insulated – 1.4 ° C for one hour.

In practice, there are many ways to ensure the technical readiness of a vehicle at low temperatures. However, most of them require the solution of complex design and technical problems and, under operating conditions, turn out to be ineffective or quite energy consuming. Therefore, the proposed work considers those that are based on the methods of storage battery thermal control through use of secondary energy resources of the internal combustion engine, which arise in large quantities during its operation.

Research results

With the rapid growth in the number of vehicles over the past decades, combined with the tightening of standards for fuel consumption and emissions of harmful substances, the utilization of thermal energy of exhaust gases as part of the secondary energy resources of a transport engine is becoming a promising direction for solving the above problem. This allows the implementation of energy-efficient technologies for road transport. Exhaust gases have a high thermal potential, take about 30% of the fuel energy into the environment, not only wasting primary energy resources, but also increasing the heat load on the environment.

Application of heat accumulators using phase transition heat-accumulating materials is an effective and promising way of storing heat energy on board a vehicle. This method makes it possible to provide a high density of accumulated energy with an isothermal nature of the accumulation process and makes it possible to store accumulated thermal energy on board a vehicle for quite a long time.

In this regard, it seems promising to develop systems that would have the ability to convert the thermal energy accumulated in phase transition heat accumulator into electrical energy. To solve this problem, according to the authors, thermoelectric energy converters can be effectively used [4]. The advantages of the latter are the absence of moving parts, silent operation, environmental friendliness, versatility in terms of methods of supply and removal of thermal energy, potentially high reliability [5, 6].

This article presents the results of computational studies of the thermoelectric system proposed in [7,8], which provides the optimal thermal regime of the starter battery at the end of the operation of the internal combustion engine during the maintenance of the vehicle at low ambient temperatures.

Thermoelectric generators (TEG), as autonomous direct current sources, received intensive development after semiconductor thermopiles were taken as the basis for their design. Over the past decades, there has been a constant improvement of semiconductor thermoelectric materials, which is aimed primarily at increasing their thermoelectric figure of merit in order to increase the electricity they produce and improve the efficiency [9].

Significant disadvantages of semiconductor TEGs are their fragility, high cost and complexity of the design of an automobile thermoelectric generator (ATEG) to ensure efficient operation, due to the need for an external source of cooling, which makes it possible to obtain the necessary (stable) temperature gradient and the presence of an electronic converter, which allows maintaining the necessary output voltage. The need for such a scheme is explained by the fact that the electromotive force generated by ATEG is not constant, since the temperature difference constantly changes its value in different operating modes of the transport ICE.

In the conditions of real operation of the vehicle, the ATEG, from the point of view of the efficiency and stability of its thermoelectric properties, must have the necessary mechanical strength and chemical resistance under the conditions of prolonged vibration and shock loads, with sharp drops in the temperature, pressure, and humidity.

Thus, it is fair to assume that in order to obtain electrical energy sufficient to power low-power devices under conditions of a small temperature gradient, metal conductors are more suitable for the manufacture of ATEG.

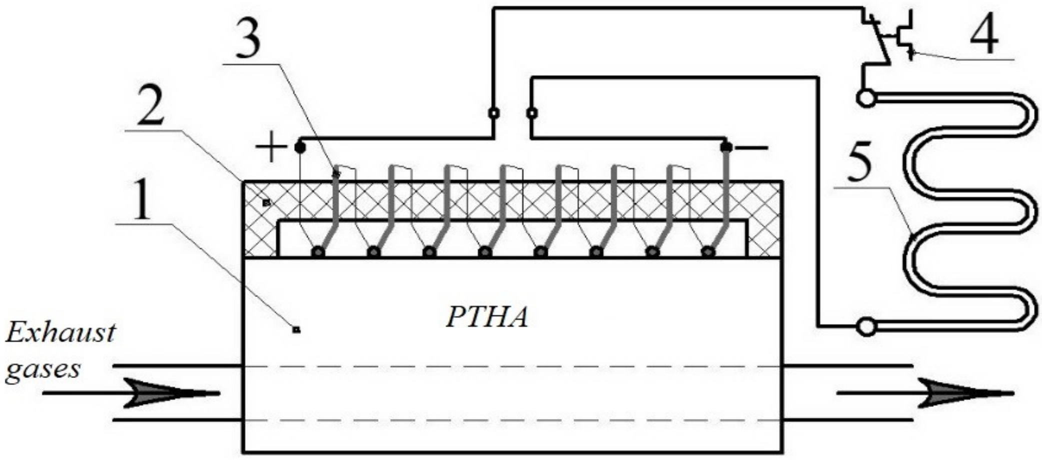

Fig. 1. Thermoelectric system for utilization of thermal energy of exhaust gases with phase transition heat accumulator:
1 – phase transition heat accumulator,
2 – layer of heat-resistant compound,
3 – thermoelectric generator,
4 – heat regulator, 5 – heating element.

Taking into account the above, the authors proposed a method for increasing the thermal readiness of a vehicle, in particular, the electrical starting system, under low temperatures. The implementation of this method and, as a consequence, the provision of the optimal thermal mode of the storage battery, is possible due to the use of a device for compensating heat losses of storage battery by thermostating with heating elements.

The heat capacity of the battery is quite high, so when you install it in a container with insulated walls (thermocase), the rate of drop of the electrolyte temperature will be quite low. Heating elements are added inside the thermocase. The built-in temperature regulator turns off heating on reaching + 25 ° C and turns it on again at + 15 ° C.

The operating principle of the proposed system is as follows (Fig. 2): after stopping the internal combustion engine the storage battery naturally cools down (section I), upon reaching the storage battery temperature 15 °C, electric heating elements are connected to ATEG to heat the storage battery to 25 °C (section II), following which the heating elements are turned off. After reducing the temperature of the storage battery to 15 °C (section III) – the process is repeated. Responsible for the switching of electrical circuits is the electronic control unit that receives information from the temperature sensor of the storage battery (the temperature sensor is installed on the negative terminal of the storage battery).

The proposed technical solution makes it possible to generate electrical energy without any additional energy transmitted to the system both the internal combustion engine is in operation and when the vehicle is kept in open areas under low temperatures. Based on the results of previous experimental studies, the possibility of using metal TEGs for generating electrical energy for quite a long time after the end of the ICE operating cycle was confirmed [7].

Fig. 2. Operating principle of a device for compensating heat losses of storage battery

Computational studies

Calculation of the amount of energy required for thermal stabilization of the 6CT-44A battery of ZAZ Tavria class cars with a capacity of 44 A·h in the temperature range 15...25 °C.

The mass of the specified battery is 13.6 kg, of which the mass of the electrolyte is 3.6 kg. To simplify the calculation, we assume that another mass – 10.0 kg falls on lead (the mass of the body of the storage battery and separators is neglected). Some design parameters of the 6CT-44A battery are shown in Table 1 [10].

Table 1

Some design parameters of the 6CT-44A storage battery

Overall dimensions, mm			Mass, kg	
length	width	height	without electrolyte	with electrolyte
207	175	175	10	13,6

The amount of heat required to heat the battery (Q_b) is defined as the sum of the amount of heat for heating the lead (Q_{Pb}) and the amount of heat for heating the electrolyte (Q_{El}):

$$Q_{АБ} = Q_{Pb} + Q_{Ел} \quad (1)$$

The amount of heat is defined by the formula:

$$Q = m \cdot c_p \cdot \Delta t, \tag{2}$$

where m is mass of heated substance, kg;
c_p is specific heat, J/kg·K;
Δt is temperature difference, K.
The values of specific heats of storage battery components are given in Table 2.

Table 2

The values of specific heats of storage battery components

Storage battery components	c_p, J/(kg·K)
Water H_2O	4182
Sulphuric acid (100%) H_2SO_4	1380
Lead *Pb*	128

The heat capacity of electrolyte with a density of 1.28 g/cm^3 was determined using the data given in Table 3 [11].

Table 3

The amount of distilled water and acid, required to prepare 1 l of electrolyte with a density of 1.28 g/cm^3 (at 25 °C)

The required electrolyte density, g/cm^3	The amount of water, l	The amount of sulphuric acid with a density of 1.83 g/cm*	
		l	kg
1.28	0.781	0.285	0.523

Using the data in Table 1 and 3, we received the required amount of sulfuric acid with a density of 1.83 g / cm^3 - 1.88 kg; distilled water - 2.81 kg. Based on the obtained values and data of Table 2 we calculated the specific heat of the electrolyte with a density of 1.28 g/cm^3 - 1.15 kJ/(kg·K).

Based on the obtained values and formulae 1, 2, we calculated the amount of heat required to heat the 6ST-44A battery from 15 ° C to 25 ° C:

$$Q_b = 10\cdot 10.0\cdot 128 + 10\cdot 3.6\cdot 1150 \approx 54 \text{ (kJ)}$$

If the calculated thermal energy is converted into consumed electrical power, then we get about 15 W · h.

In practice, it is impossible to achieve the full use of storage battery active materials involved in current-forming process. Moreover, the electrolyte (height h_3), which is located in the mud space between prisms 5 and the electrolyte reserve (height h_2 in a battery with a sheet separator and height h_2+h_3 in a battery with an envelope separator), does not take part in current-generating process during electrical starting of the internal combustion engine. In this connection, the paper proposes to limit the heating area of storage battery (side and end surfaces with height h_1) by the height of the electrode to reduce the power of the electric heating element 7 (Fig. 3).

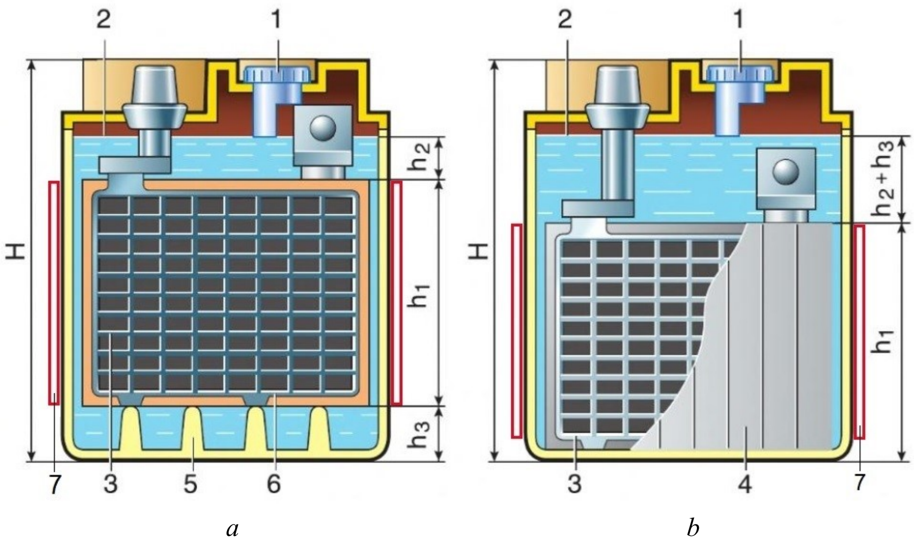

Fig. 3. Schematic of storage battery: [12]
a – conventional battery; b – battery with unattended envelope separators;
1 - plug; 2 – electrolyte level in a battery; 3 - electrode; 4 – envelope separator;
5 – mud space prisms; 6 – card separator;7 – electric heating element;
H – battery height; h_1 – electrode height; h_2 – electrolyte reserve in a battery with
a sheet separator; h_3 – height of prisms; $h_2 + h_3$ – electrolyte reserve in
a battery with an envelope separator

Therefore, the value of the required electric power of the electric heating element can be much lower than the calculated and with regard to the volume of electrolyte that does not participate in the current-generating process it can be reduced by 40… 60%, which will make up to 9 W · h.

Calculation of thermoelectric generator.

Based on the analysis of possible electric heating materials for heating storage battery, the use of carbon fiber material as an external electric heater of storage battery is proposed (Fig. 4).

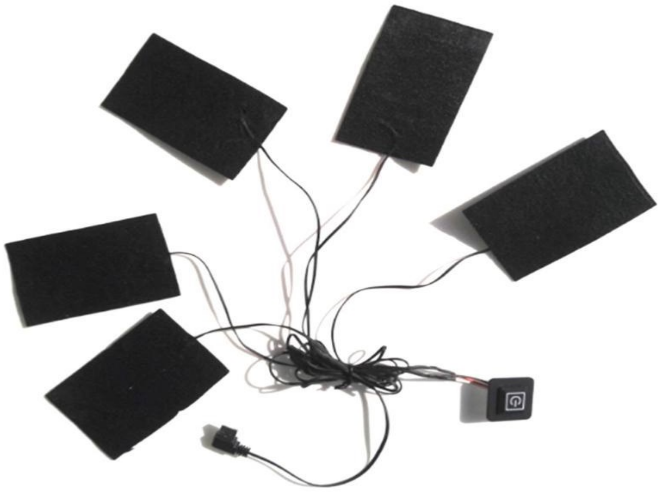

Fig. 4. Electric heating elements based on carbon fiber materials

The use of carbon fiber materials as heating elements helps provide:
• larger area with a uniform temperature distribution on the surface;
• high heat transfer rates;
• reliable operation for a long time;
• low cost of electricity consumption compared to counterparts about 30%;
• heating in 3s after power supply and the same fast cooling.
The technical characteristics of the proposed heating element are as follows:
• thickness: about 0.3 mm
• substrate size: about 110 * 70 mm
• heating temperature: 50…55 °C
• voltage: 3.7 ... 5.0 V
• current: 1.85 ± 0.05 A
• power output: 8.5 ± 0.2 W
• resistance: 3 Ohm

Based on the technical characteristics of the heating element, we calculated a thermoelectric generator based on chromel-copel (L) thermocouples to power an external electric heater of 6CT-44A storage battery. As a heat source, a phase transition thermal accumulator was used, assuming its average temperature in the zone of contact with TEG (t_h) = 78.5 °C, the temperature of the cold junction (t_c) = 0 °C. The calculations used the method proposed in [13].

The purpose of the calculation is to determine the required number of series-connected *L* type thermocouples to ensure the operation of the external electric heater of storage battery.

The required number K of thermocouples in TEG, each of which having internal resistance *r* and thermoEMF e_t, was calculated by the formula (3):

$$K = \frac{U}{e_t - Ir} \quad (3)$$

where U is voltage on the load, V;
e_t is thermoEMF developed by thermocouple, V;
I is current flowing in the thermocouple circuit, A
r is internal resistance of thermocouple, Ohm.

Current flowing in the thermocouple circuit was calculated by the formula (4):

$$I = \frac{e_t}{r + R} \tag{4}$$

where R is load resistance, Ohm.

The internal resistance of thermocouple was calculated by the formula (5):

$$r = \frac{\rho_1 l}{s_1} + \frac{\rho_2 l}{s_2} \tag{5}$$

where ρ_1, ρ_2 are the resistivities of materials of which thermocouples are made, Ohm·mm^2/m;
l is the length of thermocouple conductor (assumed to be equal for both conductors), m;
s_1, s_2 are cross-sectional areas of thermocouple conductors, mm^2.

According to [14], the thermoEMF developed by thermocouple of L type is on the average 4.1 mV. According to [14], the resistivity of chromel metal alloy was assumed to be 0.038 Ohm•mm^2/m and the resistivity of copel alloy – 0.027 Ohm•mm^2/m, with the wire diameter 0.7 mm and the length of both thermocouple conductors assumed to be 0.02 m.

Based on the results of calculating the cross-sectional area of the thermocouple conductors, we obtained 0.38 mm^2.

According to formula (5), the resistance of thermocouple was determined as r = 0.0034 Ohm. Formula (4) was used to calculate current flowing in thermocouple circuit, I = 0.0014 A, formula (3) – to determine the required number of thermocouples in TEG, K ≈ 1200 pcs.

Conclusions

1. Based on the results of the studies, a system was proposed for compensating the heat losses of the battery during the maintenance of the vehicle at low temperatures by the thermostating method using thermoelectric energy converters.
2. The proposed technical solution makes it possible to generate electrical energy, both when the internal combustion engine is operating and when the vehicle is kept in open areas at low temperatures, using a phase transition heat accumulator as a heat exchanger, which accumulates the thermal energy of exhaust gases.
3. To power the external electric heater of a car battery, it is proposed to use a thermoelectric generator on chromel-copel (L) thermocouples.
4. According to the calculation results, to ensure thermoelectric stabilization of the optimal temperature of the 6ST-44A automobile battery, the required number of series-connected L type thermocouples was determined, to ensure the operation of an external electric heater with a total power of up to 9 W - about 1200 pieces.

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Submitted 20.07.2020

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ЗАСТОСУВАННЯ ТЕРМОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ ЕНЕРГІЇ ДЛЯ ЗМЕНШЕННЯ ВПЛИВУ ПРИРОДНО-КЛІМАТИЧНИХ ФАКТОРІВ НА ТЕХНІЧНУ ГОТОВНІСТЬ ТРАНСПОРТНОГО ЗАСОБУ

У статті розглядається проблема, пов'язана з експлуатацією транспортного засобу в умовах низьких температур оточуючого повітря, обґрунтовується необхідність прийняття спеціальних заходів для підтримки оптимального теплового режиму акумуляторної батареї. Проведено аналіз факторів, що впливають на пуск холодного двигуна. Показано вплив низької температури акумуляторної батареї на енергетичні показники електростартерної системи пуску. Проведені розрахункові дослідження запропонованої системи для компенсації теплових втрат акумуляторної батареї під час утримання транспортного засобу в умовах низьких температур методом термостатування з застосуванням термоелектричних перетворювачів енергії. Бібл.14, рис.4, табл. 3.

Ключові слова: технічна готовність, акумуляторна батарея, термоелектричний генератор, тепловий акумулятор фазового переходу, електронагрівальні елементи.

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ПРИМЕНЕНИЕ ТЕРМОЭЛЕКТРИЧЕСКОГО ПРЕОБРАЗОВАТЕЛЯ ЭНЕРГИИ ДЛЯ УМЕНЬШЕНИЯ ВЛИЯНИЯ ПРИРОДНО-КЛИМАТИЧЕСКИХ ФАКТОРОВ НА ТЕХНИЧЕСКУЮ ГОТОВНОСТЬ ТРАНСПОРТНОГО СРЕДСТВА

В статье рассматривается проблема, связанная с эксплуатацией транспортного средства в условиях низких температур окружающего воздуха, обосновывается необходимость принятия специальных мер для поддержания оптимального теплового режима аккумуляторной батареи. Проведен анализ факторов, влияющих на пуск холодного двигателя. Показано влияние низкой температуры аккумуляторной батареи на энергетические показатели электростартерной системы пуска. Проведены расчетные исследования предложенной системы для компенсации тепловых потерь аккумуляторной батареи во время содержания транспортного средства в условиях низких температур методом термостатирования с применением термоэлектрических преобразователей энергии. Библ.14, рис.4, табл. 3.

Ключевые слова: техническая готовность, аккумуляторная батарея, термоэлектрический генератор, тепловой аккумулятор фазового перехода, электронагревательные элементы.

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Submitted 20.07.2020

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EFFECTIVENESS OF THERMOELECTRIC RECUPERATORS FOR RATIONAL TEMPERATURES OF HEAT SOURCES

The paper presents the results of analysis of thermoelectric recuperators of waste heat for the temperature range 100 -300^{O}C of the heat carrier. Based on computer model, optimization of sectional recuperators is carried out, the efficiency of each section and recuperator as a whole is calculated. The specific cost and payback time of sectional generators is calculated. Conclusions are made on the economic feasibility of using such recuperators. Bibl. 130, Fig. 9, Tabl. 1.
Key words: thermoelectric recuperator, waste heat, efficiency, power, specific cost.

Introduction

General characterization of the problem. Most types of equipment for technological processes in industry, heat engines (turbines, internal combustion engines, etc.) generate a large amount of waste heat during their operation. In so doing, more than half of this heat is not only not used in any way, but also leads to negative consequences for the environment – to its thermal pollution [1 – 4]. In this case, the majority of thermal waste (nearly 90 %) has temperature up to 300 °C (Fig. 1). This determines the relevance of creation of waste heat recuperators for this temperature level.

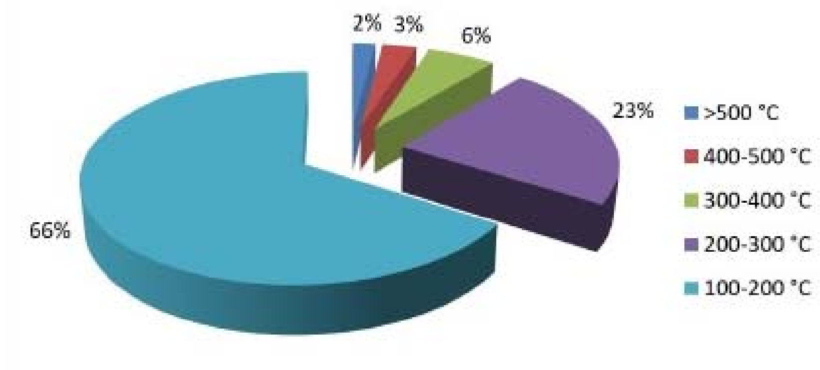

Fig. 1. Distribution of thermal waste sources by temperature range [6].

The most popular ways of thermal into electrical energy conversion are mechanical. Their characteristics are shown in the table. As is seen from the table, mechanical methods are efficient at high temperatures. At low temperatures (up to 300°C) they considerably lose their effectiveness or do not work altogether. Another disadvantage is the need to use bulky equipment (boilers, evaporators, turbines). Under such circumstances, direct thermal into electrical energy conversion by means of thermoelectricity can become a competitive mechanical method.

Table.

Mechanical methods of waste heat conversion into electrical energy [7- 11]

№	Method	Efficiency	Operating temperatures	Electrical energy cost	Service life
1.	Rankine cycle	20-30 %	> 350 °C	0.8 – 1.8 $ / Wт	15 - 20 years
2.	Kalina cycle	~ 15 %	100 – 540 °C	1.2 – 1.8 $/Wт	20 - 30 years
3.	Organic Rankine cycle	~ 8-15 %	100 – 590 °C	1.4 – 2.2 $/W	20 - 30 years

Therefore, *the purpose of the work* is to establish general features that thermoelectric recuperators must meet, which will ensure their rational use.

Unlike thermoelectric generators which use costly heat sources and for which the main criterion of effectiveness is their efficiency, thermoelectric recuperators use waste heat. Therefore, to determine their effectiveness, it is necessary to apply other approaches, namely to establish their specific cost and payback time [129].

Known thermoelectric recuperators of waste heat

Based on the analysis of literature data, it is possible to identify the most common areas of using thermoelectric heat recuperators, namely industrial plants, internal combustion engines, thermal power plants, boilers, gas turbines, and domestic heat. Waste heat recuperators [43-51] from such energy-intensive industrial facilities as steel plants [26, 36-41, 54, 55], cement kilns [27-35, 38-40, 52, 54], glass furnaces [38-40, 52], furnaces for annealing lime [38, 39, 52], furnaces for the production of ethylene [38, 39], garbage recycling plants [104, 105], furnaces for smelting aluminum and other metals [38, 39, 52] are under active investigation.

Thus, the scientists of KELK Ltd. and JFE Steel Corporation (Japan) [36, 37] jointly developed and tested a thermoelectric recuperator using waste heat from a steel furnace. Its power is about 9 kW with the efficiency of 8%.

A thermoelectric recuperator using waste heat from a cement kiln was installed at the Awazu plant of Komatsu (Japan). The power of such a recuperator is about 10 kW. The waste heat recuperator from cement kilns [35] was also developed by scientists from Industrial Technology