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Experimental studies of thermal preparation of internal combustion engine

N N Karnaukhov, Sh M Merdanov, Konev V V and D M Borodin

Industrial University of Tyumen, 38 Volodarskogo St., Tyumen, 625000, Russia

E-mail: karnauhovnn@tyuiu.ru, merdanovsm@tyuiu.ru, konevvv@tyuiu.ru

Abstract In conditions of autonomous functioning of road construction machines, it becomes necessary to use its internal sources. This can be done by using a heat recovery system of an internal combustion engine (ICE). For this purpose, it is proposed to use heat accumulators that accumulate heat of the internal combustion engine during the operation of the machine. Experimental studies have been carried out to evaluate the efficiency of using the proposed pre-start thermal preparation system, which combines a regular system based on liquid diesel fuel heaters and an ICE heat recovery system. As a result, the stages of operation of the preheating thermal preparation system, mathematical models and the dependence of the temperature change of the antifreeze at the exit from the internal combustion engine on the warm-up time are determined.

1. Introduction

The practice of operating the construction and road machines in the North shows that their potential for productivity, reliability, serviceability and other indicators is not fully realized [1,2,3,4].

One of the main problems of efficient operation of road construction machines in the conditions of the Russian North is to ensure the thermal state - pre-start thermal preparation of the internal combustion engine (ICE). Pre-heating of the internal combustion engine can reduce its starting wear, fuel consumption, toxicity of exhaust gases; increase the service life of the starter and battery. At the same time, it must be taken into account that the equipment is operated autonomously away from bases in the field. This makes it difficult or completely excludes the possibility of using traditional pre-start thermal preparation systems (PTPS) of ICE. Therefore, there is a need to use autonomous heat sources [5,6,7].

Rational use of fuel and energy resources can be achieved through the utilization of heat during the operation of internal combustion engines.

One of the solutions to the problem of pre-start heat preparation is the provision of mobile equipment with heat recovery systems (HRS) using heat accumulators (HA). This makes it possible to provide the need for additional heat energy necessary for pre-start thermal preparation of the ICE by using heat that is lost in the surrounding space during the operation of the machine (about 40% of the thermal energy is transferred to the cooling liquid during operation of the internal combustion engine, and up to 25% of heat is lost with exhaust gases) [1,2].

In accordance with the foregoing, the purpose of the work is to increase the efficiency of the pre-start heating of the ICE of road construction machines operated in conditions of temperatures below freezing.

Theoretical research has shown that it is advisable to combine the existing systems of thermal preparation of the machines of "Cold execution" and the heat recovery system based on thermal accumulators of different potentials [8,9]. As a result, the system of pre-start thermal preparation (PTPS) of the internal combustion engine was developed [10, 11].

At the same time, it is necessary to determine by experimental studies the stages of application of the liquid diesel preheater (LDP) and HRS by the temperature limits.

2. General methods of experimental studies

The aim of the experimental studies was to test the hypotheses put forward in theoretical studies and to determine the numerical values of the parameters of mathematical models.

During the experiment, the following tasks were solved:

1. To check the form of the mathematical model and its parameters, describing the dependence of the heating of the internal combustion engine from the developed pre-start system.

2. To compare the heating time with the help of LDP-44 and the developed PTPS at different stages of its operation at various ambient temperatures (-15 ^{0}C,-30 ^{0}C,-40 ^{0}C).

To solve the problems, an experimental setup was designed and built, containing a HRS and from LDP-44. The diagram of the system for pre-start thermal preparation of the ICE is shown in Fig. 1.

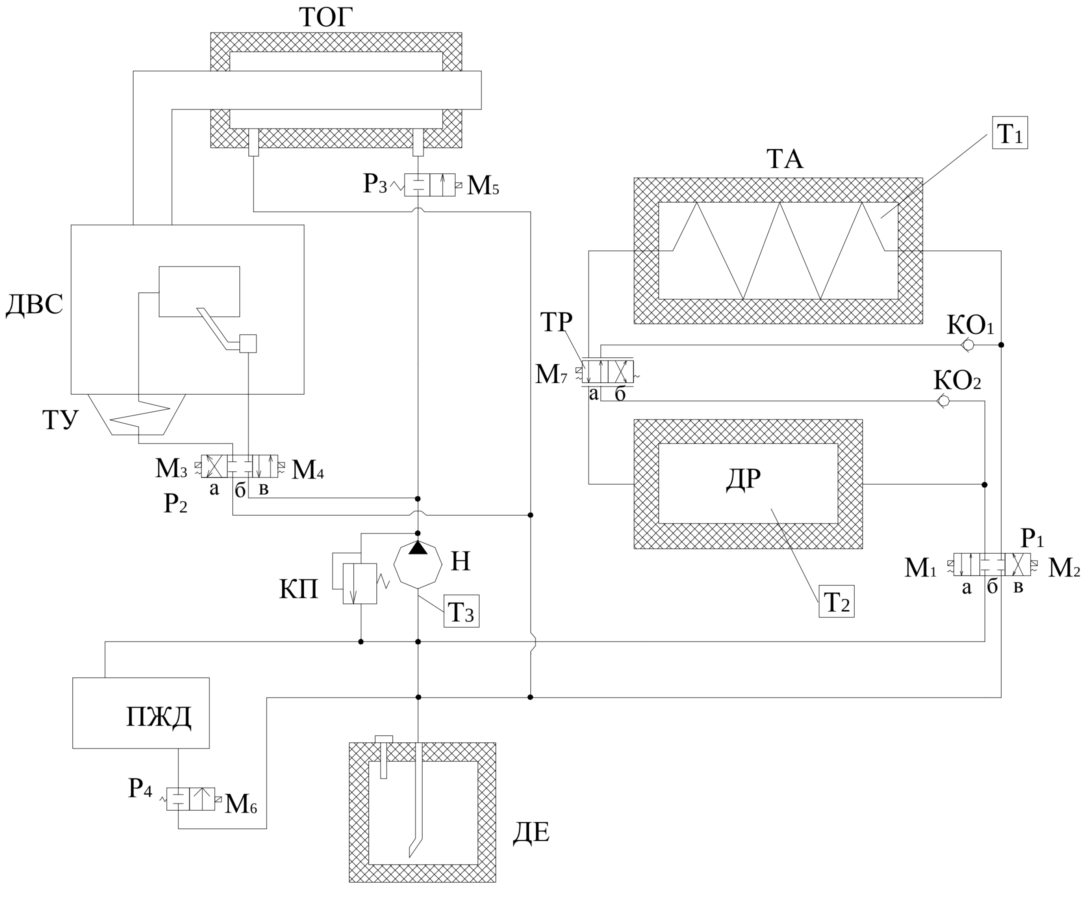

Figure 1. A scheme of the system of pre-start thermal preparation of ICE: ДВС (ICE) - internal combustion engine, ДЕ(AT) - additional tank, ДР (AR) - additional reservoir, ТА (HA) - heat accumulator, LDP)- liquid diesel preheater, ТОГ (EGHE) - exhaust gas heat exchanger, ТУ (HE) - heat exchanger, P_1-P_3 – distributor, ТР (TR) - thermoregulator, Н – pump, КП – bypass valve, T_1-T_3 – temperature sensors, M_1-M_7- pressure sensors

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3. Devices and equipment

To measure the temperature on the street, a liquid thermometer with a measurement range from -50°C to +50°C, an accuracy class of 1.0 and a division rate of 1°C was used. A systematic error over the whole measurement range is:

$$(50-(-50)) \times 1{,}0/100 = 1\ {}^{0}\mathrm{C}. \quad (1)$$

The temperature inside the tank was measured by a digital multimeter, working with a thermocouple of "K" type. The measurement error from -20 to +250 ^{0}C is not more than ±3 ^{0}C. In order to reduce the error in measuring the temperature with a multimeter with a thermocouple, they were subjected to a control test and selection, which made it possible to increase the accuracy of the temperature measurement up to ± 1 ^{0}C. This is determined by comparing the thermocouple readings with the reference thermometer. Multimeters with thermocouple of type "K" have high reliability in operation and allow one to observe the temperature changes visually, directly during the experiment.

Cooling chamber - Refrigerant: R134A, EK35BASIC DK 9620. Characteristics: minimum temperature is (-40 ^{0}C), volume-1m^3.

A manometer with a single-turn tubular spring was used to measure the pressure. The accuracy class is 2.5; the measurement range is from 0 to 10 kgf/cm^2. A systematic error is: (10-0)·2,5/100= 0,25 (kgf/cm^2). Thus, the systematic (instrumental) error is within the permissible deviation when monitoring the pressure in the line.

The LDP-44 pump with mass flow - G_a = 0,2…0,3 kg/s was chosen from the condition of optimal circulation of the coolant, which is justified in the work [5].

4. Description of the experimental unit

To test mathematical models, evaluate their adequacy and also to compare the heating time of the ICE A-01M from LDP-44 and the developed PTPS at various stages of its operation, active experiments were conducted. Preliminary experiments have shown that the prevailing error is a systematic one. Therefore, 3 parallel experiments at a point can be considered sufficient [12,13].

A pilot plant for pre-start heat preparation of the A-01M diesel engine was developed and manufactured. The pilot system was placed on a turntable next to the counterweight of the excavator, and next to the regular pre-heater LDP-44, making up one system (Fig. 2). Experimental studies were carried out on the street by selecting for the experiment the periods of the year with justified maximum and minimum ambient air temperatures [1,5]. Analysis of the methods of pre-start thermal preparation showed that the boiler of a LDP-type preheater is the closest in terms of indicators in accordance with the basic requirements for operation. This made it possible to propose the use of LDP-44 in conjunction with the HRS, and to compare the rate of ICE heating from the developed PTPS and LDP-44.

Figure 2. Pilot plant

The PTPS was developed, which was built with reference to the A-01M engine of the EO-4121 single-bucket excavator. Tests of a standard sample of such system have shown that it is possible to heat the A-01M engine for 25...30 minutes, after which it is launched at the first attempt. Unlike systems with standard preheaters like LDP-44, in the pilot system, oil in the diesel crankcase is heated by a tubular radiator [1], structurally installed at the entrance to the "jacket" of the internal combustion engine. As a heat transfer fluid, grade 65-antifreeze is used. The tests were carried out using a single-bucket excavator EO-4121.

The diagram of the pilot unit (Fig. 3) contains: A-01M internal combustion engine in modular construction (1). Heat accumulators with different thermal potentials are made in three versions: additional tank (AT) (2), additional reservoir (AR) (3), thermal battery (TB) (4) and LDP-44 (5). All heat accumulators are insulated (as a heat insulator, foam was used over the asbestos sheet). AT (2) with a capacity of 40 liters, AR (3) with a capacity of 50 liters and TB (4) with a capacity of 70 liters. Electric heaters with a capacity of 6 kW are built into AT and TB, in addition, the following things are built in the TB: a water-antifreeze heat exchanger, reverse and safety valves (4); heat transfer device (TU) (6) for heating the diesel oil in the form of a tubular coil; pump unit (7) with a direct current motor; pipelines connecting DE-AT (2), DR-AR (3), TA-TB (4), pump unit (7); TU-HU (6) and the cooling system of the starting motor (8); valves (9,10,11,12,13,14,15,16) - to disconnect the heat accumulators DR-AR (3) and TA-TB (4) from the system and to regulate the inlet temperature of the coolant in the heated ICE. The temperatures of heat accumulators and antifreeze at the inlet and outlet of the ICE were measured by multimeters with thermocouples built into the pipeline. The liquid pressure in the line was fixed by the MP4-U manometer, and the time - by a stopwatch.

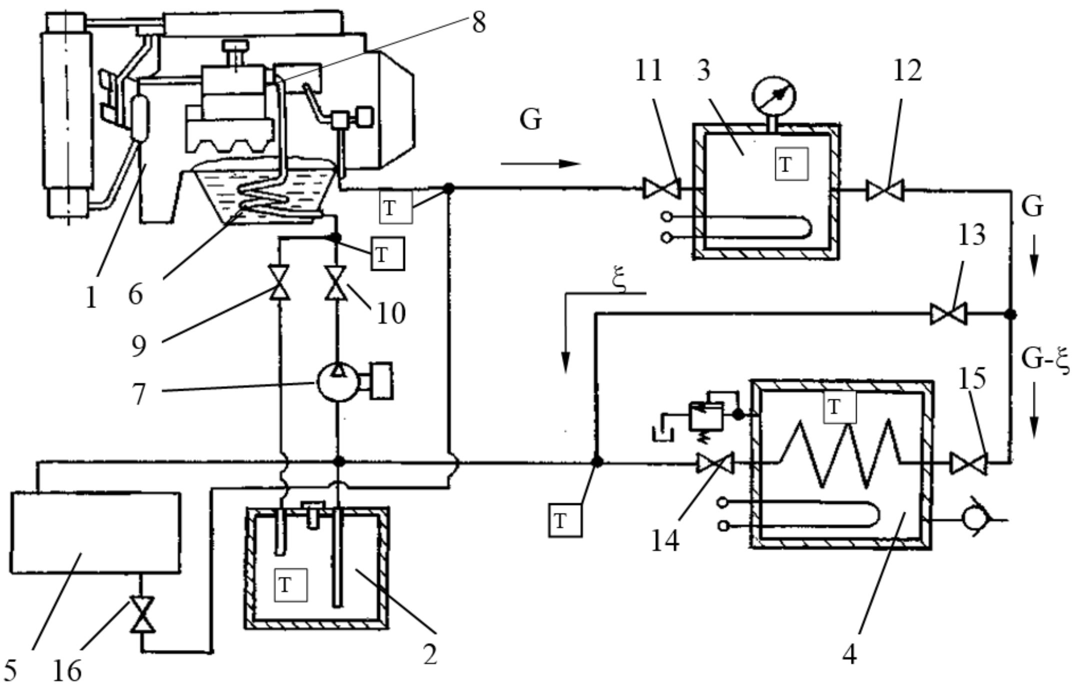

Figure 3. The scheme of the pilot unit

Lubrication and power supply systems for ICE are refueled, in accordance with the instruction manual for the ICE A-01M, with oil M-8G and diesel fuel of grade "3".

The completion of the heating process and the possibility of launching the ICE into operation is determined by the temperature of the antifreeze at the outlet of the ICE [1, 5], as noted in the work of other researchers and confirmed by experimental data on the heating of the ICE with the experimental PTPS.

The operating principle of the pilot unit is as follows (see Fig. 3). Initially, the antifreeze is drained from the "jacket" of the engine in the AT (2) through the valve (9), then the ICE cools to ambient temperature, the valves are closed. At the end of this process, electric heaters are turned on; antifreeze in AR (3) and water in TB (4) are heated to the set temperatures.

Three stages of heating the internal combustion engine were studied. At the first stage, the engine was heated from AT (2). The valve (10) is opened and the electric motor of the pump unit (7) is activated, by means of which the coolant in the AT (2), through the tubular heater (6), and the cooling system of the starting motor (8), is pumped into the "jacket" of the internal combustion engine (1).

In the second stage, the valves (11, 12) are opened on the AR and the electric motor of the pump unit (7) is activated, which ensures the circulation of the heat carrier through the ICE (1) and simultaneous flow of the heat transfer from the two heat accumulators AR (3) and TB (4) while maintaining the inlet temperature coolant +110 ^{0}C in the ICE (1) with the help of valves (13, 14, 15) [10,11,14]. The experiments were stopped when the temperatures were equalized in the heat accumulators and at the exit from the ICE. In this case, the measurement error was ±2 ^{0}C. A low error in measuring the temperature of heat accumulators is due to the high thermal conductivity of the steel and the made blind holes in the metal wall where the thermocouples were placed.

At the third stage, the A-01M engine was heated from LDP-44 (5) with the valves opened (16) and closed (9,11,12,13,14,15).

At all stages of the work of the PTPS with the HRS and LDP, the heating time of the engine was measured. The temperature changes in the heat accumulators and in the internal combustion engine were fixed in every 30 seconds at the first stage. At the second and third stages of heating the engine - every minute.

The ICE start after effective heating is carried out in accordance with the operating instructions by the operator in the excavator's cab. The idling work of ICE continued during the testing lasts no more than 15 minutes.

5. The results of the experiment, their processing and evaluation

Tests of the pilot pre-start heating system of the A-01M engine in the range of negative temperatures (from -40 ^{0}C to -15 ^{0}C) have shown its efficiency. The system in this range of negative ambient temperature has always ensured a qualitative heating of the ICE when it is subsequently launched at the first attempt.

The tables show the temperature change of the antifreeze in the A-01M ICE in the first stage of the PTPS (AT) operation and in comparison with the preheating from the LDP-44 (Table 1), at the second stage of the PTPS (AT + TAU) - (Table 2), at the third stage of work of PTPS (AT + TAU + LDP) - (see Table 3).

Table 1. Change in the temperature of antifreeze in the A-01M engine at the first stage of the PTPS (AT) operation and comparison with the LDP-44

at 263K	of PTPS						of LDP-44					
Time (min.)	Temperature at input (K)			Temperature at output (K)			Temperature at input (K)			Temperature at output (K)		
0	349	350	349				262	262	263			
0,6	353	352	351				273	272	273			
1,3	351	351	351	262	263	262	280	281	280	271	273	272
2,2	352	351	352	266	267	267	285	286	286	280	279	279

Table 2. Change in the temperature of the antifreeze in the A-01M engine at the second stage of the PTPS (AT + TAU) operation and comparison with the LDP-44

at 243K	of PTPS						of LDP-44					
Time (min.)	Temperature at input (K)			Temperature at output (K)			Temperature at input (K)			Temperature at output (K)		
0	349	349	350				242	243	243			

0,5	353	352	353				254	255	254			
1,3	351	352	351	245	246	245	269	270	270			
2,1	352	352	352	246	247	247	279	278	280	270	272	271
3	359	360	359	292	293	291	297	296	297	279	281	280
4	374	375	375	310	312	311	310	311	312	294	295	293
5	377	377	378	322	322	323	318	319	317	304	303	305
6	376	376	377	331	330	332	322	321	323	310	312	311
7	377	377	376	337	338	337	327	325	326	312	313	314
8	375	379	374	343	344	343	334	335	334	317	316	316
9	374	374	374	347	349	348	340	342	341	318	318	318
10	372	372	373	351	351	352	344	346	345	322	321	323
11	371	371	372	354	355	354	342	344	343	328	328	329
12	368	369	368	356	356	355	346	345	347	333	334	335
13	367	367	366	358	357	356	352	350	351	335	336	337
14							356	354	355	341	340	342

Table 3. Change in the temperature of antifreeze in the A-01M ICE at the third stage of the PTPS (AT+ TAU + LDP) and comparison with LDP-44

at 233K	of PTPS						of LDP -44					
Time (min.)	Temperature at input (K)			Temperature at output (K)			Temperature at input (K)			Temperature at output (K)		
0	233	234	233				234	233	233			
0,5	235	236	234				249	250	251			
1,3	235	235	235	237	235	235	267	268	267			
2,1	236	237	238	238	236	237	276	276	275	271	271	270
3	376	378	377	268	269	269	296	298	297	279	279	280
4	375	376	376	281	280	282	307	306	308	294	296	295
5	375	377	375	297	298	296	319	320	319	305	304	304
6	373	373	373	306	307	308	321	323	322	310	311	311
7	361	363	362	314	315	315	325	326	326	315	314	313
8	357	355	356	320	320	319	333	332	333	315	316	315
9	350	349	348	324	323	322	338	339	339	319	320	319
10	352	351	350	326	325	326	341	342	341	323	323	324
11	350	349	348	330	331	330	343	344	344	325	327	326
12	350	350	351	339	340	347	346	346	345	335	334	334
13	353	352	352	346	345	350	349	350	349	340	340	339
14	358	359	357	346	345	345	351	352	352	342	341	341
16	360	361	361	344	346	346	353	352	353	343	343	342
17	369	371	370	346	348	347	354	353	354	343	344	343
18	373	375	373	352	352	353	356	355	354	342	347	342
19	377	376	377	357	358	357	359	356	355	344	349	344
20	378	379	378	365	367	366	362	360	361	353	354	353
21	379	379	379	366	368	367	368	369	370	359	358	359
22							372	373	371	364	363	364
23							376	375	374	367	368	367

24	377	379	378	368	369	368
25	382	380	381	368	368	367
26	380	379	381	369	368	368

Based on the correlation-regression analysis of the experimental results, one-factor models of the antifreeze heating at the output of the ICE were obtained:

for the second stage: $$T = 336.37-310.78e^{-\tau}; \quad (2)$$

for the third stage: $$T = 329.12-439.34e^{-\tau}, \quad (3)$$

where, T- antifreeze temperature at the output of the ICE; τ- heating time.

Numerical values of the basic statistical characteristics of models, determined on the basis of experiments. The values of Fisher's dispersion ratio were 2.17-2.9. These values are greater than the table values of the F-criterion for the confidence probability of 0.9, which indicates sufficient adequacy of single-factor models for heating the antifreeze at the output of the internal combustion engine based on the results of the experiment. The average approximation error is within acceptable limits (5-7 %) [12,15].

Based on the calculation results and the experimental data, the graphs are constructed shown in Fig. 4. When heating from the AT (the first stage), the temperature of the A-01M engine rises slightly (on average - 4 ^{0}C); however, no additional energy is required to raise the temperature of the antifreeze in the "jacket" of the internal combustion engine.

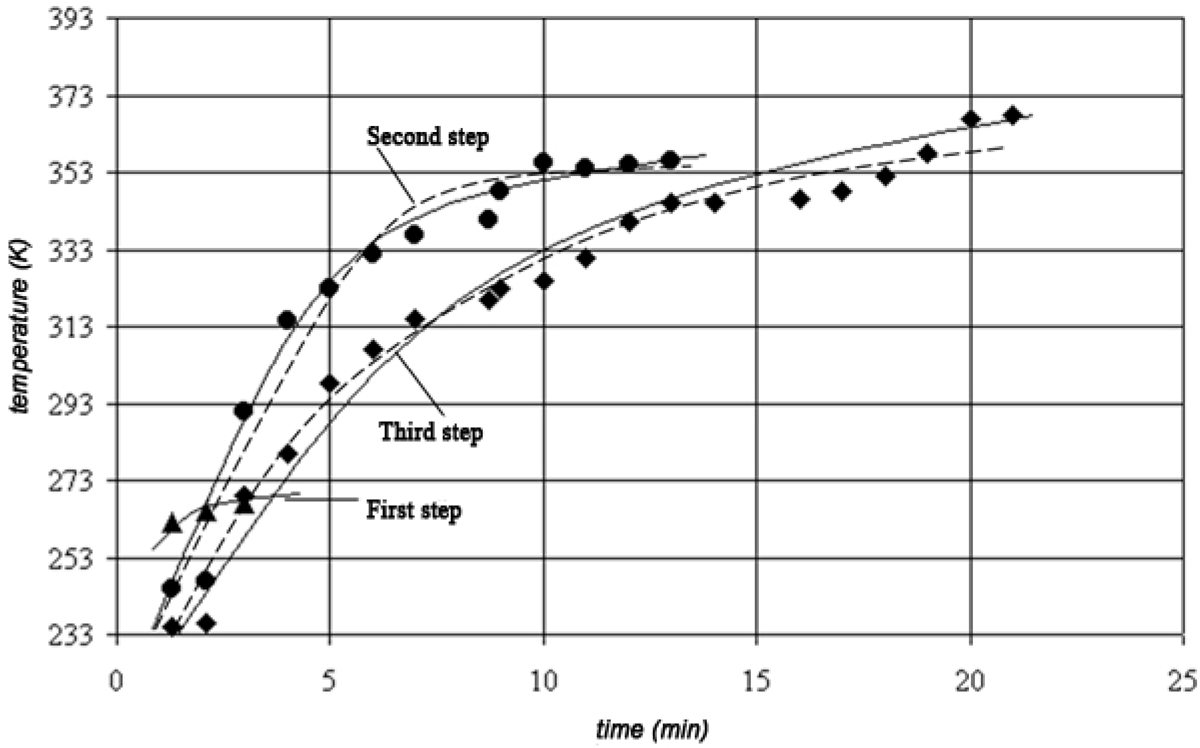

Figure 4. Dynamics of heating the antifreeze at the output of the A-01M engine:
●, ♦, ▲ - the results of the experiment; --- - calculation results

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The results of the experiments were processed using Microsoft Excel, Regress software packages [15].

From the analysis of the graphs, it can be seen that the heat transfer processes during the heating of the internal combustion engine are qualitatively consistent with the calculated data, which indicates the correctness of the theoretical premises for the representation of these processes. However, the available quantitative discrepancies show that the heat transfer from the antifreeze to the massif of the internal combustion engine parts proceeds somewhat more intensively than it does in the simulation model of the diesel engine. This indicates a high efficiency of heat transfer from the antifreeze to the ICE in its course in the aisle space and inaccuracies of the model. In the middle of the stages, the errors reached 8 ... 12%, which is explained by inaccuracies in the accepted models of the heat transfer process and the inertia of the heat transfer process during the ICE heating. However, inaccuracies in the model make it possible to obtain results within acceptable limits and do not lead to appreciable errors in determining the temperature of the internal combustion engine (Fig. 4).

It is also established that as a result of the specificity of the heat transfer processes in the internal combustion engine, the equalization of the thermal fields in it proceeds more intensively than it does with the LDP-44. In the initial periods of ICE warming from the pilot system, the heat flow reached 35-45 kW, while for the regular system it did not exceed 20 kW.

6. Conclusion

As a result of the study, the following conclusions were obtained:

- good convergence of analytical studies and experimental data in the process of heating the A-01M ICE has been obtained. The temperatures of the antifreeze at the input and output of the ICE vary exponentially;
- It is determined that when the internal combustion engine is heated by the developed PTPS, the temperature of the antifreeze at the ICE output increases faster than the preheating from the regular LDP-44 system. The heating time of the engine A-01M at an air temperature of -40 °C is 21 minutes and 26 minutes, respectively.

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