Досліджено проблему захисту рятувальників від теплового ураження на початковому етапі ліквідації пожежі, коли немає повної інформації про пожежну небезпеку об'єкта й не задіяні протитеплові засоби. Обґрунтовано конструктивні підходи до розроблення автоматичного автономного теплозахисного пристрою для захисту рятувальників від теплового ураження. Випробувано макетний зразок пристрою, який продемонстрував ефективність охолодження організму рятувальника

Ключові слова: автоматичний автономний теплозахисний пристрій, захисний одяг пожежника, охолодження тіла пожежника

Рассмотрена проблема защиты спасателей от теплового поражения на начальном этапе ликвидации пожара, когда нет полной информации о пожарной опасности объекта и не задействованы противотепловые средства. Обоснованы конструктивные подходы к разработке автоматического автономного теплозащитного устройства для защиты спасателей от теплового поражения. Испытан макетный образец устройства, который продемонстрировал эффективность охлаждения организма спасателя

Ключевые слова: автоматическое автономное теплозащитное устройство, защитная одежда пожарного, охлаждение тела пожарного

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AUTOMATIZATION OF INDIVIDUAL ANTI-THERMAL PROTECTION OF RESCUERS IN THE INITIAL PERIOD OF FIRE SUPPRESSION

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1. Introduction

Over recent years, it is possible to trace a tendency of an increase in the annual number of fires on the territory of Ukraine [1]. Despite this, the number of people injured during fires decreased almost by half, though the toll remains steadily high and exceeds this rate in the developed countries [2].

A special feature of activities of rescue units is that all executed work is related to danger of injury and life risk. Main types of negative injury-causing factors include explosions and collapses, limited visibility or its complete absence, extreme temperature conditions, air humidity, a threat of getting electric traumas, and chemical injuries, etc.

Protective devices that defend firefighters-rescuers from a variety of dangerous factors are being created and improved in order to prevent injuries or minimize their effects. Special attention is paid to developing protection devices from the action of high temperatures [3–7].

At present, the means of protection of rescuers from the effect of extreme temperatures at the initial stage of fire suppression are not used due to their considerable weight and dimensions. Such means of protection stifle movements of rescuers and slow down performance of emergency operations. In addition, premature usage of additional ammunition will increase the time before fire suppression starts. In this situation, rescuers work only in special clothes for general purposes, which has no significant heat-shielding properties and do not protect from extreme temperatures and radiation. Such an approach to the application of special clothing exists in all foreign emergency services that the authors are aware of.

In addition, there is a lack of information about the limits of injury zones, which determines the hazard of a sudden change in the situation and the risk of inadequate human response to it. At the same time, individual means of thermal protection are applied after detection of thermal injury zones. The relevance of scientific research is caused by the need to solve the problem of protection of rescuers from thermal injuries at the initial stage of fire suppression. It is required to substantiate constructive approaches to the development of an automated autonomous device for the protection of rescuers from thermal injuries.

2. Literature review and problem statement

For evaluation of the situation with industrial injuries in subdivisions of the State Emergency Service of Ukraine (SES of Ukraine), the results of investigation into accidents that happened over 2005–2016 were analyzed.

In general, during emergency operations on the territory of Ukraine for 12 years, there happened 877 accidents, in which 1,034 rescuers were injured (Fig. 1, 2).

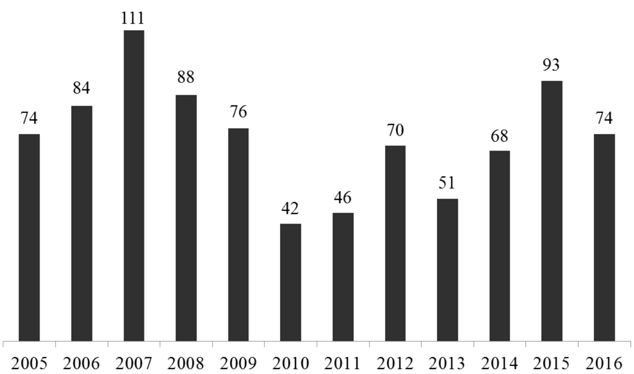

Fig. 1. Dynamics of accidents among personnel of SES of Ukraine

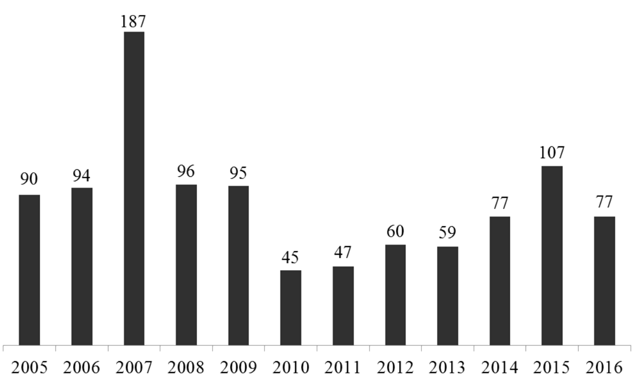

Fig. 2. Number of victims among rescuers during fulfillment of official duties

About 7 % of the total number of victims were fatally injured over 12 years, which is shown in Fig. 3.

Analysis of causes of injuries to rescuers showed that the largest number of people – 464 – received mechanical injuries of different nature (fractures, wounds, blows, dislocations, etc.). 79 people got thermal injuries, namely, thermal burns, hyperthermia, and hypothermia. 55 people were chemical burnt and poisoned. 11 rescuers suffered from dangerous effect of electric current (Fig. 4).

According to data, which were obtained from SES of Ukraine, 16 people, who participated in the anti-terrorist operation in the East of Ukraine, were injured over the last three years. 45 rescuers suffered through road accidents, diseases (coronary heart disease, pulmonary edema, acute coronary failure), insect and animal bites.

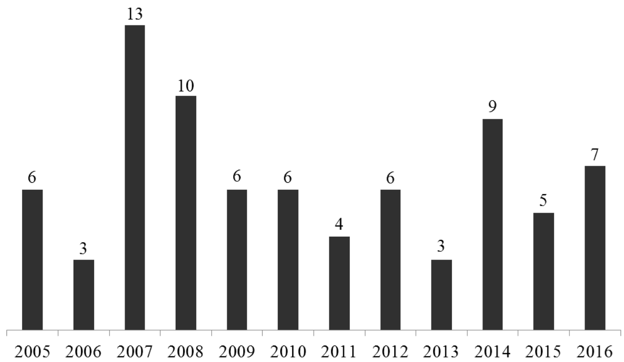

Fig. 3. Number of rescuers, fatally injured during fulfillment of official duties

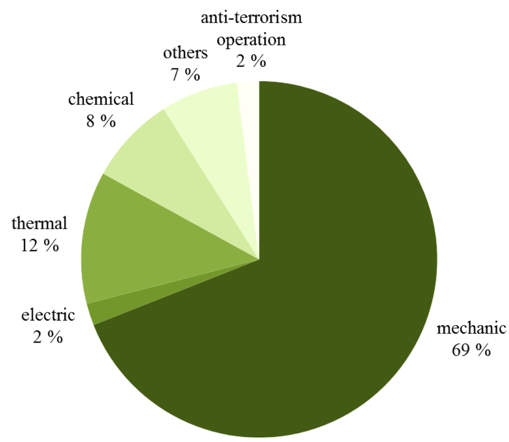

Fig. 4. Types of injuries to rescuers over the period of 2005–2016

According to results of investigation into accidents in SES of Ukraine, most people died (Fig. 5) from mechanical injuries (14), as well as due to a sudden deterioration of the state of health (15 people). 5, 2 and 1 person, respectively, died because of thermal, electric, and chemical injuries. No rescuer died while fulfilling official duties in the zone of anti-terrorism operation.

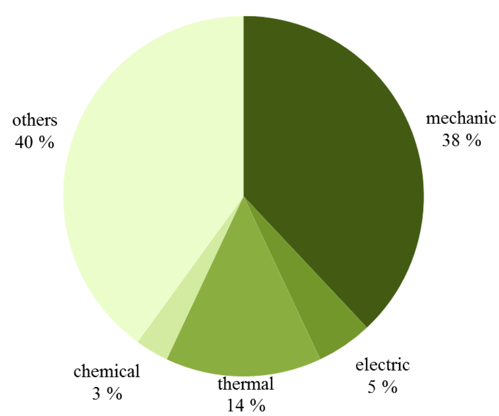

Fig. 5. Deadly injuries of rescuers over 2005–2016

A large number of mechanical and electrical injuries are caused by the fact that operative rescue operations are often performed under conditions of poor visibility, high temperature and air humidity, in the environment, which is unsuitable for respiration. The reason that leads to thermal injuries to rescuers at the initial stage and their complications is insufficient defensive action of special protective clothing for general purposes, rescue units are equipped with. During fire reconnaissance, people evacuation or in the course of performance of urgent operations involving localization of emergency situation, abrupt changes of thermal situation are possible. Inadequate or untimely rescuer's reaction to such change increases the risk of getting thermal injuries.

Results of investigations into accidents show that about 12 % of the rescuers during elimination of accidents and fires received injuries as a result of exposure to an open flame or intense heat flow. An example of such course of events is the fire that occurred on June, 8, 2015, on the territory of petroleum depot of "BRSM-Nafta" company in the village of Hlevakha in Vasylkiv region of Kyiv Oblast. Due to thermal radiation and convection flows from burning fuel, 20 people, including 3 rescuers, who had fatal consequences, were injured in the process of fire extinguishing. That is why improvement of the ways and means of protection of personnel of rescue units from the negative thermal effect is a relevant problem, the solution of which will increase operation and safety efficiency of rescuers while extinguishing fires.

Professional activities of personnel of SES units in Ukraine involve operation on sites of various purposes, long-term stay in areas of high temperature influence, in smoke and gas contaminated environment. These kinds of extreme activity are characterized by risks of thermal injuries and professional diseases, therefore the problem of providing safe working conditions and prevention of injuries to personnel of rescue units is particularly important.

In accordance with requirements of safety rules for working in bodies and subdivisions of SES in Ukraine, staff is not allowed to organize and perform urgent operations on fire sites without appropriate protective clothing. During emergency operations in the environment, unsuitable for breathing, rescuers must perform operations using the means of personal protection of the body.

The emergency elimination process can be conditionally divided into two stages. The first stage runs from the moment of arrival of units at an emergency site and involves reconnaissance of an area and a source of danger, detection of limits of the zone of destruction by hazardous emergency factors. At the same time, operations on the search and rescue of people who suffered in emergency are performed. According to the plan of priority actions, urgent work, aimed at emergency localization, is performed.

At the first stage, the plan of operations, which are implemented at the second stage, is developed. The second stage involves direct elimination of the emergency source by using appropriate methods and tools.

The least protected group includes rescue workers, who perform urgent operations involving reconnaissance of emergency sites, rescue and evacuation of injured people, perform immediate priority operations on emergency localization. This period of operations is characterized by insufficient information about destruction zones, thermal fields, areas of smoke and gas contamination with toxic and poisonous substances. At the same time, water, powder, and foam means of fire extinguishing are not deployed at this stage, and equipment of gas and smoke protection is not applied either. An additional problem is shortage of time it takes a rescuer to react to an unexpected change in the situation. It is known that it takes the organism 15–20 s to respond to a sudden change in the situation. On fire sites with possible rapid increase in temperature of heat flows (up to 1000 °C/s and more), it is necessary to apply additional protection means that work regardless of human response. Therefore, to prevent injury, it is important to use quickly acting automatic means of individual protection from thermal injuries.

Research, aimed of improvement of special clothes of firefighters and means of protection from thermal effects is actively carried out throughout the world. Attention is paid to the problem of substantiation of rational thermoinsulation characteristics of layers of material, which is used to make the ammunition of a rescuer. In this case, protective clothing or its fragments were subjected both to convective and radiation thermal resistant testing [8]. Design features and properties of fabrics were found to be key factors that influence its thermoprotective properties. Existence of a thicker thermal insert in a multi-layered fabric system leads to higher thermal conductivity. A multi-layered fabric system that contains moisture barrier in the outer layer showed the least conductivity. Moreover, it was demonstrated that weight, thickness and heat resistance make a significant impact on performance of clothing [9]. The order was varied and parameters of layers of thermal insulation materials in designs of protective clothing were selected to minimize thermal load on a firefighter. To measure insulating properties, evaporation resistance and total heat losses through the shells at various combinations of protective layers, mannequins that simulate human sweating are used [10].

To assess the influence of moisture on heat protective properties of multi-layered fabric systems of protective clothing for a firefighter, different conditions of humidity for the outer shell were simulated. For this purpose, a tester with the change in heat protection characteristic was used [11]. Individual simulation of thermal protection at various wind velocity was carried out on a life-size mannequin. Heat flow on the surface of the mannequin decreased as wind velocity increased. A decrease in radiative capacity was offered as protective strategies [12].

Behavior of fire-technical equipment when exposed to elevated temperatures was considered in paper [13]. It was proposed to wash the bodies of firefighters with a special composition for cooling them, however, its use is implied after performing rescue operations [14].

Electronic devices for personnel safety are widely used in fire-rescue units throughout the world. The company "VIKING Life-Saving Equipment" (Denmark) manufactures protective clothing for firefighters-rescuers, which is supplied with electronic devices for temperature control [15] in the under-clothing space and on its surface. Heat sensitive items that show measurement results are connected to LED-displays with current conductive buses, sewn between the layers of fabrics and materials of protective clothing. The device indication is maximally simplified and it includes three LED indicators that warn about the values of critical temperatures by scintillation or constant glowing.

The German company DR GER is the developer and manufacturer of safety device Bodyguard 1000 [16]. This device determines the state of immobility, as well as fireman-rescuer staying in the zone of the critical temperature value. In case of alarm, the device gives sound and light signals.

VDI company (Germany) created textile material that conducts electrical signals in order to manufacture protective clothing of firefighters-rescuers [17]. Clothing made of this material contains microsensors and sensitive fibers, that register a rescuer's heart rate, body temperature and existence of carbon monoxide in the premises.

Thus, the principle of passive thermal barrier is used in all modern types of rescue clothing that protects from elevated heat flows. In other words, materials with a low coefficient of thermal conductivity and high thermal capacity are used, or heat removal by a cold carrier with limited resource is provided [18]. Possibilities of protective action of such clothing are very limited. Means of individual protection from thermal injuries have a relatively large weight and a significant thickness of insulating layers of clothing, which prevents actions associated with movement over considerable distances, bendings, movements in confined spaces, etc. It is appropriate to use these means provided there are determined limits of thermal injury zones, within which urgent emergency operations must be performed.

It is worth paying attention to the idea of forced feed of cold carrier that allows us to enhance significantly the thermoprotective resource of equipment, which provides improved tactical capabilities of the units and increases effectiveness of fire extinguishing [19, 20]. To use such means, it is necessary to have a deployed water supply system, which is not implemented in the initial period of the emergency. In addition, there is a risk of thermal injuries to a rescuer, because the decision to turn on cooling is made independently based on individual sensations and may be untimely.

Summarizing the overview of information sources, it can be argued that the known technical and design solutions do not make it possible to provide for protection of rescuers automatically at the initial stage of fire suppression. That is why it is a relevant problem to provide rescuers with protection from heat injuries during the site reconnaissance, people evacuation and execution of urgent priority operations involving emergency localization.

3. The aim and objectives of the study

The aim of present study is to substantiate constructive approaches to the development of autonomous device of individual protection of a rescuer from thermal injuries at the initial stage of emergency elimination.

To reach the set aim, the following tasks have to be solved:

– to motivate feasibility of application of automatic autonomous means of protection of rescuers from thermal injuries at the initial stage of emergency elimination;

– to create a physical model of automatic autonomous device of protection of rescuers from thermal injuries and to verify efficiency of this device;

– to conduct preliminary testing of the sample model of automatic autonomous device of rescuers' protection from thermal injuries.

4. Study of structural approaches to rescuers' protection from thermal injuries at the initial stage of emergency elimination

At the initial period of operations on emergency elimination, there is no need for long-term protection of a rescuer from the influence of thermal factors – radiation, hot objects (conductive heating) or convection gas flows. To achieve this goal, a rescuer needs to have a mobile stock of a cooling agent, which makes possible the short-term protection from thermal injuries. This will provide for execution of short-term operations on emergency localization or will allow leaving the area of thermal injuries safely.

The device must be actuated automatically, regardless of the subjective feelings of a person.

The authors proposed automatic autonomous heat protective device, the design system of which includes hydraulic and automatic parts and looks as follows (Fig. 6). The hydraulic part contains a tank filled with the cooling agent under pressure. The pipeline for feeding the cooling agent from the tank to the atomizer, fixed on the rescuer's helmet is attached to it. In addition, the hydraulic part includes the shutter of the electromagnetic valve, located on the neck of the tank. In the initial state, the shutter overlaps the pipeline.

The automatic part of the device consists of the control unit with the independent battery, located in the under-clothing space, connected by wiring to the temperature sensor, and the driving part of the electromagnetic valve.

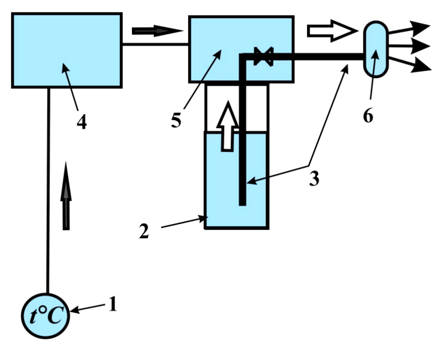

Fig. 6. Structural diagram of automated autonomous thermoprotective device: 1 – temperature sensor; 2 – tank; 3 – pipelines; 4 – control unit; 5 – electromagnetic valve; 6 – atomizer; dark arrows – direction of giving electric signals; light arrows – direction of a cooling agent

Autonomous thermoprotective device operates at several stages. At the initial stage of an emergency rescue operation, site reconnaissance, rescuing and evacuation of injured people are carried out, and urgent operations on emergency localization are performed. When water supply systems are not deployed and other refrigerant sources are missing, rescuers use protective clothing for general purposes. A firefighter puts on an autonomous automatic thermoprotective device for protection from thermal injuries.

After that he attaches to his belt or puts in a special bag a tank, filled with autonomous resource of a cooling agent (Fig. 7). The air pressure, which serves as a source of pushing a cooling agent to the pipeline, is created in the tank in advance.

The electromagnetic valve, mounted on the neck of the tank, in the initial state keeps the pipeline overlapped. It is desirable to provide for the possibility of emergency disconnection of the tank with the valve after a cooling agent is over in order to decrease the loading of a rescuer. The control unit is placed in an inside pocket of clothing, wires from the unit are connected to the temperature sensor and the driving part of the electromagnetic valve. The temperature sensor, set to the temperature, which is maximal permissible for the human body (50 °C), is fixed on the chest of a rescuer near the heart between the body and the inner layer of underwear. The spray-nozzle, connected to the valve with flexible piping, is fixed on the helmet. There may be one injector or more. The jet hollow spray is directed at the front part of a rescuer's protective clothing for its uniformed sprinkling.

Fig. 7. Equipment of a rescuer in the protective clothing with automated autonomous thermoprotective device. Front and rear view: 1 – temperature sensor; 2 – tank; 3 – pipelines; 4 – control unit; 5 – electromagnetic valve; 6 – atomizer

During execution of operations, the rescuer gets into the zone of extreme heat injuries, in this case the surface of his operational clothing is intensively heated (due to its thermal conductivity), and the body is heated up to the temperature of 50 °C. The person is not able to assess the temperature level in the under-clothing space promptly and accurately, which creates the risk of thermal injuries in the form of overheating of the body or heat stroke, loss of consciousness, etc. Existence of the temperature sensor makes it possible to improve accuracy of assessment of the degree of body heating and to make the process of bringing the cooling device into effect automatic. After reaching the critical temperature (50 °C) the sensor gives an electric signal that gets to the control unit, where the valve receives the command to open the shutter in the pipeline. Through the open pipeline a cooling agent under the influence of excess air pressure gets from the tank to the atomizer. Duration of cooling agent feed is controlled by setting on the control unit and is supposed to be 3–8 s, after the set time and spraying of a cooling agent are over, the control unit gives the command to close the valve. Sprinkling of the surface of protective clothing leads to a decrease in body temperature of a rescuer due to cooling the surface of clothing with a cooling agent, as well as due to energy absorption during evaporation of a cooling agent. Short-term cooling enables a rescuer to leave the area of thermal injury safely. In case urgent actions in the area of thermal injuries continue, the automatic autonomous thermoprotective device provides periodic cooling in the pulsed mode until the resource of a cooling agent is exhausted. Pulsed supply of a cooling agent, which begins when the critical temperature in the under-clothing space is reached and stops after cooling to a safe level, allows spending it sparingly, which increases the term of protective operation of the device. Cooling of the surface of protective clothing can decrease thermodestruction of material and increase its operation term.

5. Results of research into the model and the model sample of automated autonomous thermal protective device

To prove feasibility of creating an automatic autonomous thermoprotective device, we manufactured and tested its model. As the sensor, we used the waterproof termistor NTC 10 k 1 % 3950, which can measure temperature in the range from –20 to +105 °C. The sensor was connected to the control unit, created on the basis of microprocessor AT MEGA 32 (manufactured by Atmel Corporation Co, Hong Kong).

As a cooling agent, we used three liters of water at room temperature (approximately 21 °C), poured into a metal tank of five-liter capacity. The air under pressure of 0.02 MPa was pumped into the tank. An electromagnetic valve, capable to withstand the maximum pressure of 0.17 MPa in the system, was fixed at the neck of the tank.

As an analogue of the human body we used a plastic cylindrical tank of the capacity of six liters, filled with water, heated to 37 °C. The temperature sensor, preliminarily set to actuation when heated to 50 °C, was placed on the surface of the tank and covered with cloth. The model tank was heated using the infrared heater of UFO Ecoline/30 type (Turkey) with a capacity of 2,900–3,200 W, located at the distance of about one meter from the model. The temperature was controlled in the sensor location area using the thermometer of Mastech MS 6531a type (China). The temperature was measured at the intervals of five seconds and as well as on condition of the valve actuation, starting of operation or stop in sprinkling on the tank through the nozzle. Water feed through the nozzle was 0.1 l s^{-1}. The duration of water feed was determined by setting a control unit; it was five seconds. The measurement results are given in Table 1.

Table 1

Dynamics of temperature of tank surface during operation of cooling device*

T, s	0	5	10	15	17	20	22	25	30	35
t, C	35	35	42	45	50	38	37	42	50	37

*Note: * – the period of heating of the model is designated in italics, heating and sprinkling are designated in bold; T is the time from the beginning of the experiment, s; t is the temperature of the tank surface, °C*

The device timely reacted to the change in the tank surface temperature and cooled it for five seconds in automatic mode. Automatic device actuated at heating the surface of the tank-analogue to the assigned level of t=50 °C. Supply of the cooling agent lasted for T=5 s after actuation of the device, which provided cooling of the tank surface to the level of the human body model of 37 °C. Obtained data demonstrated effectiveness of the proposed technical solution.

Having taken into account the test results based on the elements of the model, designers created and tested under laboratory conditions the model sample of automatic autonomous thermoprotective device (Fig. 8). The sensor for temperature measurement in the under-clothing space was set taking into account the inertia subsystem "clothing-body". The sensor is located under the surface of protective clothing of a firefighter. Actuation occurs at heating to the temperature of 45 °C. Additionally, the temperature in the sub-clothing space was measured with the help of the thermocouple and temperature of the outer surface of protective clothing was measured in the place of heating using the contactless thermometer of MastechMS 6531 type (China). It was heated by using an open flame source (a gas burner), which was located at the distance of about 0.3 m from the surface of operational clothing. Temperature measurement was performed at intervals of 10 s. Water feed through the nozzle was 0.1 $l \cdot s^{-1}$. Duration of water feed was determined by setting of the control unit and was 5 s.

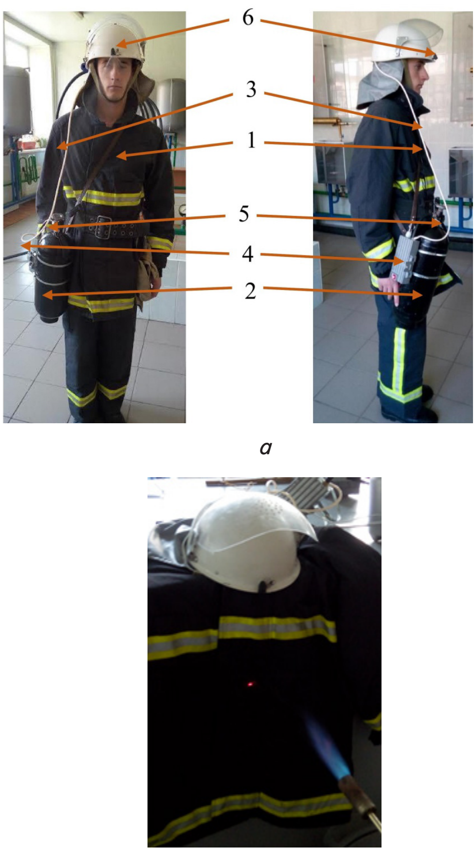

Fig. 8. Model sample of the automated autonomous anti-thermal device: *a* — physical appearance of a rescuer in protective clothing; *b* — laboratory fire tests: 1 — temperature sensor; 2 — tank; 3 — pipelines; 4 — control unit; 5 — electromagnetic valve; 6 — atomizer

Measurements were performed on empty clothing, because involvement of volunteers requires special safety measures. A total of 12 test cycles were held within five days. Identical indicators of temperature dynamics in the sub-clothing space during operation of the autonomous automatic thermoprotective device were obtained. Error evaluation in previous testing of the model sample is not implied.

Test results of the model sample of the cooling device demonstrate its operation efficiency in terms of protection of a rescuer. The automatic operation mode of the device provides reliable evaluation of thermal environment in the under-clothing space and protection from the "human factor". Pulsed mode of the device operation provides economical consumption of a cooling agent and an increase in duration of a rescuer's protection from heat injuries. Temperature (t_{tun}), at which the device actuated, was 45 °C. The test results, particularly the change in temperature during heating and actuation of the automatic device in the under-clothes space are shown in Fig. 9

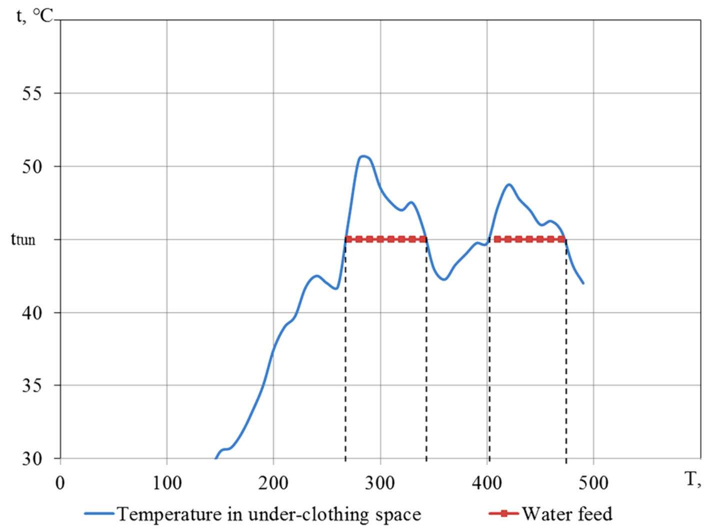

Fig. 9. Dynamics of temperature in under-clothing space during operation of autonomous automatic thermoprotective device

6. Discussion of results of laboratory study of the model sample of automated autonomous anti-thermal protective device

Obtained testing result proves the possibility of provision of rescuers' protection from the influence of negative fire factors at the initial stage of operations on emergency elimination. In this period, rescuers determine the limits of zones of damage by negative fire factors and existence of victims, as well as perform operations according to the plan of priority actions on emergency localization and elimination.

Such operations are performed in special protective clothing for general purposes, which does not provide protection of the human organism from intense heat loading. This can be explained by the need to perform rapid reconnaissance, lack of time to prepare for usage the means of individual and collective protection from thermal factors and lack of information on location of areas of injuries to humans by negative fire factors.

In comparison with the known means of protection from thermal injuries, in the course of operation, the device does not need additional sources of power or materials. The refrigerant is refueled and the battery is charged in advance on the location of a fire unit. The device is brought into readiness when a rescuer puts on the clothing for special purposes. The automatic autonomous device of protection from thermal influence, characterized by small weight and dimensions, must be a part of a rescuer's equipment along with respiratory equipment. Automatic operation mode of the device, which allows avoiding subjective assessments of the state of environment, is also important.

The operation speed of the device exceeds reactions of consciousness of a rescuer. Estimation accuracy of the temperature sensor in the under-clothing space exceeds the accuracy of the human subjective assessment. Unlike the existing means, the proposed device independently assesses the state of environment and gives a signal to actuation of hydraulic spraying system. Most of the existing means of thermal protection perform the signal function, alerting to dangers. It is expedient to use a part of protection devices for operation only in explored areas of thermal injuries [18]. Mobility, small weight, and dimensions of the proposed automatic autonomous device of rescuers' protection from heat exposure possess a significant advantage over existing designs. This advantage is evident not only during the use at the initial stage, but also at other stages of fire suppression.

The proposed structural scheme, as well as the results of testing of the model and the model sample of automatic autonomous thermoprotective device demonstrated its efficiency and effectiveness. The device actuated when the assigned temperature t_{tun} in the under-clothing space was reached. Within fixed time T, it fed a portion of a cooling agent, sufficient for cooling of protective clothing to a safe temperature in the under-clothing space.

It was additionally found that due to sprinkling of the surface of special clothing with the cooling agent, the fiber, it was made of, was not heated more than the temperature of thermal destruction of fibers. This allows us to increase significantly the operation period of the special protective clothing.

In conclusion, it can be argued that structural approaches to designing autonomous means of individual protection of a rescuer from heat injuries at the initial stage of emergency elimination were substantiated.

Subsequently, such a design can be brought to serial production and equip the SES units. For this, the structural and design refinement of individual components and the system as a whole is required. It is necessary to optimize the tank weight and capacity, decrease the weight of separate elements, study the problem of reliability and thermal resistance of pipelines, wires, etc. It is also essential to carry out field fire testing of model samples.

7. Conclusions

1. To prevent thermal injuries of firefighters, we substantiated feasibility of application of autonomous automated device for protection against thermal injuries, including hydraulic and electrical parts.

2. For preliminary verification of efficiency of the proposed scheme, the model of the automatic autonomous device was created. Conducted tests demonstrated the adequacy of device operation to the assigned temperature and time parameters. In automatic mode, the device actuates at reaching permissible temperature of 50 °C, the pulse of feeding the cooling agent, which was 0.1 l s^{-1} within 5 s, was sufficient to cool down the protective coating (clothing analogue) to the body temperature.

3. The model sample of the automated autonomous device for protection of rescuers in the initial period of fire suppression was created. Cooling was provided by pulsed feed of a cooling agent through the atomizer on the surface of special protective clothing. Conducted preliminary tests proved the possibility to prevent heating of under-clothing space to the temperature of higher than 50 °C under automated mode.

4. It was additionally established that external sprinkling of special firefighters' clothing for general purposes opens a possibility to increase its operation term as a result of countering thermal destruction of fabric it is made of.

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