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COMPUTER DESIGN OF A THERMOELECTRIC GENERATOR FOR HEAT AND ELECTRICITY SUPPLY TO HEAVY-DUTY VEHICLES

The physical model of the thermoelectric generator for the autonomous system of pre-heating of high-power vehicles is considered. The design of heat exchangers of heat supply and exhaust systems, which allow to ensure the optimal mode of operation of thermoelectric modules, has been determined by computer design. The design of a thermoelectric generator with an electric power of up to 350 W has been developed, which will be enough to supply electric energy to preheaters with a thermal power of 25-30 kW. Such a system, taking into account the thermal energy of the thermoelectric generator, will be equivalent to more powerful preheaters (36 - 40 kW), but will not require the use of battery electricity. Bibl. 8, Fig. 9, Table. 1.

Key words: starting heater, thermoelectric generator, physical model, computer simulation.

Introduction

Operation of vehicles at low ambient temperatures requires the use of methods of preliminary thermal preparation of engines for start-up. The most common methods of preheat treatment of engines used for heavy-duty civil and military equipment include refuelling the engine cooling system and lubrication system with hot antifreeze and engine oil, the use of furnaces that heat the crankcase by direct flame, heating air filters by introducing filter heads for small amounts of fuel from a special electric glow plug, the use of heaters to heat the air entering the engine cylinders, etc. However, these methods of preheating engines are inefficient and time consuming. Therefore, pre-heaters are used more and more, which run on vehicle fuel and heat the engine coolant [1, 2]. An effective method of solving the problem of discharging the battery of vehicles during the operation of preheaters is the use of a thermoelectric generator that operates from the heat of the heater and provides autonomous power to its components [3 - 5]. Moreover, the electric energy excess of thermal generator can be used for battery charging and power supply to other equipment.

The Institute of Thermoelectricity has created an experimental sample of a thermoelectric preheater with a thermal power of 3.5 kW and a maximum electric power of 100 W for heating vehicles with an engine capacity of up to 4 liters [6, 7].

Preliminary analysis [8] shows the prospects for such uses to improve the operational capabilities of heavy-duty vehicles, including armoured vehicles.

The purpose of this work is to develop and optimize the design of a thermoelectric generator for the autonomous source of heat and electricity for heavy-duty vehicles.

Physical model of a thermoelectric generator and its mathematical description

To find the optimal design of the generator, it is necessary to consider its physical model (Fig. 1). The model consists of five sections, each of which containing a hot heat exchanger, thermoelectric modules and a cold heat exchanger. The design of heat exchangers of each section must be optimized to achieve the optimal mode of operation of all thermoelectric modules. The model provides a separate heat source – air heater on diesel fuel. Heat is supplied to the hot heat exchanger of the generator due to forced convection of hot fuel combustion products moving in the heat exchanger channels. Heat removal from thermoelectric modules is carried out by a liquid coolant that is forcibly circulating in the system.

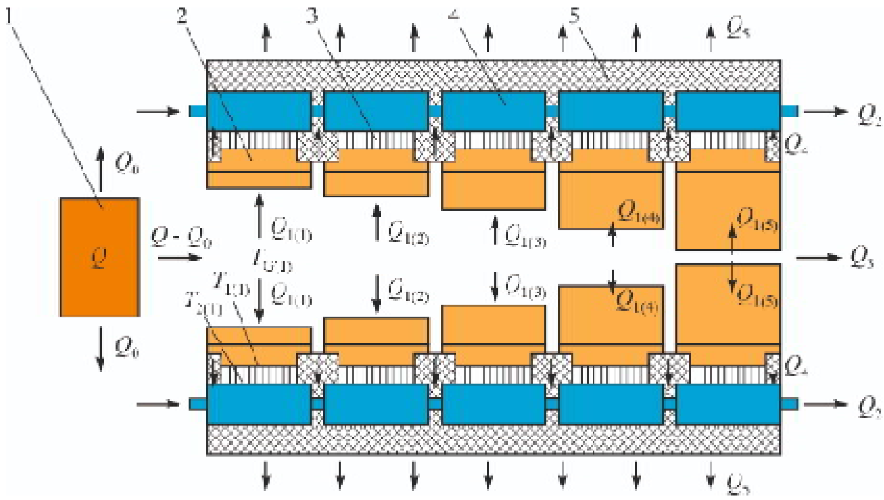


Fig. 1. Physical model of a thermoelectric generator for heat and electricity source for armoured vehicles.: 1 – heat source; 2 – hot heat exchanger (radiator); 3 – thermopile; 4 – cold heat exchanger; 5 – thermal insulation

The thermoelectric converter is composed of standard thermoelectric modules Altec - 1061 that are most suitable for creation of thermoelectric recuperators. The optimal temperature of the hot side of modules is about 280 - 300°C, and of the cold side – 30 - 50 °C.

The heat $Q_{1(i)}$ which comes to the hot heat exchanger of i-th section is passed by way of convection and radiation:

$$Q_{1(i)} = \alpha_{(i)} \cdot \left(T_{G(i)} - T_{r(i)}\right) \cdot S_{R(i)} + \varepsilon_{(i)} \cdot \sigma_0 \cdot \left(\varepsilon_G \cdot \left(\frac{T_{G(i)}}{100}\right)^4 - A_{r(i)} \cdot \left(\frac{T_{r(i)}}{100}\right)^4 \right) \cdot S_{R(i)}, \tag{1}$$

where $\alpha_{(i)}$ is convective coefficient of heat exchange from the hot gas to heat receiving surface of the hot heat exchanger of the i-th section; $T_{G(i)}$ is the average gas temperature in the hot heat exchanger of the i-th section; $T_{r(i)}$ is the average temperature of the heat receiving surface of the hot heat exchanger of the i-th section; $S_{R(i)}$ is the area of heat receiving surface of the hot heat exchanger of the i-th section; $\varepsilon_{(i)} = (\varepsilon_{r(i)}+1)/2$ is the effective degree of blackness of the "hot gas-heat receiving surface" system of the hot heat exchanger of the i-th section; $\varepsilon_{r(i)}$ is the degree of blackness of the heat receiving surface of the hot heat exchanger of the i-th section; σ_0 is Stephan-Boltzmann constant; ε_G is the degree of blackness of gas; $A_{r(i)}$ is the absorptivity of the heat receiving surface of the hot heat exchanger of the i-th section.

Heat Q_2 is removed from the cold side of thermoelectric modules with the flow of heat carrier which circulates in the cold liquid heat exchanger 4:

$$Q_2 = g_T \cdot c_{pT} \cdot \left(T_{вх} - T_{вих}\right), \tag{2}$$

where g_T is heat carrier consumption; c_{pT} is heat capacity of heat carrier T_{in}, T_{out} are temperatures of heat carrier at the inlet and outlet of system for cooling thermoelectric modules, respectively.

As long as the cold liquid heat exchangers are combined into one hydraulic loop with engine cooling system 5, the heat dissipated from the modules is used to preheat the engine.

The main losses of heat are determined as follows:

1) Q_3 – with reaction products (water H_2O, carbon dioxide CO_2 and nitrogen N_2):

$$Q_3 = C_c \cdot m_c \cdot \left(T_{G(вих.)} - T_0\right), \tag{3}$$

where C_c is the average heat capacity of reaction products, m_c is the mass of reaction products, $T_{G(out)}$ is the temperature of reaction products at the outlet from the generator.

2) Q_4 – on the thermal insulation:

$$Q_4 = \frac{\lambda S_{рг}}{L}(T_Б - T_0), \tag{4}$$

where λ is thermal conductivity of insulation material; $S_{рг}$ is the surface area of the hot heat exchanger not occupied by thermopile; L is the thickness of thermal insulation layer.

Thus, the heat balance equation for this physical model of thermoelectric generator can be written as:

$$\begin{cases} Q = Q_0 + \sum_{i=1}^{n} Q_{1(i)} + Q_3 + Q_5, \\ Q_6 = P + Q_2 + Q_4. \end{cases} \tag{5}$$

where n is the number of sections in the hot heat exchanger of thermoelectric generator.

The relationship between the velocity v and the hot gas temperature T_G in the heat exchanger is determined by the formula:

$$v = 5 \cdot \left[\frac{\dfrac{G_n}{T_G - T_0} - K_1}{K_2} + 1 \right] \cdot \frac{K(O_2) \cdot g_n}{\rho_{T0} \cdot \pi \cdot d^2 / 4}, \tag{3.36}$$

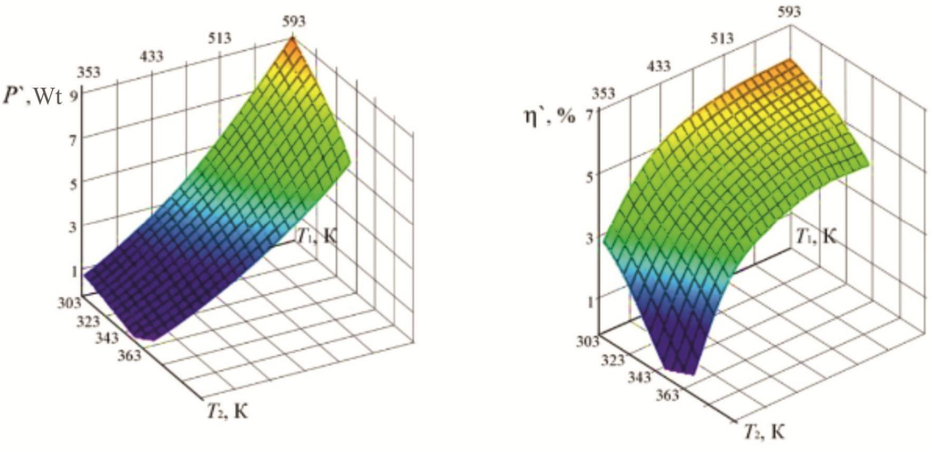
where $K(O_2)$ is coefficient that determines the amount of oxygen necessary for full combustion of fuel, d is the diameter of combustion chamber; K_1 and K_2 are coefficients that determine the amount of carbon dioxide, water, nitrogen and air which formed as a result of full combustion of fuel and are derived with regard to specific values of gas volatility degrees i, Mendeleev-Klapeyron constant R and gas molar mass μ; g_n is air consumption; ρ_{T0} is air density at a given ambient temperature T_0.

The solution of the system of thermal balance equations (5) allows determining the main energy and structural parameters of the generator. It was implemented in the Comsol Multiphysics application package by finite-element method in two steps which aimed at determining:

– the effective geometry of the hot heat exchanger and optimal fuel consumption and air velocity v to assure maximum operating temperature of thermopile hot junctions;

– the effective geometry of the cold heat exchanger and optimal heat carrier consumption to assure the necessary operating temperature of thermopile cold junctions.

The input data for the calculation of structural parameters of the heater hot heat exchanger are the dependences of electric power P_{mod} and the efficiency η_{mod} of the used thermoelectric generator modules of the type Altec-1061 (Fig. 2).



a) *b)*

Fig. 2. Dependences of efficiency η (a) and electrical power P (b) of thermoelectric module of the type Altec-1061 on the hot T_1 and cold T_2 module side temperatures

Results of computer design of a thermoelectric generator

Computer model comprises 5 sections, each of which has landing pads for 8 thermoelectric modules (Fig. 3). Each section has N_i channels of diameter d_i for passing of heat carrier. In so doing, the total cross-sectional area of channels in each section was the same, and increasing the number of channels with a simultaneous reduction of their diameter was achieved by increasing the area of heat exchanger of each successive section.

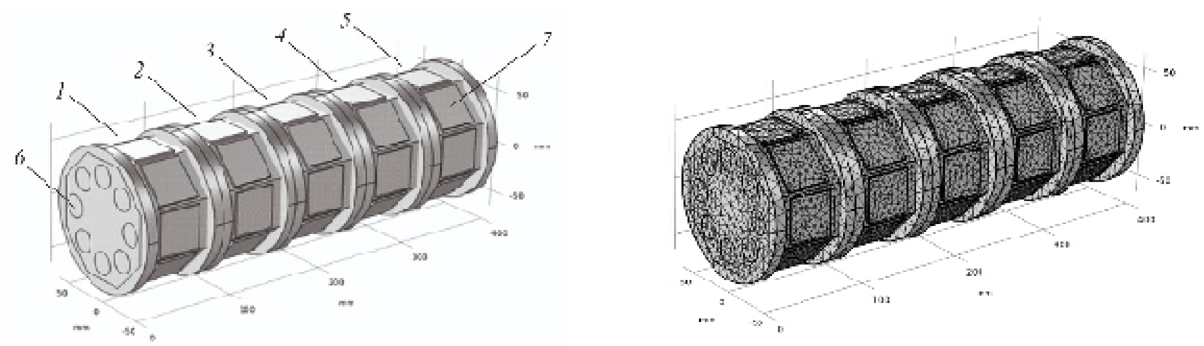


Fig. 3. Computer model of the hot heat exchanger of thermoelectric generator in the Comsol Multiphysics applied package: 1-5 – heat exchanger sections, 6 – channels for heat carrier passing; 7 – places of thermoelectric modules arrangement

Optimal geometry of each section was determined from the condition of assuring optimal temperature mode on the hot side of all thermoelectric modules – about 280-300°C.

An example of temperature distribution in the hot heat exchanger of thermoelectric generator in the Comsol Multiphysics application package is given in Fig. 4.

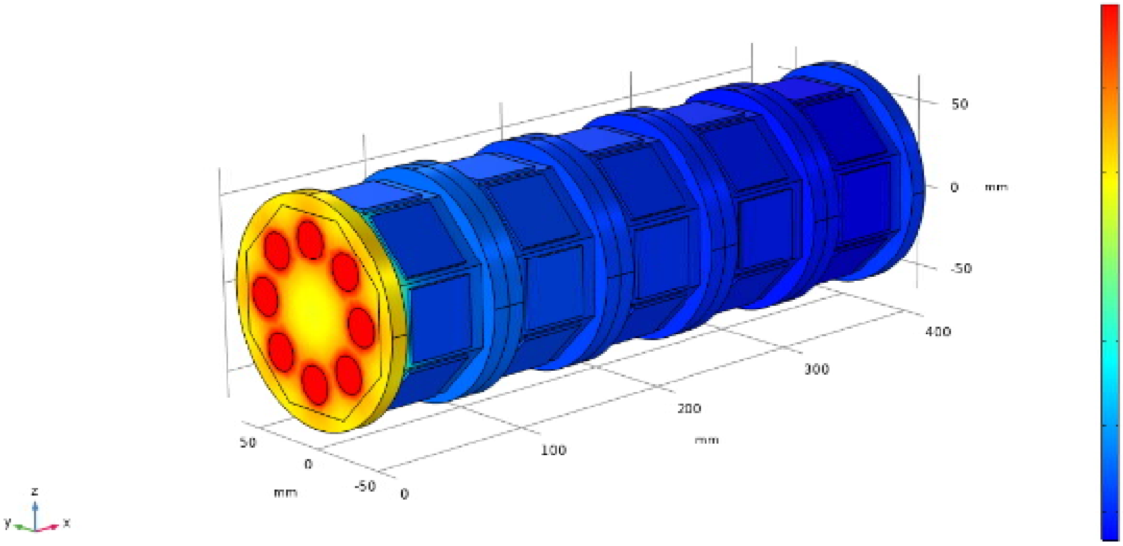


Fig. 4. Example of temperature distribution in the hot heat exchanger of the generator

Table 1 shows the computer simulation of the geometric parameters of the heat exchanger (number N_i of channels of each section and their diameter d_i, area of the heat exchanger), which allow providing the required temperature mode.

Table 1.

Results of optimization of the hot heat exchanger design

	Section 1	Section 2	Section 3	Section 4	Section 5
Number of channels N_i	8	16	32	72	144
Channel diameter d_i, mm	21.2	15.0	10.6	7.1	5.0
Heat exchanger area $S_{R(i)}$, m^2	0.037	0.053	0.075	0.112	0.158
Average temperature of module landing pad $T_1(i)$, °C	308.0	309.1	301.6	293.3	281.8

The temperature distribution of gas passing through the heat exchanger is shown in Fig. 5. Coordinate x defines the position in the direction of the gas flow in relation to the heat exchanger.

In order to determine the temperature distribution in the cold heat exchangers of the heater (Fig. 6), the process of heat transfer from the thermoelectric module to the vehicle heating system by heat exchange between the cold side of the thermopile and the heat carrier flow, which circulates in the channels of the cold heat exchanger at speed v and temperatures $T_{in.}$ and $T_{out.}$, respectively at the inlet and outlet of the heat exchanger was studied.

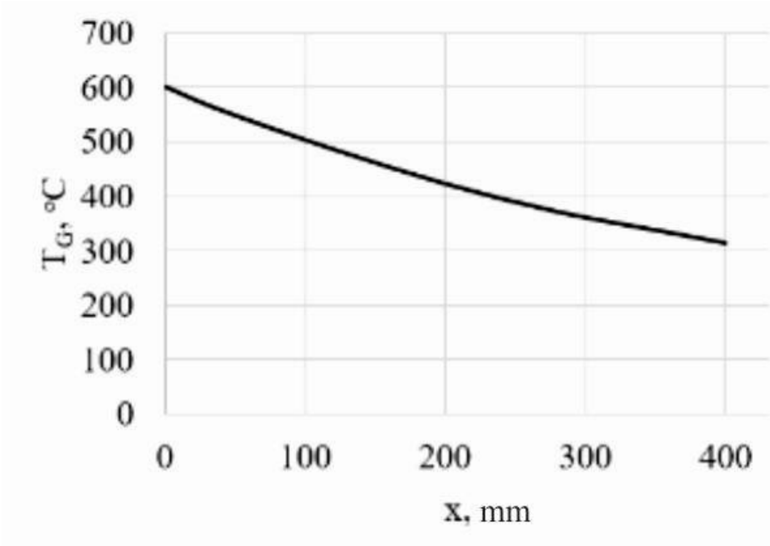


Fig. 5. Temperature distribution of gas inside the hot heat exchanger of thermoelectric generator (for a heat exchanger design with the parameters given in Table 1)

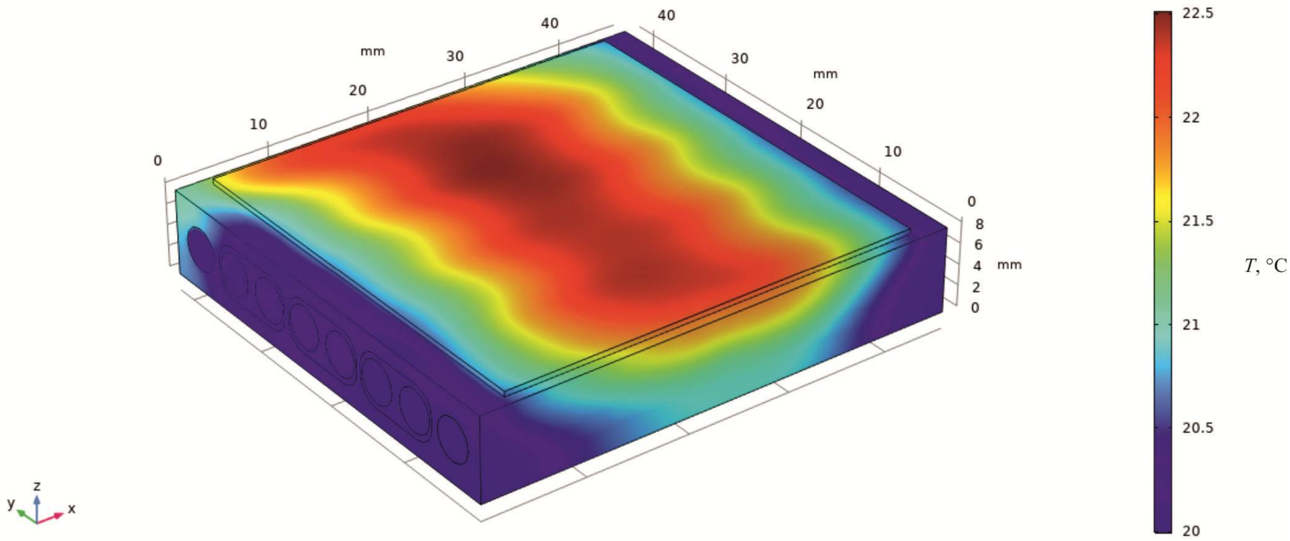


Fig. 6. Example of temperature distribution in the hot heat exchanger of the generator

Fig. 6 shows an example of a heat exchanger with channel diameter 4 mm with heat carrier consumption 0.05 m^3/h. Figs. 7, 8 also show the distributions of heat carrier velocity and temperature in the heat exchanger.

As a result of simulation, we obtained the dependences of temperature difference between the inlet and outlet from the cold heat exchangers on the geometry of channels and on the heat carrier consumption (Fig. 9).

v, m/s *T*, °C

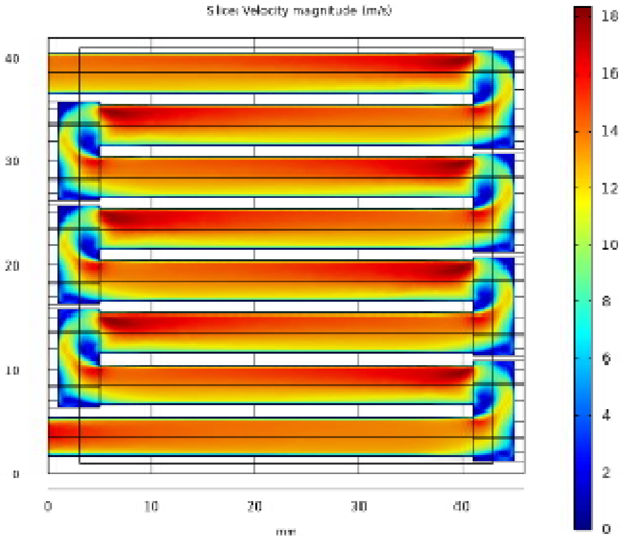


Fig. 7. Example of distribution of heat carrier velocity in the cold heat exchanger of thermoelectric generator

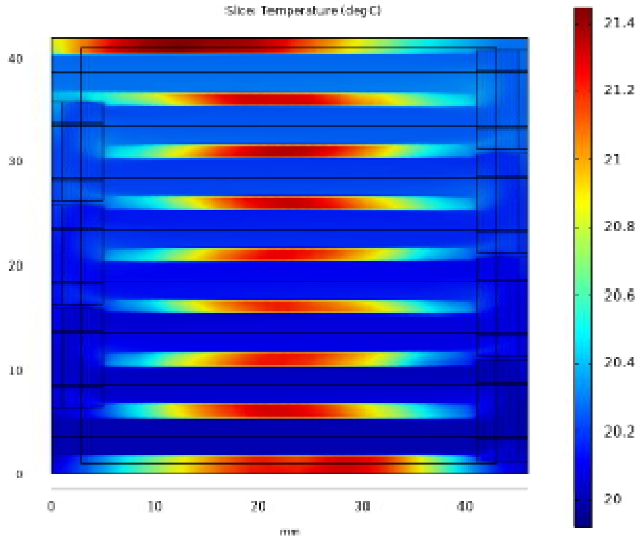


Fig. 8. Example of distribution of heat carrier temperature in the cold heat exchanger of thermoelectric generator

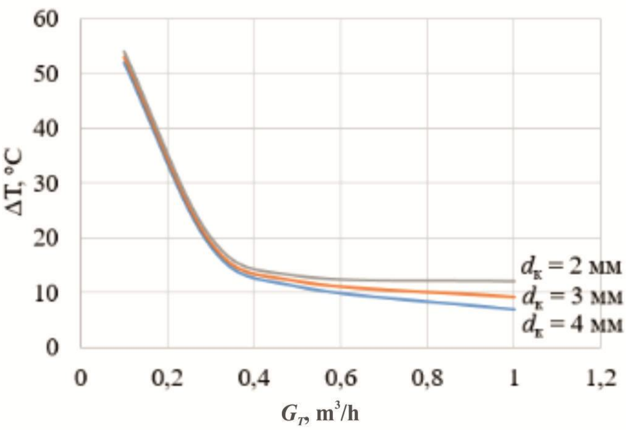


Fig. 9. Dependence of temperature difference ΔT between the inlet and outlet of cold heat exchanger system on heat carrier consumption G_m and channel diameter $d_к$

For the case of heat exchanger system comprising 40 individual heat exchangers with channel diameter 4 mm, combined into one hydraulic loop by two series links, 20 pcs each, to ensure the necessary operating temperatures of the cold module side (30 - 50°C), the consumption of heat carrier pumped through the system should be 0.5 - 0.7 m^3/h.

The results served the basis for the design development of thermoelectric generator with electric power up to 350 W which will be sufficient for supply with electric energy of starting preheaters of the type PROHEAT M90 24V (with useful thermal power 26 kW and electric power consumption up to 230 W) or OJD30.8106010 (with useful thermal power 30 kW and electric power consumption up to 140 W). Such a system with account of thermal energy of thermoelectric generator (about 10 kW) will be equivalent in thermal power 36 - 40 kW (but autonomous) and will allow replacing the starting preheater of the type PJD - 44Ш (with useful thermal power 37 kW and electric power consumption up to 340 W), which is widely used in heavy-duty civil and military equipment.

Conclusions

1. A physical, mathematical and computer models of a thermoelectric generator for the heat and electricity supply to heavy-duty vehicles were developed. Computer simulation has been used to determine the optimum design of heat exchanger systems for heat supply and removal, which allows to ensure the required operating mode of thermoelectric modules.
2. A design of thermoelectric generator of electric power up to 350 W and thermal power up to 10 kW was developed. Combined with a starting preheater of thermal power 25-30 kW, the generator creates an autonomous starting preheat system with thermal power up to 40 kW This system can replace a similarly powerful starting preheater and does not require the use of battery power.

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КОМП'ЮТЕРНЕ ПРОЕКТУВАННЯ ТЕРМОЕЛЕКТРИЧНОГО ГЕНЕРАТОРА ДЛЯ ДЖЕРЕЛА ТЕПЛА ТА ЕЛЕКТРИКИ ДЛЯ ТРАНСПОРТНИХ ЗАСОБІВ ВЕЛИКОЇ ПОТУЖНОСТІ

Розглянуто фізичну модель термоелектричного генератора для автономної системи передпускового розігріву транспортних засобів великої потужності. Шляхом комп'ютерного проектування визначено конструкції теплообмінників систем підведення та відведення тепла, які дозволяють забезпечити оптимальний режим роботи термоелектричних модулів. Розроблено конструкцію термоелектричного генератора електричною потужністю до 350 Вт, якої вистачатиме для живлення електричною енергією передпускових нагрівників тепловою потужністю 25-30 кВт. Така система, з врахуванням теплової енергії термоелектричного генератора, буде еквівалентною більш потужним передпусковим нагрівникам (36 – 40 кВт), але не потребуватиме при роботі використання електричної енергії акумулятора. Бібл. 8, рис. 9, табл. 1.

Ключові слова: передпусковий нагрівник, термоелектричний генератор, фізична модель, комп'ютерне моделювання.

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КОМПЬЮТЕРНОЕ ПРОЕКТИРОВАНИЕ ТЕРМОЭЛЕКТРИЧЕСКОГО ГЕНЕРАТОРА ДЛЯ ИСТОЧНИКА ТЕПЛА И ЭЛЕКТРИКИ ДЛЯ ТРАНСПОРТНЫХ СРЕДСТВ БОЛЬШОЙ МОЩНОСТИ

Рассмотрена физическая модель термоэлектрического генератора для автономной системы предпускового разогрева транспортных средств большой мощности. Путем компьютерного проектирования определены конструкции теплообменников систем подвода и отвода тепла, позволяющие обеспечить оптимальный режим работы термоэлектрических модулей. Разработана конструкция термоэлектрического генератора электрической мощностью до 350 Вт, которой будет хватать для питания электрической энергией предпусковых отопителей тепловой мощностью 25-30 кВт. Такая система, с учетом тепловой энергии термоэлектрического генератора, будет эквивалентна более мощным предпусковым отопителям (36 – 40 кВт), но не потребует при работе использования электрической энергии аккумулятора. Библ. 8, рис. 9. Табл. 1.

Key words: preheater, thermoelectric generator, physical model, computer simulation.

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