DOI: https://doi.org/10.17816/0321-4443-625989

Original Study Article

Justification of usability of the heat accumulator of phase transition in vehicles' engines pre-start warming-up procedure

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ABSTRACT

BACKGROUND: The trend of activity increase in exploration of transpolar areas has been observed for recent years. Negative temperatures, the key feature of the North, have a negative impact on state of piston engines of on-ground transport. In engine's cylinders, the process of transition of liquid fuel in gaseous state goes before the mixture ignition. Negative temperatures affect the phase transition process and impede the working body homogenization. Therefore, engine pre-start warming-up procedure goes before successful engine start. Existing typical methods of pre-start warming-up demand fuel consumption and, generally, significant staff resources. Achievements of modern science offer new technologies for solving the issues of warming-up procedures based on accumulating, storage and deployment of heat energy produces by an engine during its operation.

AIM: Justification of usability of the heat accumulator of phase transition in pre-start warming-up procedure for vehicles' engines operating in conditions of negative temperatures of cold climate.

METHODS: Numerical values of heat accumulator charging period depending on temperature of heat-accumulating material at various initial temperatures of coolant as well as values of the discharging period depending on temperature of heat-accumulating material at various coolant rates were defined experimentally. High-density polyethylene was used as a heat-accumulating material.

RESULTS: As a result of the described experiment, curves of heat accumulator charging period depending on heat-accumulating material temperature at various initial temperatures of coolant and curves of heat accumulator discharging period depending on coolant temperature at various coolant rates were built.

CONCLUSIONS: It is found that the heat accumulator of phase transition with high-density polyethylene as a heat-accumulating material can be used for improving the reliability of vehicles' piston engine start in conditions of negative temperatures of cold climate.

Keywords: heat accumulator of phase transition; high-density polyethylene; coolant rate; negative temperatures; pre-start engine warming-up procedure; successful engine start; heat-accumulating material; heat-transfer processes.

To cite this article:
Kolunin AV, Kaminky VN, Apelinsky DV, Lazarev ES, Korytov MS. Justification of usability of the heat accumulator of phase transition in vehicles' engines pre-start warming-up procedure. *Tractors and Agricultural Machinery.* 2024;91(1):55–64. DOI: https://doi.org/10.17816/0321-4443-625989

Received: 08.10.2023 **Accepted:** 20.01.2024 **Published online:** 15.03.2024

DOI: https://doi.org/10.17816/0321-4443-625989

Оригинальное исследование

Обоснование применимости теплового аккумулятора фазового перехода в тепловой подготовке двигателей автотранспортных средств

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АННОТАЦИЯ

Обоснование. В последние годы наблюдается тенденция подъёма активности к освоению заполярных территорий. Характерной особенностью Севера являются отрицательные температуры. Отрицательные температуры оказывают негативное воздействие на состояние поршневых двигателей наземного транспорта. В цилиндрах двигателя воспламенению предшествует процесс перехода жидкого топлива в газообразное состояние. Отрицательные температуры негативно влияют на процесс смены фазовых состояний препятствуют гомогенизации рабочего тела и успешному пуску двигателя. В целях обеспечения такого пуска предусмотрена тепловая подготовка. Существуют типовые методы тепловой подготовки, требующие расхода энергоносителей и как, правило значительных трудозатрат. Достижения современной науки предлагают новые технологии в решении вопросов тепловой подготовки на основе аккумулирования, хранения и реализации тепловой энергии, вырабатываемой двигателем в процессе применения.

Цель работы — обоснование применимости теплового аккумулятора фазового перехода в тепловой подготовке двигателей автотранспортных средств, эксплуатируемых в условиях отрицательных температур холодного климата.

Материалы и методы. Экспериментальным методом определялись численные значения времени зарядки теплового аккумулятора в зависимости от температуры теплоаккумулирующего материала (ТАМ) при различных начальных температурах теплоносителя и времени разрядки теплового аккумулятора в зависимости от температуры теплоаккумулирующего материала при различных объёмных расходах теплоносителя. В качестве теплоаккумулирующего материала применялся полиэтилен высокой плотности.

Результаты. В результате описанного эксперимента построены графические зависимости времени зарядки теплового аккумулятора от температуры теплоаккумулирующего материала при различных начальных температурах теплоносителя и времени разрядки теплового аккумулятора от температуры теплоносителя при его различных объёмных расходах.

Заключение. Установлено, что тепловой аккумулятор фазового перехода с теплоаккумулирующим материалом (полиэтиленом) высокой плотности применим для повышения надёжности пуска поршневых двигателей автотранспортных средств в условиях отрицательных температур холодного климата.

Ключевые слова: тепловой аккумулятор фазового перехода, полиэтилен высокой плотности, расход теплоносителя, отрицательные температуры, тепловая подготовка двигателя, успешный пуск двигателя, теплоаккумулирующий материал, теплообменные процессы.

Как цитировать:
Колунин А.В., Каминский В.Н., Апелинский Д.В., Лазарев Е.С., Корытов М.С. Обоснование применимости теплового аккумулятора фазового перехода в тепловой подготовке двигателей автотранспортных средств // Тракторы и сельхозмашины. 2024. Т. 91, № 1. С. 55–64.
DOI: https://doi.org/10.17816/0321-4443-625989

Рукопись получена: 08.10.2023 **Рукопись одобрена:** 20.01.2024 **Опубликована онлайн:** 15.03.2024

BACKGROUND

The Russian Federation lies in the middle and high latitudes of the continent. Weather conditions in most territories of the country can be classified as rigorous, and seasonal changes are contrasting in nature, with winters being lengthy and frosty. The cold climate zone, whose average temperature during winter months decreases to below −20°C and whose number of cold days reaches 270, covers more than 50% of the area, including the regions of Siberia, the Far North, and the Far East.

The Northern Sea Route covers the shortest communication between the European part of Russia and the Far East. The Northwest Passage represents the sea route between the Atlantic and Pacific oceans. Meanwhile, the air bridge between North America and Southeast Asia passes through polar territories of the Russian Federation. The intact mineral reserves found in these areas belong to Russian people. Such territorial locations offer not only natural resources but also a strategic advantage for the economy and defense sector. The protection and provision of national interests of Russia can be found in the Presidential Decree No. 645 of October 26, 2020 "On the Strategy for the Development of the Arctic Zone of the Russian Federation and Ensuring National Security for the Period until 2035," and inter alia based on the usage of advanced technologies and equipment adapted to harsh conditions of polar regions. Road transport contributes to the long-term development of northern territories. According to the analytical agency «Autostat», by mid-2023, 3.7 million motor lorries would have been located in Russia. The auto giant KamAZ accounts for more than a quarter (26%) of this fleet; 963 thousand of such trucks are registered in Russia. These trucks are followed by those produced by GAZ rank (600 thousand vehicles), ZIL brand vehicles (402 thousand units), and MAZ and Ural vehicles (265 thousand and 170 thousand units, respectively). Russian brands holds more than 65% of the Russian trucks fleet. Amount of trucks for some regions of Russia is given in Table 1.

Table 1. Trucks fleet in some Russian regions

Таблица 1. Численность парка грузовых автомобилей по некоторым регионам России

No.	Name of region	Number of motor vehicles
1	Arkhangelsk region	23457
2	Sverdlovsk region	68725
3	Irkutsk region	70315
4	Krasnoyarsk region	67443
5	Murmansk region	9817
6	Omsk region	52428
7	Primorsky region	41432
8	Republic of Buryatia	60217
9	Republic of Karelia	138014
10	Republic of Komi	27277
11	Tyumen region	97049

These regions are known by negative winter temperatures. Successful engine start under such conditions necessitates thermal preparation. Mixture ignition in engine cylinders is preceded by the transition of liquid fuel into a gaseous state. Negative temperatures negatively influence the process of phase states changing and prevent the homogenization of the fuel–air mixture. The probability of a successful engine start also decreases due to other reasons related to the viscosity of engine oil and electric battery capacity [1, 2].

Scientists have been attempting to solve the problematic of starting low-temperature engines [3–5]. Days of bonfires making or blowtorches using for successfully engine start are gone in past. Modern society has arrived at a new stage of development. Currently, advanced technologies can ensure successful engine start at negative temperatures within a short period, with minimal energy consumption and minimal labor intensity.

The heat generated by the engine itself during vehicle use can be used for thermal preparation of engines. 25% of the heat introduced with the fuel into the combustion chamber is converted and used in efficient operation during an actual cycle. The thermal potential is wasted due to incomplete combustion of fuel, activation of its internal systems and mechanisms, loss with exhaust gases, and dissipation into the atmosphere through the cooling system. The application of advanced technologies based on modern achievements in science and technology can ensure the rational application of unused heat in efficient engine operations.

PROBLEM FORMULATION

Start-up reliability can be increased and engine resource damage be reduced during low-temperature start-up without additional consumption of energy-producing material via the principle of accumulating its thermal energy in relation to piston engine systems. One of the cardinal ways to solving this problem is using of a device, that can accumulate, store, and use thermal energy. Such devices are termed "thermal accumulators" [6–9]. The most acceptable for thermal preparation among known types of heat accumulators is the phase transition heat accumulator; this type of heat accumulator operates on the principle of “melting – crystallization,” with a thermal effect involving the release or absorption of phase transition heat. Thermal accumulators operate based on the implementation of heat exchange processes among various means. The principle of heat transfer contributes to the general doctrine of heat, whose foundation was laid by Lomonosov on the basis of corpuscular theory of the structure of matter, which was put forward in the middle of the 18th century. Heat transfer processes show associations with heat transfer from more heated bodies to less heated ones. When the state of aggregation changes (melting–solidification, evaporation–condensation), considerable amounts of energy are absorbed or released. Therefore, the enthalpy of substances in such devices does not increase considerably due to the increase in temperature, but because of alterations in the state of aggregation. The primary storage matter (depository) comprises a heat-storing material (HSM) enclosed in hermetically sealed capsules and which is in thermal interaction with the heat transfer fluid. Cooling fluids can be considered as heat transfer fluid if the accumulator is integrated in engine cooling system. The heat-exchange interaction of the heat-storing material with the coolant, using the example of a cooling system, is ensured by the operation of a circulation pump, which sets the low labor intensity of thermal preparation. Various thermal accumulator designs have been patented and described. Figure 1 displays a diagram of the longitudinal section of the simplest design of a cylindrical-phase-transition-heat accumulator.

The heat accumulator comprises a heat-insulated cylindrical body and inlet and outlet pipes connected to the cooling system. The housing contains a heat exchanger equipped with coaxially located cylindrical capsules. The hermetically sealed capsules are filled with the heat-storing material [9]. Heat-storing materials include high-density polyethylene, paraffin, and barium hydroxide octohydrate. Thermal insulation materials ensure long-term readiness of heat accumulators during equipment storage. Thermal accumulators may vary in design and amount of heat-storing material [10].

Table 2 presents the characteristics of a heat accumulator, whose design includes 18 kg heat-storing material.

With all the works conducted in the field of thermal accumulators, there are no substantive and objective assessment of their adaptability for vehicle engines is available. In addition, the charging/discharging duration of thermal accumulators under different conditions is unknown. Moreover, comprehensive practice and experience of application is lacking. Thus, an experiment was conducted to determine the possibility (rationality) of using a heat accumulator.

EXPERIMENT

An experiment, which involved the preparation of a special installation, was conducted as a part of the development of innovative technical solutions

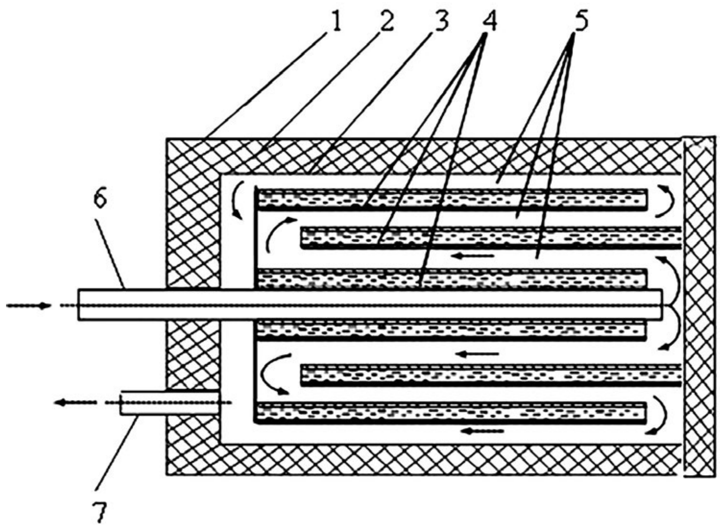

Fig. 1. The heat accumulator of phase transition in longitudinal section: *1* — an outer housing; *2* — heat isolation; *3* — an inner housing; *4* — metal cylindrical capsules with a heat-accumulating material; *5* — coolant path gaps; *6* — an inlet; *7* — an outlet.

Рис. 1. Тепловой аккумулятор фазового перехода в продольном разрезе: *1* — наружный корпус; *2* — тепловая изоляция; *3* — внутренний корпус; *4* — металлические цилиндрические капсулы с теплоаккумулирующим материалом; *5* — щелевые зазоры теплоносителя; *6* — входной патрубок; *7* — выходной патрубок.

DOI: https://doi.org/10.17816/0321-4443-625989

Table 2. Specification of the heat accumulator
Таблица 2. Характеристики теплового аккумулятора

Name	Characteristics
Heat-storing material	High-density polyethylene
Weight of heat-storing material, kg	18
Weight, kg	31,45
Overall dimensions, mm	174×270×460
Thermal insulation	Foam plastic and two-layer foamed polymer covered with aluminum foil
Housing material	Stainless steel
Heat exchanger material	Brass
Thermal capacity, J/kg K	46,5
Thermal charge storage time, hours	39

aimed at the improvement of thermal preparation means. The experimental technique included tests in charging (receipt of thermal energy) and discharging (release of thermal energy) modes. Atmospheric air was used as a coolant. High-density polyethylene was used as a heat-storing material in the phase transition. Table 3 shows properties of high-density polyethylene.

The experiment was performed to determine the dependence of charging time of heat accumulators on various coolant temperatures and that of discharge time on the heat accumulator circuit's coolant volumetric flow rate. Thus, the volumetric flow rate of the coolant and its initial temperature should define the activities of the heat exchange processes in two different modes and during heat charge/discharge [11].

The former case is charging mode, where heat accumulator's chargingon time depends of the coolant temperature. The the latter case is in the discharge mode, in which the dependence of heat accumulator's discharge time on the volumetric flow rate of the coolant was determined.

The experimental parameters were categorized into fixed and varied ones. Table 4 presents a summary of the experimental parameters in various modes.

The degree of reliability was ensured using an adequate number of measurements obtained and the permissible error of instruments (Table 5).

Following the classification, this experiment was categorized as a laboratory experiment [10]. The experiment was conducted in a specialized laboratory with an air temperature of 20°C, an atmospheric pressure of 768 mmHg, and air humidity of 82%. Figure 2 presents the experiment used a special unit.

The experimental technique involved seven cycles of charging and discharging modes performed sequentially. Repeated cycles promote the increase in the reliability of information for the achievement of the experimental aim [11]. The thermal accumulator was charged until a phase-transition temperature of the heat-storing material of 125°C with various coolant temperatures a constant flow rate. Heat accumulator discharge was achieved at a certain temperature of the heat-storing material of 20°C with various activities of coolant circulation and at its constant initial temperature, after which another charge was performed.

Table 3. Properties of high-density polyethylene
Таблица 3. Свойства полиэтилена высокой плотности

Parameter	Characteristic
Density, kg/m^3	0,956
Phase transition temperature, K	398–408
Specific heat of phase transition, kJ/kg	230
Specific heat capacity, kJ/kg·K	2,5
Thermal conductivity coefficient, W/m·K	0,25

Table 4. Experiment parameters in charging/discharging modes of the heat accumulator
Таблица 4. Параметры эксперимента в режиме зарядки/разрядки теплового аккумулятора

Charging mode				
Parameter	**Temperature of the heat storage material**	**Charging time**	**Initial temperature of the coolant**	**Volumetric flow rate of the coolant**
Value	Argument 20–125	Required function	110, 120, 130, 140, 150, 160, 170	const 0.22
Dimension	t, °C	τ, c	t, °C	m^3/s
Discharge mode				
Value	Argument 20–125	Required function	const minus 25	0,1; 0,12; 0,14; 0,16; 0,18; 0,2; 0,22
Dimension	t, °C	τ, c	t, °C	m^3/s

Table 5. Measuring devices
Таблица 5. Измерительные приборы

Device name	Characteristics
TPP thermocouple	measurement range from 0 to +600°C error ±1°C material of manufacture – platinum
Sensor Zentec HS1-01	measurement range from –40 to +300°C error ±0.5°C
Multichannel temperature meter MIT-12	number of channels 12 error ±1°C
Coolant flow meter G4 UGI Meters LTD	maximum permissible flow rate 380 dm^3/min error ±0.5 %
Timer Kaiser	Laboratory electronic type

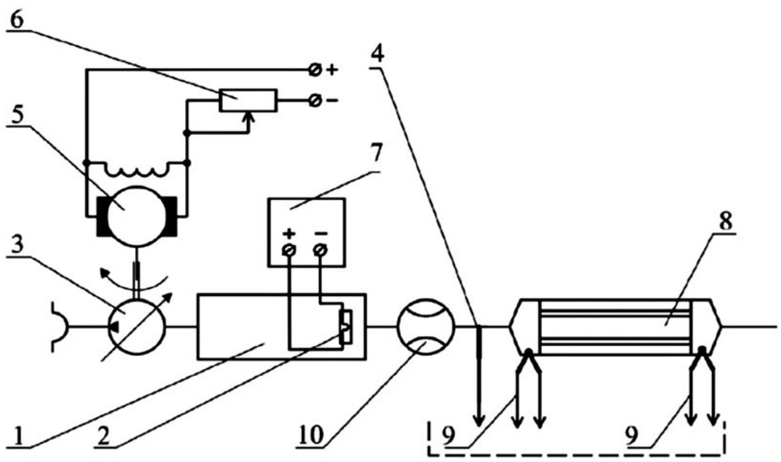

Fig. 2. Diagram of the experimental facility: *1* — an initial coolant temperature adjuster; *2* — a heating-cooling element; *3* — a supercharger; *4* — a thermal couple; *5* — an electric engine; *6* — a variable resistance element; *7* — an automatic control system of the heating-cooling element; *8* — a heat accumulator; *9* — thermal couples; *10* — the UGI Meters G4 gas flowmeter.
Рис. 2. Схема экспериментальной установки: *1* — регулятор начальной температуры теплоносителя; *2* — нагревательно-охладительный элемент; *3* — воздушный нагнетатель; *4* — термопара; *5* — электрический двигатель; *6* — переменное сопротивление; *7* — автоматическая система управления нагревательно-охладительным элементом; *8* — тепловой аккумулятор; *9* — термопары; *10* — расходомер газовый G4 фирмы UGI Meters LTD.

In accordance with the experimental plan, a fixed temperature of the coolant was set in heat accumulator 8 using the heating element power control system, after which the coolant was supplied by a supercharger 3. The duration was quantified from the initial charging of the heat accumulator, that is, from 20°C, and recorded depending on temperature modifications every 10°C to the set temperature of the heat-storing material (125°C). Temperature change the of the heat-storing material can influence the charging cycle duration [10]. Each initial temperature of the coolant corresponded to its own series of measurements. In this work, seven series of measurements were performed. Table 6 presents the charging times of the heat accumulator depending on the coolant temperature.

The dependence of heat-accumulator charging time on the heat-storing material temperature was constructed graphically at various initial temperatures of the coolant based on the values obtained. Figure 3 presents the dependencies.

Under discharge conditions, the experimental technique provided a nonvariable initial value of the coolant and different volumetric flow rates. The temperature of the heat-storing material can influence the discharge duration of thermal accumulators [10]. Each volumetric flow rate of the coolant corresponded to its own series of measurements. In this work, seven series of measurements were performed. Table 7 presents a summary of the numerical values of the discharge time of the heat accumulator depending on the coolant flow rate.

Based on numerical values, we plotted the graphical dependences of the discharge period of the heat accumulator on the coolant temperature at different volumetric flow rates of the coolant (Fig. 4).

Table 6. Heat accumulator charging period depending on the heat-storing material temperature at various coolant initial temperatures
Таблица 6. Время зарядки теплового аккумулятора в зависимости от температуры теплоаккумулирующего материала при различных начальных температурах теплоносителя

Heat-storing material temperature, °C		20	30	40	50	60	70	80	90	100	110	120	125
		Charge time, s											
Coolant temperature, °C	110	0	102	125	358	552	753	983	1262	1544			
	120	0	91	201	325	491	662	880	1141	1452	1795		
	130	0	89	178	295	431	569	778	1028	1361	1709	2051	
	140	0	85	155	262	371	493	672	908	1227	1601	1998	2434
	150	0	79	133	231	295	421	578	802	1150	1495	1921	2145
	160	0	60	120	176	221	315	448	683	1003	1402	1804	2032
	170	0	60	102	131	167	250	350	550	850	1250	1650	1896

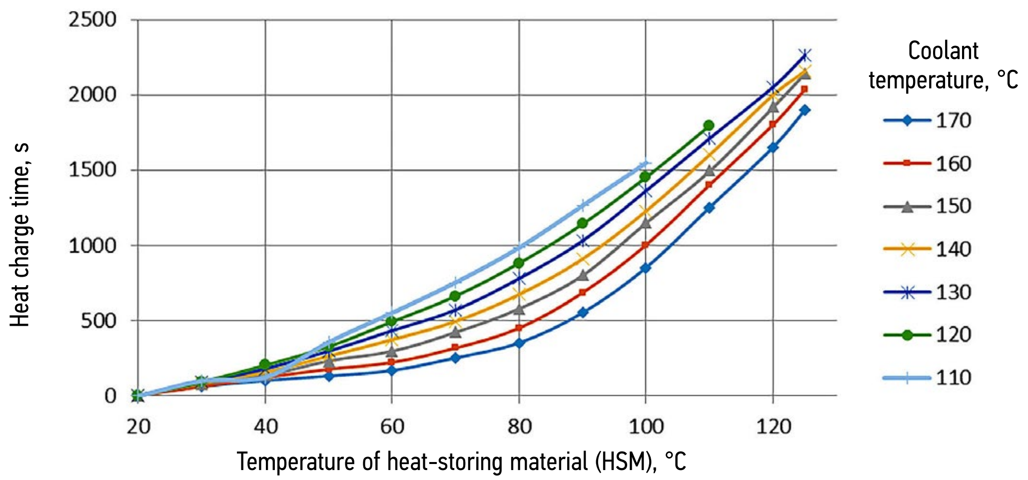

Fig. 3. Curves of heat accumulator charging period depending on the heat-storing material temperature at various coolant initial temperatures.
Рис. 3. Зависимости времени зарядки теплового аккумулятора от температуры теплоаккумулирующего материала при различных начальных температурах теплоносителя.

DOI: https://doi.org/10.17816/0321-4443-625989

The following conclusions were formulated from the described experimental results.

1. Under various temperatures of the heat-storing material, the established dependences of the thermal accumulator charge duration indicate the influence of initial coolant temperatures on charging cycle duration. The coolant temperature increase reduced the charging time. The charging time under experimental conditions ranged from 1896 s to 2434 s.
2. The dependences of the discharge duration of a thermal accumulator under various activities of coolant movement werer established, and they indicate the influence of the temperature of the latter on discharge cycle duration. The discharge duration under experimental conditions ranged from 366 s to 674 s.
3. The duration of charge–discharge cycles and the low labor intensity of the work can technologically fit using various measures to improve the heat exchange processes of a cold engine. At negative temperatures during a cold climate, phase-transition thermal accumulators with a high-density heat-storing material (polyethylene) can be used to increase the reliability of starting piston engines of vehicles.

CONCLUSIONS

The device described in this work applies to the improvement of heat exchange processes as a part of the thermal preparation of vehicle piston engines at subzero temperatures. The new technical solution can be recognized through its high technology, low labor intensity, and energy efficiency. The device, described in this article,can increase the temperature of lubrication system oil, coolant of the cooling system, and the mixture of atmospheric air gases in the air supply system. High thermal insulation efficiency is a necessary condition

Table 7. Heat accumulator discharging period depending on heat-storing material temperature at various coolant rates
Таблица 7. Время разрядки теплового аккумулятора в зависимости от температуры теплоаккумулирующего материала при различных объёмных расходах теплоносителя

Heat-storing material temperature, °C		125	120	110	100	90	80	70	60	50	40	30	20
		Discharge time, s											
Coolant flow rate, m^3/s	0,1	0	10	22	62	104	153	214	275	345	436	538	674
	0,12	0	9	21	56	95	140	191	246	315	391	487	617
	0,14	0	8	20	50	86	127	168	216	278	346	438	567
	0,16	0	7	19	45	77	111	145	186	237	301	389	505
	0,18	0	6	19	40	68	95	122	155	198	255	349	456
	0,2	0	5	17	28	48	68	92	125	168	222	301	414
	0,22	0	4	10	18	28	43	66	97	140	194	257	366

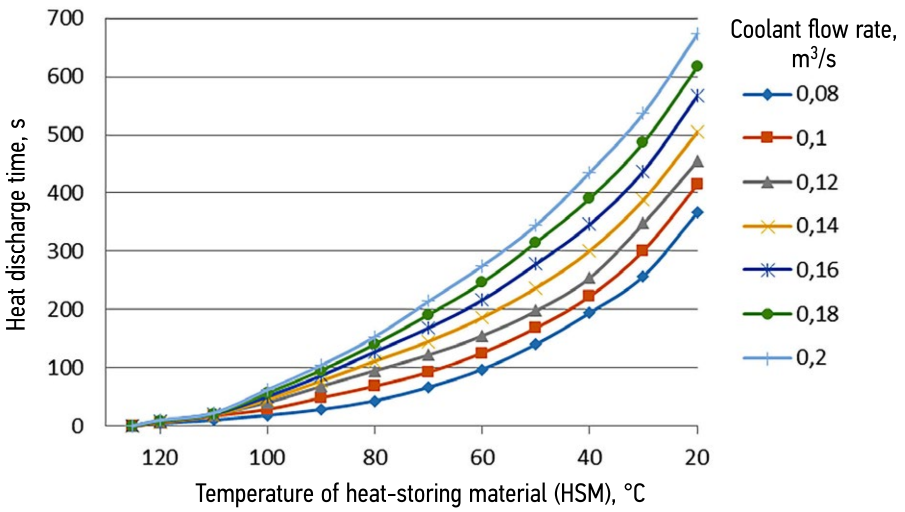

Fig. 4. Curves of heat accumulator discharging period depending on heat-storing material temperature at various coolant rates.
Рис. 4. Зависимости времени разрядки теплового аккумулятора о.т температуры теплоносителя при ра.зл.ич.ны.х объёмных расходах теплоносителя.

for such application, which preserves the acquired energy for a long time in order to avoid self-discharge due to heat exchange processes with the environment.

ADDITIONAL INFORMATION

Authors' contribution. A.V. Kolunin — search for publications on the topic of the article, writing the text of the manuscript; V.N. Kaminsky — expert opinion, approval of the final version; E.S. Lazarev — editing the manuscript text; D.V. Apelinsky — editing the manuscript text, creating images; M.S. Korytov — creating images and tables. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

Competing of interests. The authors declare the absence of obvious and potential conflicts of interest.

Funding source. This study was not supported by any external sources of funding.

ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. А.В. Колунин — поиск публикаций по теме статьи, написание текста рукописи; В.Н. Каминский — экспертная оценка, утверждение финальной версии; Е.С. Лазарев — редактирование текста рукописи; Д.В. Апелинский — редактирование текста рукописи, создание изображений; М.С. Корытов — создание изображений и таблиц. Авторы подтверждают соответствие своего авторства международным критериям *ICMJE* (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

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