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FORMATION OF INDICATORS THE PROCESSES OF PREHEATING AND HEATING AFTER THE VEHICULAR ENGINE START BY USING COMPLEX HEATING SYSTEM WITH PHASE-TRANSITIONAL THERMAL ACCUMULATOR

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Abstract. *The article deals with the features of applying a vehicular engine complex heating system with phase-transitional thermal accumulator. The results of experimental studies of heating the vehicular engine are shown. Using a phase-transitional thermal accumulator in the engine coolant heater system allows to considerably reduce the time for heating.*

Key words: *complex heating, vehicular engine, pre-start and after-start heating, heating processes, vehicle.*

ФОРМИРОВАНИЕ ПОКАЗАТЕЛЕЙ ПРОЦЕССОВ ПРЕДПУСКОВОГО И ПОСЛЕПУСКОВОГО ПРОГРЕВА АВТОМОБИЛЬНОГО ДВИГАТЕЛЯ С КОМПЛЕКСНОЙ СИСТЕМОЙ ПРОГРЕВА С ТЕПЛОВЫМ АККУМУЛЯТОРОМ ФАЗОВОГО ПЕРЕХОДА

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Аннотация. *Рассмотрены особенности применения комплексной системы предпускового и послепускового прогрева автомобильного двигателя с тепловым аккумулятором с фазовым переходом. Представлены результаты экспериментальных исследований прогрева автомобильного двигателя. Использование теплового аккумулятора с фазовым переходом в системе охлаждения двигателя позволяет существенно сократить время прогрева.*

Ключевые слова: *комплексный прогрев, транспортный двигатель, предпусковой и послепусковой прогрев, режимы прогрева, транспортное средство.*

ФОРМУВАННЯ ПОКАЗНИКІВ ПРОЦЕСІВ ПЕРЕДПУСКОВОГО ТА ПІСЛЯПУСКОВОГО ПРОГРІВУ АВТОМОБІЛЬНОГО ДВИГУНА З КОМПЛЕКСНОЮ СИСТЕМОЮ ПРОГРІВУ З ТЕПЛОВИМ АКУМУЛЯТОРОМ ФАЗОВОГО ПЕРЕХОДУ

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Анотація. *Розглянуто особливості застосування комплексної системи передпускового та післяпускового прогріву автомобільного двигуна з тепловим акумулятором з фазовим переходом. Наведені результати експериментальних досліджень прогріву автомобільного двигуна. Використання теплового акумулятора з фазовим переходом у системі охолодження двигуна дозволяє істотно скоротити час прогріву.*

Ключові слова: *комплексний прогрів, транспортний двигун, передпусковий і післяпусковий прогрів, режими прогріву, транспортний засіб.*

Introduction

Thermal pre-start development occupies an important place among the main problems of efficient operation of internal combustion engines (ICE) [1, 2]. The main difficulties occur during the start of cold engine at low outside temperatures, especially for the cases when the engine is under load immediately after starting. At low temperatures the process of starting is complicated, the reliability of it is significantly reduced and time of preparation for load increases.

Vehicular engine starting characteristics are estimated by limit temperature of reliable start and the time needed to prepare for load. In practice, therefore, the operation of vehicular engine during pre-start development, start and post-start heating at low temperatures is differentiated, namely, the idle heating, the operational heating, heating during the load, etc.

Previous experimental and computational studies have shown that it is appropriate to use heating system (HS) of ICE to ease the start and to rapidly heat the engine coolant [1]. Thermal accumulator (TA) with heat accumulating material and a phase transition was developed for this purpose [2–4] It allows us to accumulate thermal energy of exhaust gases. The amount of heat accumulated by TA corresponds with the required amount of thermal energy needed for the preheating of engine coolant from the lowest outside temperature to the coolant temperature at which the load may be held [1, 3, 4].

Heating systems have been widely applied in the processes of pre-start development and heating of vehicular ICE [1, 2]. The peculiarity of heating systems with phase-transitional TA [3. 4] is mutual involvement of both heating control system and the driver, using relevant devices readings, in the pre-start and the subsequent after-start heating of the engine.

The efficiency of HS with TA of manual control directly depends on the participation of the person in the process of heating and monitoring engine performance parameters. To ensure high efficiency of HS in a distant mode the information of OBD (On Board Diagnostic) system should be taken into account, especially the information obtained by scanning memory of on-board computer of the vehicle using special technology [5–7]. The analysis of reference sources showed that the research on the estimation of time and modes of thermal development in engine pre-start and after-start heating with the HS using phase-transitional TA was not carried out. A measuring system, providing distance monitoring of engine and vehicle engineering data within intelligent transport systems (ITS), was not developed for this research [5, 7].

At the heart of numerous experimental studies lies the necessity of heating car engine at a low outside temperature during pre-heating to the temperatures of «hot start». The temperatures of «hot start» should be 40° C, 50° C and 60° C. In this case we can at least begin to move. When the temperatures are higher it is possible to accept the load. And when the vehicle is in motion, the temperature should be heated up to 85 ± 1,5° C [8]. During the research, the standard engine cooling system (excluding combination heating system) of the vehicle and the improve – one – where HS was connected – were used. The registration of parameter changes of coolant temperature and fuel consumption of ICE was conducted in various conditions of heating. In general, 32 diagnostic parameters from automotive engine and vehicle were obtained in real time by using virtual and software diagnostic complex [7, 8] «on-line». It allowed us to trace the processes of ICE start and heating. Pre- and after-start heating of the engine was executed at low outside temperatures, namely – 5° C, – 10° C, – 20° C.

The changes of the main parameters of vehicular engine are shown in fig. 1. These parameters characterize the processes of starting and heating the engine by classical method (without using HS with thermal accumulator) at t_e = – 5° C and in various mode of heating (Heating in an idling mode; Heating in an idling mode with electrical consumers switched on; Heating in an idling mode with gradual heating in motion; Heating in motion): coolant temperature, t, °C, rotation speed (x100) min^{-1}, fuel consumption (l/h), catalyst temperature (x10), T, K and intake air temperature, t_i, °C.

In this mode (fig. 1 a) the peculiarity of heating in an idling mode with electrical consumers switched on (mode 2) is as follows. In the process of loading the engine in an idling mode (starting from coolant temperature of + 50° C) available electrical consumers of the vehicle were used: electric heating of 2 seats, mirrors and rear window heating, switching of all lights and alarm system, as well as switching of vehicle climate control system.

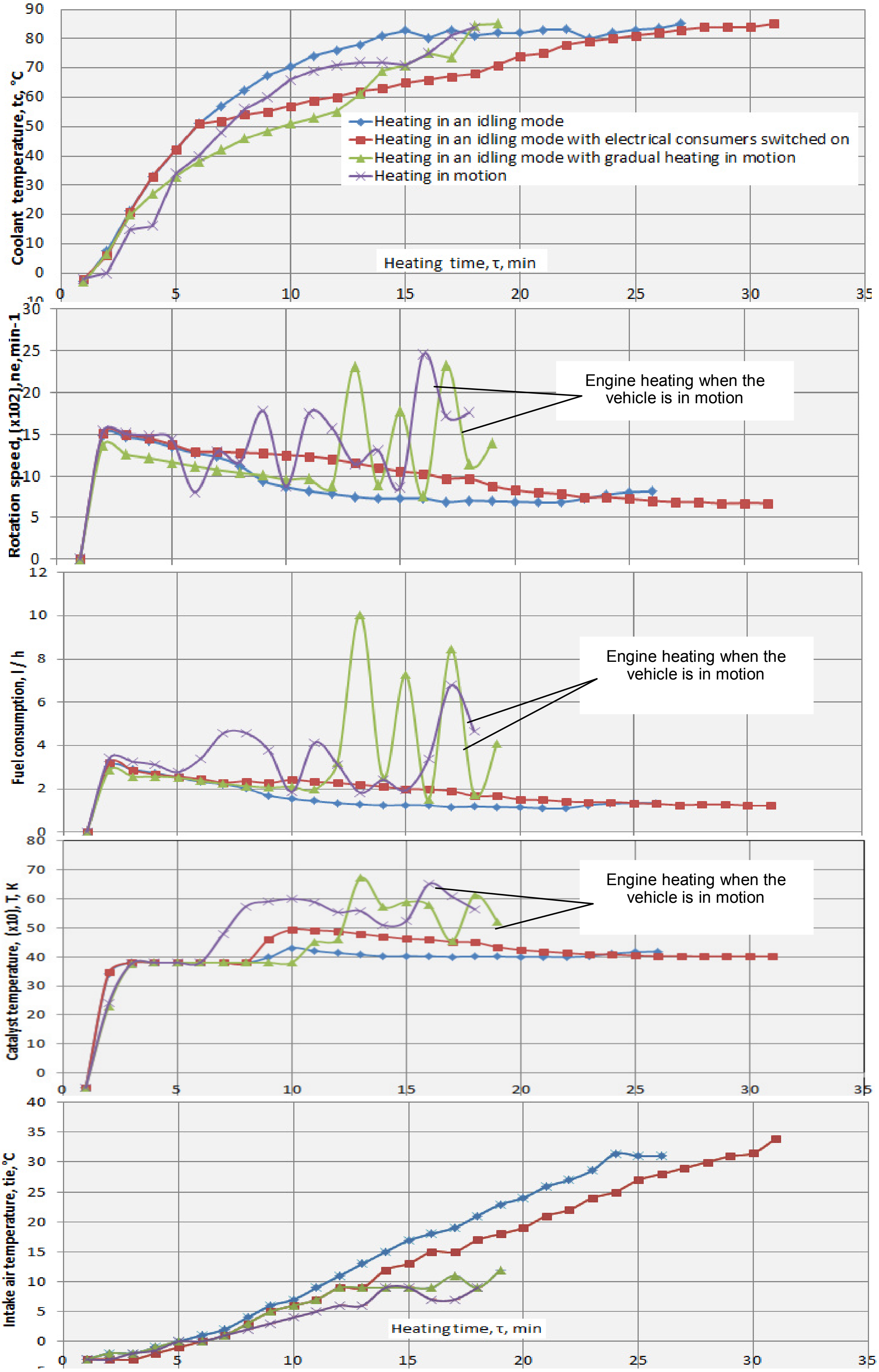

Fig. 1, a. Changing of the basic parameters of vehicular engine which characterize the processes of its starting and heating when t_e = – 5° C: without HS and TA

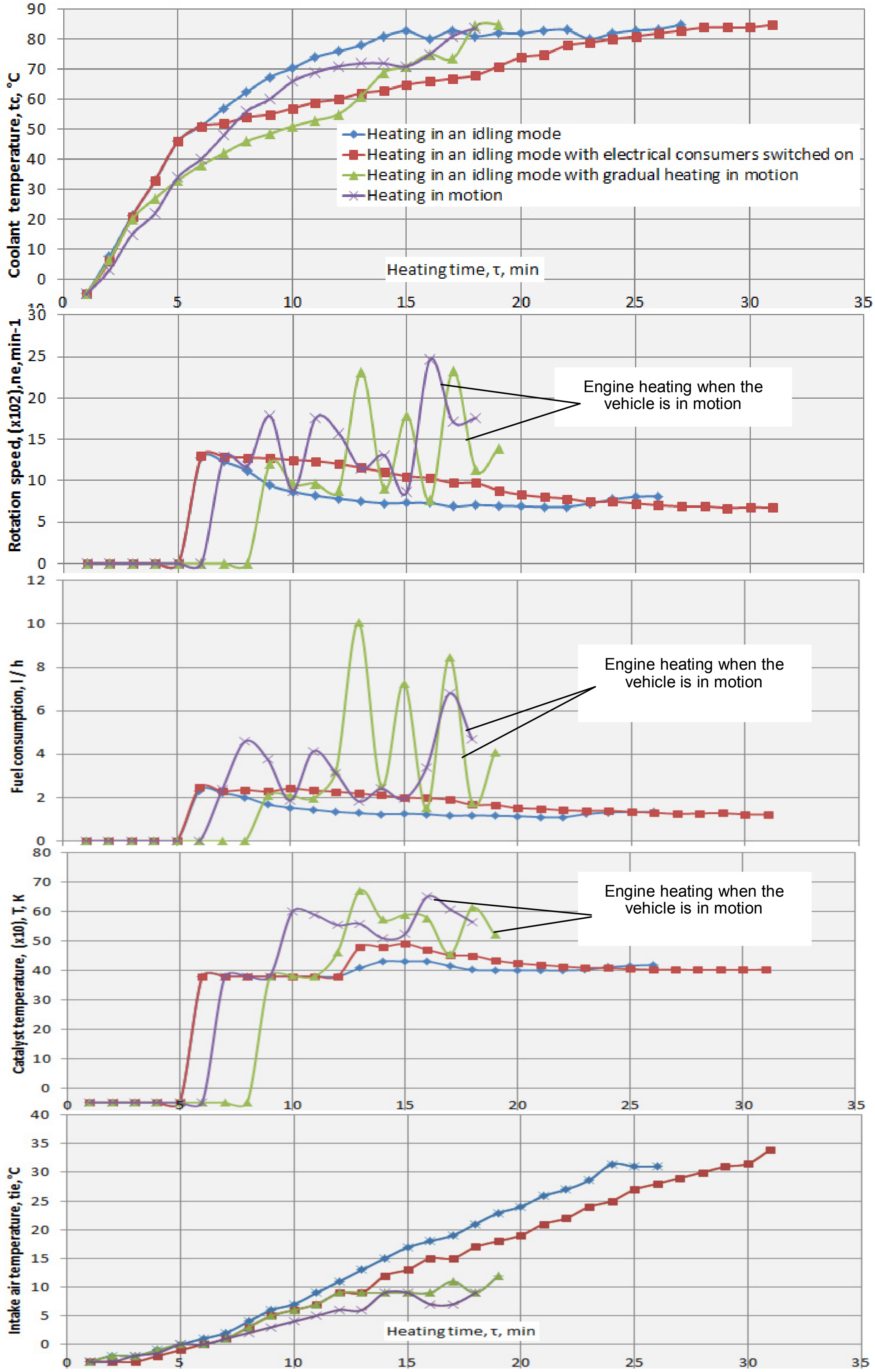

Fig. 1, b. Changing of the basic parameters of vehicular engine which characterize the processes of its starting and heating when $t_e = -5°$ C: with HS and TA

Thus, in addition to this equipment, car interior was also heated. This explains the curve on the graph (mode 2 – blue line). There was a delay in heating the engine because of taking off the additional thermal heat from the coolant designed to heat the engine up to 85° C, just to heat the car interior. Naturally, the heating of the engine is delayed when heating the car interior from coolant thermal heat. It should be noted that in the other three modes (fig. 1, a) of heating (1, 3, 4) electrical consumers and climate control system were switched off. Comparing the results we may say that the process of heating the vehicular engine with electrical consumers and climate control system switched on requires additional research. It is so because of the fact that such switching together with the heating of the car interior most significantly increase the time of ICE and vehicle heating under operating conditions.

Fig. 1, b illustrates the changes of the main parameters of vehicular engine which are similar to fig. 6, a. The parameters (fig. 1, b) characterize the processes of starting and heating the engine using HS with TA in similar versions of heating. In this mode (fig. 1, b) the engine start in all modes was performed after a cooling system temperature reached 50° C because of using the HS in pre-start event. In this case (with the HS switched on) the peculiarity of heating in an idling mode with electrical consumers switched on (mode 2) is as follows. During pre-start heating from the HS electrical consumers were not switched on and the car interior was not heated. On reaching the coolant temperature of 50° C the engine start and electrical load were carried out. The vehicular engine was idling and the HS was turned off (to have equal terms while studying the pre-start and after-start heating of the vehicular engine). When loading, there were used the above-mentioned available electrical consumers of the vehicle. To heat the car interior only the climate control system (without the HS) was used. This explains the curve on the graph (mode 2 – blue line). It should be noted that in the other three modes (fig. 1, b) 0of heating (1, 3, 4) electrical consumers and climate control system were switched off. Comparing the results and reaffirming the above-mentioned facts, we may say that the process of heating the vehicular engine with electrical consumers and climate control system switched on requires additional research. It is so because of the fact that such switching together with the heating of the car interior most significantly increase the time of ICE and vehicle heating under operating conditions.

Analyzing the obtained results, we can see that the coolant temperature, t, °C during pre-start thermal development of HS with TA changes similarly to fig. 1, a. This provides effective pre-start heating of vehicular engine (the time interval of development almost coincides with the classical method of heating, but vehicular engine is not running). Rotation speed (x100) min^{-1} and fuel consumption (l / h) during pre-start heating is zero, which ensures fuel saving and resource saving of vehicular engine during this period. The changes of catalyst temperature parameters (x10), T, K are similar to fig. 1, a (with the exception of the period of pre-start heating of vehicular engine from heating system). The intake air temperature, t_i, °C in fig. 1, b changes similarly to fig. 1, a, and it can be explained by design features of the engine G4GC (4FS 8.2/9.35) and the layout of the engine compartment of KIA CEE'D 2.0 5MT2. Significant fluctuations of basic parameters of vehicular engine in fig. 1, b (as well as in fig. 1, a) can be explained by changes of fuel supply and rotation speed of the crankshaft during heating in motion.

The analysis of the obtained results showed that HS works at selected temperatures as follows: pre-start heating of vehicular engine coolant from TA takes 7–8 min, 11–12 min, 15–20 min. Then when the temperature of the engine coolant is t = 40, 50, 60° C, the engine starts running and heating of vehicular engine coolant from TA continues. It consequently causes the loss of thermal energy during fuel combustion in the engine until engine coolant temperature arises up to 85° C. As soon as the temperature reaches this level, the heating of engine from TA stops and the process of TA charging starts. At the same time heating of ICE coolant by classical method (without using heating systems with thermal accumulator) will last, as shown in fig. 1, a.

The following modes of heating were used to study pre- and after-start heating of vehicular engine: 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.

Fig. 2 shows the comparative diagrams of average time values of heating engine coolant for

4FC 7.72 / 8.45 by using TA of HS to 85° C (50° C) for different heating mode at outside temperatures of –5° C, –10° C, –20° C. Fig. 3 shows the comparative diagrams of average values of the distance required for vehicle engine to heat to 85° C (50° C) in motion at outside temperatures of –5° C, –10° C, –20° C according to heating modes: heating in an idling mode with gradual heating in motion and heating in motion.

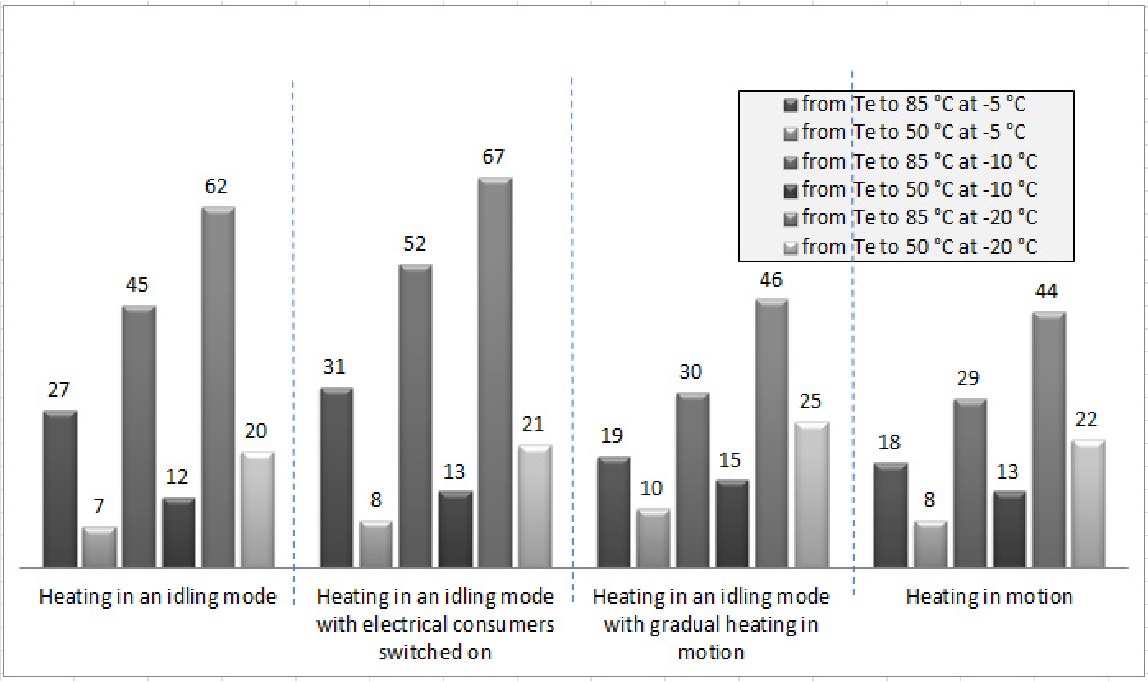

Fig. 2. Comparative diagrams of average time values of heating the engine coolant for 4FS 7.72 / 8.45 from -5° C (-10° C / -20° C) to 85° C (50° C) without the use of TA of the HS for different heating mode, min

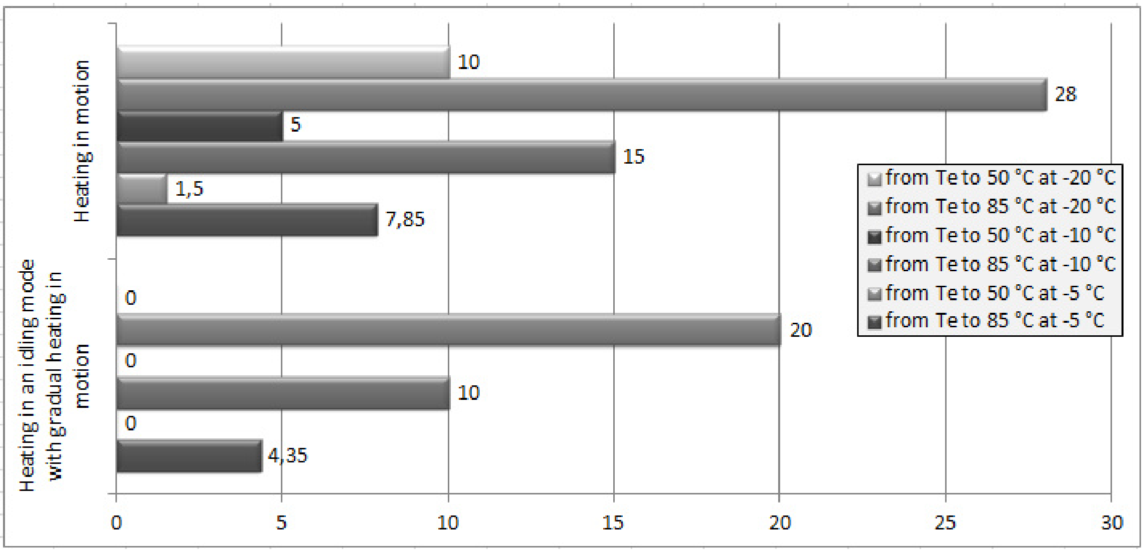

Fig. 3. Comparative diagrams of the average distance required for vehicular engine heating to 85° C (50° C) without the use of TA of HS at different outside temperatures, when the vehicle is in motion, km

It can be seen from Fig. 2 that heating engine coolant without HS at -5° C at different heating mode up to 85° C is carried out during 27, 31, 19, 18 min and up to 50° C – during 7, 8, 10, 8 min. accordingly. For mode 3 and 4 to heat the engine up to 85° C a car must pass 4.35 and 7.85 km respectively (Fig. 3) and up to 50° C – 0 and 1.5 km respectively (Fig. 3). Heating engine coolant without the use of HS from -10° C up to 85° C at different heating mode was conducted during 45, 52, 30, 29 min respectively and up to 50° C – during 12, 13, 15, 13 min respectively (fig. 2). For mode 3 and 4 to heat the engine up to 85° C a car must pass 10 and 15 km. respectively and up to 50° C - 0 and 5 km (fig. 3). Heating engine coolant from -20° C to 85° C without the use of HS at different heating mode was conducted during 62, 67, 46, 44 min respectively and up to 50° C – during 20, 21, 25, 22 min respectively (fig. 2). For mode 3 and 4 to heat the engine up to 85° C a car must pass 20 and 28 km respectively and up to 50° C - 0 and 10 km. respectively (fig. 3). The results showed that the best mode in terms of time savings are mode 3 and 4. But not sufficiently heated engine can get significant load due to the need to be heated when the vehicle is in motion. Based on engine operability during heating we can recommend mode 3 as the best one for certain operating conditions. In this mode heating time and the distance needed are compromised.

Table 1 shows that the use of HS with TA for heating vehicular engine unambiguously provides less time to heat a coolant compared to basic cooling system with a classical method of heating. Heating time is significantly reduced compared to the classical heating method for modes: heating in an idling mode with gradual heating in motion and heating in motion.

Table 2 shows a comparison of average fuel consumption values for heating the coolant of vehicular engine at different temperatures of pre-start heating of the coolant from TA of combination HS - 40° C, 50° C, 60° C to 85° C, at different outside temperatures in different ways of heating processes: 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.

According to Table 2, to heat the engine coolant without using the HS with TA (basic system with classical heating method) at -5° C in different ways of heating to 85° C, the engine requires 0.49, 0.689, 0.747 and 0.709 kg of fuel respectively. The fuel consumption is significantly reduced if HS is used to heat the coolant at different temperatures - 40° C, 50° C, 60° C to 85° C at -5° C in comparison with the basic cooling system. When heating the engine coolant without using HS with TA (basic system with classical heating method) at -10° C and -20° C respectively with various heating modes up to 85° C, the engine consumes 0.853, 1.088, 1.178 and 1.14 kg and 1.16, 1.41, 1.91 and 1.76 kg of fuel respectively. While using HS during the coolant heating from 40° C, 50° C, 60° C up to 85° C at -10° C and -20° C respectively, the fuel consumption for engine heating is reduced in comparison with the basic cooling system. It is especially visible during the process of heating with the use of HS with TA at -20° C for various heating modes of vehicular engine.

The achieved positive effects can be explained by the fact that coolant heating before start was carried out by using TA of heating system, i.e. start of the engine for coolant heating is not needed. Pre-start coolant heating can be done only due to the heat accumulated by phase-transitional TA from the heat of exhaust gases.

The comparison of the average parameters of coolant heating of vehicular engine characterizing the savings in time and fuel consumption are presented in table 3.

Table 1 The comparison of average values of heating time up to 85° C of engine coolant with various heating modes, different temperatures of pre-start heating of the coolant from TA of combined heating: 40° C, 50° C, 60° C at different outside temperatures, min

Mode of heating	from 40° C to 85° C			from 50° C to 85° C			from 60° C to 85° C		
	-5 ° C	-10 ° C	-20 ° C	-5 ° C	-10 ° C	-20 ° C	-5 ° C	-10 ° C	-20 ° C
1. Heating in an idling mode	21	37	47	20	33	42	18	30	39
2. Heating in an idling mode with electrical consumers switched on	25	42	50	23	39	46	19	35	38
3. Heating in an idling mode with gradual heating in motion	12	17	25	9	15	21	6	13	19
4. Heating in motion	12	19	27	10	16	22	9	13	19

Table 2 The comparison of average values of fuel consumption for heating the coolant in vehicular engine with various heating modes, different temperatures of pre-start heating of the coolant from TA of combined heating – from 40° C, 50° C, 60° C to 85° C at different outside temperatures, kg

Mode of heating	without HS			from 40° C to 85° C			from 50° C to 85° C			from 60° C to 85° C		
	-5° C	-10° C	-20° C	-5° C	-10° C	-20° C	-5° C	-10° C	-20° C	-5° C	-10° C	-20° C
1	0,49	0,853	1,16	0,3558	0,603	0,7	0,301	0,487	0,64	0,28	0,443	0,564
2	0,689	1,088	1,41	0,554	0,811	0,92	0,469	0,729	0,824	0,356	0,608	0,66
3	0,747	1,178	1,91	0,592	0,81	1,3	0,49	0,693	1	0,307	0,561	0,951
4	0,709	1,14	1,76	0,517	0,771	1,1	0,462	0,662	0,99	0,362	0,61	0,77

Table 3 The comparison of average parameters characterizing saving in time and fuel consumption by heating engine coolant of G4GC (4FS 8.2 / 9.35) of KIA CEE'D 2.0 5MT2 with various heating modes and different outside temperatures

Mode of heating	Saving		from 40° C to 85° C			from 50° C to 85° C			from 60° C to 85° C		
			-5° C	-10° C	-20° C	-5° C	-10° C	-20° C	-5° C	-10° C	-20° C
1	time,	min	6	8	15	7	12	20	9	15	23
		%	22,2	17,8	24,2	25,9	26,7	32,3	33,3	33,3	37,1
	fuel,	kg	0,134	0,25	0,46	0,189	0,366	0,55	0,21	0,41	0,596
		%	27,3	29,3	39,66	38,6	42,9	47,4	42,86	48,1	51,4
2	time,	min	6	10	17	8	13	21	12	17	29
		%	19,35	19,23	25,37	25,81	25	31,3	38,71	32,69	43,28
	fuel,	kg	0,135	0,277	0,49	0,22	0,359	0,586	0,333	0,48	0,75
		%	19,5	25,45	34,75	31,9	32,99	41,56	48,3	44,12	53,2
3	time,	min	7	13	21	10	15	25	13	17	27
		%	25,9	43,3	45,65	52,6	50	54,35	68,4	56,67	58,69
	fuel,	kg	0,155	0,368	0,61	0,257	0,485	0,91	0,44	0,617	0,959
		%	20,75	31,2	31,9	34,4	41,2	47,6	58,9	52,38	50,21
4	time,	min	6	10	17	8	13	22	9	16	25
		%	33,3	34,48	38,64	44,4	44,8	50	50	55,17	56,8
	fuel,	kg	0,192	0,369	0,66	0,247	0,478	0,81	0,347	0,53	0,99
		%	27,08	32,37	37,5	34,84	41,9	46,02	48,9	46,49	56,25

In general, it is possible to conclude that the use of HS with TA can significantly improve time indices for heating (up to 17.8 – 68.4%) and efficiency (up to 19.5 – 56.25%) of the researched vehicular engine G4GC (4FS 8.2 / 9.35) of KIA CEE'D 2.0 5MT2.

Conclusions

The development of pre-start and after-start heating processes of vehicular engine was considered. A system of forming pre-start and after-start heating of the engine and the vehicle in operation was developed. The vehicle was equipped with an experimental model of the studied system. In the process of experimental research, there the result showed a significant fuel saving by using phase-transitional TA in the vehicle during pre-start and after-start thermal development. Thus, the use of coolant HS of vehicular engine G4GC (4FS 8.2 / 9.35) with compromise between heating time of the vehicular engine from HS with phase-transitional TA from the outside temperature to the temperature of 85° C (50° C) and a distance needed for the vehicle to be heated in motion and fuel consumption. It is engine heating in an idling mode when the vehicle isphase-transitional TA in KIA CEE'D 2.0 5MT2 reduces the heating time by 17.8 – 68.4 % and the fuel consumption by 19.5 – 56.25 % in different operating conditions and using different modes of vehicle heating. Mode 3 is the most reasonable in terms of a stopped and gradual motion of the vehicle. The process of engine heating with electrical consumers and climate control system switched on under operating conditions (mode 2) requires an additional research.

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