Chapter 7

Improving the Vehicular Engine Pre-Start and After-Start Heating by Using the Combined Heating System

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Additional information is available at the end of the chapter

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Abstract

The chapter focuses on the use of the combined thermal development system with phase-transitional thermal accumulators. The peculiarity of the combined system is that it uses thermal energy of exhaust gas, coolant and motor oil for rapid pre-start and after-start heating of the vehicular engine. The structure of the combined thermal development system and a mathematical model have been developed to study the impact of the system parameters on the heating processes of the engine. The results of experimental and estimation studies of thermal accumulator materials and the combined heating system of the vehicular engine are shown. For a truck engine 8FS 9.2/8, it is shown that the use of the combined system reduces the time of coolant and motor oil thermal development by 22.9–57.5% and 25–57% accordingly compared with the use of a standard system. The peculiarities of forming and using the system depend on operational and climatic conditions and the category of the vehicle.

Keywords: vehicular engine, phase-transitional thermal accumulator, thermal development system, heating processes, mathematical model

1. Introduction

One of the promising ways to improve engine cooling systems is the introduction of modern technology into their design in order to increase efficiency and adapt to operating conditions, etc. These measures include a variety of methods of analysis, design, experimental studies,

both at the system level and at the component level. These suggested methods are particularly relevant to those modes of vehicular engines that require significant efforts for their thermal development under cold operating conditions. They are as follows: pre-start and after-start heating of the engine, keeping the engine heated for a successful start under cold operating conditions. Apart from ease of use, the decisive factors are low cost of devices for engine thermal development, state legislation and standards, the need for full power immediately after the engine starts, improved fuel economy and reduced emissions during pre-start and after-start thermal development. The limiting factors are weight and size characteristics of the devices and their compact installation space according to modern vehicle design. In this regard, the most relevant is the development of complex systems for solving these problems in both the design of the engine and the vehicle. In this case one of the promising ways is the development and the study of the combined heating system with phase-transitional thermal accumulator (TA) to carry out pre-start and after-start heating of the engine under cold operating conditions.

2. Creating the scheme of the ICE and vehicle combined heating system and its operating principle

To create the ICE and vehicle heating system, a combination of phase-transitional thermal accumulators was used (combination by function). Thermal accumulator is a device for accumulating thermal energy based on physical or chemical process associated with heat absorption and release [1–11]. The main processes are: accumulation-release of internal energy when heating–cooling solids or liquids, phase transitions with absorption-release of latent heat, the process of sorption–desorption or a reverse chemical reaction occurring with heat release-absorption. Accumulation of thermal energy or heat accumulation is a process of accumulating thermal energy, when its supply is maximum, for later use when the need arises. The process of accumulating energy is called charging, the process of its use is called discharging [1–5]. Substances used to accumulate thermal energy are called heat accumulating materials. The amount of accumulated energy depends on the temperature at which heat accumulating material is heated and its specific heat capacity. The main operating procedures in thermal accumulators, namely the accumulation of thermal energy, are based on the reverse phase-transitional process of melting-solidification. In this case, phase change material is used as the heat accumulating material. The implementation of this method is more difficult because of the need to make the design more complicated. However, much greater amount of heat per unit of volume is accumulated in such thermal accumulators. The process of charging and discharging can be performed in a narrow temperature range, which is very important when there is a need for thermal accumulators to work at small temperature differences. In vehicles the use of thermal accumulators is advantageous to facilitate the engine start and heating the vehicle interior during cold weather. The heat is accumulated during engine operation and can be stored for several days. To do this, thermal accumulator is placed in a Dewar flask (thermos) which provides the best thermal insulation.

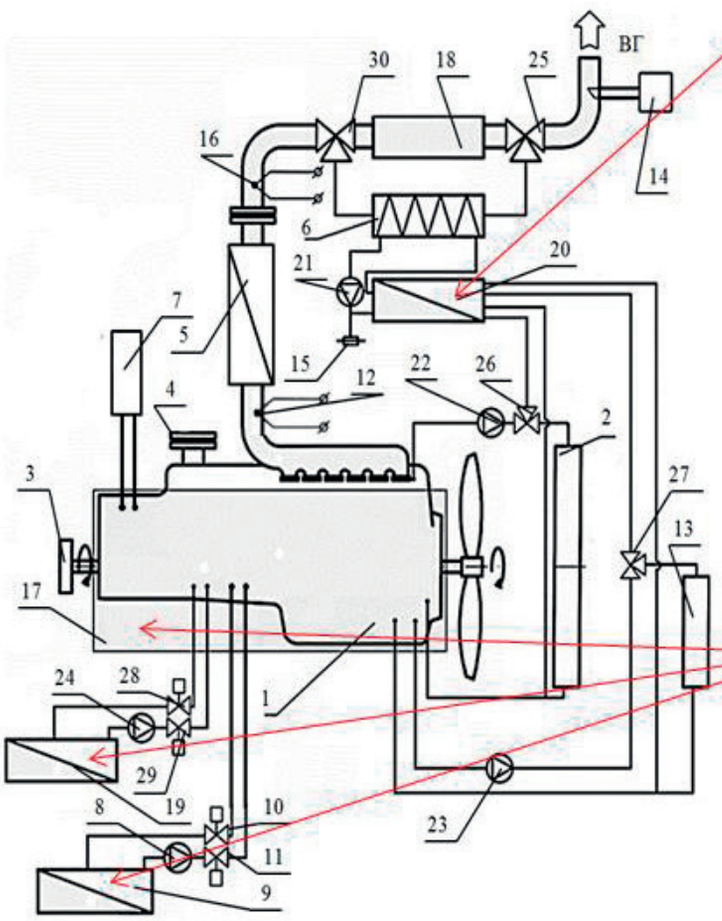
In [1, 2], the main stages of creating the combined heating system (CHS) of the vehicular engine and the vehicle are shown. To ensure the required temperature condition during pre-start and

after-start heating of the internal combustion engine (ICE) and the vehicle under cold operating conditions, a scheme and components of the CHS are formed on the basis of vehicular engine main systems. The suggested CHS consists of the following subsystems: rapid heating of the engine (RHE), the utilization of thermal energy of exhaust gases (EG) by phase-transitional TA (UTETA), contact thermal accumulator (CTA), thermal accumulator for storing motor oil (TASMO), thermal accumulator for storing a coolant (TASC), TA of EG cleaning system (TAEGCS). The CHS itself is a part of a cooling system (CS), lubrication system (LS) and exhaust system of the vehicular engine. It performs some functions of the systems and has a significant influence on the operation of the vehicular engine [1–4]. It is the CHS that provides pre-start and rapid after-start heating of a coolant and motor oil, exhaust gases cleaning system (EGCS) of the engine to the temperature at which the engine can be loaded and then to an operating temperature. The operating temperature is maintained for a long time within specified limits.

The elements of the combined heating system, such as the subsystems of rapid heating of the engine, the utilization of thermal energy of exhaust gases by phase-transitional TA, contact thermal accumulator and thermal accumulator for storing a coolant are the components of the engine cooling system. TA of EG cleaning system is a component of the engine exhaust system. The elements of the combined heating system, such as the subsystems of rapid heating of the engine, the utilization of thermal energy of exhaust gases by phase-transitional TA, contact thermal accumulator and thermal accumulator for storing motor oil are the components of the engine lubrication system. All the above-mentioned subsystems can work together within and according to the algorithm of the combined heating system operation or separately from each other performing their inherent functions [1, 5].

The combined heating system generally works on the principle of thermal energy of EG accumulation by phase-transitional thermal accumulator of the utilization of thermal energy of EG subsystem. It also implies the accumulation of engine thermal energy by contact thermal accumulator in the form of convection and thermal radiation of the vehicular engine during its operation. The "free" thermal energy generated during the fuel combustion is emitted into the atmosphere and is not used usefully.

Figure 1 shows the implementation of the combined heating system for the vehicular engine. EG thermal energy accumulation of the vehicular engine 1 by phase-transitional thermal accumulator, namely by the subsystem of the utilization of thermal energy of exhaust gases 20, is made possible by parallel installing the engine silencer 18 in the EG heat exchanger (HE) 6. The circulation of a heat carrier between TA 20 and exhaust gases heat exchanger 6 is provided by a modulating pump 21. The heat carrier passing through HE 6 in the exhaust manifold is heated by thermal energy of EG to a temperature of 150–190°C (a process fluid with a boiling point of 220°C was used as the heat carrier). Heat exchanger 6 is installed in a bypass, in parallel with the main EG manifold of the vehicular engine. Such a decision was made in order to ensure the disconnection of the heat exchanger 6 after phase-transitional TA 20 of the subsystem of the utilization of thermal energy is fully charged. The switching of EG flow is carried out by electromagnetic gas valves 30 and 25 with an electric drive based on control system commands. The EG flow adjustment is carried out following a special algorithm [4, 9, 10] according to a developed cycle of heating the engine. From the heat exchanger 6 the heat carrier delivers the heat into phase-transitional TA 20 of the subsystem of the utilization of thermal energy. In an



Title	Specification
Heat accumulating material properties:	high-density polyethylene
Density, kg/м^3 ρ_s / ρ_l	925 / 800
Temperature of phase transition, K	408
Specific heat of phase transition, kJ/kg	230
Specific heat capacity, kJ/(kg-K), C_s / C_l	2.5 / 3.3
Thermal conductivity, WT/(м·K), λ_s / λ_l	0.25 / 0.04
Heat accumulating material weight, kg	18.5
Weight of thermal accumulator with HAM, kg	32.75
TA dimensions, mm	164x280x480
Thermal insulating material	double layer of polyethylene foam coated on both sides with layers of aluminum foil
TA frame material	stainless steel
TA heat exchanger material	brass
TA heat capacity, kJ/K	46.25

Title	Specification
Heat accumulating material properties (according to the relevant standards):	Paraffin - a mixture of high-molecular hydrocarbons C_{18}-C_{35}
State	Solid
Melting temperature, °C (K)	45-52 (318- 325)
Boiling temperature, °C (K)	350 (623)
Latent heat of melting, K	35
Specific heat of phase transition, kJ/kg	190
Thermal insulating material	double layer of polyethylene foam coated on both sides with layers of aluminum foil

Figure 1. The scheme of the combined heating system of the engine and the vehicle, and specifications of phase-transitional TA and its HAM.

insulated tank of TA with three heat exchangers (for TA charging and heating of the engine coolant and motor oil) the heat carrier cools down and gives off the accumulated thermal energy to a phase-transitional heat accumulating material (HAM).

In the process of HAM energy accumulation the most efficient is the process of a phase transition of the material (TA filler), i.e., the change of its physical state which requires a large amount of EG energy. The most energy-intensive process is the phase transition of HAM. All the other processes of HAM energy accumulation do not require such a large amount of energy. The peculiarities of phase-transitional TA 20 at different periods of thermal energy accumulation and release are detailed in [1, 5, 10, 11].

Contact thermal accumulator 17 of the vehicular engine (**Figure 1**) is a multi-layered case. To ensure close fitting it is mounted on the outside of the cylinder block and the engine oil pan [8]. The peculiarity of the contact thermal accumulator design 17 is the availability of individual sections of container-based phase-transitional HAM that are fitted to the outside of the cylinder block and the oil pan. They are covered by several layers of thermal insulation material [1, 5, 9].

Using contact thermal accumulator 17 does not require significant changes in the design of the vehicular engine and its systems. It is easily installed, is easy to maintain and does not require additional energy. The contact thermal accumulator operation is based on the change of the phase state of heat accumulating material when the energy is emitted and absorbed during convection and thermal radiation of the cylinder block and the engine oil pan. Due to contact thermal accumulator, an insulating function of the engine is performed and the minimum loss of thermal energy in the form of convection and thermal radiation is achieved during engine operation. In this way it is also possible to avoid thermal stresses in the engine during its heating at low temperatures. The contact thermal accumulator operation provides a long-term maintenance of the set coolant and motor oil temperatures when the engine is switched off, unlike the well-known TA by means of which the ICE is heated after stop [1, 5, 9].

The peculiarity of the thermal accumulator for storing motor oil design 19 (**Figure 1**) is an additional phase-transitional contact TA in an accumulation vessel membrane for motor oil. It is similar in design and operating principle to contact thermal accumulator 17, but is mounted on the accumulation vessel case for draining motor oil. Due to thermal accumulator for storing motor oil 19 the minimum loss of thermal energy is achieved. It is released by motor oil after its draining by electromagnetic hydraulic valves 28 and 29 in the insulated vessel with TA during long-term stop of the vehicular engine. When motor oil is pumped backwards into the engine oil pan by the modulating pump 24 it is possible to rapidly heat the engine components and lubrication system parts. They are as follows: a crankshaft area, an oil channel and an oil case of the vehicular engine. The motor oil temperature in thermal accumulator for storing motor oil 19 is controlled by the built-in motor oil temperature sensor.

The peculiarity of the thermal accumulator for storing a coolant design 9 (**Figure 1**) is an additional phase-transitional contact TA in the accumulation vessel membrane for the coolant. It is similar in design and operating principle to thermal accumulator for storing a coolant 19, but is mounted on the accumulation vessel case for draining the coolant. Due to thermal accumulator for storing a coolant 9 the minimum loss of thermal energy is achieved. It is released by the coolant after its draining by electromagnetic hydraulic valves 10 and 11 in the insulated vessel 9 with TA during long-term stop of the vehicular engine. When the coolant is pumped backwards into the engine cooling system by the modulating pump 8 it is possible to rapidly heat the engine components and cooling system parts. They are as follows: a coolant case and the ICE cylinder head. The coolant temperature in thermal accumulator for storing a coolant 9 is controlled by the built-in coolant temperature sensor.

EG thermal energy for rapid heating of a catalytic converter 5 in the exhaust system is accumulated in TA of exhaust gases cleaning system during engine operation. A rapid heating of catalytic converter composition 5 after starting the engine occurs when EG pass through TA of exhaust gases cleaning system.

The interior of the vehicle is heated by the heat exchanger 7 during engine operation when the coolant circulates in the engine cooling system through the heat exchanger.

In addition to the above-mentioned components, the combined heating system also includes standard components of the engine and its cooling and lubrication systems (**Figure 1**). They are as follows: a cooling system radiator 2, an engine output shaft 3 an intake manifold 4, EG

temperature sensor 12; a lubrication system radiator 13; gas analysis equipment 14 (in the form of appropriate sensors); a tank for expanding the heat carrier 15; EG temperature sensor 16. The circulation of the coolant and motor oil in the combined heating system is provided by modulating pumps 22 and 23. The coolant and motor oil regulation is provided by electromagnetic hydraulic valves 26 and 27.

Pre-start and after-start heating of the coolant and motor oil is possible with standard heating of the engine and (or) in the following modes of the combined heating system operation. The examples are: when operating only the rapid heating of the engine subsystem in the process of after-start heating of the engine, when operating the rapid heating of the engine subsystem with the utilization of thermal energy of exhaust gases by phase-transitional TA, the combined functions of contact thermal accumulator (thermal accumulator for storing motor oil and (or) thermal accumulator for storing a coolant) or joint operation of contact thermal accumulator + thermal accumulator for storing motor oil + thermal accumulator for storing a coolant and the utilization of thermal energy of exhaust gases by phase-transitional TA. Storing thermal energy, accumulated by the coolant and motor oil, is possible with standard ICE assembly and (or) in the following modes of the combined heating system operation. The examples are: when operating the rapid heating of the engine subsystem with the utilization of thermal energy of exhaust gases by phase-transitional TA, when operating only contact thermal accumulator or thermal accumulator for storing motor oil (thermal accumulator for storing a coolant), the combined functions of contact thermal accumulator (thermal accumulator for storing motor oil and (or) thermal accumulator for storing a coolant) or joint operation of contact thermal accumulator + thermal accumulator for storing motor oil + thermal accumulator for storing a coolant and the utilization of thermal energy of exhaust gases by phase-transitional TA.

If it is necessary to start the engine after a long stop, the combined heating system is involved. It works according to its own algorithms and includes electric modulating pumps 21, 22, 23 of the rapid heating of the engine subsystem. They circulate the coolant and motor oil in the vehicular engine and phase-transitional TA for the utilization of thermal energy of exhaust gases. Passing through TA, the coolant gets thermal energy accumulated by HAM and transfers it by the coolant to the engine cooling system and by motor oil to the lubrication system and to the engine design elements. The right choice of TA 20 thermal capacity allows you to quickly heat the ICE from low ambient temperature (−20°C) to the coolant and motor oil temperatures at +40–60°C. The choice of TA thermal capacity by HAM weight is based on a calculation of the heat balance of the engine with the combined heating system and the vehicle. It helps determine the amount of thermal energy required for heating the coolant and motor oil, cylinder block, cylinder head, connecting branch pipes and manifolds considering heat loss [1, 5, 10, 11].

After receiving thermal energy from the coolant and motor oil, the engine elements transfer it to the combustion chamber. It positively affects the process of ICE start which occurs after the combined heating system sensors record the coolant and motor oil temperatures at +40–60°C. After that the ICE starts running and it is possible to load the engine. After starting the ICE, the combined heating system continues its work and facilitates more rapid and efficient

heating of the working engine up to the coolant and motor oil temperatures at +85°C. This is achieved due to further use of the accumulated heat in TA and thermal energy from the working engine. After reaching the coolant and motor oil temperatures of +85°C, the combined heating system maintains it within the limits set, i.e., 85 ± 5°C and then the engine standard system (SS) starts working (in the meanwhile, the combined heating system stops working).

Taking into consideration the data from temperature sensors, the control system of the combined heating system calculates the optimal rotational speed of circulation pumps 21, 22, 23. It gives commands to the system valves directing the flow of working fluids through certain CSPSH elements. The combined heating system functioning is based on the analysis of temperature values of the coolant and motor oil heat carriers [1, 5, 10, 11].

During a stop and storage of the heat accumulated by contact thermal accumulator 17 of the engine being shut off, the contact thermal accumulator operation implies giving off HAM phase-transitional heat of contact thermal accumulator backwards to provide long-term maintenance of the coolant and motor oil temperatures. In low ambient temperature and when phase-transitional TA 20 for the utilization of thermal energy of exhaust gases subsystem is charged, when the heat accumulated by contact thermal accumulator 17 is insufficient, the engine 1 heating is carried out similarly as described above.

During a long stop of the engine, when it is necessary to maintain the coolant and motor oil within the "hot heating" for a long time, thermal accumulator for storing motor oil 19 and (or) thermal accumulator for storing a coolant 9 are used (**Figure 1**), in which the coolant and motor oil are drained from lubrication system and cooling system of the engine. If it is necessary to start the engine when phase-transitional TA 20 for the utilization of thermal energy of exhaust gases subsystem is charged, thermal accumulator for storing motor oil (thermal accumulator for storing a coolant) is combined with lubrication system (cooling system) of the engine by using valves 28 and 29 (9 and 11). By using the circulation pump 24 (8), motor oil (the coolant) goes to the engine cylinder block. Further heating of the engine 1 is carried out similarly as described above. By using motor oil and coolant temperature sensors, working capacity of the combined heating system is controlled in relation to heat capacity of its components and subsystems and its further use.

3. Objects of experimental studies

The research on using the CHS in vehicles was based both on experiments and numerical modeling.

The results of experimental studies conducted by the authors under the ITS information conditions are detailed in [1, 5, 10, 11–13] (**Figure 2**). The authors developed a mathematical model [1, 5, 10, 11–13] for the estimation studies (**Figure 3**). It is based on a systems approach used in the processes of the vehicular thermal development when using phase-transitional thermal accumulators [1, 4–19].

Figure 2. The truck during pre-start and after-start heating of the ICE and the vehicle interior.

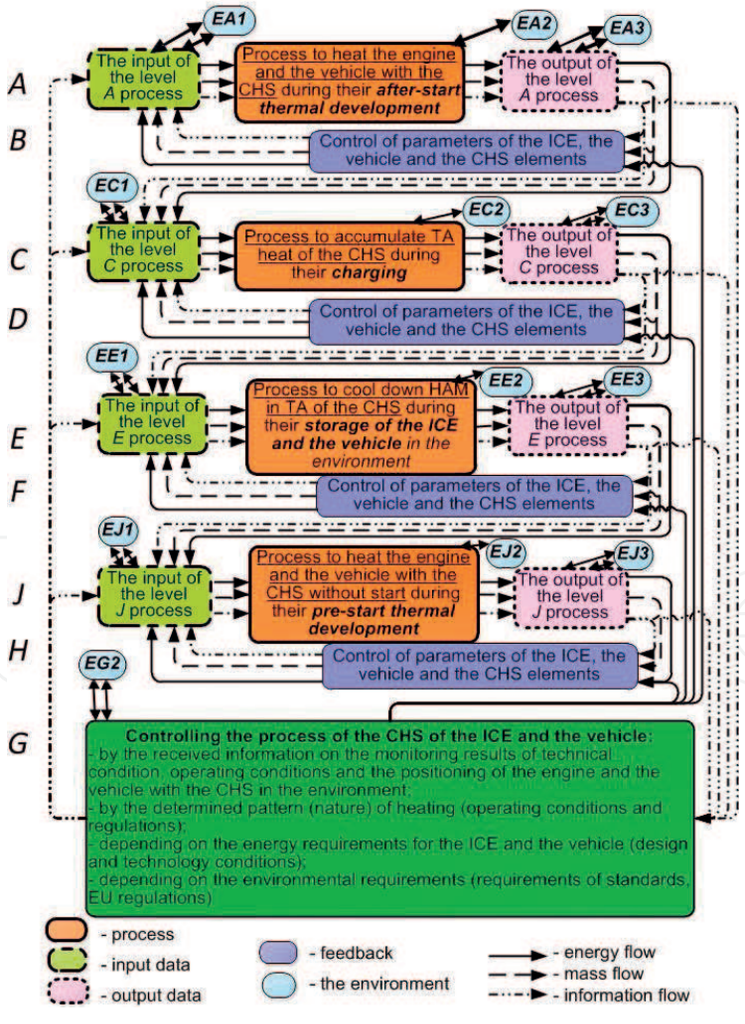


Figure 3. The flowchart of "combined heating system of the engine and the vehicle."

4. The study results of the influence of the combined heating system different options on engine thermal development indicators

The general process of pre-start and after-start heating (PSASH) during engine and vehicle operation can be split into the following components: pre-start and after-start processes of thermal development and industrial (commercial) process of the ICE and vehicle operation. The engine pre-start heating without actual start and the operation of the engine in an idling mode can be only realized using the developed heating system. It is a set of subsystems, elements and means of thermal development and maintenance of the thermal state of the engine and the vehicle using the combined heating system based on phase-transitional thermal accumulators. During after-start thermal development of the engine and the vehicle, it is possible to heat them either without using the combined heating system (engine and vehicle standard systems) or using the CHS. During industrial (commercial) process of engine and vehicle operation, the heating system is used only when it is not possible to maintain the thermal state of the engine and the vehicle in a corresponding range under operating conditions. After-start heating of the engine and the vehicle can be carried out in various modes of vehicle operation (both steady and transitional modes of the engine operation when the vehicle is stopped and when in motion). These modes are: (1) heating in an idling mode; (2) heating in an idling mode with electrical consumers switched on; (3) heating in an idling mode with gradual heating in motion; (4) heating in motion. The study of the vehicle heating according to the above-mentioned modes is detailed in [1, 16–19].

The article presents the study results of thermal development of the truck engine 8FS 9.2/8 in operation. The investigation was conducted in the mathematical model of the "combined heating system of the engine and the vehicle" for option 1 - Heating in an idling mode. In evaluating different options of the CSPSH operation the following considerations were taken into account. The combined heating system is a combination of five independent subsystems: the utilization of thermal energy of EG (with TA), rapid heating of the engine, contact thermal accumulator, thermal accumulator for storing motor oil and thermal accumulator for storing a coolant [1, 16–19]. The first two subsystems, working together, provide the work of TA with accelerated circulation of the coolant, motor oil and standard systems of the truck engine 8FS 9.2/8 during pre-start and after-start heating of the truck. Contact thermal accumulator provides long-term storage of accumulated heat in the coolant and motor oil in the cylinder block using an insulated membrane. Thermal accumulator for storing motor oil and thermal accumulator for storing a coolant provide long-term storage of accumulated heat by motor oil and the coolant in separate insulated tanks with TA. The results of pre-start and after-start heating of the engine were assessed and compared in the study depending on the combined heating system different options or their combination.

Based on the developed algorithms for pre-start and after-start heating of the engine coolant and motor oil, 19 combinations of options were suggested to analyze the sets of components of the developed combined heating system (**Table 1**) [1, 2, 5, 12, 15–19]. Thus, for all options during pre-start and after-start heating of the engine with CSPSH mode parameters of its work were estimated. They are as follows: heating the coolant and motor oil from T_{amb} to

# of option	The combined heating system components (the definition of the option)	Structural and technology features and the use of the combined heating system option according to its purpose
1	2	3
1	Engine standard systems without the combined heating system—SS without the CHS	Engine pre-start heating is impossible to do. After-start heating is carried out by the elements of cooling and lubrication systems of the standard engine. To ensure the maintenance of $T_c \approx 50°C$ and $T_{MO} \approx 50°C$ when the engine is not running, the elements of cooling and lubrication systems of the standard engine can only be used.
2	Engine standard systems with the combined heating system—SS with the CHS	Engine pre-start heating is impossible to do. For rapid after-start heating, only additional electric modulating pumps for the coolant and motor oil of the rapid heating of the engine subsystem are used. To ensure the maintenance of $T_c \approx 50°C$ and $T_{MO} \approx 50°C$ when the engine is not running, the elements of cooling and lubrication systems of the standard engine can only be used.
3	Phase-transitional thermal accumulator—TA	Engine pre-start and rapid after-start heating is carried out by phase-transitional TA. Besides, additional electric modulating pumps for the coolant and motor oil of the rapid heating of the engine subsystem (#2), the subsystem of the utilization of thermal energy of EG by phase-transitional thermal accumulator are also used. To ensure the maintenance of $T_c \approx 50°C$ and $T_{MO} \approx 50°C$ of the engine with phase-transitional TA when the engine is not running, additional electric modulating pumps for the coolant and motor oil of the rapid heating of the engine subsystem can be used.
4	Phase-transitional contact thermal accumulator—CTA	Engine pre-start and after-start heating is impossible to do. To ensure the maintenance of $T_c >$ or $\approx 50°C$ and $T_{MO} >$ or $\approx 50°C$ of the engine with phase-transitional CTA when the engine is not running, the elements of cooling and lubrication systems of the standard engine can be used.
5	Thermal accumulator for storing motor oil ($T_{HAM} = Tamb$) – TASMO ($T_{HAM} = Tamb$)	Engine pre-start and after-start heating is impossible to do. The maintenance of $T_{MO} >$ or $\approx 50°C$ of the engine with TASMO when the engine is not running is possible with the elements of lubrication system of the engine with thermal accumulator for storing motor oil without HAM thermal development ($T_{HAM} = Tamb$). To ensure the maintenance of $T_c \approx 50°C$ when the engine is not running, the elements of cooling system of the standard engine can only be used.

# of option	The combined heating system components (the definition of the option)	Structural and technology features and the use of the combined heating system option according to its purpose
6	Thermal accumulator for storing motor oil (T_{HAM} = 85°C) – TASMO (T_{HAM} = 85°C)	Engine pre-start and after-start heating is impossible to do. The maintenance of T_{MO} > or ≈ 50°C of the engine with TASMO when the engine is not running is possible with the elements of lubrication system of the engine with thermal accumulator for storing motor oil with HAM thermal development (T_{HAM} = 85°C). To ensure the maintenance of T_c ≈ 50°C when the engine is not running, the elements of cooling system of the standard engine can only be used.
7	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator (# 3 and # 4): TA + CTA	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator and phase-transitional contact thermal accumulator. # 3 and # 4 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
8	The combination of separate CHS components, namely: thermal accumulator + thermal accumulator for storing motor oil (T_{HAM} = *Tamb*): # 3 and # 5 – TA + TASMO (T_{HAM} = *Tamb*)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator and thermal accumulator for storing motor oil without HAM thermal development (T_{HAM} = *Tamb*). # 3 and # 5 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
9	The combination of separate CHS components, namely: thermal accumulator + thermal accumulator for storing motor oil (T_{HAM} = 85°C): # 3 and # 6 – TA + TASMO (T_{HAM} = 85°C)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator and thermal accumulator for storing motor oil with HAM thermal development (T_{HAM} = 85°C). # 3 and # 6 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
10	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator + thermal accumulator for storing motor oil (T_{HAM} = *Tamb*): # 3, #4 and # 5 – TA + CTA + TASMO (T_{HAM} = *Tamb*)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator, phase-transitional contact thermal accumulator and thermal accumulator for storing motor oil without HAM thermal development (T_{HAM} = *Tamb*). # 3, # 4 and # 5 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.

# of option	The combined heating system components (the definition of the option)	Structural and technology features and the use of the combined heating system option according to its purpose
11	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator + thermal accumulator for storing motor oil (T_{HAM} = 85°C): # 3, #4 and # 6 – TA + CTA + TASMO (T_{HAM} = 85°C)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator, phase-transitional contact thermal accumulator and thermal accumulator for storing motor oil with HAM thermal development (T_{HAM} = 85°C). # 3, # 4 and # 6 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
12	Thermal accumulator for storing a coolant ($T_{HAM} = Tamb$) – TASC ($T_{HAM} = Tamb$)	Engine pre-start and after-start heating is impossible to do. The maintenance of T_c > or ≈ 50°C of the engine with TASC when the engine is not running is possible with the elements of cooling system of the engine with thermal accumulator for storing a coolant without HAM thermal development ($T_{HAM} = Tamb$). To ensure the maintenance of T_{MO} ≈ 50°C when the engine is not running, the elements of lubrication system of the standard engine can only be used.
13	Thermal accumulator for storing a coolant (T_{HAM} = 85°C) – TASC (T_{HAM} = 85°C)	Engine pre-start and after-start heating is impossible to do. The maintenance of T_c > or ≈ 50°C of the engine with TASC when the engine is not running is possible with the elements of cooling system of the engine with thermal accumulator for storing a coolant with HAM thermal development (T_{HAM} = 85°C). To ensure the maintenance of T_{MO} ≈ 50°C when the engine is not running, the elements of lubrication system of the standard engine can only be used.
14	The combination of separate CHS components, namely: thermal accumulator + thermal accumulator for storing a coolant ($T_{HAM} = Tamb$): # 3 and # 12 – TA + TASC ($T_{HAM} = Tamb$)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator and thermal accumulator for storing a coolant without HAM thermal development ($T_{HAM} = Tamb$). # 3 and # 12 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
15	The combination of separate CHS components, namely: thermal accumulator + thermal accumulator for storing a coolant (T_{HAM} = 85°C): # 3 and # 13 – TA + TASC (T_{HAM} = 85°C)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator and thermal accumulator for storing a coolant with HAM thermal development (T_{HAM} = 85°C). # 3 and # 13 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.

# of option	The combined heating system components (the definition of the option)	Structural and technology features and the use of the combined heating system option according to its purpose
16	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator + thermal accumulator for storing a coolant ($T_{HAM} = Tamb$): # 3, # 4 and # 12 – TA + CTA + TASC ($T_{HAM} = Tamb$)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator, phase-transitional contact thermal accumulator and thermal accumulator for storing a coolant without HAM thermal development ($T_{HAM} = Tamb$). # 3, # 4 and # 12 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
17	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator + thermal accumulator for storing a coolant (T_{HAM} = 85°C): # 3, # 4 and # 13 – TA + CTA + TASC (T_{HAM} = 85°C)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator, phase-transitional contact thermal accumulator and thermal accumulator for storing a coolant with HAM thermal development (T_{HAM} = 85°C). # 3, # 4 and # 13 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
18	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator + thermal accumulator for storing motor oil ($T_{HAM} = Tamb$) + thermal accumulator for storing a coolant ($T_{HAM} = Tamb$): # 3, # 4, # 5 and # 12 – TA + CTA + TASMO+TASC	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator, phase-transitional contact thermal accumulator, thermal accumulator for storing motor oil without HAM thermal development ($T_{HAM} = Tamb$) and thermal accumulator for storing a coolant without HAM thermal development ($T_{HAM} = Tamb$). # 3, # 4, # 5 and # 12 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.
19	The combination of separate CHS components, namely: thermal accumulator + contact thermal accumulator + thermal accumulator for storing motor oil (T_{HAM} = 85°C) + thermal accumulator for storing a coolant (T_{HAM} = 85°C): # 3, # 4, # 6 and # 13 – TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C)	The combination of separate components of the combined heating system, namely: phase-transitional thermal accumulator, phase-transitional contact thermal accumulator, thermal accumulator for storing motor oil with HAM thermal development (T_{HAM} = 85°C) and thermal accumulator for storing a coolant with HAM thermal development (T_{HAM} = 85°C). # 3, # 4, # 6 and # 13 describe structural and technology features and the use of the combined heating system option according to its purpose during engine pre-start and after-start heating and long-term keeping in an idling mode without the operation.

Table 1. The options of the combined heating system components to analyze the efficiency of pre-start and after-start heating of the truck engine 8FS 9.2/8.

50°C, min., heating the coolant and motor oil from 50 to 85°C, min., maintaining $T_c \approx 50°C$ and $T_{MO} \approx 50°C$ min. The operating parameters were analyzed separately for the coolant and motor oil at different ambient temperatures, namely 20, 0 and −20°C.

Figures 4–6 show the results of pre-start and after-start heating according to the duration of thermal development of the truck engine coolant and motor oil using the combined heating system. **Figure 4** shows the duration of the coolant and motor oil heating from *Tamb* to 50°C, min. **Figure 5** shows the duration of the coolant and motor oil heating from 50 to 85°C, min. **Figure 6** shows the duration of maintaining $T_c \approx 50°C$ and $T_{MO} \approx 50°C$, min. The comparison of indicators for every option of the combined heating system components and the technology for use was provided in absolute values (and in %). Every indicator for a corresponding option was compared with the similar one for a standard system of the engine ZMZ-66-06 (8FS 9.2/8) of the truck GAZ-66-11 (**Figures 4–6**). Based on the calculation results of pre-start and after-start heating of the coolant and motor oil according to the appropriate options of the combined heating system components (**Figures 4–6**), it is obvious that the use of the above-mentioned ways of heating according to the operating algorithms ensures both pre-start and rapid after-start heating of the engine ZMZ-66-06 (8FS 9.2/8) of the truck GAZ-66-11. It also increases the length of the long stop of the engine without idling. Meanwhile, according to the temperature values of the coolant and motor oil, the engine is in pre-start availability that corresponds to the thermal state to enable the engine load.

The indicators of the engine thermal state during pre-start heating of the coolant and motor oil of the ICE with the combined heating system were compared with the standard systems of the engine (option 1, **Table 1**) from *Tamb* to 50°C, min (**Figure 4**). The greatest reduction in the heating time was obtained in options 3, 7–11, 14–19 for all ambient temperatures, i.e., at *Tamb*

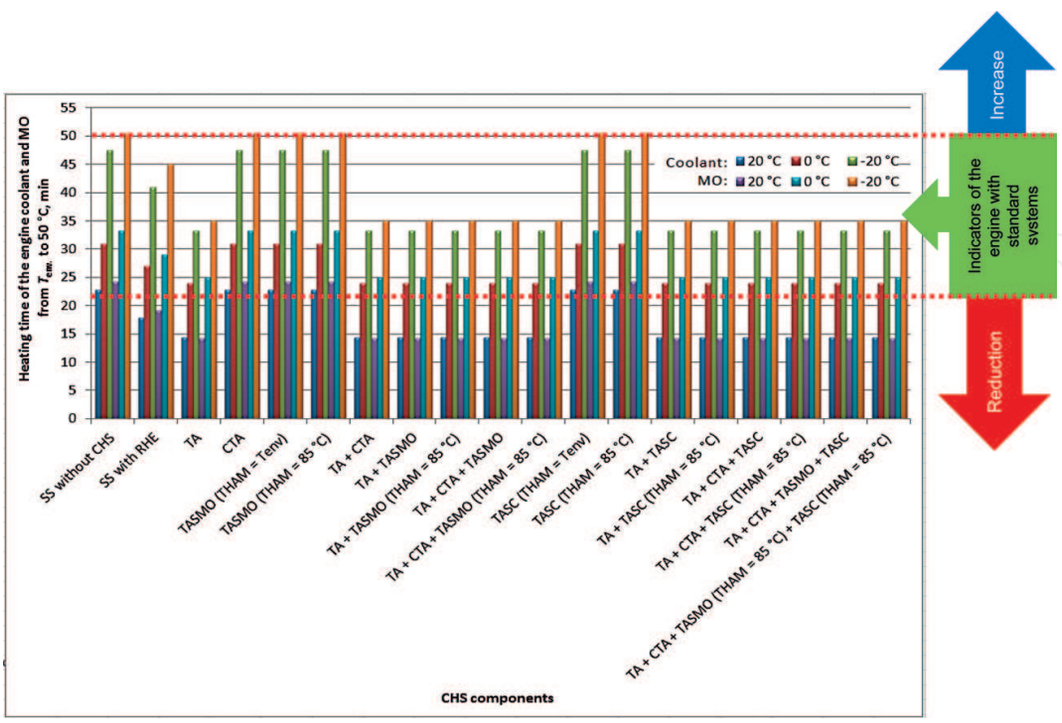


Figure 4. The influence of options of the combined heating system components on the heating time of the engine coolant and motor oil from *Tamb* to 50°C.

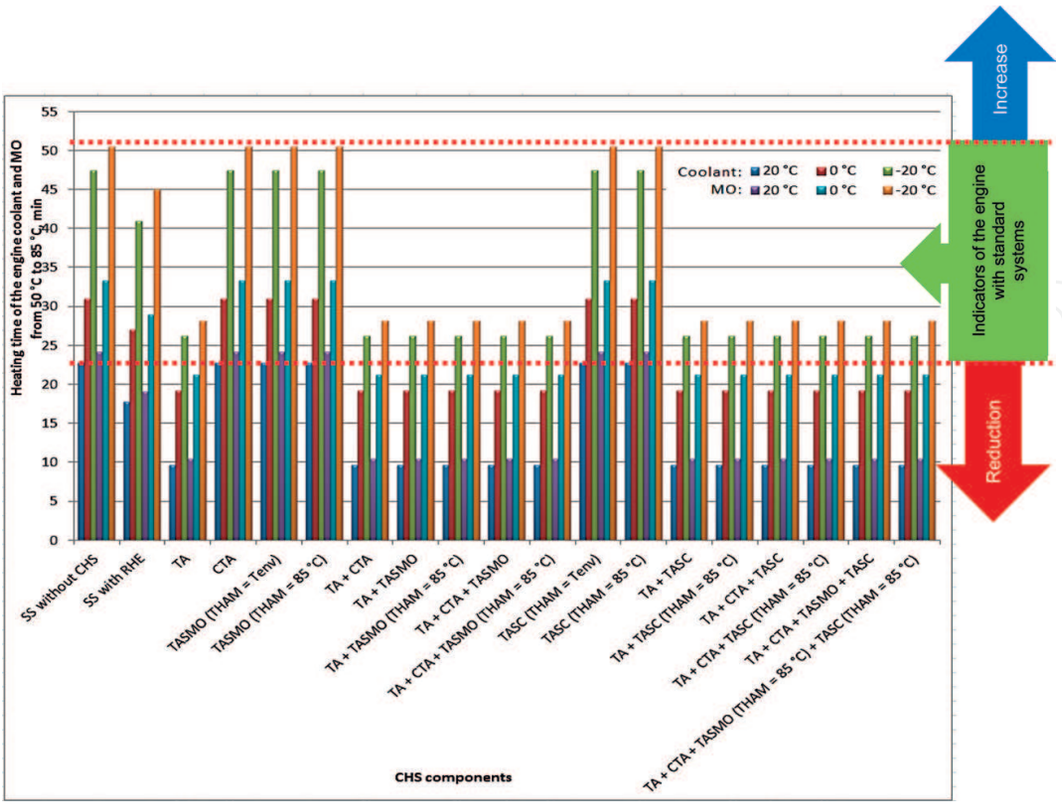


Figure 5. The influence of options of the combined heating system components on the heating time of the engine coolant and motor oil from 50 to 85°C.

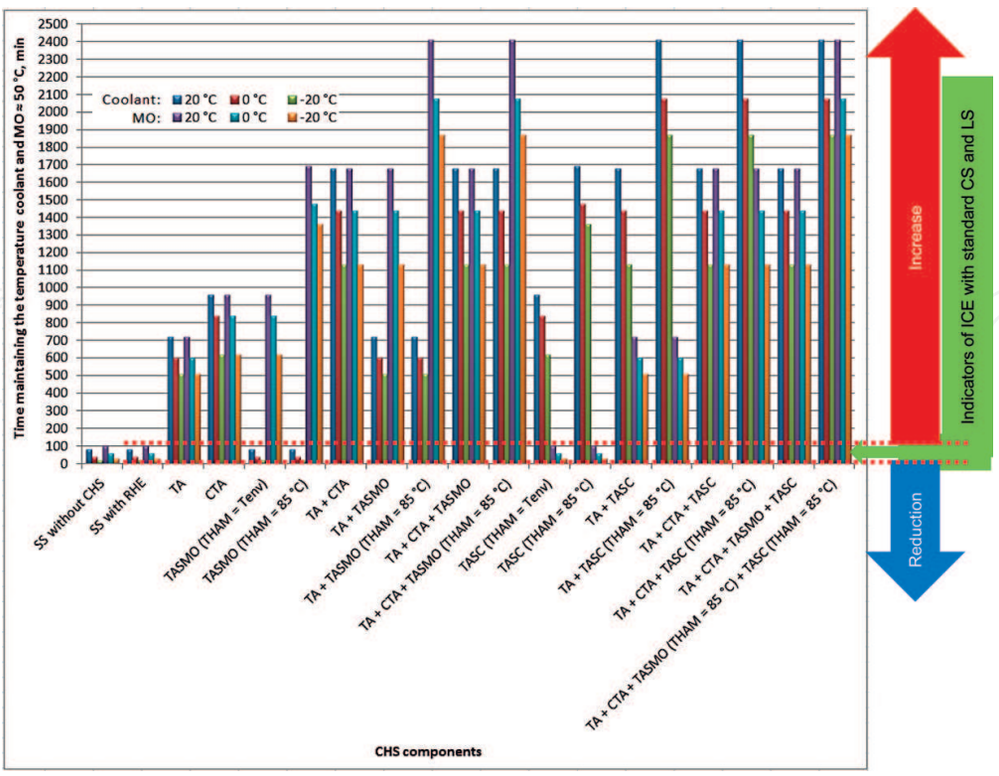


Figure 6. The influence of options of the combined heating system components on the duration of maintaining the coolant and motor oil temperatures within ≈50°C.

= 20 (0/−20)°C. These options are characterized by the operation of phase-transitional TA and the rapid heating of the engine subsystem at the same time. For relevant temperatures of *Tamb* = 20 (0/−20)°C, the duration of heating is reduced according to the values 14.4 (24/33.3) min for the coolant and 14.2 (25/35) min for motor oil. This option is compared with the standard systems of the engine (option 1), i.e., 22.8 (31/47.5) min for the coolant and 24.2 (33.3/50.5) min for motor oil. Thus, the duration of heating is reduced by 8.4 (7.1/14.2) min or by 36.9 (22.9/29.9)% for the coolant and by 10 (8.3/15.5) min or by 41.3 (25/30.8) % for motor oil.

The indicators of the ICE thermal state during rapid after-start heating of the coolant and motor oil of the engine with the combined heating system were compared with the standard systems of the engine (option 1, **Table 1**) from 50 to 85°C, min (**Figure 5**). The greatest reduction in the heating time was obtained in options 3, 7–11, 14–19 for ambient temperatures at *Tamb* = 20(0/−20)°C. These options are characterized by the operation of phase-transitional TA and the rapid heating of the engine subsystem at the same time. The duration of heating is reduced according to the values 9.7 (19.2/26.2) min for the coolant and 10.5 (21.2/28.2) min for motor oil. This option is compared with the standard systems of the engine (option 1), i.e., 22.8 (31/47.5) min for the coolant and 24.2 (33.3/50.5) min for motor oil. Thus, the duration of heating is reduced by 13.1 (11.8/21.3) min or by 57.5 (38/44.8)% for the coolant and by 13.7 (12.1/22.3) min or by 57 (36/44.2)% for motor oil.

The duration of maintaining the engine $T_c \approx 50$°C and $T_{MO} \approx 50$°C, min (**Figure 6**) within the combined heating system (option 1, **Table 1**) was compared with the standard systems. A substantial increase in long-duration stop of the engine with the combined heating system when the engine was not running in an idling mode was obtained. The duration of maintenance did not change in option 2 for the coolant and motor oil, in options 5 and 6 for the coolant, in options 12 and 13 for motor oil. According to **Figure 6**, the increase in the maintenance duration occurred in options 3–18 for both the coolant and for motor oil for ambient temperatures *Tamb* = 20 (0/−20)°C. The most significant increase in duration occurred in option 19 for the coolant and motor oil, in options 15 and 17 for the coolant, in options 9 and 11 for motor oil respectively. These options are characterized by simultaneous operation of phase-transitional TA and the rapid heating of the engine subsystem, contact thermal accumulator subsystem as well as thermal accumulator for storing motor oil and thermal accumulator for storing a coolant previously heated to $T_{HAM} = 85$°C. The duration of maintaining $T_c \approx 50$°C and $T_{MO} \approx 50$°C is increased according to the values from 720 (600/510) min to 2410 (2078/1870) min for the coolant and from 720 (600/510) min to 2410 (2078/1870) min for motor oil. This option was compared with the standard systems of the engine (option 1), i.e., 80 (40/20) min for the coolant and 100 (60/30) min for motor oil. Thus, the duration of maintaining the temperatures is increased from 640 (560/490) min. to 2330 (2038/1850) min or ranging from 9 (14/24) to 29.13 (50.95/92.50) times for the coolant and from 620 (540/480) min to 2310 (2018/1840) min or ranging from 6.2 (9/16) to 15.9 (33.63/61.33) times for motor oil for appropriate operating conditions.

The use of the combined heating system is generally effective (**Figures 4–6**) for pre-start and after-start thermal development of the vehicular engine and for maintaining it for a long time when it is not running under different climatic conditions. The peculiarities of the combined heating system components and the technology for use are chosen depending on operational needs, climatic conditions and the category of the vehicle.

5. Estimating the indicators of optimum temperature (OT) of the engine and the vehicle under operating conditions

The estimation was based on the mathematical modeling of the "combined heating of the engine and the vehicle" system. The mathematical modeling was carried out for various components of the CHS used for the truck and a car. The options of operating conditions and methods of the engine and the vehicle heating were chosen in accordance with the provisions of [1, 5, 10, 11, 16–19].

The influence of various components of the CHS on pre-start heating of the engine was analyzed in terms of fuel consumption (kg/h). The results revealed the most significant components of the CHS, namely in options 2 and 3. For them, additional estimation studies were carried out to determine the specific indicators of the total influence of the CHS components on the coolant and MO heating time from $T_{amb.}$ to 50°C and from 50 to 85°C. All indicators were compared with thermal development indicators of the engine standard systems. **Figure 7(a)** shows the main indicators of the truck engine thermal development when heating the coolant and MO from $T_{amb.}$ to 50°C. The most significant components of the CHS were studied. They have the greatest influence on thermal processes in the engine coolant and MO. Thus, a phase-transitional TA has the greatest influence on the parameters of the engine coolant heating for all ambient temperatures +20 (0/−20°C) − 0.085 (0.134/0.168) kg/h; and for MO heating, respectively 0.085 (0.133/0.167) kg/h.

To estimate the total influence of the CHS components on the coolant and MO heating time, the most significant components were chosen, namely in options 3–6, 12, 13 and 19 (**Figure 7(b)**. All indicators were compared with the indicators of the engine standard systems. The total influence on thermal development processes implies the total time of pre-start (from $T_{amb.}$ to 50°C) and after-start heating (from 50 to 85°C) and the time of maintaining the coolant and MO temperature within ≈50°C in relation to the fuel consumed for thermal development. **Figure 7b** shows the main study results of the influence of the CHS components on the total time of the coolant and MO thermal development. It is determined in the specific indicators of fuel consumption, kg/h. The lowest fuel consumption indicators were obtained for the CHS with such components: TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C). Phase-transitional TA indicators are worth mentioning as well. They are optimal for all options of the heating, both according to the options of the heating and the ambient temperatures.

In general, to provide the OT of the engine with the CHS, it is advisable to use all options of simultaneous influence on the coolant and MO.

To provide the temperature influence on the CC of the EGCS indicators, it is advisable to use TA installed in the exhaust system of the engine. When using TAEGCS, depending on the option of the engine heating, the time of reaching the temperature at the Light-off point (250°C/523 K) of the CC heating curve is 3–5 min of the CC operation for all options. This indicator is almost twice as good as the experimentally obtained indicators of the CC heating.

To ensure the compliance with the requirements for the heating periods of different areas of the vehicle interior and the driver, the use of the CHS is completely stipulated. In this case,

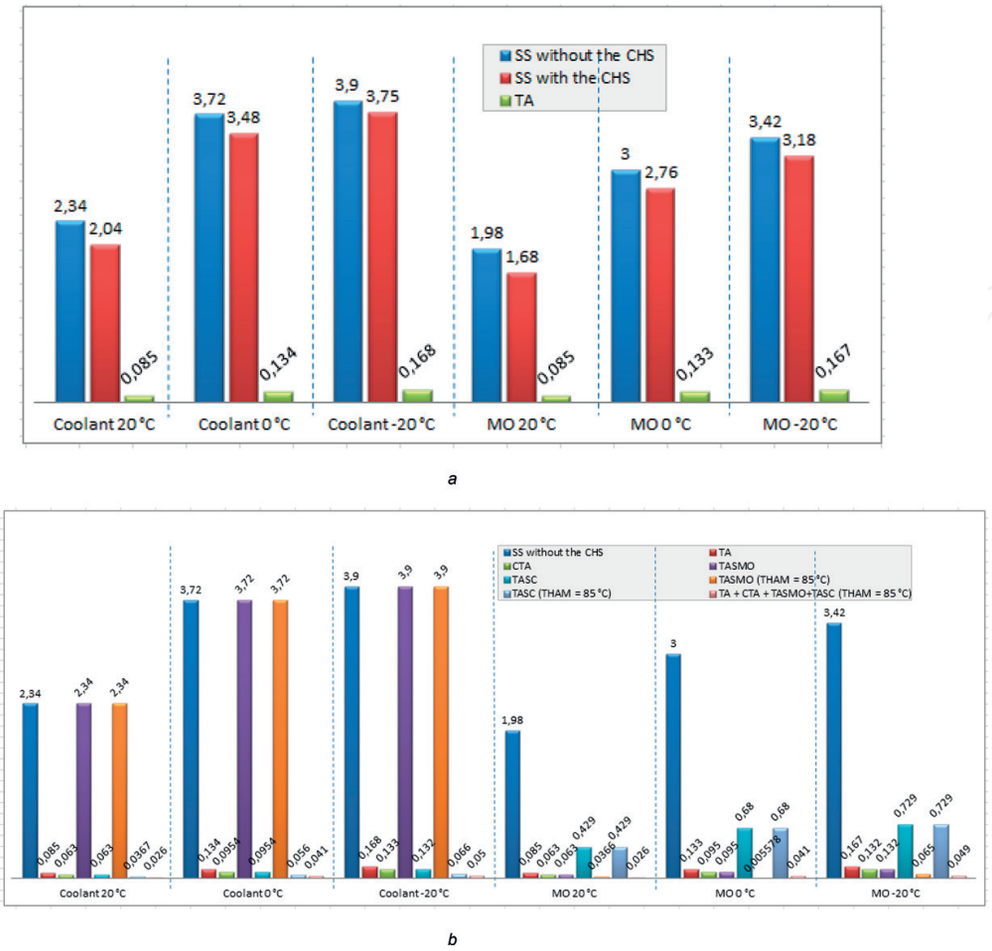


Figure 7. The results of investigating the influence of the CHS components on the coolant and MO heating time (a) and on the total time of the coolant and MO thermal development (b) in terms of fuel consumption (kg/h).

the interior and the driver are heated by the engine CS, that is, without changing the design of the vehicle. The results of the mathematical modeling of the interior heat transfer processes confirmed the feasibility of using the CHS. When using the CHS, the requirements are fully met in terms of the efficiency and safety of the heating system. It means that 15 min after the vehicle starts its motion at the ambient temperature to −25°C the requirements of the standard for heating the driver's head, legs, and body are fully met.

6. Summary

The development and the study of the engine combined heating system with phase-transitional thermal accumulators for pre-start and after-start heating under cold operating conditions were considered. To ensure optimal temperature condition of the ICE and the vehicle, general and individual tasks were determined. The combined heating system scheme of the ICE and the vehicle in operation was developed. The objects of experimental studies in operation were described. Using a systems approach to ensure optimal temperature condition of the vehicle in operation, the "combined heating system of the engine and the vehicle" and its application methods were developed. The results of significant impact of the

combined heating system on thermal development indicators of the engine and the vehicle were obtained. The use of the combined heating system in the vehicular engine for different ambient temperatures enables to improve the indicators of the duration of coolant and motor oil thermal development. It is possible at: pre-start and after-start heating by 22.9–57.5% and 25–57%, and for a long storage ranging from 9 to 92 times and from 6.2 to 61 times, without the engine operation in an idling mode. The use of the combined heating system is generally effective for pre-start and after-start thermal development of the vehicular engine and for maintaining it for a long time when it is not running under different climatic conditions. The peculiarities of the combined heating system components and the technology for use are chosen depending on operational needs, climatic conditions and the category of the vehicle.

Thus, in order to ensure safety in terms of maintaining the OT of the engine and the vehicle, it is advisable to use the following options:

- heating from $T_{amb.}$ to 50°C - SS + RHE and phase-transitional TA;
- heating from 50 to 85°C - SS + RHE and phase-transitional TA;
- maintaining the coolant and MO temperature within ≈50°C when the vehicle is stopped – TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C) and phase-transitional TA;
- by total specific indicators - TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C) and phase-transitional TA.

To ensure the harmless environmental impact, it is expedient to use TAEGCS, TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C) and phase-transitional TA.

To ensure the transportation comfort, it is expedient to use any means of thermal development in the engine CS. The best of them are – the vehicle - TA + CTA + TASMO (T_{HAM} = 85°C), the vehicle - TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C) and phase-transitional TA.

In order to ensure the engine capacity at its start, that is the ability to have the load on the engine immediately after its start, it is expedient to use TAEGCS, the vehicle - TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C) and phase-transitional TA.

In order to ensure specific efficient fuel consumption when maintaining the OT of engines and vehicles, it is expedient to use TA + CTA + TASMO (T_{HAM} = 85°C) + TASC (T_{HAM} = 85°C).

Definitions/acronyms

CC	catalytic converter
CHS	combined heating system
CS	cooling system
CTA	contact thermal accumulator
EG	exhaust gases
EGCS	exhaust gases cleaning system

HAM	heat accumulating material
HE	heat exchanger
ICE	internal combustion engine
LS	lubrication system
PSASH	pre-start and after-start heating
RHE	rapid heating of the engine
SS	standard system
TA	thermal accumulator
TAEGCS	TA of EG cleaning system
TASC	thermal accumulator for storing a coolant
TASMO	thermal accumulator for storing motor oil
UTETA	utilization of thermal energy of exhaust gases by phase-transitional TA

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