator. This is possible under the condition for the maximum temperature gradient between the TEM hot and cold sides. At the optimum working temperature for Altek 1024, the maximum temperature of the inner wall of the generator pipe is 700 K. Fig. 3 shows the relevant estimation graphical dependences of exhaust gas temperature distribution on the length of the generator pipeline at different values of the diesel engine shaft speed.
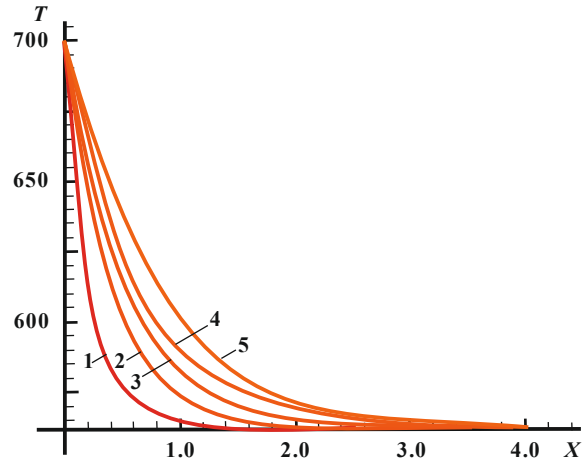

Fig. 3. Distribution of gas temperature (T, K) lengthwise the generator pipeline (X, m) at different speeds of the diesel engine shaft rotation: 1 — 500 rpm; 2 — 1,000 rpm; 3 — 1,500 rpm; 4 — 2,000 rpm; 5 — 2,500 rpm

For further analysis, the generator was divided into three constituent sections that operate as separate generators (to compare data with a single-section generator). We estimated the one- and three-section generators. The results of calculating the dependence of thermal power that is absorbed by the wall inside the generator on the position lengthwise the pipeline at different values of the shaft rotation speed in the diesel engine are shown in Fig. 4. Curves 1–5 correspond to the one-section generator, curves 6, 7 – three-section generator.

An analysis of dependences in Fig. 3, 4 allows us to conclude the following. At a distance exceeding 0.4 m from the beginning of the pipeline, a significant decrease in the energy absorption by the wall occurs (the final 1.2 m accounts for less than 30 %). But the gas temperature naturally remains higher than the pipe wall temperature (the unused energy exists). Therefore, this confirms the need to divide the generator into constituent sections, which under different temperature conditions, operate as separate generators.

We determine the length of each section. The length should be multiple to the size of TEM. Given the size of Altek 1024, an optimum length of the first section is 0.4 m. This section consists of 16 TEMs (four on four sides).

Based on the graphic dependences in Fig. 3 for X=0.4 m, one can derive, for the second section, the value of the input gas temperature at different shaft speeds. The optimum wall

temperature of the generator is 250 °C. Similar to the first section, the optimum length of the second section is 0.4 m.
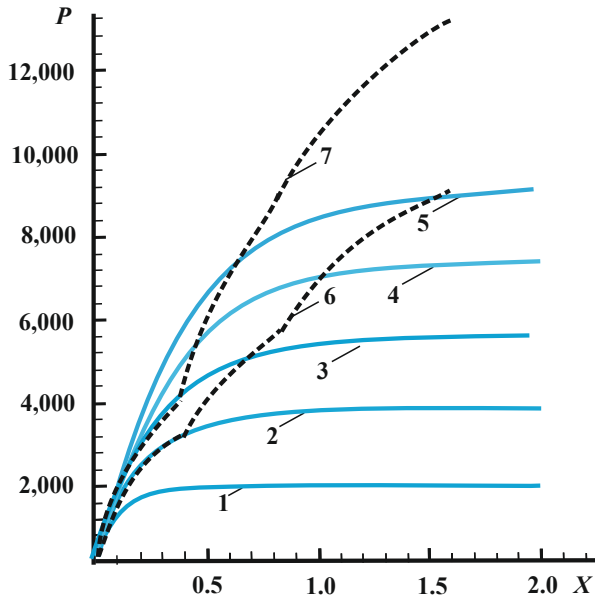

Fig. 4. Dependence of thermal power absorbed by the wall inside the generator (*P*, W) on the position lengthwise the pipeline (*X*, m) at various speeds of the diesel engine shaft rotation: 1 — 500 rpm; 2, 6 — 1,000 rpm; 3, 7 — 1,500 rpm; 4 — 2,000 rpm; 5 — 2,500 rpm; 1—5 — one-section; 6, 7 — three-section generator

The gas input temperature of the third section equals the original temperature of the second section. The optimum pipe wall temperature for it is 200 °C. The temperature of the exhaust gas supplied to the third section is significantly lower than that in the preceding sections. Therefore, its length is larger, 0.8 m (accordingly, the section contains 32 TEMs).

The calculation results, obtained for each section in a three-section generator system at the engine shaft rotation speed 1,000 and 1,500 rpm, are shown in Fig. 4 by curves 6 and 7, respectively. Fig. 4 shows that compared with a single-section generator, at both values of the engine shaft speed there is a significant (almost three times) increase in the efficiency of energy release. Results of the corresponding calculation for all speeds of engine rotation are given in Table 5.

Table 5

Power of energy absorption by the generator wall and the total TEM electric power

Frequency, rpm	500	1,000	1,500	2,000	2,500
Power, kW					
Section 1	1.7	3.4	4.8	5.1	6.1
Section 2	1.3	2.4	4.0	5.4	5.8
Section 3	1.9	3.2	4.6	7.3	9.6
Total electric power	0.32	0.53	0.80	1. 19	1.4

According to the approximate model [6], the generating thermoelectric module could be considered as a heat-flux-regulated voltage source with a certain internal resistance. In this case, the efficiency of the conversion of the power of a heat flow η is determined from formula:

$$\eta = \frac{\Delta T}{\Delta T_0} \cdot \eta_0, \qquad (16)$$

where η_0 and ΔT_0 are, according to TEM specifications, its efficiency and the difference between the maximum and minimum temperature for the hot side of the module; ΔT is the real temperature difference between the hot and cold side of the module.

Calculation based on formula (16) yields the following values of efficiency for three sections of the generator: for the first section, 7.0 %; for the second, 5.5 %; for the third, 5.0 %. The total generator electric power is calculated based on the specified values for different motor shaft rotation frequencies. Power values are given in Table 5. Thus, in the middle of the considered frequency range (approximately 1,500 rpm) the TEG power reaches 0.8 kW. The specified power, when calculating the fuel consumed, would exceed 2 %.

6. Determining the optimum way to utilize the generator electric energy

While the engine is running, the electric energy is constantly produced by TEG. Some of its amount is consumed by a vessel's network. The rest could be directed to help the engine. Consider the technical conditions to ensure both processes.

The mode of electric energy generation by a thermoelectric generator fully satisfies a battery recharge in the system of vessel power. Each TEG section has its own voltage. Based on the data from chapter 5. 2, the output voltage would be: for the first section, 24 V; for the second, 20 V; for the third, 16 V. The voltage value in a ship's network is typically equal to 12 V. Therefore, to enable the direct supply of energy from the TEG sections to the vessel's network, there is a need to reduce the alignment of these voltages. We propose using the two-stroke reducing voltage converter with double adjustable switching LTC3802.

A separate issue is a way to use the TEG excess, relative to the needs of the vessel's electrical network, electrical energy. Directing the energy produced by a generator to supplement the engine shaft rotation could improve the engine efficiency. A structural continuation of the advancement is to replace the electromechanical generator with an electric engine, which would rotate the diesel shaft through a belt gear designed for the generator. The engine must have a wide range of speeds, the high torque of shaft rotation, and, importantly, a properly-functioning control system. Such requirements are satisfied by a motor-wheel, which provides an additional opportunity to generate electrical energy from the residual mechanical energy of shaft rotation at its braking. The wiring diagram of the motor-wheel is shown in Fig. 5.
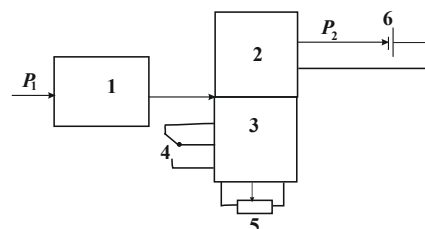

Fig. 5. Wiring diagram of the motor-wheel: P_1 — input power, P_2 — output power, 1 — voltage converter, 2 — motor-wheel, 3 — controller, 4 — mode switch, 5 — motion speed regulator, 6 — network rechargeable battery

Electric power of the motor-wheel would equal approximately 300 W. For such a power, the voltage coming from TEG should equal 48 V. Therefore, it is necessary to increase the voltage from each TEG section to the specified value through a voltage converter. To this end, the four-phase synchronous increasing voltage converter LTC3810 [20] could be applied.

The operation of the motor-wheel is enabled by a controller – a device responsible for the operation of the entire electronic system. A motion speed controller and a mode switch are connected to it (Fig. 5). The latter enables a transition from the power supply to the ship network (rechargeable battery 6 in Fig. 5) to rotate the engine motor shaft. The main functions of the controller include the supply of current from a rechargeable battery or TEG to the motor-wheel, an indication of the battery charge level, control over the shaft rotation speed of the motor-wheel to save the energy of a rechargeable battery. Control over the motor-wheel shaft rotation speed is executed by changing the voltage pulse frequency from the controller.

7. Discussion of results of the technological modeling of a recuperator of the exhaust gas energy in the diesel engine of a small-sized vessel

The results of the technological modeling of the diesel engine exhaust energy recuperator based on search design methods have been obtained. A distinctive feature of the proposed generator is its use on small-sized vessels, where the exhaust gas energy is still released outside.

The arrangement of the generator is planned for ships with a "dry" exhaust because a "wet" exhaust system is equipped with devices, which will interfere with the installation of TEG. To exclude a bypass from the exhaust system, the TEG structure includes the high-temperature semiconductor modules ALTEK 1024. To increase heat transfer from gas to the generator and to effectively stir the gas, we use a spiral-type cylinder (Fig. 2). The cylinder is made of stainless steel in the form of a strip of small thickness twisted in a spiral. The round shape and cylinder flexibility ensure its easy installation inside the pipeline of complex shape.

We divide the generator into constituent sections that operate as separate generators under different temperature conditions. Estimation data on the distribution of gas temperature lengthwise the generator pipeline at different speeds of the diesel engine shaft rotation in Fig. 3 make it possible to determine the length of each section and the number of TEMs (for the first and second, 16; for the third, 32).

The dependence of a three-sectional generator thermal power, absorbed by the pipeline wall in its middle, on the TEM arrangement lengthwise the pipeline in Fig. 4 makes it possible to perform appropriate calculations. Thus, based on curve 7, it is possible to determine that at the engine shaft rotation with a frequency of 1,500 rpm the thermal power of the thermoelectric generator is 1,300 W. Conversion to electrical energy gives an appropriate value of 0.8 kW (Table 5).

Such power makes it possible to exclude an electromechanical generator from the engine design.

It is assumed that the energy that is constantly produced by TEG during engine operation is partially consumed by the vessel's network and the rest is to be directed to help the engine. To this end, we use a motor-wheel, connected in line with Fig. 5, which provides an additional opportunity to generate electrical energy and could contribute to the onboard network during its peak load.

The functional limitation of the proposed technological model of TEG is the use of only high-speed diesel engines. When the frequency of rotation is less than 1,000 rpm the TEG efficiency is too low. However, work is currently underway to use, in TEM, electronic materials based on quantum wells [8]. Their application could improve efficiency by three or more times compared to the TEM made of bismuth telluride. The new materials would allow TEGs to be installed on small-sized vessels equipped with medium-speed engines.

Further improvement in TEG requires the utilization of exhaust gas heat, which remains at the output of the third section of the generator. In addition, it is possible to use a TEG to recover energy, which is released on small-sized vessels through the water cooling of the engine.

8. Conclusions

1. For the optimal implementation of energy recovery of exhaust gases from diesel engines, the following technical solutions are proposed for small-sized vessels:
– installation of a thermoelectric generator could be implemented on vessels that have a "dry" gas exhaust from the engine;
– for the optimum arrangement of thermoelectric modules, the generator cross-section should be square;
– TEG should employ modules with a working temperature above 1,000 °C. This makes it possible not to use a bypass for separate gas release from the generator, which improves its efficiency;
– to increase the efficiency of heat transfer of exhaust gas, it is proposed to place a spiral-like cylinder inside the generator pipeline.

2. Our study of the thermal model of the thermoelectric generator has made it possible to determine the basic parameters of heat exchange in the TEG pipeline. We have established the need to divide the generator into three constituent sections, working as separate generators. The possibility of obtaining up to 0.8 kW of electric energy when using TEG has been demonstrated provided the shaft rotation speed of the diesel engine is 1,500 rpm.

3. To directly supply energy from the TEG sections to a ship's network there is a need to reduce the voltage alignment from the TEG sections. To convert the excess electrical energy into mechanical energy (to assist the main engine) within a comprehensive improvement of fuel utilization efficiency, the use of a motor-wheel has been proposed.

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