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Thermal Regime of Automobile Exhaust System at Low Temperature

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ABSTRACT

Currently operation of cars in large cities in winter is the most unfavorable from the point of view of the risk of blocking the exhaust system by condensate accumulated in it. Frequent starts during relatively short period of time, or the cycle of start-up – short run – and subsequent long-term parking at low temperatures are dangerous because the exhaust system does not have time to warm up and remove the accumulated condensate. Daily operation in such modes contributes to rapid accumulation of condensate, and subsequent long-term parking at ambient temperatures below 0˚C are equally dangerous because, depending on the design features of the exhaust system elements, condensation may occur and freeze in the exhaust system, icing can occur inside it or at its exit, causing inability to start the engine.

Given that most of the territory of Russia is located in the areas of moderate and cold climate, the relevance of studies, aimed at identifying the patterns of condensate formation and accumulation in the exhaust system, at adjusting on this basis the frequency of condensate removal from the exhaust system, as well as at optimizing the design parameters of the exhaust systems, is quite evident.

The objectives of this study were: to identify the features of changes in temperature of the elements of the exhaust system when the automobile engine warms up at low ambient temperature, the effect of various modes of the heater operation on the temperature of the elements of the exhaust system, as well as the features of the temperature change of individual elements of the exhaust system depending on time for various ambient temperatures.

To achieve those objectives a series of experiments has been conducted to study the process of starting the «cold» engine, and of its warming up in idle mode.

The found dependencies can be used to develop methodology to adjust the recommended periodicity of warming up of the exhaust system, as well as a model of a device that will ensure the absence of condensate in exhaust systems during the operation of cars in large cities during winter period.

Keywords: *car, automobile, exhaust gases, exhaust system, thermal regime, condensate, winter period.*

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Introduction. In a modern metropolis, car operation is characterized by frequent short trips, prolonged downtime in traffic jams, prolonged engine idling, etc. Practices show that at low ambient temperatures, continuous operation of an automobile engine under such conditions does not provide sufficient heating of either the engine itself or of the elements and components of the exhaust system. The engine is considered fully warmed up when the temperature of all its elements and working fluids enters the operating mode, that is, during stationary operation of the engine, the temperatures ceases to change. Warming up of coolant and parts of the upper part of the engine is the quickest. Oil in the oil pan heats up much more slowly. Even after the coolant reaches operating temperature, the engine oil temperature does not reach the operating temperature. The same situation is observed in the catalytic converter. As a result, the process of reaching the required level of exhaust emissions is slowed down. The catalytic converter is heated by the flow of exhaust gases, and the greater are their flow rate and temperature, faster it is heated. However, at negative ambient temperatures, at idle mode, the catalytic converter does not enter the operating mode.

During wintertime operation, the walls of the exhaust system remain cold, and water vapor moving along the exhaust system along with hot exhaust gases condenses on a cold surface inside this system [1–3]. As a result, during prolonged operation of the engine at low speeds, condensate accumulation is observed in the exhaust system of the car [4, p. 51].

Frequent starts of the car engine for relatively short periods of time, warming up the car in winter conditions through remote starting, driving in short-run mode and subsequent long-term parking at air temperatures below 0˚C are dangerous because condensation can appear and freeze in the exhaust system. A formation of an ice plug inside it or at its outlet is also possible, causing inability to start the engine [5, p. 10; 6, p. 3].

The influence of various combinations of climatic conditions and operating intensity on accumulation of condensate in the exhaust system has not been enough studied. This issue misses due attention in car manuals. In this regard, it is necessary to study the described phenomenon and to develop, on the basis of research, recommendations for maintaining operability of the exhaust system in a state that ensures reliable engine start and proper operation of the vehicle during low temperatures period.

Objectives of the study were:

1) to identify factors affecting the temperature of the elements of the exhaust system of a passenger car in winter;

2) to establish the laws of influence of various ambient temperatures on the heating temperature of the surface of the exhaust system;

3) to establish the patterns of influence of various modes of operation of the heater of a passenger compartment on the temperature of the heating of the surface of the exhaust system.

Methods. A series of experiments has been conducted to study the process of starting of a «cold» engine, and of its consequent warming up at the idle mode for 30 minutes. Simultaneously with the engine starting, the temperature of the elements of the exhaust system was recorded. To measure the surface temperature of the exhaust system, the contact method of measurement using thermocouples was used.

Results.

Physical conditions for condensation

Condensate is formed upon contact of hot exhaust gases [7–9] moving in the exhaust system with the walls of this system having a temperature close to the temperature of the ambient air. The exhaust gases contain water in the vapor state that is formed during combustion of fuel (more than 1,2 kg per 1 kg of burnt fuel [10, p. 66]). Besides, water vapor enters the engine with air from the atmosphere (up to 0,38 kg per 1 kg of burnt fuel, depending on the ambient temperature [11, p. 83]).

The work [8, p. 99] showed the dependence of the amount of water in the exhaust gases on the composition of the fuel-air mixture used. So, with an exhaust gas pressure of 1 bar under stoichiometric conditions, the proportion of water vapor in the exhaust gases is 13 %, and water condensation occurs at a temperature close to 52°C. In a mixture that contains twice as much air than it is necessary for burning fuel, that is, with an excess air coefficient of two, concentration of water vapor reaches 6 %, while the dew point drops to 36°C. The highest dew point temperatures correspond to stoichiometric conditions when there is no excess air, or when there is an excess of fuel, as a result of which there is no depletion of the fuel mixture.

When the exhaust gas is cooled, the excess water present is deposited on the relatively cold walls of the exhaust system and accumulates in the system.

Obviously, condensate does not accumulate if the walls of the exhaust system are heated to temperatures at which water vapor in contact with the walls of the exhaust system does not cool to the dew point temperature. Accordingly, moisture does not condense on the walls of the exhaust system. The required heating is achieved when the car engine is running under a sufficient load, accompanied by evaporation of the formed condensate and emission of exhaust gases containing water in a vapor state from the exhaust system, i.e. when traveling for long distances or when driving in high-speed sections.

The experimental stage of the study

Since the main reason for formation of condensate inside the exhaust system is the temperature difference between the exhaust gases and the walls of the exhaust ducts, the authors have conducted a series of experiments to determine the temperature of the elements of the exhaust duct system during engine warm-up when it is idling.

The temperature of the elements of the exhaust system was measured using special equipment [12, p. 7]:

- an analogue input module OWEN MV110-8A, designed to read and convert an electrical signal from temperature sensors to degrees Celsius;
- an automatic converter of USB/RS-485 OWEN AS4 interfaces, which communicates between OWEN MB 110-8A input module and a personal computer used to collect, store, convert, display experimental research results;
- thermocouple with an operating temperature range from -50 to +500°C used to measure the temperature of the elements of the exhaust system;
- SCADA OwenProcessManager (OPM) software that performs real-time data exchange with OWEN devices connected via OWEN AS4 interface converters.

In the process of experimental research, the influence of the main factors on the temperature of the elements of a passenger car exhaust system in winter was studied. The studied factors were:

- ambient temperature in the range from -23°C to +9°C;
- frequency of rotation of the crankshaft in idle start-up and warm-up modes in the range from 750 to 1500 rpm;
- operation mode of the fan of the heater of the passenger compartment of the car in the range from the inoperative state to the maximum rotation speed.

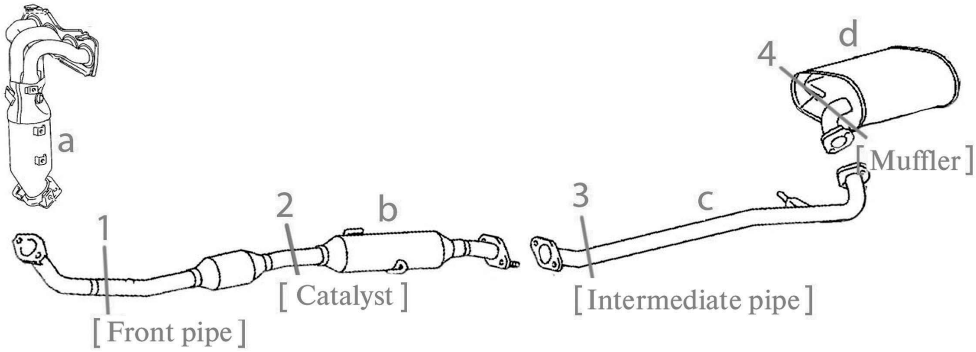
The sequence of the experimental study consisted in starting a «cold» engine, the temperature of which (like the temperature of the exhaust system) is equal to the temperature of the ambient air, and in operating the engine in the idle mode for 30 minutes. Simultaneously with the engine starting, the temperature of the elements of the exhaust system was recorded. The experience of the practical operation of the car shows that in most cases this time is enough to warm the engine to operating temperature.

From the analysis of the results of the considered works, it follows that the most acceptable measurement method is the contact measurement method using thermocouples and resistance thermometers. Thermocouples were used to measure the surface temperature of the exhaust system.

Thermocouple readings were recorded at various ambient temperatures and various modes of operation of the interior heater.

To reduce the influence of secondary factors on the heating/cooling process of passenger car elements, experiments were carried out in a territory protected from the wind. Before the start of the measurements, the temperature of the exhaust system and other parts of the car was equal to the ambient temperature, to obtain those conditions the vehicle had been kept at the site for at least eight hours before the measurements.

An experimental study was carried out for elements of the exhaust system of the exhaust



Pic. 1. Installation points of thermocouples on the surface of the exhaust system: 1 – front pipe; 2 – catalyst; 3 – intermediate pipe; 4 – muffler.

system of a Toyota Camry car, consisting (Pic. 1) of an exhaust manifold (pos. a), which simultaneously serves as a preliminary catalytic converter; middle part of the exhaust system, consisting of lower catalyst and front muffler (pos. b); intermediate pipe (pos. c) and rear muffler (pos. d). Thermocouples 1–4 (Pic. 1) were installed on the outer surface of the elements of the exhaust system.

Table 1 shows the test conditions for measuring the temperature of the elements of the exhaust system. During experiments, the automatic operation of the heater (climate control) was turned off.

The results of measuring the temperature of the elements of the exhaust system depending on time and location of the thermocouples for some ambient temperatures are presented in Pic. 2.

The obtained measurement results show that at all negative ambient temperatures, the temperature distribution of various elements of the exhaust system is of the same type. At the first measurement point, there is an intense increase in temperature when the engine is warming up.

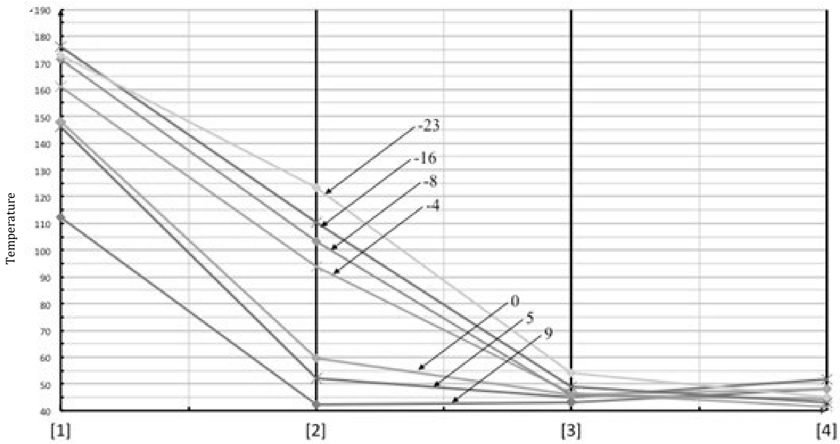
A gradual decrease in temperature is observed from location of the first thermocouple to the last one, which is consistent with the physical idea of cooling the exhaust gas as it moves from the exhaust manifold (outer wall temperature was of 115–175˚C depending on the external temperature) to the rear muffler (temperature was of 40–58˚C). At the end of the considered 30-minute period of time, there is a general slight decrease and equalization of the surface temperature of the exhaust system.

Table 1

Experimental conditions

No. test	Ambient temperature	Air humidity	Wind speed[1]	Heater mode[2]
1	+9˚C	36 %	3 m/s	1/7
2	+5˚C	40 %	1 m/s	1/7
3	0˚C	50 %	2 m/s	1/7
4	-4˚C	62 %	1 m/s	1/7
5	-8˚C	60 %	1 m/s	1/7
6	-16˚C	75 %	3 m/s	1/7
7	-23˚C	71 %	3 m/s	1/7

[1] It is indicative, since the experiments were conducted in a space protected from wind.
[2] 1/7 – first (minimum) of seven possible heater modes.



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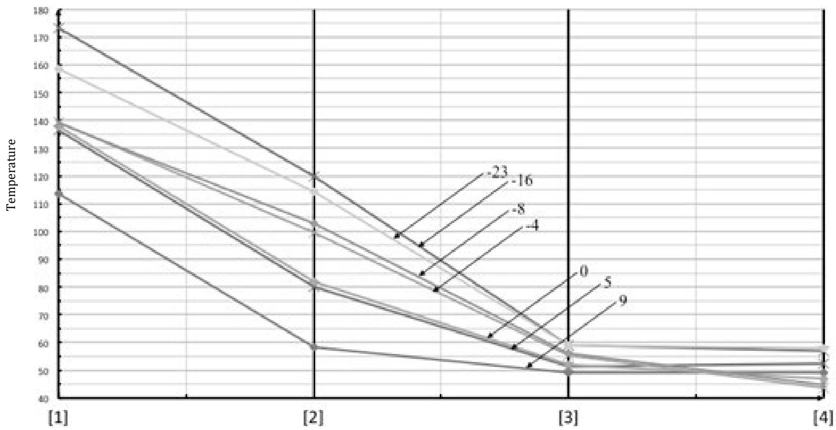

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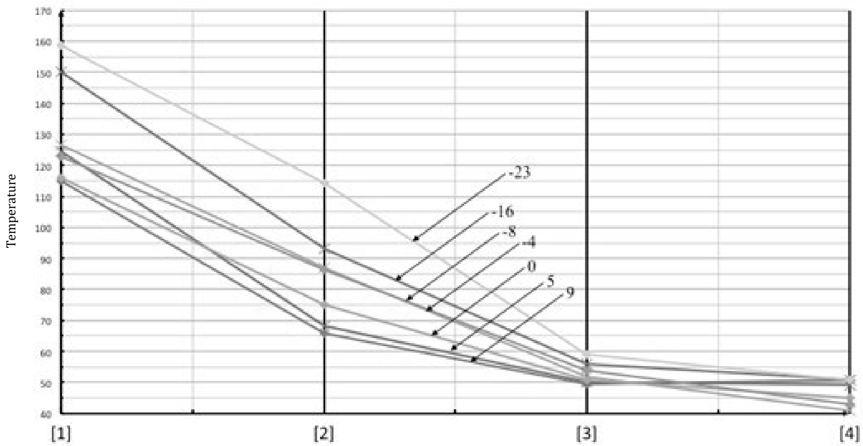

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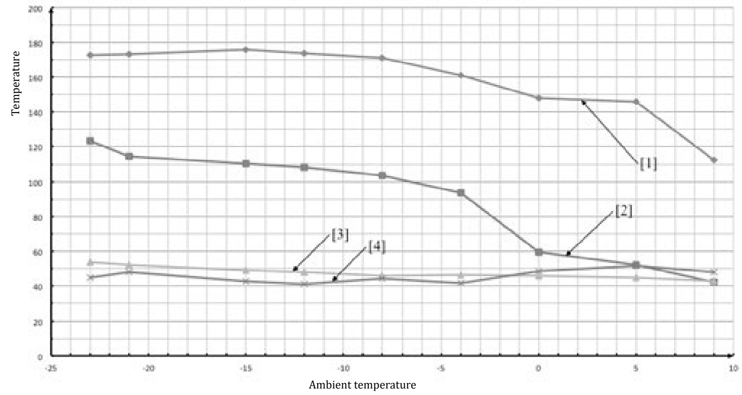
Pic. 2. The surface temperature of the exhaust system when the engine is idling; warm-up time: a – 10 minutes; b – 20 minutes; c – 30 minutes; the numbers above the curves indicate the ambient temperature; the square brackets indicate the position of the thermocouples according to the chart in Pic. 1.



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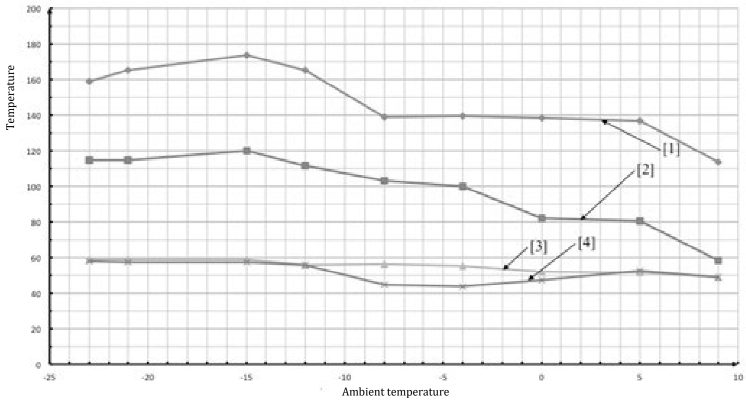

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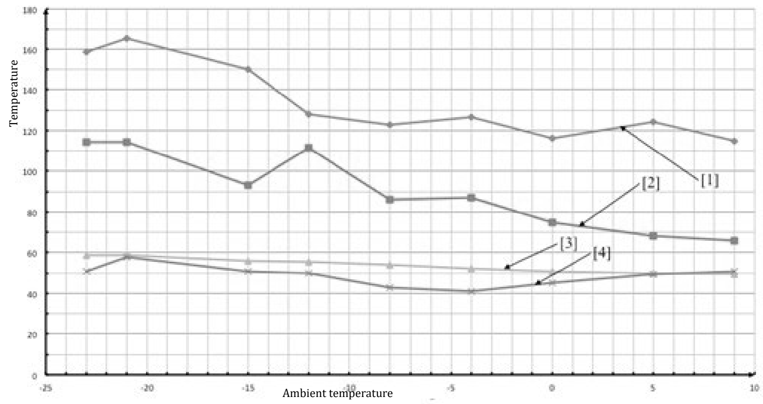


c)

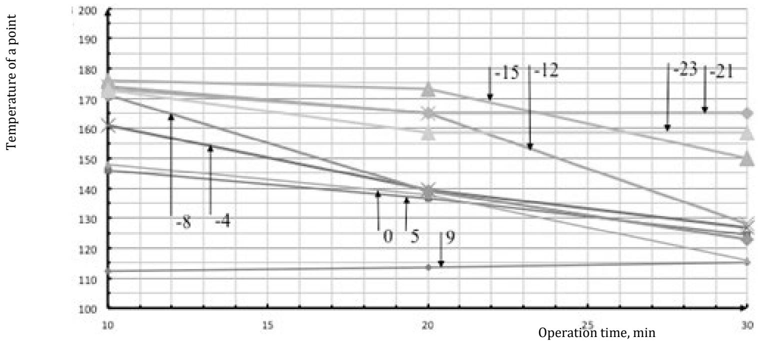
Pic. 3. The dependence of the surface temperature of the exhaust system on ambient temperature when the engine is idling; engine operating time: a – 10 minutes; b – 20 minutes; c – 30 minutes; the square brackets indicate the positions of thermocouples according to the chart in Pic. 1.

Some regularities of influence of ambient temperature on the heating temperature of the surface of the exhaust system are identified:

• the smallest heating of the walls of the exhaust system is observed at positive ambient temperatures;

• with a decrease in negative values of the ambient temperature, an increase in the surface temperature of the exhaust system is noted (Pic. 2, points 1, 2, 3).

The increase in the surface temperature of the exhaust system with a decrease in the negative ambient temperature is apparently



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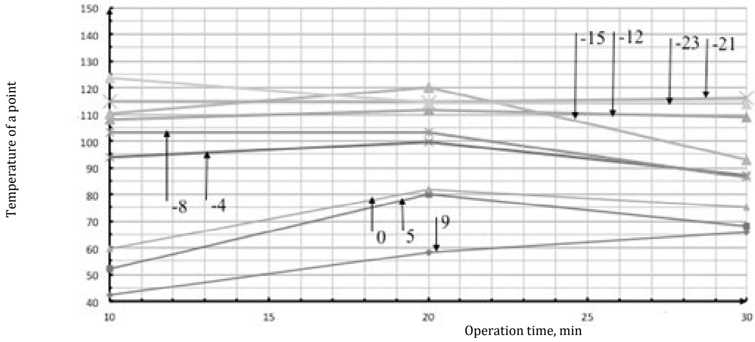

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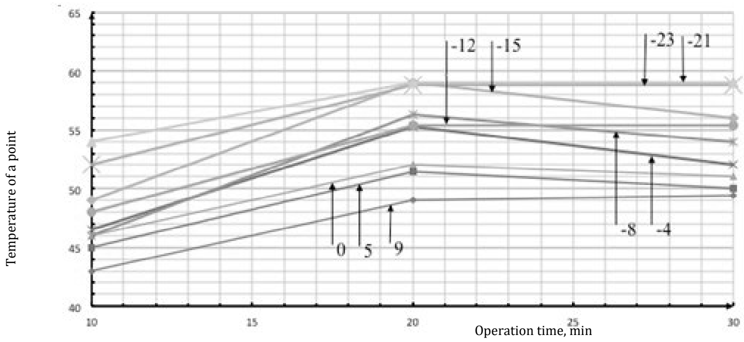

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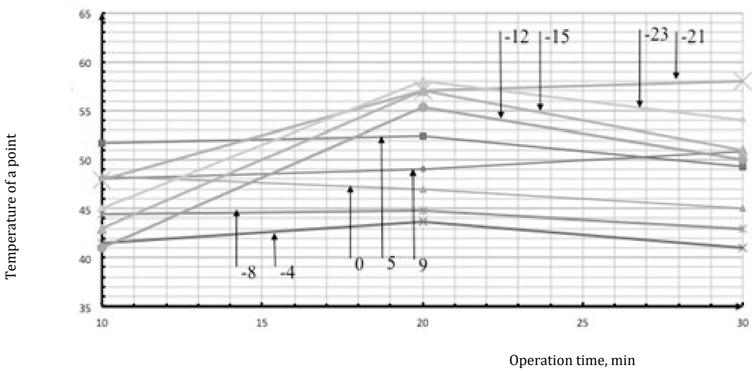
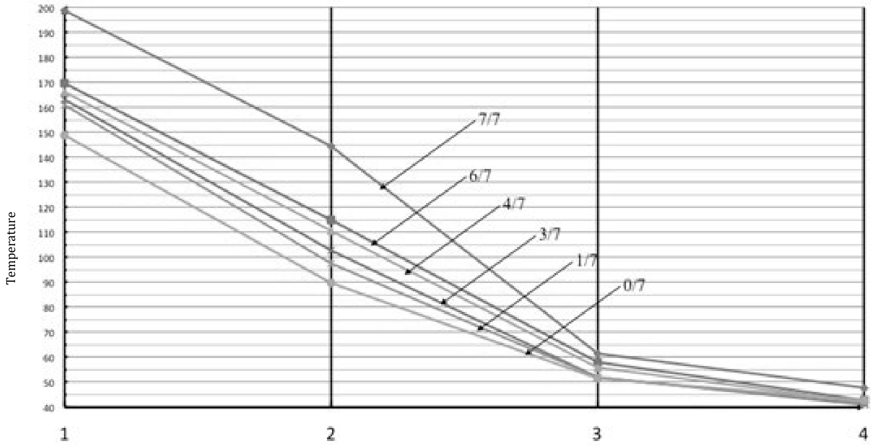


Pic. 4. Dependence of surface temperature of the elements of the exhaust system on time when the engine is idling; a – front pipe, b – catalyst, c – intermediate pipe, d – muffler.



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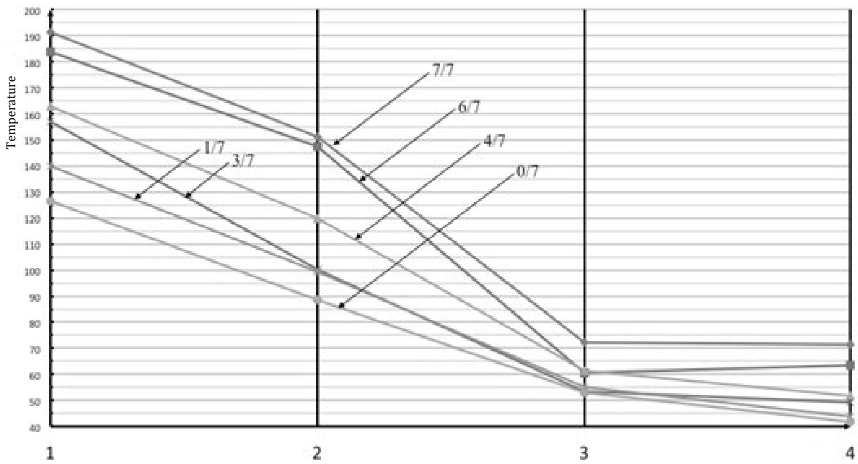

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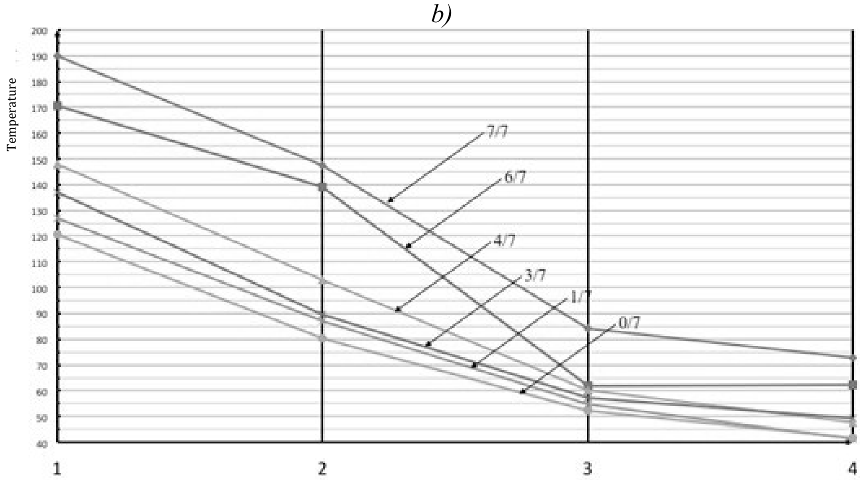

c)

Pic. 5. Dependence of the surface temperature of the elements of the exhaust system from the position of the thermocouple (numbers on the axis) and the operating modes of the heater; warm-up time: a – 10 minutes; b – 20 minutes; c – 30 minutes; fractions – operating modes of the interior heater (explanation in the text).

due to a later reaching by the engine of operating thermal mode: if, when starting the engine, the coolant has a lower temperature corresponding to the ambient temperature, then warming up the engine takes a longer time. Heating the coolant and the engine itself requires longer operation at an increased crankshaft speed than is required at higher ambient temperatures.

At increased engine speeds, a larger volume of hot exhaust gas passes through the car exhaust system, intensely heating the elements of the exhaust system, and this leads to a higher surface temperature of the exhaust system.

At the same time, as the ambient temperature decreases, the temperature at point 4 also decreases, and this may be due to the fact that the muffler of the exhaust system has a significant volume and slightly warms up at low temperatures during idle operation.

Pic. 3 presents data on dependence of the surface temperature of the exhaust system on ambient temperature at different time stages of the engine idling. From a comparison of the curves presented in this picture, it follows that:

• in the area of location of the first thermocouple (Pic. 3, curve 1), the exhaust system is heated to a temperature of 110–176°C, which ensures evaporation and removal of the previously accumulated condensate with the exhaust gas flow (surface temperature exceeds the boiling point of water) in the entire studied range of ambient temperature;

• in the area of location of the second thermocouple (Pic. 3, curve 2), the exhaust system is heated to a temperature of 92–122°C at negative air temperatures, and to 42–83°C at positive temperatures; in the latter case, the possibility of condensation and accumulation of moisture in the exhaust system remains, and this can lead to freezing of the accumulated condensate when the temperature drops to negative;

• in the area of location of the third and fourth thermocouples, the elements of the exhaust system warm up to a temperature not exceeding 60°C; in these areas, favorable conditions arise for formation and accumulation of condensate in the entire range of the considered ambient temperatures.

Pic. 4 shows the time dependence of the surface temperature of the exhaust system elements on which the thermocouples are installed, for various values of ambient temperature when the engine is idling:

• at ambient temperature of -4°C to -15°C, there are maxima in the heating temperature of the exhaust system elements during an unsteady engine operation mode (Pic. 4b, c, d) and a decrease in temperature of these elements by the end of the 30-minute period under considered period with further access to the stable thermal regime;

• at ambient temperature from -21°C to -23°C, the temperature of the surface of the exhaust system at the control points quickly reaches stable values and practically does not change during the considered period of time.

The influence of the operating modes of the passenger compartment heater on temperature of the elements of the exhaust system is shown in Pic. 5. Designation 7/7 corresponds to the maximum rotation speed of the fan blades; 0/7 indicates the fan is off. During the considered tests, air temperature was -8°C.

In the area where the first thermocouple is located, after 30 minutes (Pic. 5c), the temperature reaches 120°C with the heater turned off and 190°C with the heater operating mode 7/7; in the zone of location of the second thermocouple, respectively, 80°C and 147°C, in the zone of the third thermocouple, respectively, 52°C and 85°C under the indicated modes of heating the passenger compartment.

It is necessary to pay attention to the later exit of the engine to the operating mode and an increase in temperature of the elements of the exhaust system with an increase in the number of revolutions of the fan of the heater of the passenger compartment at constant ambient temperature. A longer exit of the engine to the operating thermal mode is explained by the fact that the circulating coolant, heating the air in the car interior, is itself cooled in the radiator of the heater, thereby slowing down the heating of the working engine.

In particular, with an increase in the speed of rotation of the fan of the passenger compartment heater, heat extraction from the coolant in the heater radiator occurs more intensively and, accordingly, the engine warms up even at higher idle speeds more slowly.

At the same time, at increased engine speeds over the same period of time, a larger volume of hot exhaust gases, intensively heating the elements of the exhaust system, passes through the exhaust system of the car, which leads to an increase in surface temperature of the elements of the exhaust system. Thus, the relationship of an increase in surface temperature of the elements of the exhaust system with an increase in the number of revolutions of the heater fan of the passenger compartment is fixed.

It should be noted that since an increase in speed of rotation of the fan of the heater of the passenger compartment leads to an increase in duration of warming up of the car engine to operating temperature, it is possible on modern cars to turn off the fan of the heater of the passenger compartment in the first minutes of starting the engine at lower ambient temperatures, contributing to a faster transition of the engine to working thermal mode.

The conducted experimental studies made it possible to additionally establish that:

• it takes 3 to 4 hours to cool the exhaust system to ambient temperature, depending on ambient temperature;

• at a negative ambient temperature, the rear muffler of the exhaust system of the car in question is not able to warm up when the engine is idling to a temperature of 100°C.

Conclusions. An experimental study was carried out to determine temperature of elements of the exhaust system at the stage of unsteady operation of a car engine at low temperatures. That study has shown that:

• lowering ambient temperature leads to a slowdown in heating of a car engine and, at the same time, to an increase in temperature of the exhaust system elements;

• increase in speed of the fan of the heater of the passenger compartment leads to a decrease in temperature of the coolant, helps to increase temperature of the elements of the exhaust system and, at the same time, increases the time the engine enters operating mode.

The value of the established patterns can be helpful for development of a methodology for adjusting frequency of heating of the exhaust system, the use of which will reduce costs of monitoring the technical condition of the exhaust system and the costs incurred in the event of an unsuccessful start of ICE in cold climatic conditions. Practical value can be also attributed to substantiation of development of a model of the device that will ensure the absence of condensate in the exhaust system when operating cars in large cities in winter.

REFERENCES

1. Silencers & pipes. [Electronic resource]: https://www.ernst-hagen.de/en/products/silencers-pipes/. Last accessed 18.03.2019.

2. Kuznetsov, N. I., Petukhov, M. Yu., Khaziev, A. A. Development of recommendations for operation of cars in a metropolis [*Razrabotka rekomendatsii po ekspluatatsii avtomobilei v usloviyakh megapolisa*]. *Problems of technical operation and car service of rolling stock of motor vehicles: proceedings of 72nd scientific methodological and scientific research conference MADI.* Moscow, MADI publ., 2014, pp. 227–233.

3. Kuznetsov, N. I., Petukhov, M. Yu., Shcheludyakov, A. M. On the features of starting a car engine in a modern metropolis at low ambient temperatures [*Ob osobennostyakh zapuska dvigatelya legkovogo avtomobilya v sovremennom megapolise pri nizkikh temperaturakh okruzhayushchei sredy*]. *Bulletin of PNIPU. Environmental protection, transport, life safety*, 2012, Iss. 1, pp. 137–143.

4. Kuznetsov, N. I., Petukhov, M. Yu., Khaziev, A. A., Laushkin, A. V. Problem of Accumulation and Freezing of Condensate in the Exhaust Gases of Cars at Low Temperatures. *Applied Mechanics and Materials*, June 2016, Vol. 838, pp. 47–55. [Electronic resource]: https://www.scientific.net/AMM.838.47. DOI: https://doi.org/10.4028/www.scientific.net/AMM.838.47.

5. Court decisions and regulations of the Russian Federation. Court decision No. 2–1747/2015 2–1747/2015~M-374/2015 M-374/2015 dated July 24, 2015 in case No. 2–1747/2015. [Electronic resource]: http://sudact.ru/regular/doc/UP2TFt0dJ9Vj/. Last accessed 18.03.2019.

6. Court decisions and regulations of the Russian Federation. Court decision of Kurchatovsky district court of Chelyabinsk, Case No. 2–6/11 dated April 13, 2011. [Electronic resource]: http://sudact.ru/regular/doc/p7OrtXeRoBdy/. Last accessed 18.03.2019.

7. Heil, B., Enderle, C., Herwig, H., Strohmer, E., Margadant, A., Ruth, W. The Exhaust System of the Mercedes SL500. *MTZ worldwide*, January 2002, Vol. 63, Iss. 1, pp. 2–5. [Electronic resource]: https://doi.org/10.1007/BF03227514. Last accessed 18.03.2019.

8. González, N. G. Condensation in Exhaust Gas Coolers. In: Junior, C., Jänsch, D., Dingel, O. (eds). Energy and Thermal Management, Air Conditioning, Waste Heat Recovery, ETA 2016, *Springer, Cham.*, 2017. [Electronic resource]: https://doi. org/10.1007/978-3-319-47196-9_9. Last accessed 18.03.2019.

9. Hashimoto, R., Mori, G., Yasir, M., Tröger, U., Wieser, H. Impact of Condensates Containing Chloride and Sulphate on the Corrosion in Automotive Exhaust Systems. *BHM Berg- und Hüttenmännische Monatshefte,* September 2013, Vol. 158, Iss. 9, pp. 377–383. *Springer-Verlag Wien.* [Electronic resource]: https://link.springer.com/article/10.1007/s00501-013-0180-6.

10. Laushkin, A. V., Khaziev, A. A. Reasons for flooding motor oil in operation [*Prichiny obvodneniya motornogo masla v ekspluatatsii*]. *Vestnik MADI*, 2012, Iss. 1, pp. 63–67.

11. Kuznetsov, N. I. Quantitative assessment of the content of water entering the engine with atmospheric air, in the exhaust gas [*Kolichestvennaya otsenka soderzhaniya v otrabotavshikh gazakh vody, postupayushchei v dvigatel s atmosfernym vozdukhom*]. *Bulletin of PNIPU. Transport. Transport facilities. Ecology*, 2017, Iss. 1, pp. 77–87. DOI: 10.15593/24111678/2017.01.06.

12. Boyarshinov, M. G., Lobov, N. V., Kuznetsov, N. I., Martemyanov, A. O. Temperature condition of the exhaust system of car's exhaust gases at low temperatures [*Temperaturniy rezhim sistemy vypuska otrabotannykh gazov avtomobilya v usloviyakh ponizhennykh temperatur*]. *Vestnik PNIPU. Transport. Transport facilities. Ecology*, 2018, Iss. 3, pp. 5–16. DOI: 10.15593/24111678/2018.03.01