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ENERGY RECOVERY DEVICE FOR THE INTERNAL COMBUSTION ENGINE

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РЕКУПЕРАЦІЙНИЙ ПРИСТРІЙ ДО ДВИГУНА ВНУТРІШНЬОГО ЗГОРЯННЯ

Purpose. The purpose of the work is to develop an effective device for utilization of exhaust gas heat energy of the gasoline Internal Combustion Engine (ICE) that meets the design of current car models; to create an appropriate model and analytical calculations of the basic parameters of the thermoelectric generator that runs on exhaust gas heat energy substantiating the possibility of electric power generation in amount sufficient to replace the existing electromechanical car generator.

Methodology. Physical and mathematical modeling of the processes of heat transfer and generation of electric energy in thermoelectric generators was used.

Findings. A physical analysis of the heat backflow process from the flow of exhaust gas in a generator pipeline and defined the principle of calculations of the basic parameters has been provided. A mathematical model of heat transfer in the pipeline block thermoelectric generator has been developed. A program using Wolfram Mathematica software has been created and the relevant parameters for each block with different loads of ICE have been calculated. A possibility of creating a device for the recovery of fuel energy emitted from the car ICE has been substantiated. The correspondent device is a thermoelectric generator consisting of blocks using the exhaust gas heat. We proposed an air cooling process to reach the optimum conversion efficiency. The possibility to generate up to 1 kW of electrical power has been proven.

Originality. An innovative exhaust gas energy recovery device for existing vehicle models was developed. For the first time the division of the thermoelectric generator into three units operating as separate thermoelectric generator as well as insertion of special hollow cylinder in a gas flow were proposed and substantiated. The cylinder has lengthwise ribbing on a surface to improve the heat transfer by thermal radiation.

Practical value. The proposed thermoelectric generator allows replacing the electromechanical car generator using a process of excess energy recovery. The energy saved as a result of recovery is at least 2 % in terms of fuel consumed which is important from both economic and environmental perspective.

Keywords: *energy conservation, thermoelectric generator, waste heat recovery, exhaust gases*

Introduction. Tendencies of a rising cost for fuel cause the necessity to increase effectiveness of the car. But at the modern level the maximum efficiency of the petrol internal explosion engines (IEE) is already reached. The existing IEE only 25 % of fuel energy rework into mechanical energy. Taking into account losses on mechanical friction of the transmission and other devices of the car, effectiveness decreases to 15 % in practice. At the same time even very slight increase in effectiveness gives a considerable economic effect.

However, 40 % of fuel energy is made on burst in the form of thermal energy of exhaust gases. For this reason the problem of increasing effectiveness of fuel due to utilization of thermal energy from exhaust gases is extremely urgent. One of its solutions is design of the thermoelectric generators (TEG), which recuperate this energy. The obtained electric power can be used on electrical needs of a car, thereby excluding the electromechanical generator from its structure.

Unsolved aspect of the problem. The existing car industry technologies do not use energy of exhaust gases at all. An exception is production of specialized trucks and luxury models of the passenger cars, using the cogeneration installations.

Methodological basis of thermoelectric generator implementation includes research works by A. F. Ioffe, A. I. Bernshteyn, A. R. Regel. In Ukraine, the Institute of a thermoelectric of National academy of Sciences is engaged in development of energy saving technologies with involvement of the generating thermoelectric modules. The direction is headed by the academician Anatichuk L. I. The scientific and research efforts devoted to energy of exhaust gases of internal combustion engines applications have been made by such Ukrainian scientists as Anatichuk L. I., Mikhailovskyi V. Ya., Rutylo M. I., Lutsyk I. B., R. V. Kuz, as well as by American scientists T. Kaia, D. Sharp and T. Tritt; European Zh. K. Tedenak and Yu. Green, scientists from Japan and China T. Kadzikava, H. Hou and others.

When developing new cars of F class (Luxury cars), for example, in the new models of BMW X6, Ford Lincoln MKT and Chevy Suburban installation of the thermoelectric generators working with the energy of exhaust gases [1, 2] is foreseen. Generative thermoelectric modules are exclusively manufactured for them. In Ukraine, due to economic problems, and also taking into account a traditionally long term of operation of the existing cars, similar models will probably not be produced. Therefore there is a need of developing the TEG for the existing models of cars and puddle jumper cars. This development will give a chance to reduce the cost of car operation and can become economic breakthrough for Ukrainian entry into the European market of road haulage.

Analysis of the recent research. Thermoelectric generators are thermal machines for direct conversion of thermal energy into electrical one. Because of small values of the effectiveness as main power supplies they were applied in engineering in exceptional cases: at nuclear power plants, spacecrafts, sea markers, etc. Taking into account importance of the specified directions the theoretical basis of their applications has been developed since the middle of the last century. However, in power electric engineering they have been considered only as alternative power supplies.

However, rather high values of generator efficiency (to 12 %) received recently on semiconductor materials with high values of mobility of charge carriers and Q-values [3, 4], and also range extensions of their working temperatures puts the TEG into the main sources of electric energy. If the effectiveness of generators which are planned to make using compounds of samarium corresponds to calculated value of 20 % [5], then extrusion by thermoelectric generators even of internal explosion engines is quite possible. It is caused also by absence of mechanical parts, as well as the long (up to 10 years) guaranty period of their operation without maintenance.

Starting since the middle of last decade estimated and research operations on use the TEG on the exhaust system of diesel engines of vessels and trucks [6] have been published. Thermoelectric modules on the basis of the SiGe and Bi_2Te_3 [3] semiconductor were used in generators. Their boundary upper temperature depending on module modification is equal to 350–550 °C. In a collector of the engine, the temperature is more than 1000 °C. At the same time both the experimental and existing industrial constructions essentially use extension of the exhaust system pipeline [4]. However, it reduces temperature of exhaust gas. Respectively, there is a need for rather low temperature of a cooler. Therefore generators have the integral unit with water cooling and, respectively, all calculations and research developments are bound to these conditions. Water cooling for the built-in generators requires the appropriate finishing of water cooling of the engine with changeover of the heat sink and pump, and actually, development of new model of the car.

Unsolved aspects of the problem. For existing models of cars, support of air cooling of the thermoelectric generator is necessary. Yet it is accompanied by some problems of heat extraction from the generator heat sink. The first problem consists in need of increasing efficiency of thermal energy selection of exhaust gases without expansion in a pipeline diameter on the limited length of the generator which is to be placed within the distance from an engine collector to a catalytic afterburner of exhaust gases. Another problem is connected with the need of increasing efficiency of assignment of thermal energy from the generator heat sink on condition of restriction of the sizes of the latter. In this regard the proposition to divide TEG on sections, that is offered in the work, is interesting [7]. It offers an optimum approach to energy selection in process of gas passing via the generator. However, this idea requires additional studying and appropriate calculation.

Besides, the main objective of utilization is use of TEG electric power. This job has not been considered before because of her marginal values. Still the amount of the recovery energy provided by the offered instrument is sufficient, at least, for changeover of the electromechanical generator in the car. Besides, the TEG will produce also excess of this energy.

Objectives of the article. The modern models of petrol internal explosion engines practically reached a maximum of the productivity and differ in the effectiveness small values. At the same time 75 % of fuel energy is emitted into the environment. Reduction of these emissions at least by 1 % at the expense of a recuperation to electric power is an important both economic and ecological task. For passenger cars an additional installation of the cogeneration devices which are relevant to bold power generators is almost impossible because of complication of car operation and its increasing weight. Use of the thermoelectric generator makes an exception. Its installation has already been provided for the developed new luxury models. Yet there is a need to upgrade the existing cars. Development of the resource recovery device for them in the form of the thermoelectric generator working on exhaust gas exergy is a solution. It includes constructional development, development of physical model of the generator, calculation of amount of the received electric power and reviewing of methods of this energy using.

Presentation of the main research. To solve the task considered it is necessary to define a generator installation place, to make its physical model and to connect it to the IEE parameters. It is natural that the generator needs to be located as close as possible to a source of thermal energy, namely to the internal combustion engine, for reduction of losses. Installation on the pipeline immediately after the collector or instead of it meets this requiremen. The catalytic agent will be the receiver of exhaust gas after the generator.

Output data which need to be known for calculation of the thermoelectric generator is the power of a heat load. It is caused by values of intake temperatures and generator output, motion speed of a flow and its heat capacity. The operating range of gas temperatures is set by a collector on the input, and by the catalytic agent on the output. At the end of a working piston stroke of the engine pressure of a gas compound in the cylinder decreases to 0.3–0.75 MPas, and the temperature of a gas compound has values within the range of 900–1200 °C depending on the frequency of shaft turns. Further gas is cooled in the collector and its temperature decreases respectively to 800–1100 °C. Values of working temperature of the catalytic agent are in the range of 300–500 °C. Flow rate of gas is defined by the engine capacity which, in turn, depends on the frequency of shaft turns. For petrol engines its value is regulated according to balance of power of the car in the range of 1000–5000 RPM [8]. In case of movement the frequency of engine turns from 2000 to 4000 RPM is put into practice.

Volume velocity output of exhaust gas V_{EG} is directly proportional to the frequency of turns of the shaft n_i, number of cylinders producing gas for one turn (namely to two for the four-cycle engine), to the engine capacity Y_{En} and is inversely proportional to strokes n_t, therefore

$$V_{EG} = \frac{Y_G \cdot 2 \cdot n_i}{60 \cdot n_t} = \frac{Y_{En} \cdot n_i}{30 \cdot n_t}.$$

From here, the line speed of gas flow via the generator with the internal section of S_G will be

$$V = \frac{V_{EG}}{S_G} = \frac{Y_{En} \cdot n_i}{S_G \cdot 30 \cdot n_t}.$$

Heat capacity of exhaust gas of C_p corresponds to a heat capacity of a compound of its gases [8].

In TEG composition use of the serial semiconductor high-temperature generating thermoelectric modules (TEM) with efficiency of 12 % is provided. In Ukraine such modules are produced as two-stage ones on the basis of crystals of BiTe and Si-Ge in series. These are modules of Altek 1023 and Altek 1024. They have the form of a horizontal rectangular cylinder. As a prototype of the thermoelectric generator on the basis of energy of exhaust gases, the TEG of Hi-Z Corporation and Thermpoelectric Institute Altek 8044 are taken [6, 9] in which four modules are installed along the perimeter of of the pipeline. However, their shortcoming is a big section of working pass that leads to temperature decrease of working gas and as a result, to low efficiency of the generator. Therefore, in this operation it is offered to use the square section of the generator pipeline which corresponds to the area of the section of a collector of the IEE exhaust system.

For calculation of key parameters of the TEG in Fig. 1 the model of a heat flux through one of the generator sides is offered. It consists of heat source (a flow of exhaust gas), a wall of the generator pipeline, the thermoelectric module and the radiator.

Transmission of energy from exhaust gas is offered to be increased due to introduction of an empty cylinder to the middle of a gas flow. This cylinder selects energy from gas through convective exchange and transfers it to a generator wall by a radial method. It provides component transmission of thermal energy to the generator pipeline wall at the level of convective exchange. The surface of the cylinder is selected with longitudinal edges which shall provide increase in the area of an output surface at least, than three times.

For the model given in Fig. 1, the equation of heat balance counting per unit of time looks in the following way

$$Q = Q_0 + Q_1 + Q_3 \quad \text{end} \quad Q_1 - Q_4 = P_{El} + Q_2,$$

where Q is the thermal power of collector exhaust gas; Q_0 stands for losses of thermal power on elements IEE heat source; Q_1 is the thermal power proceeding from hot gases to the TEG both in a convective way, and radiation from the thin cylinder (for calculations in operation, its area is considered twice as little as the interior area of the pipe); Q_2 is the thermal power which is led out from the cold side of TEM to the environment by a forced blowing; Q_3 is the thermal power which is led out with gas; Q_4 stands for losses of thermal power on elements of the pipeline construction; P_{El} is electric power of TEM. For calculation, we accept Q_0 and Q_4 equal to zero.

The mathematical model of gas heat transfer is to consider the physical processes happening in the gener-

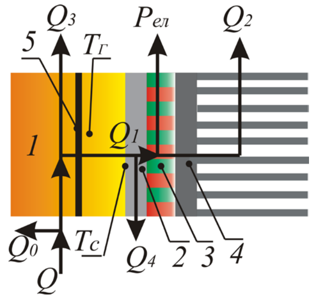

Fig. 1. Thermal process model of exchange in the thermogenerator:

1 – heat source; 2 – hot heat exchanger; 3 – module; 4 – heat exchanger (radiator); 5 – cylinder; T_G – gas temperature; T_W – wall temperature ator pipeline. Movement of exhaust gases begins in case of their pushing out from the cylinder two times for a turn of a shaft of the four-stroke engine. The main resistance to movement is shown by the catalytic agent and the resonator. At the same time the pipeline is filled according to the IEE cylinder volume. Gas pressure increases and gradually falls down before the following pushing out. With a small error it is possible to allow regularity of gas pressure along the pipeline. Gas moves to the catalytic agent and cools down gradually while moving. Therefore, the process which occurs is possible to be accepted as an isobaric one with constant change of temperature.

Let us a consider stable heat exchanging process (the physical model corresponding to a thermal process model) provided continuous pieline wall temperature (Fig. 2) and we will give its mathematical model.

From gas with a total quantity of heat of Q, we will select the layer of elementary volume with thickness dx moving along a pipe. In process of passing it gives a part of energy and cools down. At the beginning of a pipe we take temperature of gas of T_P, at the end – T_E. Energy of the gas cooling dQ passing through elementary surfaces of a wall dS of the pipeline for a unit of time, considering the radiation of the empty cylinder is

$$dQ = \left[\frac{1}{2}\varepsilon\sigma(T_C^4 - T_W^4) + \alpha(T_G - T_W)\right]dS = p(T)\cdot dS, \quad (1)$$

where ε is wall material grayness coefficient (for the steel covered with carbon film, ε = 0.80); σ is Stefan-Boltsman's coefficient; α is coefficient exhaust gas – steel heat transfer, depending on the speed of the gas flow and the diameter of the pipeline (the relevant data are provided in [8]); p is thermal power which is absorbed by wall surface unit; T_G is gas temperature from a source; T_W is the temperature of a wall of the pipeline; T_C is cylinder temperature (Fig. 1).

The temperature of the cylinder is determined by the equation

$$m\alpha(T_G - T_C) = \frac{1}{2}\varepsilon\sigma(T_C^4 - T_W^4), \quad (2)$$

where m is the relation of the total surface area of the quill cylinder to the area transferring energy of its radiation to a generator wall (when calculating $m = 3$).

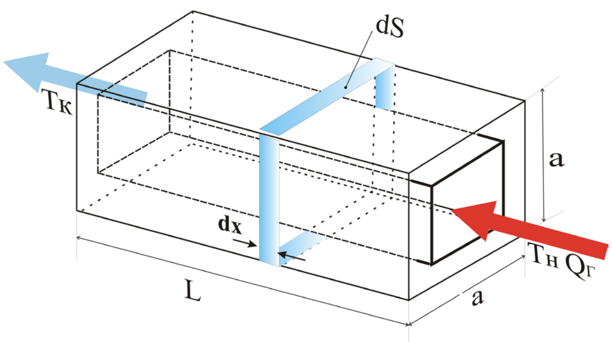

Fig. 2. Physical model of the thermogenerator

The energy which is released by the elementary volume of dY gas for a unit of time is also designated by loss of its internal energy and is $dU/dt = dQ$ taking into account (1)

$$C_p dY \frac{dT}{dt} = p(T)dS.$$

For the square section of the pipeline with the side a

$$C_p a^2 dx \frac{dT}{dt} = p(T)dS.$$

Taking into account that $dx/dt = V$ is the line gas speed, we find the area on which gas temperature from initial T_{in} will be reduced up to the finite temperature of T_f

$$S = C_p a^2 V \int_{Tin}^{T_f} \frac{dT}{p(T)}. \quad (3)$$

Along with that, the difference of energies of the gas which entered the generator and quitted it for a unit of time is the integral power left by generator gas

$$P(T_f) = \frac{C_p dY(T_{in} - T_f)}{dt} = C_p \frac{a^2 dx}{dt}(T_{in} - T_f) = C_p a^2 V(T_{in} - T_f). \quad (4)$$

It is known that solution of the equation of heat conduction is exponential dependence of temperature on the way of gas passing. However, existence of the radiating cylinder in the pipeline results in more difficult dependence than an exponential one, and requires the joint solution of the equations from (1) to (4). The appropriate program on the basis of the software of Wolfram Mathematica 10.4 was created for this purpose. Engine capacity, engine shaft turn speed, temperature of exhaust gas on a collector output, temperature of an internal wall and cross-sectional area of the generator pipeline were accepted as output data for calculation. For cars of the budget class, engine capacity is in limits of 1.5–2.0 l (on average 1.8 l). The output diameter of the collector makes 53 mm. In case of a short collector and its appropriate thermal insulation in calculations we used the appropriate average temperature of exhaust gas on an output equal to 1000 °C. Values of shaft speed were taken with a step of 1000 RPM in the range from 1000 to 5000 RPM.

The need to provide the maximum value of the effectiveness of thermoelectric modules requires the most effective selection of energy. It is possible in case of a maximum gradient of temperature in these modules, or at the greatest possible temperature of the hot side and minimum possible temperature of the cold side. Respectively, temperature of an internal wall of the generator pipeline, which is equal to 700 °C, was selected the optimum working temperature (Altek 1023 or Altek 1024). The length of the generator pipeline is restricted to a distance between the collector and the catalytic agent, or 1.1 m.

The results of calculation are provided by graphic dependences of gas temperature distribution (Fig. 3, *a*), and the thermal power absorbed by walls of the total generator (Fig. 3, *b*, curves 1–5) on length of its pipeline with different values of speed of a turn of a IEE shaft.

The analysis of the received dependences results in the following. First, in case of an engine shaft turn with a frequency of 3000 RPM the electric power of the thermoelectric generator can make up to 800 W that at least allows excluding the electromechanical generator from structure of the car. Secondly, in the distance which is more than 0.3 m from the beginning, energy absorption (less than 30 % to the last 0.8 m) sharply decreases that causes small efficiency of further absorption. However, gas temperature, naturally, does not fall lower than the temperature of a pipeline wall and at its output has much

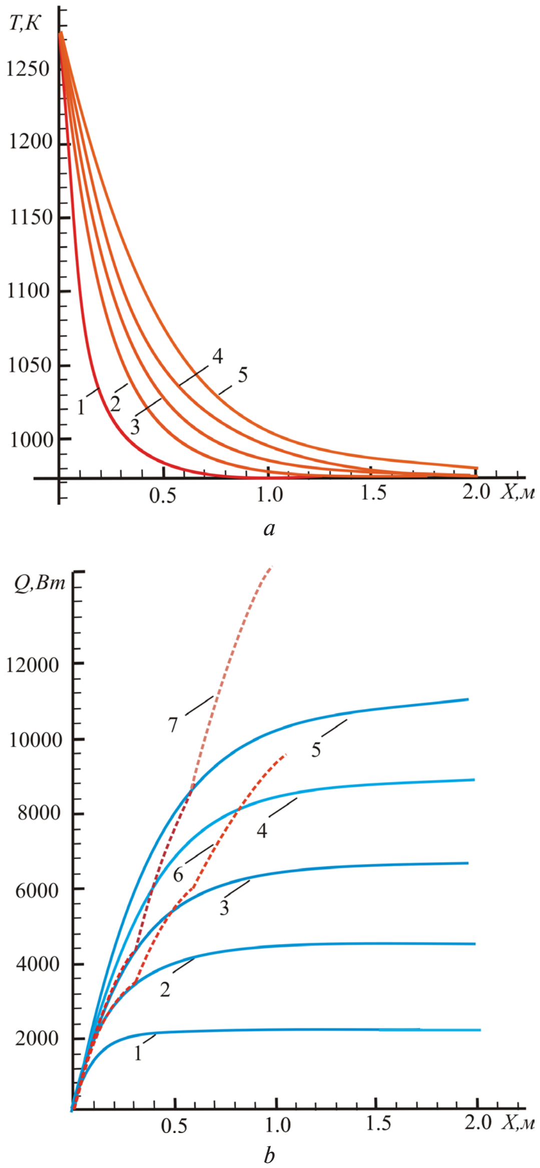

Fig. 3. Distribution of temperature (a) of gas and thermal power (b) which is absorbed by a wall, on generator pipeline length at different speeds of turns of an engine shaft:

1 – 1000 RPM; 2,6 – 2000 RPM; 3,7 – 3000 RPM; 4 – 4000 RPM; 5 – 5000 RPM; 1–5 – one-block; 6,7 – the three-block generator

internal energy not used yet. As a result, there is a need of division of the generator into composite units which work as separate generators.

Division of the generator into units provides determination of the block lengths. It must be divisible to TEM dimensions. According to the analyzed modules by the minimum size (75 × 75 the mm), and based on temperature condition, Altek 1023 is most acceptable. Then the optimum length of the first unit will be 0.3 m with 16 TEM could be located (four from four sides).

The value of the entering gas temperatures for the second unit in case of corresponding speeds of shaft turns is selected according to graphic dependence of Fig. 3, *a*, and for $X = 0.3$ m. From the proceeding data, the temperature of a generator wall is selected 500 °C.

Altek 1023 corresponds to the temperature mode and size of the second unit. The optimum length of the second unit is also 0.3 m. However, this is support of application in the third unit of thermoelectric Mars 65 modules that serves as a criterium of its length since they are much cheaper than Altek 1023 and have maximum temperature of the hot side up to 550 °C.

The length of the third unit is set by the maximum length of the generator – from the collector to the catalytic agent. Except for lengths of the previous units there is no more than 0.5 m of a pipe left. The entering temperature of gas is the output temperature of the second unit. 300 °C will be the optimum temperature of a pipeline wall for this unit. The results of calculations which are carried out for each of the units in the system of the three-block generator for shaft turn speeds of IEE are 2000 and 3000 RPM by the considered technique, are provided in Fig. 3, *b*, curves 6 and 7, respectively. It is obvious that in comparison with the integral (one-block) generator, efficiency of energy selection grew more than three times for both rotational speeds of an IEE shaft. Corresponding results of calculation for all speeds of a turn of the engine are shown in the Table.

The output temperature of the generator will be from 300 °C (in case of minimum engine shaft turn speeds) to 450 °C (in case of maximum speeds). Such a range of temperatures corresponds to operating conditions of the catalytic agent of the exhaust system of the engine.

The amount of the electric power which is worked out by the thermoelectric module is proportional to a flow of thermal energy passing through it. Yet the effectiveness of such transformation depends on a tempera-

Table

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

Frequency, RPM	1000	2000	3000	4000	5000
Power, kW					
Block 1	1.8	3.6	4.2	5.2	6.2
Block 2	1.5	2.5	5.0	5.6	6.0
Block 3	2.0	3.4	4.8	7.5	10
Total electric power	0.38	0.59	1.0	1.3	1.5

ture gradient in the module as well. It is caused by the basic principle of operation of the module – diffusion process of transfer of charge carriers in semiconductors. Therefore, it is necessary to provide power rating of a heat flow via the module. If not, the effectiveness of the transformation process will decrease. In case of uprating of rated value there is an exhaustion of process of charge carriers from the hot side of semiconductors. In case of its understating the number of the charge carriers which are moved in unit of time decreases in proportion to reduction of a temperature gradient. This value is electric current. The electric potential on the cold ends of semiconductors is proportional to quantity of a charge. It causes intrinsic current via semiconductors of the module and external loading if it is. Therefore, the generative thermoelectric module can be considered as the first approximation as the voltage source regulated by a heat flux with internal resistance. Therefore, as the first approximation, the current effectiveness of transformation η of a heat flux capacity which isn't exceeding rated, can be marked as known η_0

$$\eta = \frac{\Delta \grave{O}}{\Delta T_0} \cdot \eta_0, \qquad (5)$$

where ΔT_0 is the temperature differential between the hot and cold sides that corresponds to a difference of minimum temperature for the cold side on passport data of TEM; ΔT is the actual temeperature differntial between the hot and cold sides.

The real temperature differential will change permanently in some limits depending on certain conditions. The temperature of the hot side is set by the generator wall temperature which depends on the motion speed of gas, i. e. on the frequency of engine shaft turns. If the frequency is high, the temperature of the wall becomes higher. The temperature of the cold side is defined by amount of thermal energy of the leading-out flow, thermal resistance of the radiator and the ambient temperature (for calculation it is selected under normal conditions). Thermal resistance is set by parameters of the radiator and speed of its blowing by air, i.e. motion speed of the car. The higher the speed is, the less thermal resistance of the radiator is depending on its structure. The leading-out heat flow depends on engine shaft turn frequency. The structure of the radiator is not considered in this work. But for the purpose of reduction of its sizes when calculating effectiveness it is necessary to increase temperature of the cooled surface. At the same time such increase reduces ΔT and, according to expression (5), reduces effectiveness of TEM. A compromise between these opposite requirements is the subsequent temperature increase: for the first unit to 150 °C, for the second – to 100 °C, for the third – to 50 °C.

Air cooling has advantage in comparison with that by water because in the process of speed change of the car in case of direct blowing of the generator, there is a corresponding change of its thermal resistance. At small speeds, especially in the idling mode, the air blowing of the radiator of the generator first unit is sufficient for its normal operation. At the same time other units are not threatened by overheating as the main loss of energy of exhaust gas occurs in the first unit. In case of increase in the motion speed, surface of radiators will be blowed by external air with a speed over 15 m/s (60 km/h) that will provide the preset values of thermal resistance, small overall dimensions of radiators and the maximum effectiveness of energy transformation of exhaust gases into electric power.

When calculating effectiveness according to expression (5) values of 9.5, 7.5 and 5.0 % for the 1st, 2nd and 3rd units respectively were received. Considering this the total electric power of the generator, specified in the table, is received. Namely, in case of probable working frequency of the engine (about 3000 RPM.) power of the TEG reaches 1 kW that when calculating on the spent fuel will make more than 2 %. The TEG permanently works out this energy. Some of its quantity will be used by a car network. Residual should be directed on the help of IEE.

There is also a problem with equalization of temperature along one unit as it is necessary to have its identical values on the TEM parameters. For equalization of values of the temperature along the pipeline of the generator it is offered to use thermal vacuum heat exchangers. The project of such a heat exchanger is shown in Fig. 4. It consists of a part of the pipeline and the associated to it by means of electrical welding of a parallelepiped. In emptiness the piece of sodium is placed and after that it is vacuumized up to the pressure of $1 \cdot 10^{-5}$ mm hg. In case of high temperatures emptiness is filled by sodium vapors. Heat conduction of such gas at least is 10 times more than copper.

Methods for application TEG electric power, which is excessive for the car network, make a separate question. It is natural to direct this energy to creation of the car movement. However, it is not provided in the modern cars with IEE. At the same time the TEG is an additional source when using the electric motor and in case of association to a mechanical system of the car. Constructional continuation of development is changeover of the electromechanical generator by the electric motor which will unwind IEE shaft by means of the pass transmission intended for the generator. The engine must have a broad range of speeds, the high moment of a shaft turns and, what is especially important, waste control system. The motor-wheel which has been used since the middle of the last century meets such requirements and now is widespread in the electric transport.

Conclusions and recommendations for further research. The received results are technical and estimated reasons for creation of the innovative device for the in-

Fig. 4. Project of the Heat Exchanger

ternal explosion engine of the car for energy recuperation of the fuel which is released outside. This device is the thermoelectric generator with a block structure which works with thermal energy of exhaust gases for the existing models of cars. When calculating the generator its thermal and physical models are considered, use of air cooling for obtaining optimum effectiveness of transformation is justified. The possibility of receiving to 1 kW electric power in case of its use is shown that when calculating on the consumed fuel makes at least 2 %. It allows making replacement of the electromechanic generator of the car with further use of excessive energy of recuperation.

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Мета. Розробка пристрою для утилізації частини теплової енергії вихлопних газів бензинового двигуна внутрішнього згоряння (ДВЗ), що відповідає конструкції автомобілів, які існують. Створення відповідної моделі та розрахунок основних параметрів термоелектричного генератора, що працює на енергії вихлопних газів, з обґрунтуванням можливості отримання електричної енергії в кількості, достатній, як мінімум, для заміни електромеханічного генератора автомобіля.

Методика. Використовувалося фізичне й математичне моделювання процесів теплопередачі та генерації електричної енергії в термоелектричних генераторах.

Результати. Проведено аналіз фізичної моделі процесу, що відбувається при віддачі теплової енергії від потоку вихлопного газу у трубопроводі генератора, та визначено принцип розрахунку його основних параметрів. Розроблена математична модель теплообміну у трубопроводі блокового термоелектричного генератора. Створена програма на базі програмного забезпечення Wolfram Mathematica та проведено розрахунок відповідних параметрів для кожного блоку при різних навантаженнях ДВЗ. Технічно обгрунтовано створення пристрою для рекуперації енергії палива, що викидається назовні, для ДВЗ легкових автомобілів. Відповідним пристроєм є термоелектричний генератор із блоковою будовою, що працює на тепловій енергії вихлопних газів. Запропоновано використання повітряного охолодження для отримання оптимального ККД перетворення. Показана можливість отримання при його використанні до 1 кВт електричної енергії.

Наукова новизна. Розроблено інноваційний пристрій утилізації енергії вихлопних газів для моделей автомобілів, що вже існують. Уперше запропонована й обгрунтована структура розділення термоелектричного генератора на три блоки, що працюють як окремі термоелектричні генератори, а також введення в середину газового потоку порожнього циліндра з повздожніми ребрами на поверхні для покращення теплопередачі за рахунок випромінювання.

Практична значимість. Використання запропонованого термоелектричного генератора дозволяє провести заміну електромеханічного генератора автомобіля з подальшим використанням надлишкової енергії рекуперації. Енергія, що збережена в результаті рекуперації, у перерахунку на спожите паливо складає не менше 2 %, що є важливим як в економічному, так і в екологічному аспектах.

Ключеві слова: *енергозбереження, термоелектричний генератор, утилізація, вихлопні гази*

Цель. Разработка устройства для утилизации части тепловой энергии выхлопных газов бензинового двигателя внутреннего сгорания (ДВС) в соответствии с конструкцией существующих автомобилей. Создание соответствующей модели и расчет основных параметров термоэлектрического генератора, работающего на энергии выхлопных газов, с обоснованием возможности получения электрической энергии в количестве, достаточном, как минимум, для замены электромеханического генератора автомобиля.

Методика. Использовалось физическое и математическое моделирование процессов теплопередачи и генерации электрической энергии в термоэлектрических генераторах.

Результаты. Проведен анализ физической модели процесса, происходящего при отдаче тепловой энергии от потока выхлопного газа в трубопроводе генератора, и определен принцип расчета его основных параметров. Разработана математическая модель теплообмена в трубопроводе блочного термоэлектрического генератора. Создана программа на базе программного обеспечения Wolfram Mathematica и проведен расчет соответствующих параметров для каждого блока при различных нагрузках ДВС. Технически обосновано создание устройства для рекуперации выбрасываемой наружу энергии топлива для ДВС легковых автомобилей. Соответствующим устройством является термоэлектрический генератор блочной структуры, который работает на тепловой энергии выхлопных газов. Предложено использовать воздушное охлаждение для получения оптимального КПД преобразования. Показана возможность получения при его использовании до 1 кВт электрической энергии.

Научная новизна. Разработано инновационное устройство по утилизации энергии выхлопных газов для существующих моделей автомобилей. Впервые предложено и обосновано структурное разделение термоэлектрического генератора на три блока, которые работают как отдельные термоэлектрические генераторы, а также введение внутрь газового потока полого цилиндра с продольными ребрами на поверхности для улучшения теплопередачи за счет излучения.

Практическая значимость. Использование предложенного термоэлектрического генератора позволяет провести замену электромеханического генератора автомобиля с последующим использованием избыточной энергии рекуперации. Энергия, сохранённая в результате рекуперации, в пересчете на потребляемое топливо составляет не менее 2 %, что является важным как в экономическом, так и в экологическом аспектах.

Ключевые слова: *энергосбережение, термоэлектрический генератор, утилизация, выхлопные газы*

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SYMMETRIZATION OF THREE-PHASE SYSTEM WITH NEGATIVE COMPONENT FILTER USING SIMULATION

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СИМЕТРУВАННЯ НА МОДЕЛІ ТРИФАЗНОЇ СИСТЕМИ З ФІЛЬТРОМ ЗВОРОТНОЇ СКЛАДОВОЇ

Purpose. The determination of the optimal mode of asymmetric three-phase electrical system using the symmetrical component filters and computer power system model is considered.

Methodology. The system is represented as a visual model that uses a resistive-capacitive filter to select reverse symmetrical components. Its amplitude is a function of the target value, which in the process of optimization is reduced to zero. The variables used to be optimized are the parameters of the balun. Optimization is performed by a zero-order method.

Findings. In the process of optimizing the balun device parameters are calculated. The power supply system is set to symmetrical mode. Changing the angle of the line currents with respect to the phase voltages by changing the parameters of the balun device, and at the same time symmetric mode in the system is maintained. Thus the optimum mode can be achieved in which the reactive power in the power system is fully compensated.

Originality. A new approach to the problem of balancing the three-phase power supply systems based on the use of the visual system models and optimization techniques is proposed. The principles of formation of the objective function in order to achieve a symmetrical mode are formulated. The possibility of using filters of symmetrical components for this purpose is shown. The method of exclusion of their direct impact on the power system with dependent sources is found.