UDC 614.8(1.23):613.6]519.673
DOI: 10.15587/1729-4061.2022.265758

DETERMINING PATTERNS OF THE INFLUENCE OF LOW TEMPERATURES OF THE EXTERNAL ENVIRONMENT ON HEAD PROTECTION FOR A MOUNTAIN RESCUER

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The basic principles of the need to develop a methodology for determining the level of protection of the rescuer's head during search and rescue operations in mountainous areas under conditions of low temperatures have been substantiated in this paper. The shortcomings of the existing system for ensuring the safe mode of search and rescue operations of rescuers in mountainous areas at low temperatures have been identified. Based on the statistical analysis of search and rescue operations, it was established that the greatest number of them occurs in the fall-winter period. It was determined that on the territory of the Carpathian Mountains the largest number of search and rescue operations is carried out in Zakarpattia, Ivano-Frankivsk, and Lviv oblasts. An analysis of working conditions was carried out. The results of studies into the effectiveness of thermal insulation of protective clothing of a mountain rescuer were analyzed. Mathematical modeling of heat and mass transfer in the body of a mountain rescuer was carried out using MATLAB software. Modeling of changes in temperature processes in the volume of the rescue head model was carried out under the influence of environmental temperatures: –10 °C, –20 °C, –30 °C, and a metabolic rate of 600 W/m^2. Modeling was carried out on a 4-layer segment of the head. It was established that the effect of low temperatures on the face, head and, accordingly, the hypothalamus through the frontal part of the rescuer's skull leads to disability already at minute 17 in the absence of head protection equipment. The use of a model for predicting a decrease in body temperature as a result of exposure to the external environment and the level of protection by the rescuer's individual means will determine the time of risky decrease in brain temperature (up to +32 °C) and prevent a negative impact on the health of the rescuer

Keywords: search and rescue operations, low temperatures, protective clothing, heat and mass transfer modeling, rescuer's head

Received date 15.07.2022
Accepted date 29.09.2022
Published date 28.10.2022

***How to Cite:** Bolibrukh, B., Tokarskiy, O., Kovalenko, O., Stasevych, S., Tykhenko, O. (2022). Determining patterns of the influence of low temperatures of the external environment on head protection for a mountain rescuer. Eastern-European Journal of Enterprise Technologies, 5 (10 (119)), 39–48. doi: https://doi.org/10.15587/1729-4061.2022.265758*

1. Introduction

In the context of the functioning of the civil protection system in the highlands, the question of finding and rescuing tourists is expected. The functioning of the search and rescue system in mountainous areas usually operates within the unified state system for preventing and responding to man-made and natural emergencies. However, as of today, the issue of rationing working hours and modes of operation of a mountain rescuer during search and rescue operations has not been determined. The problems of predicting the optimal time of search and rescue operations without causing irreparable damage to the health of the rescuer under the influence of low temperatures in countries where there are mountain systems remain solved. Risk factors have predictable indicators of the formation of an environment in which mountain rescuers can perform tasks. The term "predictable" is reasonably used for emergencies under normal conditions of operation of the technogenic load system and takes into consideration the involvement of additional specialized units in its elimination. Accordingly, during the performance of emergency and other emergency activities in the area of responsibility, workers may be affected by related dangerous and harmful factors. Factors of influence in mountainous areas have both subjective and objective origin.

Therefore, an urgent problem is to predict the optimal time of search and rescue operations in mountainous areas without harm to the health of the rescuer under the conditions of exposure to low temperatures.

2. Literature review and problem statement

Many scientific studies address the physiological state of a person under the influence of extreme temperatures. In [1], it has been proven that prolonged local exposure to cold can lead to vasoconstrictor reactions. Paper [2] states that prolonged exposure of muscle nerves and tissues to low temperatures (to –32 °C) can lead to impaired physical and thermophysical characteristics, disability, and even death. But these works do not provide information about the optimal time for conducting search and rescue operations without harm to health. In [3], the assessment of the basic thermal insulation of protective clothing of workers in the Arctic quarries is given. For research, protective clothing was chosen, taking into consideration professional (time spent in the fresh air), environmental (temperature, wind, humidity), and individual factors (cold sensitivity, general health) [4]. However, the results of studies have shown that protective clothing does not provide a sufficient level of thermal insulation at ambient temperatures below –10 °C. Analysis of literary data reveals that it is important to check the effectiveness of the loads of a mountain rescuer, especially outdoors, where temperatures can change every hour. An option to overcome the corresponding difficulties associated with the impact on the rescuer's health of low temperature may be to optimize his work time. This approach is used in [5], but the modeling of heat and mass transfer in the human body was carried out without experimental research.

Modern research on modeling the effect of low temperatures on open (unprotected) areas of the body, in particular the face, is rather limited. However, in works [6, 7], it is shown that most of the existing models are based on the equation of the energy balance of the body, which requires modeling and imitation of the heat exchange system of the human body under the condition of exposure to low temperatures. In particular, additional studies are needed on the phenomenon of heat transfer on the surface of the human body, as well as the heat transfer mechanisms arising in the volume of living tissue. In addition to those works, it is necessary to note study [8] in which specific reference points of internal temperature associated with physiological reactions are detailed. However, the methodological foundations of studies of the effect of low temperatures on the brain of a rescuer during long-term, difficult search and rescue operations were not carried out. Modeling of heat and mass transfer in the system "external environment - human brain" will provide an opportunity to improve the methodology for predicting the optimal time of work under the influence of low temperatures and various loads.

3. The aim and objectives of the study

The aim of this study is to substantiate and develop a model for predicting the optimal time of work under the influence of low temperatures and heavy loads of a mountain rescuer to minimize the impact exerted on his health by dangerous factors of hypothermia.

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

– to analyze the working conditions of the rescuer in the mountainous areas of the Carpathian region of Ukraine and determine the dominant dangerous and harmful factors affecting the health of the rescuer;

– to investigate the technical characteristics of the rescuer's personal protective equipment;

– to build a mathematical model of heat and mass transfer in the body (head) of a rescuer, depending on temperature and loads.

4. The study materials and methods

The object of this study is the safety of a mountain rescuer under the influence of low temperatures.

The main hypothesis of the study assumes that the effect of low temperatures on the mountain rescuer leads to disability. Therefore, under the conditions of search and rescue operations, it is necessary to determine the effective level of protection not only of the body, upper and lower extremities, but also of the head (face).

For the purpose of conducting research, the following materials were used: reports of garrisons of the State Emergency Service of Ukraine (Ivano-Frankivsk, Lviv, Zakarpattia, Ternopil, Chernivtsi oblasts). Data on the involvement of rescuers for search and rescue operations in the Carpathians during 2018–2020 were used [9]; physiological parameters of a person, temperature indicators of the environment, technical characteristics of the rescuer's equipment; technical characteristics of personal protective equipment.

To build and substantiate the model, methods of statistical analysis were used; MATLAB software package; standard procedures for the study of thermal insulation properties of protective clothing (PC) and ergonomics of temperature environments with the prediction of risks to the health of workers. We also used methods of international, European and US standards in the field of research of psychophysiological parameters of a person during work under the conditions of low temperatures and loads.

5. Research results and model construction

5. 1. Investigating the working conditions of a rescuer in a mountainous area

The functioning of the search and rescue system in the mountainous areas of the western oblasts of Ukraine operates within the unified state system of prevention and response to emergencies of anthropogenic and natural nature. According to [9], during the period of 2015–2020, search and rescue units of the Main Departments of the State Emergency Service of Ukraine (SES) of Ukraine in Zakarpattia, Ivano-Frankivsk, Lviv, Ternopil, Chernivtsi oblasts, the Second Special Center for Rapid Response of the State Emergency Service of Ukraine were involved in emergency rescue and other emergency activities (EROEA) in mountainous areas more than 2500 times. As a result of EROEA, 2750 people were saved, about 1500 people were provided with medical care. More than 20 units respond to citizens' requests for assistance in the mountainous region of Ukraine. In Ukraine, search and rescue operations are carried out only by units of the State Emergency Service. There is no legal framework for functioning in the field of occupational safety and working hours for rescuers in mountainous areas. In mountainous areas, as a rule, search and rescue operations at natural facilities are carried out by a small, in number, rescue unit. This may be due to a fairly large list of factors, starting with the possible absence of transport routes and ending with the technical impossibility of carrying out rescue operations by a large group of rescuers (for example, in vertical caves). It is the number of people in a rescue unit that is one of the factors for effective operational work. A large unit can perform more tasks at the same time, be equipped with more rescue equipment. A small rescue unit is more mobile, can perform purely specialized tasks, which in turn gives its advantages. The primary link of the rescue system in the highlands is the search and rescue unit, which includes mountain search and rescue departments. The number of staff of the search and rescue department is from 5 to 8 personnel. The staff list includes department commander, mountain rescuer, paramedic, car driver.

To solve the task related to the effect on the rescuer of dangerous and harmful factors, 28 main statistical indicators were selected – factors of influence. These factors are grouped according to three components of the personal safety of the rescuer: fire, man-made and natural hazards; transport and information support; technological safety of personal protective equipment (PPE) [10]. Risk indicators are given in Table 1.

Table 1

Indicators of the risk of potentially dangerous and harmful factors to a mountain rescuer

Potential sources of risk	Group
Mountain system type	fire and technogenic safety
The height of rescue operations	
Climatic conditions	
Temperature indicators of the environment	
Burning load, square, m^2	
Type and aggregate condition	
Number of population (persons) in the work area	
Presence of chemically dangerous substances	
Number of mines	
Number of hydraulic structures	
Number of careers	
Number of potentially dangerous objects	
Explosive objects	
Fire-hazardous objects	
Radiation-hazardous objects	
Hydrodynamically dangerous objects	
Biologically hazardous objects	
Flooded areas, thousand km^2	
The number of settlements in which flooding was noted, pcs.	
Flooded areas of settlements, km^2	
Number of power plants	
Length of pipeline networks in km	
Type of transport	transport and information support
Number of transport and means of communication	
Time of autonomous use of means of communication	
Type of personal protective equipment	Technological safety PPE
Protection indicators	
Duration of work, hours	

The set of indicators is established by factors characterizing risk factors in mountainous areas, taking into consideration dangerous objects and determining the nomenclature, intensity, and mechanism of influence of factors. Each of these signs has certain gradations. The intensity of the impact on the rescuer's body of temperature, dust, smoke, aggressive and non-aggressive environments, electricity is related to the characteristics of objects that may be in the emergency zone and search and rescue operations. In this regard, it is important to determine the intervals for varying the factors of rescue operations according to the specified signs and methods of their quantitative assessment.

According to the results of the analysis of reporting materials [9], we determined the number, time of day, and features of the influence of the dominant dangerous and harmful factors on the rescuer during search and rescue operations in mountainous areas, which are given in Tables 2, 3.

Table 2

Number, time of day, and duration of operation in the period 2016—2019 in the garrisons of the State Emergency Service

Garrison name	Number of search and rescue operations	Time of day (dominant, >50 % of cases)	The average duration of the operation, hours (dominant, >50 % of cases)
Lviv	762	after 18.00	>4
Ivano-Frankivsk	482	after 22.00	>3
Transcarpathian	432	after 16.00	>4
Chernivtsi	19	after 16.00	>3
Ternopilskyi	27	after 18.00	>3

Table 3

Conditions of rescue operations

Garrison name	Time of year	Ambient temperature, °C (highest/lowest)	Dangerous and harmful factors of influence
Lviv	fall-winter	28/–23	difficult terrain, high and low temperature, wind, communication problems
Ivano-Frankivsk	fall-winter	27/–24	low temperature, wind, high and low temperature, strong wind, fog, limited visibility, difficult terrain
Transcarpathian	fall-winter	30/–27	high temperature, wind, high and low temperatures, strong wind, fog, limited visibility
Chernivtsi	fall-winter	28/–23	low temperature, wind, high and low temperature, strong wind, fog, limited visibility
Ternopilskyi	fall-winter	25/–20	low temperature, wind, high and low temperature, strong wind, fog, limited visibility and communication

Thus, the main dominant dangerous and harmful factors in the winter-fall period for rescuers are low ambient temperature and significant physical exertion (600 W).

5. 2. Examination of the technical characteristics of the rescuer's personal protective equipment

Analyzing the reporting information of the search and rescue units of Ukraine [9], it was found that PPE of rescuers of different manufacturers and in its technical characteristics are intended to protect, first of all, climbers in the winter season. Taking into consideration the list of countries producing PPE, it has been established that the quality features of protective properties are harmonized only according to international standards [11, 12] and European norms [13, 14].

The priority and basic method for determining the protective properties of PPE under the action of low temperatures is the method using the Newton dummy under static and dynamic conditions. The most important criterion that makes it possible to meet the correct heat-absorbing clothing is the ambient temperature, the type of work done, and its severity. With intensive work, the body sweats, and the absorption of moisture reduces the insulation of clothing. For this reason, heat-absorbing clothing should be characterized by optimal (and not maximum) thermal insulation for this work.

We investigated the level of thermal insulation of the rescuer's PC in the laboratory at the Polytechnic University in Lodz (Republic of Poland) in accordance with the requirements set in [15]. For the experiment, three types of PC kits with different technical parameters were selected. Studies of thermal insulation properties were carried out on a stationary and a moving mannequin. The air temperature was – 20 °C. The relative humidity of the air was not taken into account. The air flow speed was 0.44 m/s. The average surface temperature of the dummy was 34 °C. Number of steps: 45 steps/min. Average sweat temperature is not taken into account. Inspiratory volume was not used. The results of research and calculations are given in Table 4.

Table 4

The value of thermal insulation of the rescuer's PC according to the results of the calculation

Clothing	Mannequin in motion, $m^2\cdot°C/W$	Mannequin fixed, $m^2\cdot°C/W$
The clothes are black	0.082	0.126
The clothes are silver	0.054	0.096
The clothes are orange	0.071	0.139

According to the results of thermal insulation indicators of a mountain rescuer, it is possible to predict the working time under the conditions of low temperatures and various physical exertion. However, the prediction will not be correct without taking into consideration the critical conditions of the rescuer and without taking into consideration the metabolic process and temperature effects on his brain. The dependence of the functional state of the brain is directly related to the process of severity of work and asphyxia under the influence of low temperatures. The use of a model for predicting a decrease in body temperature as a result of exposure to the external environment and the level of protection of the rescuer's PPE will make it possible to form a method of preventing irreparable loss of health by the rescuer. The method will also make it possible to determine the time of risky decrease in brain temperature (to +32 °C).

5. 3. Construction of a mathematical model of heat and mass transfer in the body (head) of a rescuer, depending on temperature and loads

The formation of the history of heat transfer and thermoregulation research in the human body has been known since the end of the eighteenth century. Classic is the description of heat transfer in Fourier's law, a mathematical expression of the dynamics of heat balance in solids, simplified as:

$$\rho\cdot c\partial T\partial t=\nabla k\nabla T+HE1, \qquad (1)$$

where ρ – density, g/m^3;

c – specific heat capacity, kcal/°K·kg;

k – thermal conductivity, kcal/(h·cm·°K);

T – temperature, °K;

t – time, hour;

H – net heat flux, except diffusion.

And the key work [16] on the measured temperatures of tissues and blood on the forearm enabled the construction of bioheat transmission equation. This equation turned out to be the key basis of future models, which are considered as:

$$\nabla k\nabla T+qp+qm-WCb(T-T\alpha)=\rho cp(\partial T\nabla t)E2,$$

$$\nabla k\nabla T+qp+qm-WCb, \qquad (2)$$

where k is the thermal conductivity of the fabric, W/m, °C;

T – fabric temperature in °C;

qp – energy deposit rate, W/m^3;

qm – metabolism, W/m^3;

W – local blood supply rate to the tissue, $kg/m^3\cdot s$;

Cb – specific heat capacity of blood, J/kg·°C;

Ta – arterial temperature, °C;

ρ – tissue density, kg/m^3;

cp – specific heat capacity of tissues, J/ kg·°C.

The model should describe the process of hypothermia during the simultaneous exposure to heavy physical exertion. Hypothermia is clinically described as the moment when the body temperature drops below 35 °C and has four levels of severity. The most informative is the level of moderate hypothermia where the body temperature is 85.2–89.6 °F (29–32 °C).

As a result of the analysis of the protective properties of PPE of a mountain rescuer (questionnaire tests of rescuers of the mountainous terrain of the Transcarpathian oblast) and similar protective properties of climbers' PC, the least protected parts of the body were determined. Such a part of the body was the head, namely the face. Protection of the body, upper and lower extremities turned out to be much more perfect than protecting the head. Therefore, we determined the need to develop a model of heat transfer in the head of the rescuer under the influence of low temperatures: –10 °C, –20 °C, –30 °C. Simulation was carried out using the MATLAB software package. During modeling, it is possible to control the processes that are investigated on the block model. For this, there are special blocks that play the role of windows where plots are built, or numerical information is displayed. The model represents the head as a separate 4-layer segment with the parameters given in Table 5.

To describe the mechanism of heat transfer that occurs in living tissue, we can use the bioheat equation by Penne [16]:

$$k\left(\frac{\partial^2 T}{\partial r^2}+\frac{\omega}{r}\frac{\partial T}{\partial r}\right)+q_m+\rho_{bl}w_{bl}c_{bl}\left(T_{bl\,\alpha}-T\right)=\rho c\frac{\partial T}{\partial t}, \qquad (3)$$

where k_i is the thermal conductivity of fabric, W/(m·K);

ω is the coefficient of geometry of the equation, ω=1 (for polar coordinates) and ω=2 (for spherical coordinates);

r – radius of the corresponding head tissue, m;

q_{mi} – tissue metabolism rate, W/m^3;

ρ_{bl} – blood density, kg/m^3;

w_{bl} – blood perfusion rate, l/s;

c_{bl} – blood heat capacity, J/(kg·K);

$T_{bl\,\alpha}$ – arterial blood temperature, °C;

ρ – tissue density, kg/m^3 ;

c – heat capacity of the fabric, J/(kg·K).

The model involves four tissues with corresponding characteristics: head tissues i: 1 – brain, 2 – bone, 3 – muscle, 4 – skin.

Boundary conditions at the boundary of each tissue under conditions of exposure to low ambient temperatures:

1) equality of temperature at the junction of tissues:

T_i^n at distance r_1, r_2, r_3, r_4;

2) equality of heat flows through each junction of neighboring tissues, which takes the form:

$$k_1 \frac{\partial T(r_1,t)}{\partial r} = k_2 \frac{\partial T(r_1,t)}{\partial r} \text{ at } r = r_1. \quad (4)$$

Radius of the head: $R=L_1+L_2+L_3+L_4$.

Radii of the corresponding fabric:

$r_1=L_1$;

$r_2=L_1+L$;

$r_3=L_1+L_2+L_3$;

$r_4=R=L_1+L_2+L_3+L_4$,

where L_1, L_2, L_3, L_4 – the length of the tissues of the head, skin, muscles, bone, and brain, respectively, m.

The equation of boundary conditions at the boundary R of the head with the medium is:

$$\frac{\partial T(R,t)}{\partial r} = \alpha\left(T(R,t) - T_c\right), \quad (5)$$

$$k_4 \frac{T_{4,j+1}^n - T_{4,j}^n}{\Delta r4} = \alpha\left(T_{4,R}^n - T_c\right), \quad (6)$$

where T_c is the temperature of the medium;

α is the coefficient of convective heat transfer of the scalp with the medium.

The phenomena of heat transfer on the surface of the human body, as well as the heat transfer mechanisms arising in the volume of living tissue, were modeled. In addition, the heterogeneous thermal and evaporative stability of clothing, as well as the effects of body posture on radiation heat transfer between the human body and its surrounding structures were considered. The anatomical part of a person is approximated by cylindrical and spherical elements and modeled in a component of the passive system – the head. It includes a total of four different fabric materials and simulates the dry, wet heat transfer of a person with the environment that is associated with the respiratory tract. The mechanisms of active control, which are aimed at keeping body temperature at an almost constant level of +37 °C, are modeled in the component of the active system "torso – upper and lower limbs". The control point according to the signaling approach reaches critical temperatures, which includes the skin and temperature of the hypothalamus as afferent signals that cause dynamic thermostatic reactions of tremors, sweating, vasoconstriction, and vasodilation. The nervous system monitors these changes and prevents them from going beyond the optimal values. Providing higher mental functions. The most evolutionarily developed parts of the nervous system (cerebral cortex, limbic system) are responsible for consciousness, mental activity, memory, emotions [7].

Table 5

The value of the physical and physiological characteristics of the tissues of the head

Quantity	Quantity designation	Head tissues and the value of their quantities			
		Skin 4	Muscle 3	Bone 2	Brain 1
Ambient temperature, °C	T	–10; –20; –30			
Initial fabric temperature, °C	T_0	34.58	34.81	35.07	36.96
Arterial blood temperature, °C	T_a	37			
Fabric density, kg/m^3	ρ	1085	850	1500	1080
Blood density, kg/m^3	ρ_{bl}	1060			
Specific heat capacity of fabric, J/(kg·K)	c	3680	2300	1591	3850
Thermal conductivity of fabric, W/(m·K)	(λ)	0.47	0.16	1.16	0.49
Segment radius, m	r	0.1040	0.1002	0.1005	0.086
Blood circulation speed (blood perfusion speed), l/s	w_{bl} (m^3 s^{-1} m^{-3})	0.001			
Basal value of blood perfusion, l/(cm^3)	W_{bl0}	5.48	0.0036	0	10.132
Basal value of metabolic rate, W/m$_3$	q_{m0}	368	58	0	13400
Heat capacity of blood, J/(kg·K)	c_{bl}	3617			
Coefficient of convective heat exchange of the head with the environment	α	4.06			
Head radius, m	R	0.1040			
Segment length (i), m	L	0.1040	0.1020	0.1005	0.0860

Temperature calculation is carried out for each tissue within each interval, respectively:

I. 0 ... r_1,

II. r_1 ... r_2,

III. r_2 ... r_3,

IV. r_3 ... r_4.

When calculating the temperature in interval I, the temperature T_i^n is determined by the temperature that goes beyond interval I T_{i+1}^n in medium II:

a) points that go beyond interval I towards interval II are determined from the boundary conditions (similarly for II, III, IV; for IV, it is still necessary to take into consideration the temperature of the medium).

For $j=r_1$: temperature T^n_{1,r_1+1} from this

$$k_1 \frac{T^n_{1,j+1} - T^n_{1,j}}{\Delta r_1} = k_2 \frac{T^n_{2,j+1} - T^n_{2,j}}{\Delta r_2}; \tag{7}$$

$$T^n_{1,j+1} = \frac{k_2}{k_1} \frac{\Delta r_1}{\Delta r_2} \left(T^n_{2,j+1} - T^n_{2,j} \right) + T^n_{1,j}; \tag{8}$$

b) points that go beyond interval II in the direction of intervals I and III are calculated similarly.

For $j=r_2$, the temperature T^n_{2,r_2+1} from this is:

$$k_3 \frac{T^n_{3,j+1} - T^n_{3,j}}{\Delta r_3} = k_2 \frac{T^n_{2,j+1} - T^n_{2,j}}{\Delta r_2}; \tag{9}$$

$$T^n_{2,j+1} = \frac{k_3}{k_2} \frac{\Delta r_2}{\Delta r_3} \left(T^n_{3,j+1} - T^n_{3,j} \right) + T^n_{2,j}; \tag{10}$$

c) points extending beyond interval III towards intervals II and IV are calculated similarly.

For $j=r_3$, the temperature T^n_{3,r_3+1} from this is:

$$k_3 \frac{T^n_{3,j+1} - T^n_{3,j}}{\Delta r_3} = k_4 \frac{T^n_{4,j+1} - T^n_{4,j}}{\Delta r_4}; \tag{11}$$

$$T^n_{3,j+1} = \frac{k_4}{k_3} \frac{\Delta r_3}{\Delta r_4} \left(T^n_{4,j+1} - T^n_{4,j} \right) + T^n_{3,j}; \tag{12}$$

d) points extending beyond interval IV towards interval III and environment are calculated similarly.

For $j=r_4$: the temperature T^n_{4,r_4+1} from this is:

$$k_4 \frac{T^n_{4,j+1} - T^n_{4,j}}{\Delta r_4} = \alpha \left(T^n_{4,R} - T_c \right); \tag{13}$$

$$T^n_{4,j+1} = \alpha \left(T^n_{4,R} - T_c \right) \frac{\Delta r_4}{k_4} + T^n_{4,j}. \tag{14}$$

Boundary conditions at the boundary of each tissue:

1) equality of temperature at the junction of tissues: T^n_i at a distance r_1, r_2, r_3, r_4 ;

2) equality of heat flows:

$$k_1 \frac{\partial T(r_1, t)}{\partial r} = k_2 \frac{\partial T(r_1, t)}{\partial r} \quad \text{at} \quad r = r_1; \tag{15}$$

– for interval I :

$$k_1 \frac{T^n_{1,j+1} - T^n_{1,j}}{\Delta r_1} = k_2 \frac{T^n_{2,j+1} - T^n_{2,j}}{\Delta r_2}; \tag{16}$$

– for interval II:

$$k_3 \frac{T^n_{3,j+1} - T^n_{3,j}}{\Delta r_3} = k_2 \frac{T^n_{2,j+1} - T^n_{2,j}}{\Delta r_2}; \tag{17}$$

– for interval III:

$$k_3 \frac{T^n_{3,j+1} - T^n_{3,j}}{\Delta r_3} = k_4 \frac{T^n_{4,j+1} - T^n_{4,j}}{\Delta r_4}. \tag{18}$$

Transition values of temperature at the joints of 4 layers of the head model under the influence of ambient temperature – 10 °C (without head protection) are shown in Fig. 1–6.

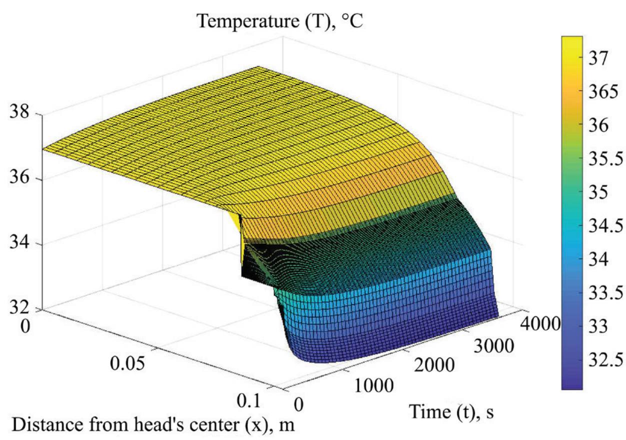

Fig. 1. Chart of the temperature fields of the rescuer's head under the influence of low temperature and – 10 °C

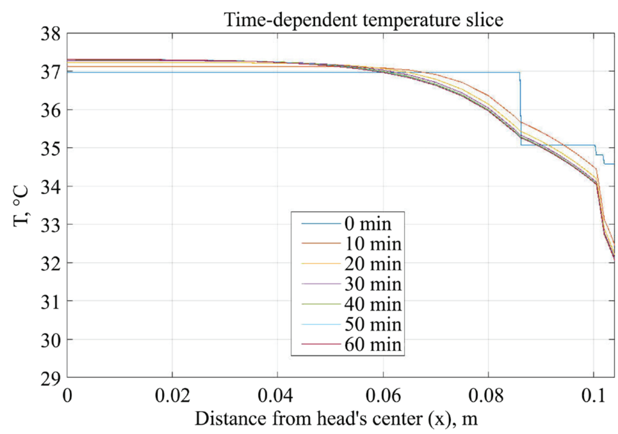

Fig. 2. Temperature slices in the layers of the head during the corresponding exposure to the external environment of low temperature – 10 °C

Transitional temperature values at the joints of the 4 layers of the head model under the influence of ambient temperature – 20 °C (without head protection) are shown in Fig. 3, 4.

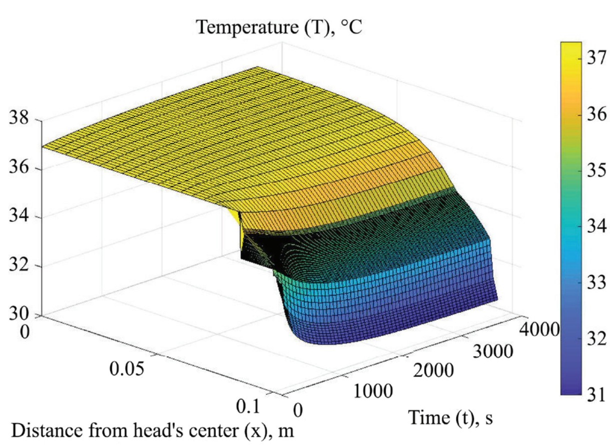

Fig. 3. Chart of the temperature fields of the rescuer's head under conditions of low temperature exposure – 20 °C

The total time in the model was projected 3600 seconds. According to the simulation results, the critical temperature indicator of +32 °C in three versions of the model is reached over 1200–1500 seconds and at a distance of 0.6 m from the center of the brain. The lifeguard's load reached 600 W – this is hard physical labor. In the process of performing search and rescue operations in winter, the load can be more than 600 W. Studies of critical temperature indicators of the brain [47–54] show that a decrease in brain temperature to +34 °C will cause the rescuer not only pain but also the lack of adequate solutions for his salvation and the hard-to-predict consequences of the state of health.

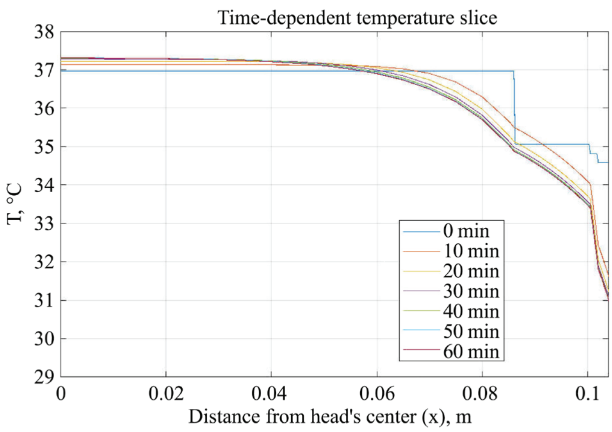

Fig. 4. Temperature slices in the layers of the head in time of the corresponding influence of the external environment of low temperature – 20 °C

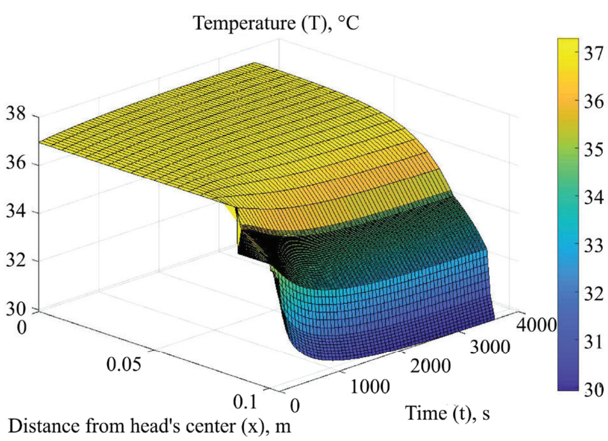

Fig. 5. Chart of the temperature fields of the rescuer's head under the influence of low temperature – 30 °C

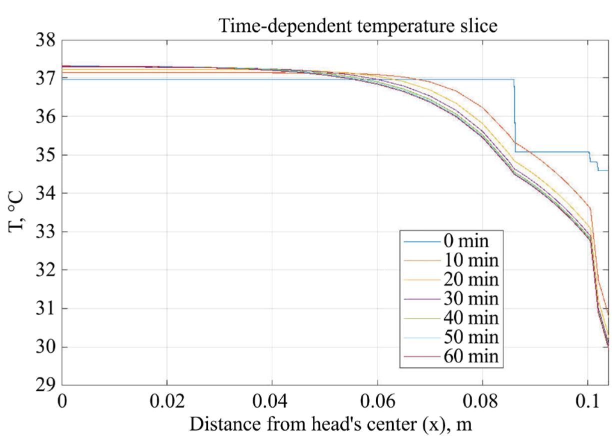

Fig. 6. Plot of slices of temperature changes in the volume of the head under conditions of exposure to low ambient temperatures – 30 °C

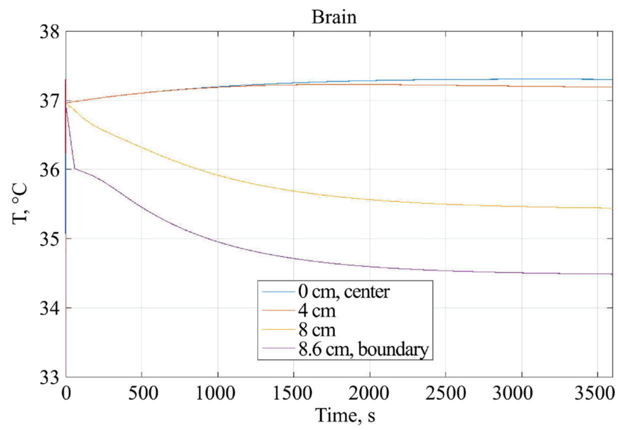

Fig. 7. Plot of modeling temperature regimes of the human brain during exposure to low temperature – 30 °C

According to the plot in Fig. 7, we can assert that at the boundary of the layer of 0.86 –0.8 m on minute 17, the temperature approached a dangerous indicator of +34 °C. Without head protection under the conditions of low temperature –30 °C.

Using the developed mathematical model of heat exchange of the head of a person with the environment, the process of cooling the head, protected with PPE, at ambient temperature of –30° was simulated. Fig. 8 shows the results of three heat transfer options when using personal protective equipment of the head with different values of the level of thermal insulation and different colors: black (thermal insulation level 0.182 m^2K/W); silver (thermal insulation level 0.362 m^2K/W); orange (thermal insulation level 0.451 m^2K/W).

The value of the brain temperature (actually the temperature of the eardrum) was controlled after a period of time of 3600 s. The following temperature values were obtained: for black head PPE (CLO_I) –40.25 °C; for silver head PPE (CLO_II) – 40.60 °C; for orange head PPE (CLO_III) – 40.95 °C.

Further processing of the obtained simulation results makes it possible to compare the projected brain temperatures at different values of the thermal insulation level of the studied protective clothing and at standard values of the thermal insulation level CLO_I=0.155 m^2K/W, CLO_II=0.310 m^2K/W, CLO_III=0.465 m^2K/W.

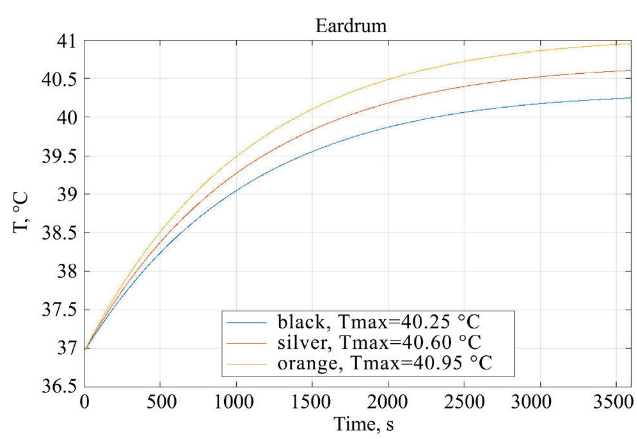

Fig. 8. Simulation results of three options for heat transfer of the head when using head PPE with different values of the level of thermal insulation

The dependence of brain temperature T on the thermal insulation of protective clothing is determined by approximation by a second-order polynomial of the obtained discrete values of brain temperature.

For this purpose, the MATLAB subsystem Curve Fitting Tools was used. Fig. 9 shows the window of this subsystem with calculated coefficients of the polynomial $p(i)$ and visualization of the plot of the approximating dependence (Fig. 10).

Thus, the obtained dependence of the temperature of the brain T on the level of thermal insulation of protective clothing A_i is represented in the form:

$$T = p_1 \cdot A_i^2 + p_2 \cdot A_i + p_3.$$

In this dependence, the coefficients of the polynomial take the following values: p_1=7.391; p_2=–2,076; p_3=40,38.

Fig. 10 shows the projected temperature values calculated according to the obtained dependence at standard thermal insulation levels (CLO_I=0.155 m^{2}K/W, CLO_II=0.310 m^{2}K/W, CLO_III=0.465 m^{2}K/W) and at the levels of thermal insulation of black, silver, and orange PPE of the head, respectively, 0.182 m^{2}K/W, 0.362 m^{2}K/W, and 0.451 m^{2}K/W.

Predicted brain temperatures, calculated from the established approximation dependence? take the following values:

– T_{CLO_I}=40.2358 °C;
– T_{black}=40.247 °C (exact value, 40.25 °C);
– T_{CLO_II}=40.4467 °C;
– T_{silver}=40.597 °C (exact value, 40.60 °C);
– T_{orange}=40.9471 °C (exact value, 40.95 °C);
– T_{CLO_III}=41.0128.

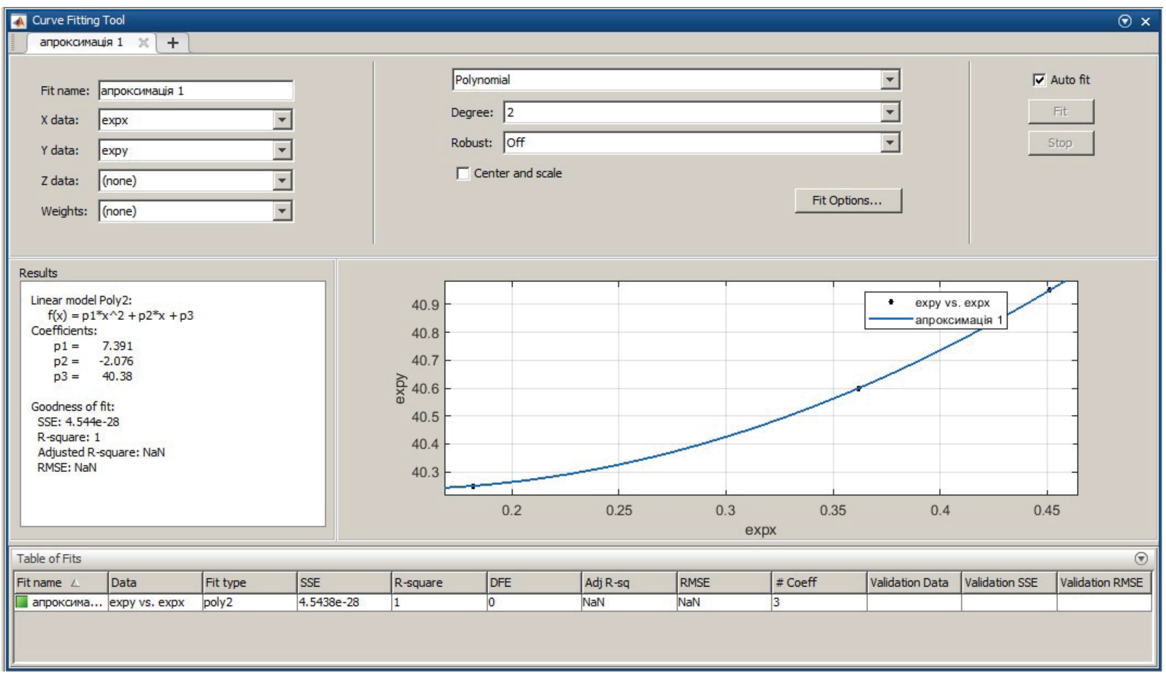

Fig. 9. The results of approximation of discrete data of the dependence of brain temperature on the level of PC thermal insulation with a second-order polynomial

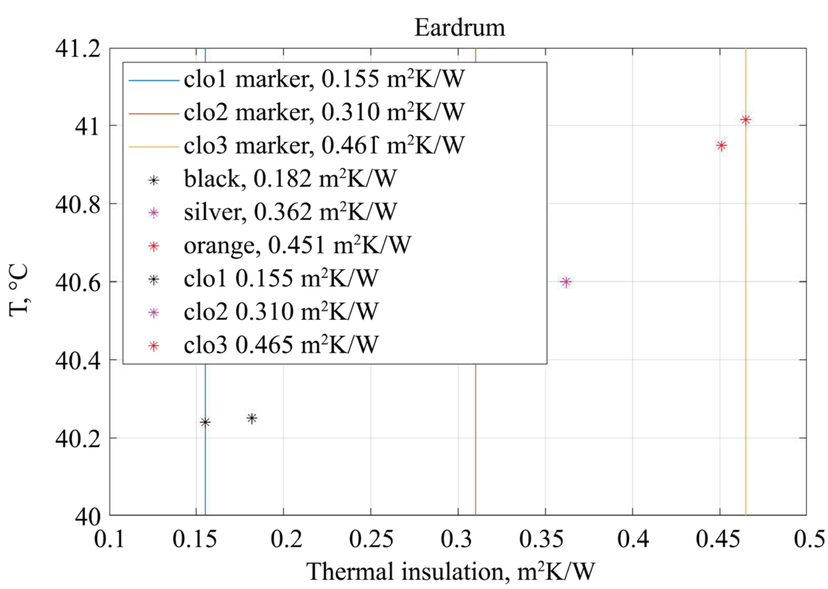

Fig. 10. Predicted values of brain temperature at specified levels of thermal insulation

6. Discussion of results of modeling and investigating the effect of low temperatures on the protection of the head of a mountain rescuer

Temperature factors affecting workers under the conditions of low temperatures, in particular rescuers in mountainous areas, require an appropriate response to protection – the construction of a heat-insulating barrier. The results of investigating the thermal insulation protection of the body, upper and lower extremities make it possible to consider a model for predicting the spread of low temperatures in the head model without taking into consideration the volume of the body and limbs. When modeling, the head is considered as a separate segment with constant characteristic parameters. These are such parameters as blood temperature, heat capacity of head tissues, basal value of blood perfusion, basal value of metabolic rate, coefficient of convective heat transfer of the head with the medium, initial temperature of the segment. The choice of the modeling object is determined by the results of an individual survey of rescuers of the garrisons of the State Emergency Service in Zakarpattia, Lviv, Ivano-Frankivsk oblasts. The results of the survey of 278 rescuers noted that the most vulnerable part of the body of a mountain rescuer is the head, namely the face.

The results of modeling the influence of low temperatures on the protection of the head of the mountain rescuer are explained by the perfect justification of the initial parameters of the model (Table 5) and by qualitatively determining the level of thermal insulation of PC (Table 4). Mathematical modeling of heat transfer processes in the layers of the rescuer's head makes it possible to trace the temperature gradient (formulas (5) to (16)). The obtained indicators of constant brain temperature (Fig. 3–5) are explained by the general intensive physical activity and high perfusion index.

The features of the proposed research method are a combination of field research, mathematical modeling under conditions of low temperatures and overtime total load. These factors of simultaneous impact on humans and the projected thermal insulation barrier of PC are not taken into consideration in modern scientific research. Also, the effect on blood perfusion by the factor of overtime total load of 600 W was not taken into consideration.

The results of modeling the effect of low temperatures on the protection of the head of a mountain rescuer can be applied when investigating the level of protection of the head of workers only under the conditions of low temperatures. Changes in the temperature conditions of environmental influence above –10 °C can significantly affect the simulation results. That is, the issues related to the inconsistency of temperature indicators, which can significantly affect muscle endurance, remained unresolved. The lack of rationing of the time of exposure to low temperatures by rescuers in mountainous areas significantly reduces the reliability of the projected work time. In addition to reducing the endurance of the rescuer and accelerating muscle fatigue outdoors at low temperatures, the process of forming a critical work time is important.

The limitation of this study is the problem of ensuring uniformity of a stable load of 600 W. Problematic is the process of validating the effect of low temperatures on the brain of a mountain rescuer. In the future, it is planned to carry out the validation process using an electroencephalogram (EEP).

The development of investigating the influence of low temperatures on the protection of the head of a mountain rescuer is to improve the methodology for determining the level of protection of a rescuer in mountainous areas from the effects of low temperatures and the prevention of occupational diseases. The simulation results can be used in the development of head protection products (HPP) to increase its thermal insulation.

Some difficulties in carrying out research may arise during the selection of volunteers for experimental loads. They must have high physical fitness. It is impossible to experimentally achieve fixation of the critical temperature of +34 °C for the hypothalamus. The location of the room with the EEP complex directly in the cryo chamber is impossible. It is necessary to locate the room with EEP in the room adjacent to the cryo chamber.

The study can be applied in creating reliable protection of the head under low temperature conditions. Also, the study can be used to develop regulations on the algorithm for conducting search and rescue operations.

In the future, it is planned to conduct research using EEP and develop separate software for the implementation of relevant experiments and the construction of models.

7. Conclusions

1. It has been established that in the system of ensuring the protection of the rescuer in the highlands in the fall-winter period, the key point is the protection of the head. The effect of low temperatures on the face, head and, accordingly, the hypothalamus through the frontal part of the rescuer's skull leads to disability as early as on minute 17 in the absence of HPP. Therefore, under the conditions of search and rescue operations, it is necessary to determine the effective level of protection not only of the body, upper and lower extremities, but also of the head (face). To study the thermal aspects of head gear, it is necessary to apply methods for determining the thermal insulation of the head protection product. It is determined that the dominant dangerous and harmful factors affecting the health of the rescuer are low ambient temperature (to –30 °C) and significant physical load (up to 600 W).

2. The technical characteristics of the rescuer's personal protective equipment have been investigated. The thermal insulation values of protective clothing of different colors for the rescuer were determined. They, accordingly, are (for a mannequin in motion and a fixed dummy): for black clothing – 0.082 $m^2{\cdot}°C/W$, 0.126 $m^2{\cdot}°C/W$; for silver clothing – 0.054 $m^2{\cdot}°C/W$, 0.096 $m^2{\cdot}°C/W$; for orange clothing – 0.071 $m^2{\cdot}°C/W$, 0.139 $m^2{\cdot}°C/W$, respectively. According to these indicators, it is possible to predict the operating time under the conditions of low temperatures and various physical loads.

3. The results of our study allow us to assert that at an ambient temperature of –30 °C and a total physical load of 600 W, a steady temperature regime of the hypothalamus functioning is observed, +37 °C for 3500 seconds. Such a temperature state is possible with the appropriate effective thermal insulation of PC. The indicated result of the research makes it possible to predict the optimal time of search and rescue operations in mountainous terrain at low exposure temperatures.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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