ECOLOGY

In most cases, fixed temperature heat detectors are used to detect fire in vehicles. The response parameter of such detectors is constant. The time of fire detection by a fire detector, as well as the probability of its false operation, are affected by heat flux from an internal combustion engine. This paper reports the development and investigation of an operational algorithm of the fixed-dynamic heat detectors with variable response parameters. Depending on the temperature influence exerted by engine operation modes, a given algorithm automatically changes a value of the minimal static response temperature of a detector, as well as value of the rate of rise in the temperature of its response. The experimental results showed that in the initial period of engine operation, the temperature change rate in the engine compartment fluctuates and is the largest. It can exceed 290 °C/min. However, regardless of the type of vehicle and the type of engine, when the temperature reaches technological, the temperature change rate would vary within small limits, approximately 30÷50 °C/min. The study results from the Simulink software package (USA) in the MATLAB programming environment (USA) confirm the effectiveness of the programmed operational algorithm of a thermal fire detector. The developed algorithm of a fire detector's operation makes it possible to detect the fire at an early stage and reduce the cases of the device's false response. The fire detector responded to both the maximal and dynamic components. As regards the maximal component, the proposed detector is triggered about 2.3 times faster than the classic maximal thermal fire detector. Detection of fire at an early stage makes it possible to quickly use the fire extinguishing system

Keywords: vehicle fire detection system, heat detector, fire detector operational algorithm

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OPERATIONAL ALGORITHM FOR A HEAT DETECTOR USED IN MOTOR VEHICLES

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1. Introduction

The number of motor vehicles (MVs) in the world is growing every year. This is explained by the expansion of tourist, trade, and economic ties both within the country and between countries, by an increase in the needs of the population in cars, etc. It is obvious that such trends lead to an increase in vehicle fleets and, therefore, the related problems. MVs should provide for the safety of people who use them or participate in traffic. An important element of the overall safety of MVs is their fire safety.

MV-related fires lead to death and injury to people, as well as significant material losses. Every year there are more than 1 million fires of this kind in the world [1] that lead to the death of about 3 thousand people while material losses exceed USD 1 billion. A particular danger is caused by fires arising from road accidents [2], and in car tunnels [3], where the largest proportion of people die. According to the Institute for Public Administration and Research in the field of Civil Protection, 2020 witnessed 4,972 fires related to MVs, which resulted in the death of 12 people with 82 people injured. Direct material losses alone exceeded UAH 400 million. The analysis of statistics reveals a tendency to increase the number of MV fires, which leads to an increase in material losses and human casualties around the world.

The magnitude of the consequences of fires (death and injury of people, the amount of material damage) is influenced by the effectiveness of the fire detection and extinguishing system. Equipping MVs of any category with systems for detecting and extinguishing fire significantly improves the fire protection of MVs.

In some countries, legislative acts have been developed and implemented that regulate the equipment of MVs with automatic fire detection and extinguishing systems. In the territory of the European Union, this is Regulation No. 107 of the United Nations' European Economic Board (UN EEB) "Unified provisions on the approval of vehicles of category M2 or M3 regarding their overall structure (2018/237)". In Sweden, these are instructions SBF 128:1 on equipment for fire detection and extinguishing systems in the engine compartment of buses [4]. Moreover, the SP Method 4912 document has been developed, which defines the effectiveness of using a particular fire extinguishing system in MVs [5].

The effectiveness of a fire detection system would depend, first of all, on the location and type of fire detector (FD), as well as on the properly developed algorithm of FD operation. FD should unmistakably detect the source of ignition at an early stage of development. Detecting fire at an early stage makes it possible to quickly use fire extinguishing systems and thereby prevent death, injury to people, and significant material losses. However, it is not easy to ensure the effective operation of FD under complicated temperature, convective, and structural conditions. All these factors affect the effective operation of FD and, therefore, the time of detection of fire. Therefore, it is a relevant task to build an operational algorithm for FD, which would unmistakably detect fire at an early stage.

2. Literature review and problem statement

The causes and features of the development of fires in MVs are described in a series of scientific papers. In [6], it is noted that most of such fires relate to passenger vehicles (more than 91 %). Most often, such fires originate in the engine compartment (about 70 %), less often – in the cabins of MVs (12 %). The main causes of fires are fire-hazardous modes of operation of the onboard power grid, about 35 %÷40 %. About 25 % of fires occur as a result of melting parts (fuel and oil pipelines, etc.) under the influence of gases emanating from a destroyed outlet manifold. Fires also occur as a result of fuel, lubricants, and hydraulic fluids entering the highly heated surfaces of the engine and turbocharger, as a result of a violation of the tightness of fittings in fuel and hydraulic systems. Arson accounts for 10 %, about 30 % of the causes have not been established. However, work [6] fails to consider the impact exerted on the development of fires in MVs by systems for detecting and extinguishing fires and their role in preventing fires. Study [7] addresses the effectiveness of the use of fire detection and extinguishing systems, which were located in the engine compartment of 70 buses. During the fire, the fire detection and extinguishing systems were triggered in two buses. In seven cases, those systems worked incorrectly. Of these, in five cases, the fire detection systems were triggered not because of the discharge of heat fluxes. In three cases, the systems were triggered by hot exhaust gases. However, study [7] does not specify what types of FDs were used in fire detection systems. That could have allowed for a more thorough analysis of the causes of the incorrect operation of the systems.

In order to design an effective fire detection system, one needs to know how the fire develops and propagates in MV. With a fire in different places of the engine compartment, the temperature rises differently. Work [8] reports the results of the experiment that showed that the flame spreads rapidly after ignition in the engine compartment of a passenger sedan car. Already in about 30 s, the temperature reaches 550–600 °C. Fire extinguishing should be carried out within 6 minutes. However, the experiment was carried out indoors without access to airflows. This affects the temperature value when an MV is operated in an open area and does not make it possible to determine the required static response temperature for a heat detector (HD). In [9], it was practically investigated how a flame from a burning car spread to the nearby parked cars. The temperature at the ignition site in the initial period ranged from 200 °C to 750 °C. The experiment was also carried out indoors. To ensure access to airflows, the windows on the ground floor of the facility were open. Work [10] reports the results that have made it possible to determine thermal radiation in spatial positions and the fire safety distances for people and cars nearby. However, the experiment was conducted indoors, without access to airflows, and the MV did not move. That affected the value of thermal radiation and, therefore, the choice of a HD with the required static response temperature. Special attention is paid in [11] to the occurrence and development of a fire in the engine compartment while driving and parking, as well as when a fire is thrown at nearby parked cars. A computer model of the development of a car fire and the impact of fire on neighboring parked cars were given. All these experiments prove that the flame spreads fastest in the engine compartment of a vehicle. However, the issue of choosing the type of FD and its location in the engine compartment remains unresolved.

In a general case, any fire detection and extinguishing systems in MV should include an FD, a control unit, and fire extinguishing modules. The general structure of such a system can be implemented in ways described in [12, 13]. An external fire extinguishing system is proposed in work [12]. It describes issues that affect the operation of the system. To detect fire, a HD with a static response temperature of 85÷150 °C is used. However, depending on the conditions and operating modes of MVs, the time of FD response with an unchanged static response temperature would be different. This would affect the detection time of the fire. The author proposes only to improve the reliability of the detector by monitoring and diagnosing its faults. An installation of fire extinguishing for wheeled vehicles is proposed in work [13]. To detect the fire, a flame FD and a HD were offered. However, the cited work does not solve the issue of choosing the types of HD and flame FD and where exactly they should be placed. The effectiveness of using a fire detection system depends on the choice of the type of FD.

As already noted, most fires occur in the engine compartment, in the cabins and luggage compartments of MVs, etc. Arranging fire detection and extinguishing systems in such places is the most suitable. Work [14] reports the physical and computer models for modeling the airflow and thermal field in the engine compartment. As the study results showed, the temperature did not exceed 72 °C. The study involved a physical model, rather than an actual MV. Paper [15] reports a comprehensive study into the temperature and convective modes in the engine compartment of MVs. It was established that the temperature of the external elements of the internal combustion engine (ICE) could reach 100 °C, and that of the outlet manifold   260 °C. However, there are no recommendations for choosing the type of a HD with a certain static response temperature and the algorithm of its operation. Paper [16] states that the air temperature in the engine compartment reaches 80÷120 °C, and, during the short-term peaks near the turbocharger and outlet manifold, 180÷190 °C. At the same time, when MV is not in operation, its temperature is equal to the ambient temperature and could equal, for example, –30 °C. The results of a study reported in [16] make it possible to draw conclusions about the location of FD in the engine compartment and how the air temperature would affect the operation of the HD. However, there are also no recommendations for choosing the type of a HD with a certain static response temperature and the algorithm of its operation.

The authors of work [17] carried out full-scale research on the operational effectiveness of various fire detection systems in the engine compartment. Using modeling, the value of temperature and concentration of smoke was determined.

It was also established how these values are affected by engine configuration and driving conditions. It was found that the effective operation of both heat and smoke FDs is significantly dependent on their location and the movement of airflows in the engine compartment. However, the cited work [17] failed to consider different types of heat and smoke FDs and the algorithms of their operation. Paper [18] investigated the dynamics of the fire in an electric hybrid bus. To detect fire in the engine compartment, a linear HD with a static response temperature of 180 °C was used. Six conventional point smoke and thermal power FDs were also used, two of which were of an aspiration type. The point HDs with a static response temperature of 54 °C. Since the static response temperature of FD is constant, the heat flux from ICE would affect the time of detection of fire. The choice of the type of HD and the algorithm of its operation affects the time of detection of fire and the probability of false response. The operating conditions of MVs are complex and must be taken into consideration when building an algorithm to operate FD.

The authors of works [19, 20] thoroughly analyzed the different types of FDs that can be used in heavy MVs. In most cases, HDs are used to detect fire. The application of optical smoke FDs is not effective, especially in engine compartments, in the luggage compartments of buses. They are more suitable for use in clean places in the absence of dust, for example in aircraft cabins, passenger railroad cars. However, works [19, 20] consider maximal HDs with a constant minimal static response temperature. Paper [21] reports a study into the use of various types of detectors in the engine compartments of mining vehicles. Based on the experiments, it was determined that smoke FDs effectively detect ignition in the engine compartment. However, gas sensors are more effective, which can detect hydrocarbon combustion products. However, as the author notes, those smoke FDs would be effective if one eliminates the negative environmental impact that is in the engine compartment.

In work [22], the authors proposed for a car a fire detection and fire control system, which is built using fuzzy logic. The fire detection system includes flame, temperature, and smoke sensors. Depending on the characteristics of the environment, all of them are located in different places. A temperature sensor was used to control the engine compartment. The proposed system is implemented on the Arduino microcontroller (Italy) and detects fire within 20 seconds. The authors continued their research in [23]. That paper proposes a fuzzy system that analyzes instant data and decides whether a fire occurred or not. An experiment was conducted using a children's electric car. However, in works [22, 23], the input linguistic variable temperature corresponds to only three variables: low, medium, high. The ranges of linguistic variables do not change depending on the modes of operation of a vehicle. In work [24], to identify and eliminate potential fires in the motor compartment of the engine and a rechargeable battery of a hybrid electric vehicle, a new fuzzy deterministic uncontrolled system is proposed. Mamdani's fuzzy regulator inputs receive signals from temperature and humidity sensors placed in the engine compartment, as well as from voltage and current sensors located in the battery compartment. The forms and parameters of the input and output membership functions were established. However, linguistic variables do not change depending on the operating conditions of a car. The authors failed to consider changes in temperature in the engine compartment due to engine heat exposure and climatic changes. A Mamdani controller is used to build the entire fire detection system. In [25], a fuzzy correction unit based on fuzzy logic theory was proposed and synthesized using Mamdani's algorithm, only for combined FD with smoke and heat sensors. A given FD makes it possible to recognize different stages of temperature change and smoke volumes in the premises. That allows the detection of ignition at an early stage. However, it was designed for indoor use and was not considered for use in MVs at a sharp change in temperature.

Thus, as indicated above, it is advisable to use a HD to detect ignition in the engine and luggage compartments. According to the principle of response, HDs could be fixed temperature detectors (static detectors), fixed-dynamic detectors (rate of rise detectors). Choosing the type of HD that needs to be installed is not an easy task. To this end, one needs to take into consideration the class of detectors. Fixed-dynamic HDs are more efficient than conventional fixed temperature HDs. They are suitable for use when the ambient temperature is low. While fixed temperature HDs – not. However, dynamic-type HDs (rate of rise detectors) are more sensitive and can emit false alarms at significant temperature fluctuations, which are due to the modes of ICE operation and climatic conditions. When an ICE operates under a rated mode, the temperature in the engine compartment is almost stable, both during movement and when stopping the MV.

MVs can for several hours be operated under different temperature conditions, with different speeds of movement, which would create different airflows, at different times of the day. The temperature can change very quickly over a short period of time and may even go beyond the temperature ranges of detectors. Such a rapid change in temperature affects the time of detection of a fire by a HD and can cause false response of a dynamic-type HD. Such an event may occur, for example, in cargo compartments equipped with large doors facing directly outwards. In winter, while the door is open, detectors are cooled, after closing the door there is a sharp increase in temperature. When driving an MV in the mountains: the temperature near the mountainside can be, for example, +20 °C, and on the pass –5 °C. In such situations, it is better not to use rate of rise detectors.

Fixed temperature HDs under the conditions of significant temperature fluctuations over short periods of time operate more stable. They are selected so that the minimal static temperature of response exceeds the standard temperature of use. It is clear that the smaller the difference between the minimal static temperature of response and the temperature of use, the greater the likelihood of false response. One can prevent these events by installing detectors with a higher response temperature. At the same time, with an increase in this difference, the time of fire detection by FD increases. However, fixed temperature HDs detect ignition at sub-zero temperatures with a time delay compared to the detection of a fire that can occur at positive temperatures. Then it turns out that, depending on the time of year, air temperature, and operating conditions of MVs, it is necessary to change the minimal static temperature of response all the time, that is, the class of HD.

Thus, when choosing HDs, it is necessary to take into consideration the speed of changes in ambient temperature, while remaining in the range of temperature of use, not only due to the effects of climatic conditions but also to the influence of ICE modes of operation. As a result, a situation arises where the minimal static response temperature of HD and a value of the temperature increase rate at which it is enabled must be changed. It is better to change at the level of software, which is easier and does not require additional costs.

The need to adjust the level of the threshold value of FD response at the software and hardware level was discussed in work [26]. It proposes an algorithm for the operation of HD, which changes the value of the minimal static response temperature and the rate of rise in the temperature at which it is enabled. However, that detector is designed to control the ambient temperature in the premises where the manufacturing equipment is installed. It is not designed to control the temperature indoors where the rate of temperature change ranges dependent on the temperature influence of manufacturing equipment.

In [27], an operational algorithm of a HD, which changes the threshold level of response, has been developed. It takes into consideration a change in the ambient temperature and its speed depending on the temperature influences from manufacturing equipment installed indoors. A given operational algorithm does not make it possible to take into consideration fluctuations in the rate of temperature increase from the moment of starting work until the moment of reaching the technological temperature. The rate of temperature increase in the engine compartment of MVs at these moments is different.

Therefore, our review of the literary sources has revealed that it is most effective to use heat detectors to detect fire in the engine compartment. When choosing HDs, it is necessary to take into consideration the heat fluxes from ICE operation. They affect the choice of values for the minimal static response temperature for a HD and the rate of rise of the temperature at which it is enabled. The values of these parameters of HD response affect the time of detection of fire and the probability of its false response. For quick detection of fire when the ICE does not work, these values must be minimal. When the ICE starts working, the temperature in the engine compartment increases. In order not to falsely trigger the HD, it is necessary that the values of the trigger parameters are greater. As a result, there is a situation where the parameters for triggering a HD need to be changed. Therefore, building an algorithm for the operation of a fixed-dynamic HD, which would ensure effective operation under complicated temperature conditions and fire detection at an early stage of development, is a difficult task. Resolving a given issue could make it possible to quickly use the fire extinguishing system and thereby improve the fire protection of MVs.

3. The aim and objectives of the study

The purpose of this work is to improve the fire safety of MVs by improving the operational algorithm for a fixed-dynamic HD. Depending on the temperature influences of the environment, due to the operation modes of ICE, the algorithm would automatically change a value of the minimal static response temperature of HD and a value of the rate of rise in the temperature of its response. That could detect fire at an early stage and reduce the cases of false response caused by temperature influences not related to the fire. Detection of fire at an early stage makes it possible to quickly use the fire extinguishing system and thereby improve the fire protection of MVs.

To accomplish the aim, the following tasks have been set:

– to determine which parameters for enabling a fixed-dynamic HD would change due to the thermal impact of ICE, and the moments of these changes;

– to determine experimentally the temperature and speed of its change in the engine compartment during ICE operation when moving and stopping an MV;

– to build a flowchart of the operational algorithm for a fixed-dynamic HD with variable response parameters;

– to investigate the constructed operational algorithm for a fixed-dynamic HD with variable response parameters using a simulation involving its computer model in order to determine its operability.

4. The study materials and methods

In modern heat detectors, various sensing elements are used to detect fire, whose parameters depend on the temperature and laws of physics. Most of all, semiconductors (thermistors, thermodiodes) and thermoelectric elements (thermocouples) that refer to electrical measurement methods are used as sensitive elements in HD. Therefore, three thermoelectric devices were used to measure the temperature in the engine compartment. They are composed of a thermocouple and digital multimeter. Thermocouples, model TR-01A, with a measuring range from –50 °C to +204 °C. The Mastech digital multimeter has a temperature measurement range from –20 °C to +1,000 °C. The device's accuracy of measurement is in the range from –0 °C to +400 °C – ±(1.0 %).

Natural conditions were used to conduct the experiment. In line with the study purpose, the experiment was of a statement nature, one-factorial. In terms of organization and place of execution, a field type. In terms of the impact on the conditions of the experiment – active. According to the type of models studied during the experiment – material.

MATLAB (USA) was used to build a model of the proposed operational algorithm for a heat detector with variable response parameters. MATLAB is a specialized package of applications designed for numerical analysis in various fields, such as electromechanics or energy engineering. MATLAB is written in the authentic programming language. The MATLAB system was developed by The MathWorks and is a modern tool for working with functions, matrices, logic, operations with algorithms. The package provides for the creation of user interfaces using programs in other programming languages, such as Fortran. The package specializes in numerical process computation. In combination with various built-in mathematical functions and large libraries of various models, the package is a complete system of analysis and design of various systems.

5. Results of constructing and investigating an operational algorithm for a fixed-dynamic heat detector with variable parameters

5. 1. Establishing the required parameters for the operability of the algorithm for a fixed-dynamic HD

Such response parameters have been set to ensure the operability of an algorithm for a maximal-dynamic heat detector that could vary depending on the temperature influence of the ICE operational modes. These parameters are the minimal static response temperature of HD T°_{resp} and a value of the rate of increase in the temperature of its response $T^{\circ\prime}_{resp}$.

To change the parameters of HD response, it is necessary to establish when exactly these changes should occur. Two time parameters have been introduced to this end. The first parameter is the time over which the temperature at the place of HD installation would reach the value of the technological temperature (operating temperature) due to the operation of ICE τ_{tech}. The second parameter is the time over which the values of the minimal static temperature of HD response are corrected and the speed of increasing the temperature of its response τ_{cor}. That is the time during which the ICE temperature would reach the value of the ambient temperature after it is stopped.

In order to detect fire at an early stage, when ICE is stopped and the MV is not in operation, it is necessary that T°_{resp} and $T^{\circ'}_{resp}$ are as small as possible. The smallest values for T°_{resp} and $T^{\circ'}_{resp}$ at which HDs reliably detect fire are inherent in classic maximal-dynamic heat detectors of class A $\left(T^{\circ}_{resp}=+54\,^{\circ}\mathrm{C}\right)$ whose $T^{\circ'}_{resp}=8\,^{\circ}\mathrm{C}/\mathrm{min}$. These values are initial.

During the ICE operation, the temperature in the engine compartment increases to the technological temperature at a certain speed. In order to prevent false response, it is necessary to change a value of the minimal static temperature of HD response T°_{resp} and a value of the rate of increase in the temperature of its response $T^{\circ'}_{resp}$. The value of T°_{resp} would depend on the maximal temperature value at the HD installation site $T^{\circ}_{\max}$. A value for $T^{\circ}_{\max}$ was determined during the experiment. The speed of temperature increase in the different periods of ICE operation would be different. To derive the new values for $T^{\circ'}_{resp}$, one needs to know two parameters: $T^{\circ'}_{\max 1}$ and $T^{\circ'}_{\max 2}$. $T^{\circ'}_{\max 1}$, $T^{\circ'}_{\max 2}$ are the maximal speeds of temperature increase in the engine compartment due to the ICE operation during and after the time τ_{tech}. They were also determined during the experiment. $T^{\circ}_{\max}$, $T^{\circ'}_{\max 1}$ and $T^{\circ'}_{\max 2}$ are higher than the temperature and ambient temperature changes due to climatic conditions.

5. 2. Experimental research

Before modeling the proposed operational algorithm for a heat detector, we shall investigate how the temperature in the engine compartment would change due to the operation of ICE when moving and stopping an MV. This is necessary to determine the minimal static temperature of HD response and a value of the speed of increase in the temperature of its operation. The research involved two cars: Renault Megan III Grandtour (France) with the diesel engine K9K (France) and Renault Megan III Grandtour (France) with the gasoline engine M4R (France). The MVs were driven in the urban cycle. Thermocouple No. 1 was placed on the side of ICE from the side of the radiator grille, thermocouple No. 2 – from the top in the middle of the engine, thermocouple No. 3 – from the side of ICE from the side of the cabin (outlet manifold) (Fig. 1). During the experiment, the ambient air temperature was t_{amb}=14 °C and the weather was sunny. Therefore, the temperature in the engine compartment at all points was almost the same, t=20 °C. The experimental results are given in Table 1 (MV with the diesel engine K9K) and Table 2 (MV with the gasoline ICE M4R). The temperature values in the engine compartment when driving and stopping the MVs are given 16 minutes after setting the so-called technological temperature of ICE operation. The maximal values for the temperature increase rate in the engine compartment are derived during the operation of ICE at the initial moment of time calculated over a short period of 10÷20 s.

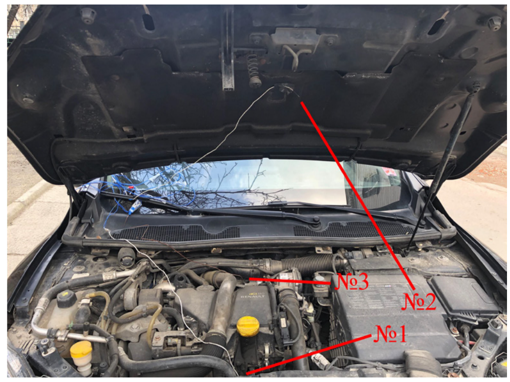

Fig. 1. Arrangement of three thermocouples in the engine compartment

Table 1

Results of experimental studies involving an MV with the diesel engine K9K

Thermocouple No.	Temperature value when driving the MV, °C	Temperature value when stopping the MV, °C	Value of the rate of temperature increase in 16 min, °C/min	Maximal temperature rise speed value at the starting point in time, °C/min
Thermocouple 1	58÷71	50÷55	7÷16	15
Thermocouple 2	35÷45	51÷67	30÷51	90
Thermocouple 3	59÷73	102÷120	50÷115	255

Table 2

Results of experimental studies involving an MV with the gasoline ICE M4R

Thermocouple No.	Temperature value when driving the MV, °C	Temperature value when stopping the MV, °C	Value of the rate of temperature increase in 16 min, °C/min	Maximal temperature rise speed value at the starting point in time, °C/min
Thermocouple 1	53÷81	49÷72	7÷15	30
Thermocouple 2	56÷72	60÷75	30÷45	68
Thermocouple 3	62÷84	76÷95	30÷50	290

Different values of temperatures in the engine compartment and the rate of its change at different points when moving and stopping the MV can be explained by the influence of airflows and different temperature values of ICE elements. The temperature value at the location of thermocouple No. 1 is affected by the flow from the radiator; at the same time, thermocouple No. 3 is more protected and is near the output manifold.

5. 3. Compiling a flowchart of the operational algorithm for a fixed-dynamic heat detector with variable response parameters

The flowchart of the built operational algorithm for a fixed-dynamic HD is shown in Fig. 2.

To demonstrate the algorithm operation, the most difficult case has been considered where the HD is located in the engine compartment. At the first switching on, the HD self-tests the performance of its main elements, checks the presence of communication with the control unit (unit 2). If faults of the elements are detected, an electrical fault signal is formed at the output of the HD (unit 4). The initial values are recorded in the memory of the HD microprocessor (unit 5) for a specific MV and the type of ICE at the beginning of operation: τ_{cor}, τ_{tech}, $T^{\circ}_{\max}$, $T^{\circ'}_{\max 1}$, $T^{\circ'}_{\max 2}$.

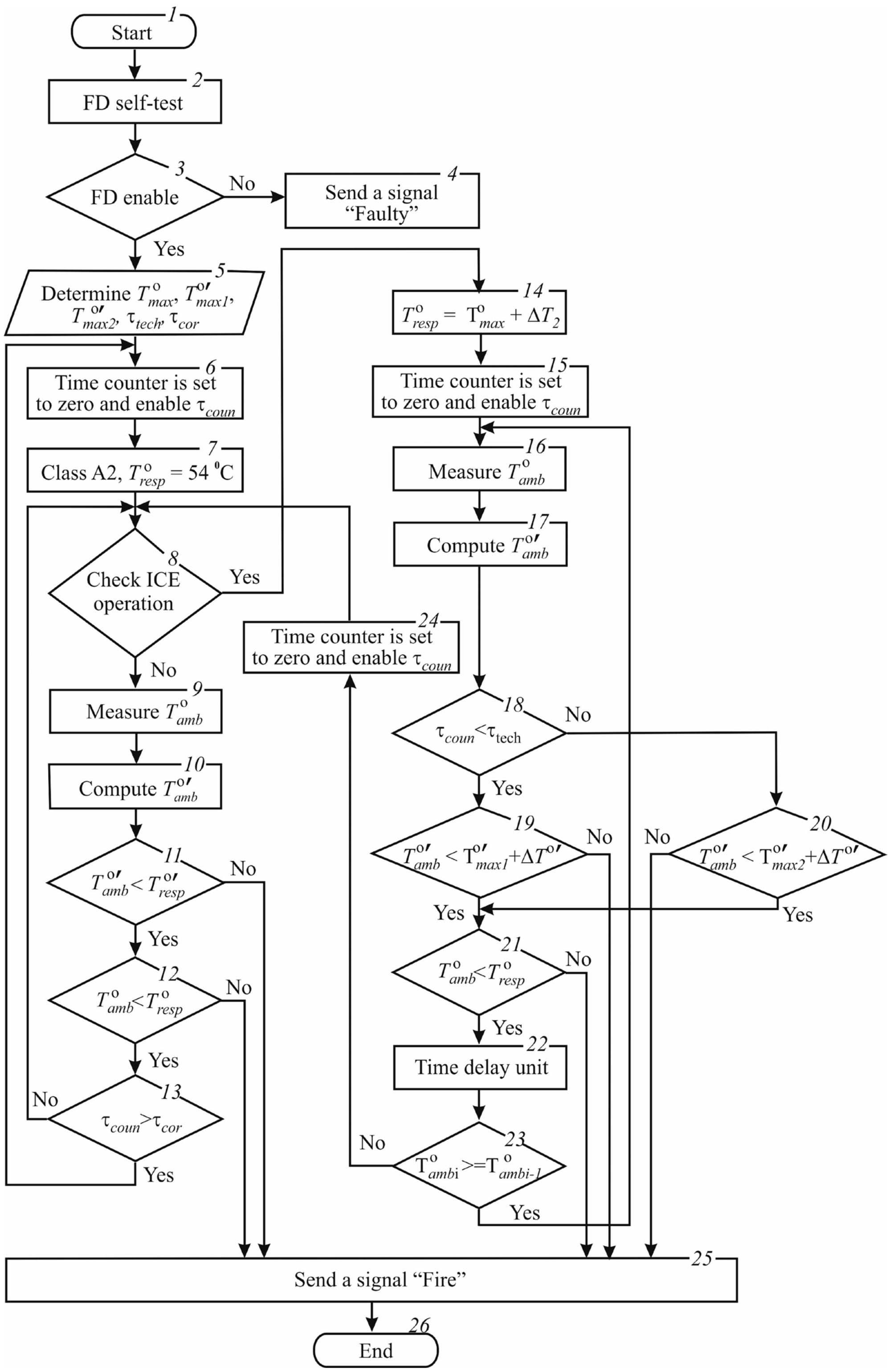

Fig. 2. Flowchart of the operational algorithm for a fixed-dynamic heat detector with variable parameters of response

At the next stage, the HD time counter τ_{coun} is set to zero and enabled (unit 6). It is necessary in order to be able to correct a value of the minimal temperature of HD response T°_{resp} and a value of the rate of increase in temperature $T^{\circ'}_{resp}$ at which it is triggered. These values depend on a change in the temperature at the place of HD installation, due to the impact of ICE operation, and the effect of climatic conditions. The class of heat detector A2 is set. That is, $T^{\circ}_{resp} = +54\,^{\circ}\mathrm{C}$ (unit 7).

In unit 8, the ICE is checked. To this end, the HD must have a relay input to receive a signal from the onboard computer. If the ICE does not work, the ambient temperature is measured at the place of HD installation T°_{amb} (unit 9) and the speed of its change is calculated $T^{\circ'}_{amb}$ (units 10). In unit 11, there is a comparison of the value of the rate of increase in the temperature of the environment $T^{\circ'}_{amb}$ with the value of the rate of increase in the temperature $T^{\circ'}_{resp}$ at which the HD is triggered: $T^{\circ'}_{resp} = 8\,^{\circ}\mathrm{C}/\min$. If the condition $T^{\circ'}_{amb} < T^{\circ'}_{resp}$ is not met, then the output of the HD forms a signal "Fire". In this case, the HD is triggered by the speed of the temperature change, that is, it works as a dynamic type HD. If the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{resp}$ is met, there is a transition to unit 12. In unit 12, the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{resp}$ is checked. If the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{resp}$ is not met, then the output of the HD forms a signal "Fire". In this case, the HD works as a maximal heat detector, that is, the rate of the temperature increase due to fire is less than the speed of an increase in the temperature of HD response, and the value for T°_{amb} increases. If the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{resp}$ is not met, there is a transition to unit 13 that compares the time of HD operation τ_{coun} to the correction time τ_{cor} allocated to change a value of the minimal static temperature of HD response. If the condition $\tau_{coun} > \tau_{cor}$ is not met, there is a transition to unit 8 to repeat the cycle (units 8–13). If the condition $\tau_{coun} > \tau_{cor}$ is met, there is a transition to unit 6 that resets the counter and defines the class of HD (unit 7). Unit 13 is needed to change a value of the minimal temperature of HD response after the temperature in the engine compartment decreased due to stopping the ICE.

If the ICE works, there is a transition to unit 1 that sets a new value for the minimal static temperature of HD response $T^{\circ}_{resp} = T^{\circ}_{\max} + \Delta T^{\circ}$ (ΔT° can be equal to, for example, 10 °C). In unit 15, the time counter τ_{coun} is reset and activated. In units 16 and 17, the temperature value is measured at the place of HD installation T°_{amb} and the calculation of the rate of its change $T^{\circ\prime}_{amb}$ is performed. In unit 18, the condition $\tau_{coun} > \tau_{tech}$ is checked. This unit is necessary so that the HD does not work when there is a rapid change in temperature due to the operation of ICE (in the first period) or the opening of the luggage compartment or cabin door. When the ICE temperature reaches the technological one, the rate of temperature change at the HD installation site, as studies show, is not significant. If the condition $\tau_{coun} > \tau_{tech}$ is met, there is a transition to unit 19. This means that the time it takes for the temperature in the engine compartment to reach the technological temperature has not yet passed. In unit 19, the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 1} + \Delta T^{\circ\prime}$ (for example, $\Delta T^{\circ\prime} = 5\,^{\circ}\mathrm{C/min}$) is checked. If the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 1} + \Delta T^{\circ\prime}$ is not met, then a "Fire" signal is formed at the outlet of the HD. This means that the ambient temperature changes rapidly as a result of a fire, rather than the operation of ICE. If the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 1} + \Delta T^{\circ\prime}$ is met, there is a transition to unit 21.

If the condition $\tau_{coun} > \tau_{tech}$ is not met, there is a transition to unit 20, where the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 2} + \Delta T^{\circ\prime}$ is checked. If this condition is not met, a "Fire" signal is formed at the output of the HD. The HD is triggered by the speed of a temperature increase (by the dynamic component). If the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 2} + \Delta T^{\circ\prime}$ is met, there is a transition to unit 21. In unit 21, it is checked whether the temperature T°_{amb} does not exceed the new set value for the minimal static temperature of response T°_{resp}. The HD operates as a maximal HD. If the condition $T^{\circ}_{amb} < T^{\circ}_{resp}$ is not met, a "Fire" signal is formed at the outlet of the HD. If the condition $T^{\circ}_{amb} < T^{\circ}_{resp}$ is met, there is a transition to unit 22. Unit 22 is a time delay unit. In unit 23, the condition $T^{\circ}_{ambi} >= T^{\circ}_{ambi-1}$ is checked (where i is the integration step), whether there is a decrease in the temperature at the place of HD installation. If the temperature does not change or increase, then there is a transition to unit 16, and the cycle is repeated (units 16–23). Temperature control is carried out. With a decrease in temperature, there is a transition to unit 8 through unit 24 where the cause of the temperature decrease in the engine compartment is checked, whether ICE is still working or not. In unit 24, the time counter τ_{coun} of the HD is reset and activated. If the temperature has decreased due to the influence of climatic conditions, and the ICE is working, then there is a transition to unit 14. If the ICE does not work, then, after the time τ_{cor}, a value for the minimal static temperature of response $T^{\circ}_{resp} = +54\,^{\circ}\mathrm{C}$ (class of detector A2) is set.

5. 4. Investigating the developed operational algorithm for fixed-dynamic heat detector by using the simulation involving its computer model

The Simulink package in the MATLAB programming environment was used to build a model of the operational algorithm for a heat detector with variable response parameters based on the flowchart shown in Fig. 1, as well as a temperature change model. The window with the developed models in the Simulink software package is shown in Fig. 3.

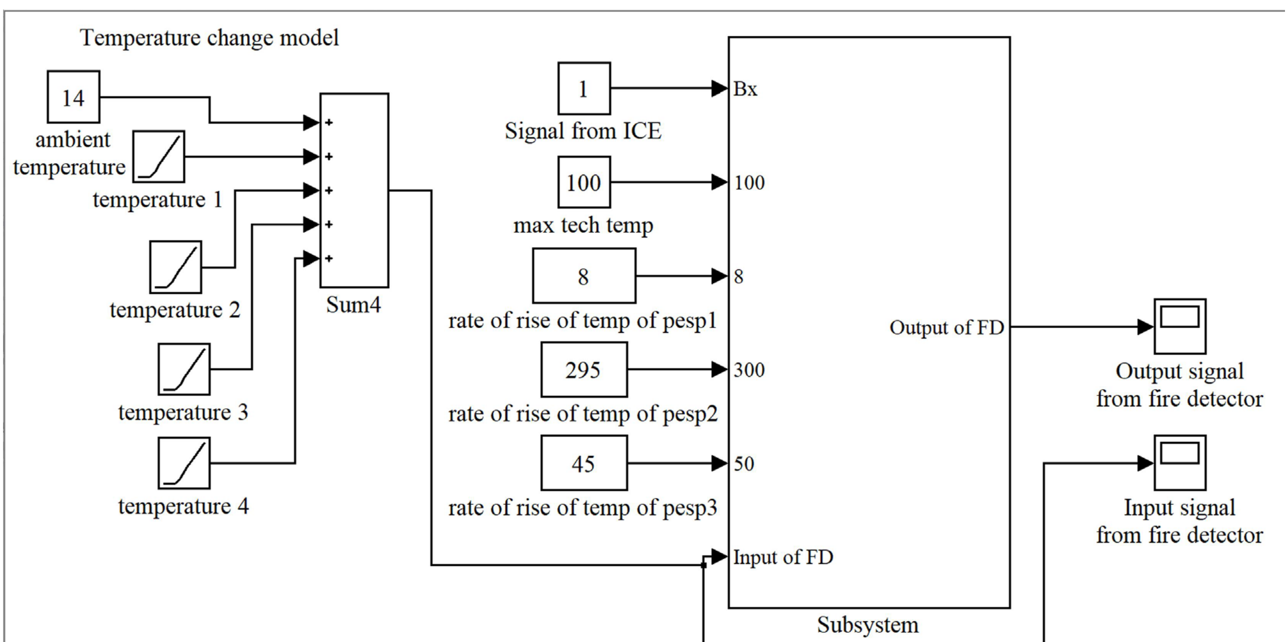

Fig. 3. A Simulink software package window in the MATLAB programming environment showing the model of a heat detector

We shall investigate how the HD would react in different cases of temperature changes in the engine compartment and under various modes of ICE operation. We shall simulate a temperature change in the worst cases. Assume that the HD is located on top in the middle of the engine. In order to prevent the HD from false response caused by the influence of engine temperature, we accept that the technological temperature in the engine compartment is 100 °C. However, as the results of experimental studies show, it did not exceed 65 °C for the diesel engine and 75 °C for a gasoline ICE. The maximal value of the speed of increasing the temperature in the engine compartment at the initial point of time is 295 °C/min, and, after reaching the technological temperature, 45 °C/min. A value of the temperature increase rate at which HD is triggered when the ICE does not work is $T^{\circ\prime}_{resp} = 8\,^{\circ}\text{C/min}$, and, when the ICE operates, $T^{\circ\prime}_{resp} = T^{\circ\prime}_{\max 2} + \Delta T^{\circ\prime} = 50\,^{\circ}\text{C}\,/\,\text{min}$.

Case 1. We shall model the situation where an MV is parked in an open space with the engine turned off and when the temperature at the place of HD installation in the engine compartment is equal to the ambient temperature $T^{\circ}_{amb} = 14\,^{\circ}\text{C}$. The minimum static operating temperature of HD response is $T^{\circ}_{resp} = 54\,^{\circ}\text{C}$. The HD operates according to the algorithm of operation under a cyclic mode (units 8–13, after the time τ_{cor} – units 6–13) (Fig. 1). The results of our modeling are shown in Fig. 4. In Fig. 4, the following designations were adopted: curve 1 – a temperature at the place of HD installation (an input signal acting on the HD); curve 2 – a temperature increase rate T°′; curve 3 – an output signal of the HD, which corresponds to a logic "0" (the HD is in a standby mode), logic "1" (the HD is in the "Fire" mode). At time t=1 min, there is an increase in the temperature, due to direct sunlight on the hood, of up to 20 °C, with the rate of the increase in temperature $T^{\circ\prime}_{amb} = 2\,^{\circ}\text{C}\,/\,\text{min}$, which is less than $T^{\circ\prime}_{resp} = 8\,^{\circ}\text{C}\,/\,\text{min}$ (Fig. 4, *b*). At time t=6 min, there is a sharp increase in the temperature at the speed of $T^{\circ\prime}_{amb} = 400\,^{\circ}\text{C}\,/\,\text{min}$ as a result of a fire. The HD enters a "Fire" mode. The HD is triggered by a dynamic component (a temperature increase speed) (unit 11, the condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{resp}$ is not met).

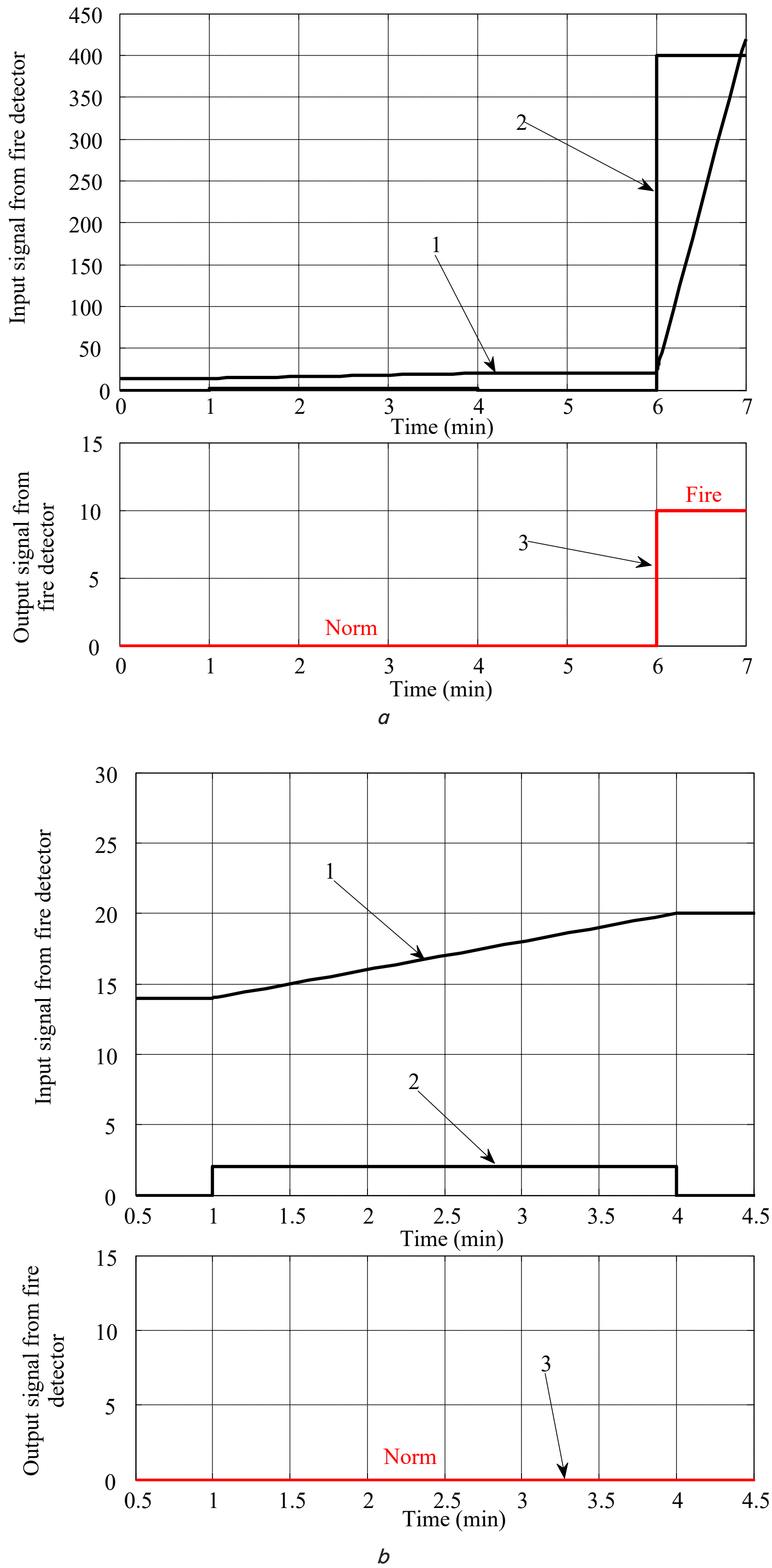

Fig. 4. The results of modeling the operation of a heat detector when the temperature changes due to the influence of climatic conditions and fire: curve 1 — a temperature at the place of installation of the heat detector (°C); curve 2 — a temperature increase rate T°′(°C/min); curve 3 — an output signal of the heat detector: *a* — the results of modeling the heat detector response over a period from 0 to 7 minutes; *b* — the results of modeling the heat detector response over a period from 0.5 to 4.5 minutes

Case 2. We shall model the situation when the temperature in the engine compartment changes due to the influence of climatic conditions, the operation of ICE, and fire. The modeling result is shown in Fig. 5. The designations in Fig. 5 are similar to those in Fig. 4. Ambient temperature is $T^{\circ}_{amb}=14\,^{\circ}\mathrm{C}$. At time t=1 min, there is an increase in the temperature due to direct sunlight on the hood with the rate of increase in the temperature $T^{\circ\prime}_{amb}=2\,^{\circ}\mathrm{C}/\mathrm{min}$, which is less than $T^{\circ\prime}_{resp}=8\,^{\circ}\mathrm{C}/\mathrm{min}$. The HD operates according to the algorithm of work under a cyclical mode (units 8–13) (Fig. 1). At time t=6 min, the ICE starts working. There is an increase in the temperature due to the operation of ICE at the speed of $T^{\circ\prime}_{amb}=20\,^{\circ}\mathrm{C}/\mathrm{min}$. According to the operational algorithm, when ICE works, there is a transition to unit 14. A new value is set: $T^{\circ}_{resp}=100\,^{\circ}\mathrm{C}+10\,^{\circ}\mathrm{C}=110\,^{\circ}\mathrm{C}$. The HD does not work, the conditions $T^{\circ\prime}_{amb}<T^{\circ\prime}_{\max 1}+\Delta T^{\circ\prime}$ (20 °C/min<295 °C/min+ +5 °C/min) and $T^{\circ}_{amb}<T^{\circ}_{resp}$ (units 19 and 21) are met. The HD operates according to the algorithm under a cyclical mode (units 16–19, 21–16). After setting the technological temperature of 100 °C in the engine compartment over a specified time, the condition $\tau_{coun}<\tau_{tech}$ is not met. The HD operates according to the operational algorithm under a cyclical mode (units 16–18, 20–16). At time t=14 min, there is an increase in the temperature: $T^{\circ\prime}_{amb}=10\,^{\circ}\mathrm{C}/\mathrm{min}$. When the temperature T°_{amb} reaches 110 °C, the HD is triggered by a minimal static temperature. The case in question is purely theoretical since $T^{\circ\prime}_{amb}$ would be much larger during the fire.

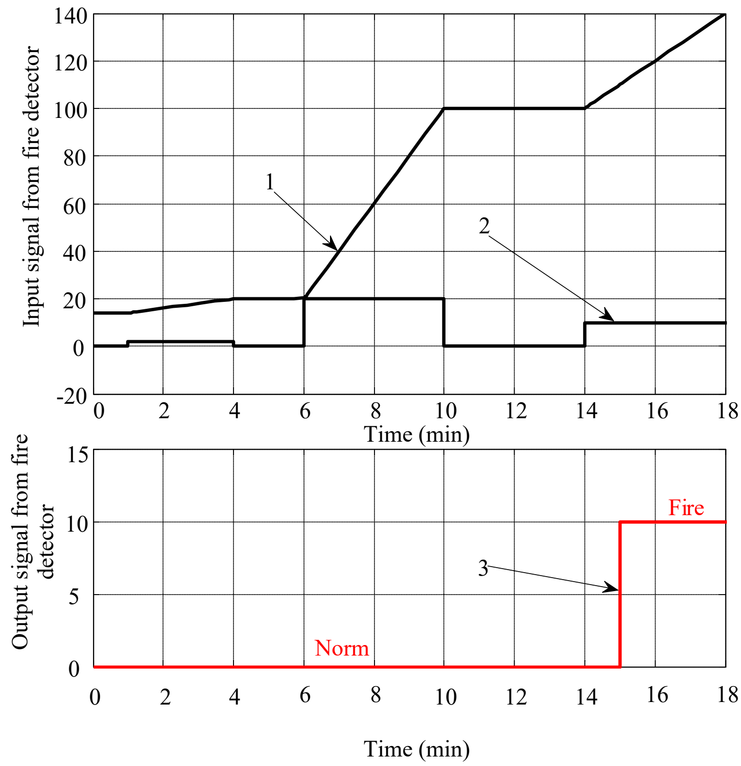

Fig. 5. The results of modeling the heat detector response when the temperature changes due to climatic conditions, the operation of the internal combustion engine, and fire: curve 1 – a temperature at the place of installation of the heat detector (°C); curve 2 – a temperature increase rate T°′(°C/min); curve 3 – an output signal of the heat detector

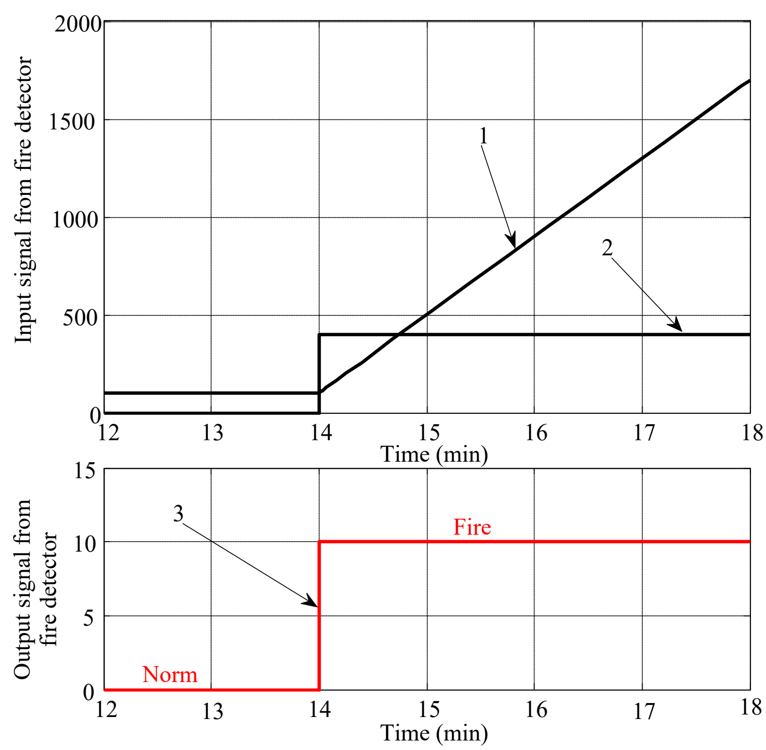

Fig. 6. The results of modeling the heat detector response when the internal combustion engine is working and the temperature changes as a result of fire: curve 1 – a temperature at the place of installation of the heat detector (°C); curve 2 – a temperature increase rate T°′(°C/min); curve 3 – an output signal of the heat detector

Case 3. Consider a case similar to the previous one, only at time t=14 min, there is a sharp increase in the temperature due to fire: $T^{\circ\prime}_{amb} = 400\,^{\circ}\mathrm{C}/\mathrm{min}$. The modeling result is shown in Fig. 6. According to the operational algorithm (units 16–18, 20–16), the HD is triggered by the speed of a temperature increase. The condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 2} + \Delta T^{\circ\prime}$ (400 °C/min<45 °C/min+5 °C/min) is not met.

Case 4. Consider the case similar to case 2, only at time t=6 min, the ICE starts working $\left(T^{\circ\prime}_{amb} = 20\,^{\circ}\mathrm{C}/\mathrm{min}\right)$ and, at t=8 min, there is an ignition at the rate of increase in the temperature of $T^{\circ\prime}_{amb} = 400\,^{\circ}\mathrm{C}/\mathrm{min}$. The modeling result is shown in Fig. 7.

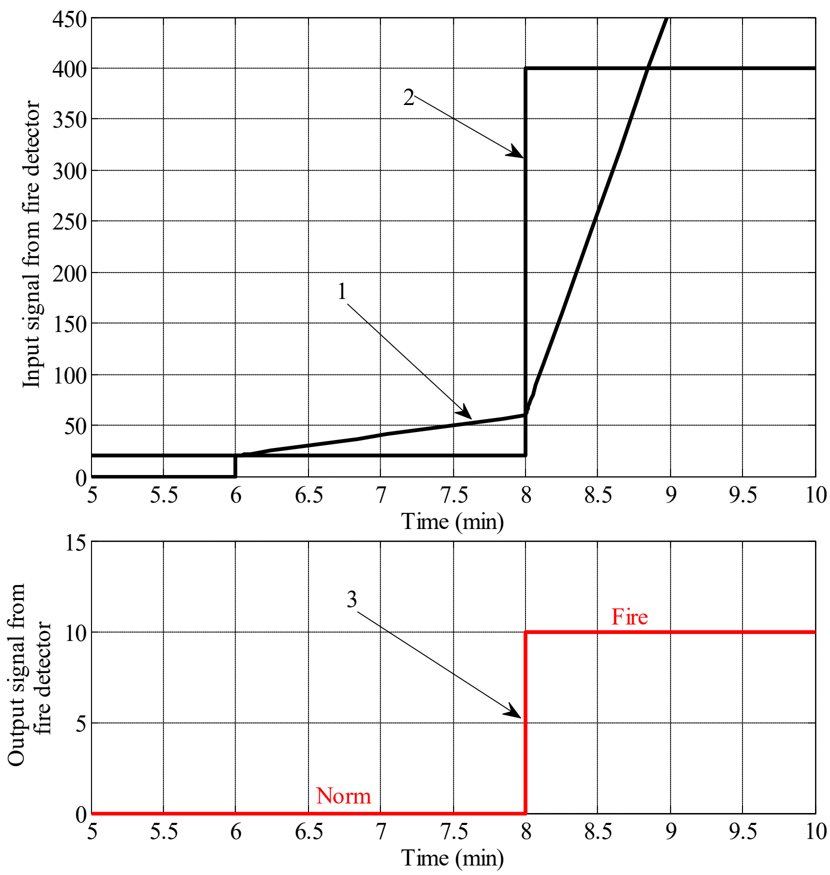

Fig. 7. The results of modeling the heat detector response when the internal combustion engine starts working and the fire occurs: curve 1 — a temperature at the place of installation of the heat detector (°C); curve 2 — a temperature increase rate T°′(°C/min); curve 3 — an output signal of the heat detector

According to the operational algorithm (units 16–19, 21–16), the HD is triggered by the speed of a temperature increase. The condition $T^{\circ\prime}_{amb} < T^{\circ\prime}_{\max 1} + \Delta T^{\circ\prime}$ (400 °C/min<295 °C/min+ +5 °C/min) is not met.

6. Discussion of results of the experimental study and the proposed operational algorithm for a fixed-dynamic heat detector

The results of our experimental study show that at all points the temperature in the engine compartment and the speed of its increase are different. At the initial time of ICE operation, the rate of a temperature increase in the engine compartment $T^{\circ\prime}_{amb}$ is the largest and ranges within significant limits. The temperature in the engine compartment and the speed of its increase depend on a series of factors. These factors include the type of ICE, a driving style, the speed of movement, whether an MV moves or stopped, uneven heating of the ICE elements, ambient air temperature, exposure to sunlight and airflows. If we analyze the rate of a temperature increase over short periods of time (10÷20 s), then it can reach 290 °C/min for MVs with gasoline ICE (thermocouple No. 3) (Table 2). However, when the temperature in the engine compartment reaches the technological temperature of ICE operation (the engine heats up to its operating temperature), it would fluctuate within small limits (Tables 1, 2), while the speed of its change would be less. For a gasoline ICE at the installation site of thermocouple No. 1 – ≈7÷15 °C/min; thermocouple No. 2 – ≈30÷45 °C/min; thermocouple No. 3 – ≈30÷50 °C/min (Table 2). For a diesel ICE at the installation site of thermocouple No. 1 – ≈7÷16 °C/min; thermocouple No. 2 – ≈30÷51 °C/min; thermocouple No. 3 – ≈ 50÷115 °C/min (Table 1). The air temperature of the environment would not affect. When an MV stops, the temperature in the engine compartment is higher than when it moves, which is explained by the influence of an airflow (Tables 1, 2).

The temperature from above in the middle of the ICE did not exceed 67 °C for an MV with the diesel engine, and 75 °C for an MV with a gasoline ICE. Thus, when placing the HD from above in the middle of ICE, in order to prevent its false response, the temperature of its response can be set to 110÷120 °C. The rate of a temperature change $T^{\circ\prime}_{amb}$ is to be calculated over 15÷20 s. It is possible to simplify the operational algorithm of HD and, during the ICE operation, not to analyze the rate of a temperature change in the engine compartment, that is, units 18–20 (Fig. 1) will be absent

Our experimental study has made it possible to determine a value of the minimal static temperature of HD response and a value of the rate of increase in the temperature of its response under different modes of ICE operation. These values are necessary for the implementation of the proposed algorithm of HD operation. Values for time τ_{cor} and τ_{tech} cannot be determined precisely. They would be different for each type of MV, the type of ICE, and different climatic operating conditions of MVs. However, they must be accepted to be the largest. That would not affect the efficiency of HD operation.

As the results of our simulations show, the proposed operational algorithm for a fixed-dynamic heat detector automatically changes the parameters of response, namely, the minimal static temperature of response, and the value of the temperature increase rate at which it is triggered. Different cases were modeled:

1. The temperature in the engine compartment changes due to climatic conditions and fire. When there is a slow

increase in the temperature, due to direct sunlight on the hood, the HD does not work. In the case of fire, a rapid increase in the temperature occurs and the HD is triggered by a dynamic component (Fig. 4). The condition $\dot{T}^{\circ}_{amb} < \dot{T}^{\circ}_{resp}$ is not met.

2. The temperature in the engine compartment changes due to climatic conditions, the ICE operation, and fire. When the ICE starts working, a new value for the minimal static temperature of HD response is set, as well as a value of the temperature increase rate at which it is enabled. The HD operates according to the operational algorithm under a cyclical mode (units 16–19, 21–16). After the time τ_{tech} (the time at which the temperature at the place of HD installation would correspond to the technological temperature), the HD operates according to the algorithm under a cyclical mode (units 16–18, 20–16). As a result of the fire, there is an increase in temperature: $\dot{T}^{\circ}_{amb} < \dot{T}^{\circ}_{resp}$. When it reaches the new value of the minimal static temperature of response, the HD is triggered (Fig. 5). The condition $\dot{T}^{\circ}_{amb} < \dot{T}^{\circ}_{resp}$ is not met.

3. When ICE works for a certain time, the HD operates according to the operational algorithm under a cyclical mode (units 16–18, 20–16). In case of fire, a sharp increase in the temperature occurs and the HD is triggered by a dynamic component (Fig. 6). The condition $\dot{T}^{\circ}_{amb} < \dot{T}^{\circ}_{\max 2} + \Delta\dot{T}^{\circ}$ is not met.

4. When ICE starts working, a new value for the minimal static temperature of HD response is set, as well as a value of the temperature increase rate at which it is triggered. The HD operates according to the algorithm under a cyclical mode (units 16–19, 21–16). At the time when the temperature at the location of the HD has not yet reached the technological temperature, a fire occurs. The temperature increases rapidly and the HD is triggered by a dynamic component (Fig. 7). The condition $\dot{T}^{\circ}_{amb} < \dot{T}^{\circ}_{\max 1} + \Delta\dot{T}^{\circ}$ is not met.

The simulations in the programming environment, shown in Fig. 4–7, confirm the correctness of the developed operational algorithm for a fixed-dynamic heat detector with variable response parameters. The use of the fixed-dynamic heat detector with variable response parameters, in contrast to the classic fixed-dynamic heat detector, makes it possible to detect fire according to the dynamic component at an early stage. That is, over the time necessary to calculate the rate of increase in the temperature $\dot{T}^{\circ}_{amb}$ over a certain period and compare it with the rate of increase in the temperature of HD response $\dot{T}^{\circ}_{resp}$. Changing the rate of a temperature increase, at which the fixed-dynamic heat detector is triggered, at the program level makes it possible to prevent its false response. If we compare the proposed operational algorithm for a heat detector with the variable parameters of response to the classical algorithm of operation of the fixed-dynamic heat detector based on the maximal component, then we can draw the following conclusion. For example, the minimal static temperature for triggering a maximal heat detector, which is used in fire detection systems in MVs, is $T^{\circ}_{resp} = 110\,^{\circ}\mathrm{C}.$ In the proposed fixed-dynamic heat detector with variable response parameters, at idling ICE, $T^{\circ}_{resp} = 54\,^{\circ}\mathrm{C},$ and when the ICE operates, $T^{\circ}_{resp} = 110\,^{\circ}\mathrm{C}.$ So, at the rate of a temperature increase due to fire, $\dot{T}^{\circ}_{amb} = 400\,^{\circ}\mathrm{C/min},$ the heat detector with variable response parameters would work about 2.3 times faster than the classic fixed-dynamic heat detector.

The proposed operational algorithm changes the values of the parameters for triggering a fixed-dynamic heat detector. Depending on the temperature influences of the environment, due to the ICE operating modes, it automatically changes a value of the minimal static temperature of HD response, and a value of the speed of increasing the temperature of its response. A given algorithm is proposed to be implemented to build the fixed-dynamic heat detector in order to use it in fire detection systems in MVs.

We investigated the proposed operational algorithm for a fixed-dynamic heat detector with variable response parameters only for the case of its location in the engine compartment. To use a given HD in the cabins and luggage compartments of MVs, it is necessary to conduct an additional study. Such a study would be necessary to determine the maximal temperature value at the HD installation site $T^{\circ}_{\max}$ and the speed of its change $\dot{T}^{\circ}_{\max}$. It is also necessary to determine the time τ_{tech} at which the temperature at the place of HD placement could reach the value of the technological temperature as well as the time τ_{cor} over which the values of the response parameters are corrected. These values are necessary to select T°_{resp} and $\dot{T}^{\circ}_{resp}$.

In further research, it is planned to improve the proposed operational algorithm. In particular, it could be supplemented with units that would automatically determine a value for the parameters of HD response by way of self-learning.

7. Conclusions

1. It was established that the feasibility of an operational algorithm for a fixed-dynamic heat detector requires two time parameters according to which the values of the minimal static temperature of HD response T°_{resp} and the rate of increase in the temperature of its response $\dot{T}^{\circ}_{resp}$ are changed. The first parameter is the time over which the temperature at the place of HD placement would reach the value of the technological temperature (operating temperature) due to the ICE operation τ_{tech}. The second parameter is the time during which the values of the minimal static temperature of HD response are corrected, as well as the speed of increasing the temperature of its response τ_{cor}. It was also established that the parameters for the operational algorithm of a fixed-dynamic heat detector should include the set values of the maximal possible temperature $T^{\circ}_{\max}$ and the rate of its change $\dot{T}^{\circ}_{\max 1}$ and $\dot{T}^{\circ}_{\max 2}$. $\dot{T}^{\circ}_{\max 1}$, $\dot{T}^{\circ}_{\max 2}$ are maximal speeds of a temperature increase in the engine compartment due to ICE operation during and after the time τ_{tech}. $T^{\circ}_{\max}$, $T^{\circ}_{\max 1}$ and $T^{\circ}_{\max 2}$ are higher than the temperature and the ambient temperature change rate due to climatic conditions.

2. It was established that in the initial period of ICE operation, the rate of increase in the temperature in the engine compartment at short intervals is the largest and ranges within significant limits. It could exceed 290 °C/min. However, regardless of MV brand and ICE type, when the temperature in the engine compartment reaches the technological temperature, it would change within small limits. Then the temperature change rate would be lower, approximately 30÷50 °C/min. The air temperature of the environment would not affect. When an MV stops, the temperature in the engine compartment is higher than when it moves. This is due to an increase in the airflow speed. The temperature from above in the middle of ICE does not exceed 75 °C for MVs with a gasoline ICE. Thus, to prevent false HD response, when the ICE is working, the minimal static temperature of operation can be set to 110÷120 °C. The values

for τ_{cor} and τ_{tech} should be chosen to be the largest, then it would not significantly affect the HD efficiency.

3. A flowchart of the operational algorithm for a fixed-dynamic heat detector with variable response parameters has been compiled, namely a value for the minimal static temperature of response and a value for the temperature increase speed at which it works. These values of response parameters change based on the analysis of MV ICE operation. That makes it possible to detect the fire at an early stage and reduce the cases of false response caused by the temperature influences from ICE operation. The flowchart describes the operational algorithm for a fixed-dynamic heat detector, depending on the conditions during the operation of MVs.

4. Using the Simulink package in the MATLAB programming environment, the work of the proposed algorithm for a fixed-dynamic heat detector with variable response parameters was investigated. A given HD recognizes the following: when a temperature in the engine compartment changes due to the influence of climatic conditions, and when due to a fire; when a temperature in the engine compartment changes due to ICE operation, and when due to a fire. The results of our study confirm the effectiveness of the operational algorithm for a fixed-dynamic heat detector. The fixed-dynamic heat detector is triggered both by the maximal and dynamic components. As regards the maximal component for the proposed HD with variable response parameters, it is triggered about 2.3 times faster than the classic heat detector with a non-variable minimal static response temperature. As regards the dynamic component for the proposed HD, it is triggered during the time necessary to calculate the rate of a temperature increase over a certain period and compare it with the rate of an increase in the temperature of HD response.

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