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BARTŁOMIEJ GŁUCH*[#]

EQUIVALENT CLIMATE TEMPERATURE ANALYSIS AS A CRITERION OF CLIMATE HAZARD EVALUATION IN POLISH UNDERGROUND MINES

ANALIZA TEMPERATURY ZASTĘPCZEJ KLIMATU JAKO KRYTERIUM OCENY ZAGROŻENIA KLIMATYCZNEGO W POLSKICH KOPALNIACH PODZIEMNYCH

The article discusses changes in Polish regulations concerning assessment of the climate hazard in underground mines. Currently, the main empirical index representing the heat strain, used in qualification of the workplace to one of the climate hazard levels in Poland is the equivalent climate temperature. This simple heat index allows easy and quick assessment of the climate hazard. To a major extent, simple heat indices have simplifications and are developed for a specific working environments. Currently, the best methods used in evaluation of microclimate conditions in the workplace are those based on the theory of human thermal balance, where the physiological parameters characterising heat strain are body water loss and internal core temperature of the human body. The article describes the results of research on usage of equivalent climate temperature to heat strain evaluation in underground mining excavations. For this purpose, the numerical model of heat exchange between man and his environment was used, taken from PN-EN ISO 7933:2005. The research discussed in this paper has been carried out considering working conditions and clothing insulation in use in underground mines. The analyses performed in the study allowed formulation of conclusions concerning application of the equivalent climate temperature as a criterion of assessment of climate hazards in underground mines.

Keywords: evaluation of microclimate conditions, climate hazard, underground mines, equivalent climate temperature, predicted heat strain model, PHS model

W artykule omówiono zmiany w polskich przepisach dotyczących oceny zagrożenia klimatycznego w kopalniach podziemnych. Obecnie głównym wskaźnikiem zaliczenia stanowiska pracy do jednego ze stopni zagrożenia klimatycznego jest temperatura zastępcza klimatu. Ten prosty wskaźnik mikroklimatu umożliwia wykonanie, w łatwy i szybki sposób, oceny zagrożenia klimatycznego. Proste wskaźniki mikroklimatu w dużej mierze posiadają uproszczenia i są opracowane do konkretnego środowiska pracy. Najlepszymi obecnie metodami oceny warunków cieplnych pracy są metody oparte na teorii bilansu cieplnego człowieka, gdzie parametrami fizjologicznymi charakteryzującymi obciążenie cieplne jest ubytek wody z organizmu oraz temperatura wewnętrzna ciała. W artykule opisano wyniki badań nad zasadnością

* STRATA MECHANICS RESEARCH OF THE POLISH ACADEMY OF SCIENCES, UL. REYMONTA 27, 30-059 KRAKOW, POLAND

Corresponding author: gluch@img-pan.krakow.pl

zastosowania temperatury zastępczej klimatu do oceny obciążenia cieplnego w wyrobiskach podziemnych. W tym celu wykorzystano model numeryczny wymiany ciepła między organizmem człowieka a otoczeniem, zaczerpnięty z normy PN-EN ISO 7933:2005. Omawiane badania zostały przeprowadzone przy uwzględnieniu ciężkości pracy oraz izolacyjności termicznej odzieży stosowanej w zakładach górniczych. Zrealizowane badania pozwoliły na sformułowanie wniosków dotyczących zastosowania temperatury zastępczej klimatu jako kryterium oceny zagrożenia klimatycznego w kopalniach podziemnych.

Słowa kluczowe: ocena warunków mikroklimatu, zagrożenie klimatyczne, kopalnie podziemne, temperatura zastępcza klimatu, model przewidywanego strumienia cieplnego, model PHS

1. Introduction

Employees of underground mines operations carrying out excavation of valuable mineral resources are often exposed to high temperature environments and heat strain. The main causes of temperature and humidity increase in underground excavations is the great depth of exploitation and high level of mining concentration. The depth of exploitation determines the geothermal parameters of the rock mass. Increased concentration of mining operations has caused almost complete mechanization of the mining process, thus increasing the electric power of the equipment used in mines. Hiring in a hot environment results in exposure of a worker to the presence of heat stress. The occurrence of heat stress causes disturbance of psychomotor capacities and cognitive processes. Such disturbance may lead to erroneous judgement of situations, limitation of the working capacity and increase in frequency of accidents at work. Assuring safety and hygiene of work is a basic obligation and responsibility of the employer. Correct evaluation of the microclimate conditions allows to create regulations for employment in hot environments in a way to assure safety and good levels of productivity. Due to the safety requirements, it is being expected that the microclimate conditions evaluation will be performed in a quick and easy way. To a major extent, simple heat indices meeting those assumptions include simplifications and are being formulated for specific working environments.

Currently, the best methods for evaluation of microclimate conditions are the ones based on the theory of human thermal balance, where the physiological parameters characterising heat strain are loss of water and internal core temperature of human body (Wacławik et al., 2004). Methods based on human thermal balance are not widely used in evaluation of microclimate conditions in the workplace because they often require determination of a large number of input parameters and numeric calculations. One of these methods is published in standard PN-EN ISO 7933:2005. The method of analytical determination and interpretation of heat strain experienced by humans in hot temperature environments is supported by extensive research of the microclimate conditions evaluation procedures. This method has allowed research of the efficiency of heat strain assessment procedures using the equivalent climate temperature t_{zk}. The analyses were performed considering metabolic rate and clothing insulation.

2. Assessment of climate hazard in Polish underground mines

From the seventies of the last century to the middle of last year, evaluation of the microclimate conditions in underground mines was mainly carried out based on dry-bulb temperature measurements and on the cooling power of air. Exception was made in the case of underground mines using self-propelled machines, where the equivalent climate temperature could be used (Regulation of the Minister of Economy of 28 June 2002). From July 1, 2017, there are new regulations in force, introducing climate hazard to the list of the basic mining hazards and set forth three levels of climate hazard (Regulation of the Minister of Natural Environment of 29 January 2013). The main indicator leading to qualification of a workplace to one of the environmental hazard levels is the equivalent climate temperature. The method of climate hazard assessment provided by the new regulations is different from the one previously applied in underground mines using self-propelled machinery. Qualification of a workplace to a particular level of environmental risk does not directly take into account the metabolic rate and clothing insulation. Parameters related to the clothing of the worker and metabolic rate have significant impact on the heat exchange between the human body and its environment. Every heat strain assessment which is not considering above parameters may impact correct assess-

TABLE 2.1

Characteristics of the microclimate evaluation methods used in Polish underground mining operations

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Old regulations	**New regulations**
1. Underground mines: • Normal working time (450 min): $t_s \leq 28$°C and $K_w \geq 11$ wet kata cooling power • Shortened worktime (360 min): $28 < t_s \leq 33$°C or $K_w < 11$ wet kata cooling power • Work forbidden: $t_s > 33$°C 2. Underground mines using self-propelled machinery: • Normal working time (450 min): Low metabolic rate $t_{zk} \leq 30$°C, Moderate metabolic rate $t_{zk} \leq 28$°C, High metabolic rate $t_{zk} \leq 26$°C, Very high metabolic rate $t_{zk} \leq 25$°C • Shortened work time (360 min): Low metabolic rate $30 < t_{zk} \leq 32$°C, Moderate metabolic rate $28 < t_{zk} \leq 30$°C, High metabolic rate $26 < t_{zk} \leq 28$°C, Very high metabolic rate $25 < t_{zk} \leq 27$°C, • Forbidden work: Low metabolic rate $t_{zk} \leq 32$°C, Moderate metabolic rate $t_{zk} \leq 30$°C, High metabolic rate $t_{zk} \leq 28$°C, Very high metabolic rate $t_{zk} \leq 27$°C.	1. Underground mines: • No climate hazard (normal worktime – 450 min): $t_{zk} \leq 26$°C, • Level I climate hazard (shortened worktime – 360 min): $26 < t_{zk} \leq 30$°C, • Level II climate hazard (shortened worktime – 360 min): $30 < t_{zk} \leq 32$°C, • Level III climate hazard (work forbidden): $t_{zk} \leq 32$°C or $t_w > 34$°C or $t_s > 35$°C, 2. Salt mines: • Work permitted under specific conditions: $t_s \leq 43$°C, $t_w \leq 27$°C.

Explanations: t_s – dry-bulb temperature, t_w – wet-bulb temperature, t_{zk} – equivalent climate temperature, K_w – cooling power of air ment of the climate hazard. Value of equivalent climate temperature is calculated using the formula below:

$$t_{zk} = 0{,}6 \cdot t_w + 0{,}4 \cdot t_s - v_a, \quad °\mathrm{C} \tag{2.1}$$

Where:

- t_s — dry-bulb temperature, °C,
- t_w — wet-bulb temperature, °C,
- v_a — air velocity expressed in m/s, the conversion factor equals to 1 s × °C/m.

In this case, the calculation method is not limited by the value of dry-bulb or wet-bulb temperature. The novelty in this case is the method used in calculation in situations, where the air velocity in the underground workings exceeds 4 m/s. Despite higher air velocities in the excavations, calculations should assume the value of 4 m/s. Following the new regulations, climate hazard occurs when equivalent climate temperature in the underground mining working exceeds 26°C. Detail regulations concerning employment of workforce for operation in climate hazard conditions are provided in the Regulation of the Minister of Energy of 23 November 2016 concerning detail requirements for underground mining operations. In workplaces qualified to levels I and II of climate hazard, there shall be technical solutions in place to reduce temperature or working time. When the working time in climate hazard-exposed workplaces exceed two hours, the persons carrying out the work shall be employed on the basis of worktime reduced to six hours, including descent and return to surface. Persons working in workplaces qualified to climate hazard level I or II shall be obliged to attend training regarding risks arising from working in high temperature conditions. The only works allowed in level III climate hazard areas are rescue operations.

3. Analytical determination and interpretation of heat stress using calculation of the predicted heat strain following the PN-EN ISO 7933:2005 standard

The method of analytical determination and interpretation of the heat stress experienced by a man in a hot environment is based on PHS (predicted heat strain) model which is a numerical model of heat exchange between the human body and the environment (Malchaire, 2006). PHS model has been developed based on the heat balance theory of human body and a database provided by 8 research institutions, composed of 747 laboratories and 336 field experiments. The main goal of PHS model is evaluation of working conditions in which human body may experience excessive increase in internal core body temperature or loss of water caused by exposure to hot environment. Due to the measurement method, internal core temperature of human body is defined in the standard as rectal temperature. This method allows to determine which of the parameters or groups of parameters concerning the employee or working environment shall be addressed to reduce the risk of overheating or dehydration of the human body. This method is also allowing determination of the permissible time of man's exposure to the environmental conditions, which would be acceptable from the perspective of physiologists. It is being assumed that no overheating or dehydration of the human body shall take place during such an exposure time. In order to perform evaluation of microclimate conditions of the working environment using the above method, it is necessary to: determine the basic microclimate parameters (dry-bulb temperature, wet-bulb temperature, air pressure, air velocity, mean radiant temperature), determine the work intensity (average metabolic rate M_{sr}), determine clothing insulation I_{cl}, determine the employee's acclimatization status and find out whether the person had a permanent access to water, to make up for water deficit caused by the sweating and estimate the assumed time of exposure to the particular microclimate conditions. Application of the PHS model is linked with some limitations. Table 3.1 specifies the ranges of parameters within which the model can be considered as accurate. If one or more parameters exceeds specified ranges, application of the model is accepted but the results should be considered with care and particular attention for persons exposed to such microclimate conditions. In its current format, the method of microclimate conditions evaluation shall not be applied in cases the employee is equipped with special protective clothing (reflective clothing, active cooling or ventilation wear, impermeable clothing) and the impacts of personal safety equipment worn by the person is not being considered. Analysis of working conditions using the calculation method discussed does not apply to the physiological reactions of particular individuals, but instead it is taking into account an average person is good health condition, adapted to the work being performed.

TABLE 3.1

Ranges of validity of the PHS model

Parameters	Symbol	Unit	Minimum	Maximum
Dry-bulb temperature	t_s	°C	15	50
Partial vapour pressure	p_a	kPa	0	4.5
Difference between the mean radiant temperature and dry-bulb temperature	$t_r - t_s$	°C	0	60
Air velocity	v_a	m/s	0	3
Metabolic rate	M	W/m^2	100	450
Clothing insulation	I_{cl}	clo	0.1	1.0

When carrying out analysis of thermal working conditions using the method of analytical determination and interpretation of the heat stress experienced by humans in hot environments one can obtain: the final value of rectal temperature after a given exposure time, body water loss (expressed in grams) after a given time, permissible exposure time, during which rectal temperature shall not exceed 38°C, permissible exposure time during which body water loss shall not exceed 7.5% of the person's weight and the permissible exposure time, during which body water loss shall not exceed 5% of the person's weight (Malchaire et al., 2000). A computer software package has been developed to perform the analyses, allowing realization of the numerical calculations with PHS model, taking into account a significant number of optional parameters, defining the working environment.

4. Computer software based on PHS model

The software developed for PhD thesis (Głuch, 2015) allows application of method of analytical determination and interpretation of heat stress in hot environments to assess heat strain in working environments. The interface of the software is shown in Figure 4.1. The software allows calculation of rectal temperature and body water loss after a given time of exposure to particular conditions of the work environment. It is also allowing evaluation of safe permissible exposure time and plotting of graphs illustrating the course of rectal temperature changes and body water loss in function of time, allowing the tracking of relevant physiological parameters. The software includes the function allowing the user to analyse greater volumes of data based on earlier prepared template.

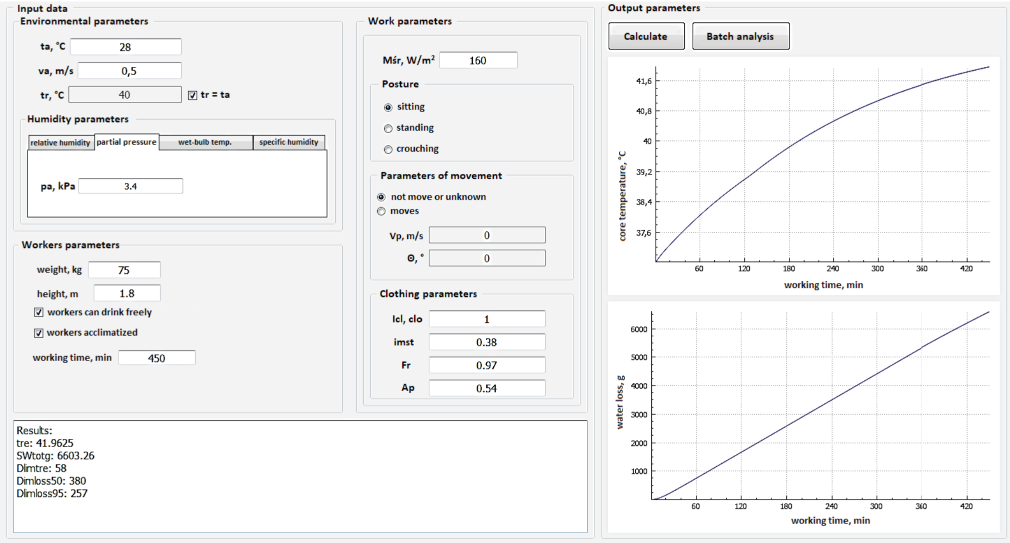

Fig. 4.1. Interface of the computer software

5. Equivalent climate temperature verified by predicted heat strain model

5.1. Research methodology

The method of analytical determination and interpretation of heat stress experienced by man in hot environments has allowed verification, considering heat strain, of the method for assessment of climate hazards based on the equivalent climate temperature. In order to perform validation of the method discussed in this paper, values of equivalent climate temperature were calculated for the assumed sets of parameters. Calculations using PHS model were carried out for the same sets of air parameters. The calculations were performed using the computer software (Głuch, 2015) considering standard parameters relevant to employee described in PN-EN ISO 7933:2005 standard. The results of extended research can be found in the monograph (Głuch, 2016). This article presents the results of calculations for the following sets of working environment parameters: two values of the clothing insulation: I_{cl} = 0.6 clo and I_{cl} = 1 clo, and two levels of metabolic rate: moderate metabolic rate M_{sr} = 165 W/m^2 and high metabolic rate M_{sr} = 230 W/m^2, four air velocity values: v_a = 0.15 m/s, v_a = 0.5 m/s, v_a = 1 m/s, v_a = 3 m/s, three relative air humidity values: φ = 90%, φ = 80%, φ = 60% and range of dry-bulb temperature t_s = 15÷50°C.

Parameters of average metabolic rate and clothing insulation were selected based on research carried out in underground mines in Poland under the strategic project entitled: „Improvement of working safety in mines" by The National Centre for Research and Development. Metabolic rate in longwalls and blind heading is characterised as moderate metabolic rate which can occasionally increase (Domagała et al., 2013). Based on the results of researches performed within above strategic project, it has been assumed that clothing insulation of a standard mining worker clothing set, without the top jacket, is 1 clo (Bogdan et al., 2012). It is essential to point out that the clothing was new and dry. Analyses of the clothing insulation were performed using a serial model. Clothing insulation decrease during the time of usage. During work, employee clothing gets wet from sweating. Clothing insulation of wet clothing is half less than of dry clothing. Equivalent climate temperature has been created to evaluate microclimate condition for work environment where employee is wearing clothes with clothing insulation equal to 0.6 clo (Turkiewicz, 1986).

Based on the binding Polish regulations, the exposure time for a set of parameters assumed in the research methodology is 450 minutes for normal working time and 360 minutes for limited working time. The studies performed are only reliable if the worker spends the whole workday in an environment having specific parameters, working at average metabolic rate. It should be pointed out that following the research the employee is spending less than 360 minutes in the workplace due the need to arrive there (Domagała et al., 2013). The route to and from the workplace is often passing through exploitation areas with better microclimate conditions than the ones in the workplace.

5.2. Analysis of the results

Results of the analyses are shown in graphic form, comparing the value of the equivalent climate temperature with the results of numerical calculations being the physiological parameters defining heat strain in the workplace. The comparison is done by relating the equivalent climate temperature (axis X) to the values of physiological parameters calculated using the PSH model, such as water loss or rectal temperature (axis Y). Evaluation of heat strain using PSH model takes those two physiological parameters into account. Exceeding the boundary value of one of those parameters means occurrence of hazardous working conditions. Each of the figures includes two graphs, presenting the results of physiological parameters calculations for normal and limited working times in compliance with the working time determination criteria set forth by the new regulations. Calculations for equivalent climate temperature that is lower or equal to 26°C ($t_{zk} \leq 26$°C) were carried out with the assumption that the worker can spend a whole working day in such microclimate conditions this means 450 minutes. In the case of equivalent climate temperature higher than 26°C ($t_{zk} \leq 26$°C) the calculations were made with the assumption that exposure to particular microclimate conditions is 360 minutes. Each of the graphs is showing ranges of equivalent climate temperature allocated to the particular level of climate hazard. It shall be remembered that qualification of workplaces to level III of climate hazard is not only being done based on equivalent climate temperature but also based on dry-bulb temperature or wet-bulb temperature. This is why, each of the graphs is additionally showing the microclimate conditions qualified to level III of climate hazard. Plots of the functions qualified to level III of climate hazard are described in the legend, below the figure.

Particular graphs are showing the course of physiological parameters in function of equivalent climate temperature determined for various values of relative humidity and air velocity identified in the assumptions. Depending on the values of particular parameters, the trends shown in graphs are indicated in a way described in the legend below the charts. Black lines, parallel to axis X on every chart are the boundary values for the physiological parameters. In case of workers in Polish underground mines it has been assumed that the threshold body water loss is 3750 g. It has been determined taking into account the fact that the workers have to undergo standard medical examination for qualification to the job. The body water loss threshold can be extended by adding specialist medical examination verifying correct functioning of the thermal regulation system. The threshold value of rectal temperature is 38°C. The threshold value has been selected based on a WHO report (World Health Organization, 1969).

Analysis of the study results indicated that with a clothing insulation equal to 1 clo and metabolic rate of 165 W/m^2 (Fig. 4.1), application of the equivalent climate temperature method in assessment of the climate hazard does not protect against exceeding of the threshold rectal temperature at air velocities of less than 0.5 m/s for microclimate conditions qualifying for normal working time $t_{zk} \leq 26$°C. Within the same equivalent climate temperature range body water loss may exceed the threshold of 3750 g at an air velocity lower than 1 m/s. Research has indicated that in the range of equivalent climate temperature qualifying workplaces to levels I and II of climate hazard ($26 < t_{zk} \leq 32$°C), with a limited working time, the rectal temperature threshold may be exceeded in most of the air parameter sets that were analysed. In the case analysed, it has also been found that shortening of the working time leads to a reduction of body water loss but despite that fact, the threshold body water loss value of 3750 g is being exceeded in all the cases analysed.

Results of calculations in the subsequent option are shown in Figure 4.2. Analyses demonstrated that reduction in clothing insulation to 0.6 clo causes reduction in heat strain. This means that with a clothing insulation equal to 0.6 clo and metabolic rate of 165 W/m^2, application of the climate hazard assessment model discussed in this paper does protect against exceeding the threshold rectal temperature. The threshold value of 3750 g body water loss in equivalent climate temperature within the range of $t_{zk} \leq 26$°C may be slightly exceed at air velocity of 0.15 m/s. Research has also shown that there are workplaces which microclimate conditions are classified to I and II climate hazard levels using equivalent climate temperature but even if working time is shorten, threshold rectal temperature and water loss values may be exceeded.

Analyses of conditions with metabolic rate levels increased to 230 W/m^2, with a clothing insulation of 1 clo (Fig. 4.3) and 0.6 clo (Fig. 4.4) have demonstrated that the negative impacts of microclimate conditions are significant enough and using equivalent climate temperature can cause employees' health loss.

6. Conclusions

Employment in hot environment results in employee exposure to heat strain. Long term work in difficult microclimate conditions may lead to dehydration and overheating of the person's body. In order to ensure working safety and hygiene rules and regulations are being formulated, aiming at elimination of such incidents. Simple microclimate indices are being used to assess climate hazard due to required simplicity and quickness of application. Disadvantages of simple microclimate indices may impact assessment of heat strain in underground mining environments. Changes in regulations concerning employment in mining excavation areas has introduced cli-

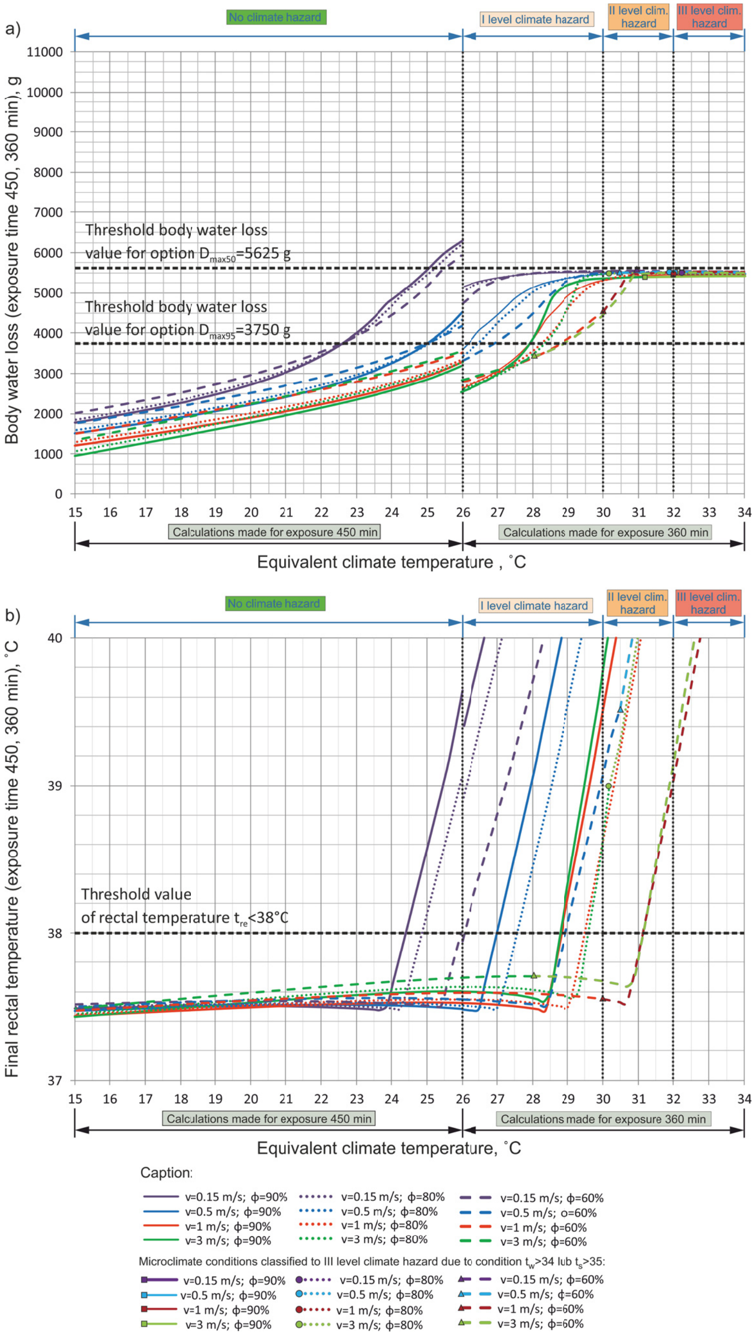

Fig. 5.1. Change in value of physiological parameters defining heat strain for clothing insulation equal 1 clo and metabolic rate equal 165 W/m^2 in function of equivalent climate temperature: a) body water loss for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C), b) rectal temperature, calculation results for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C)

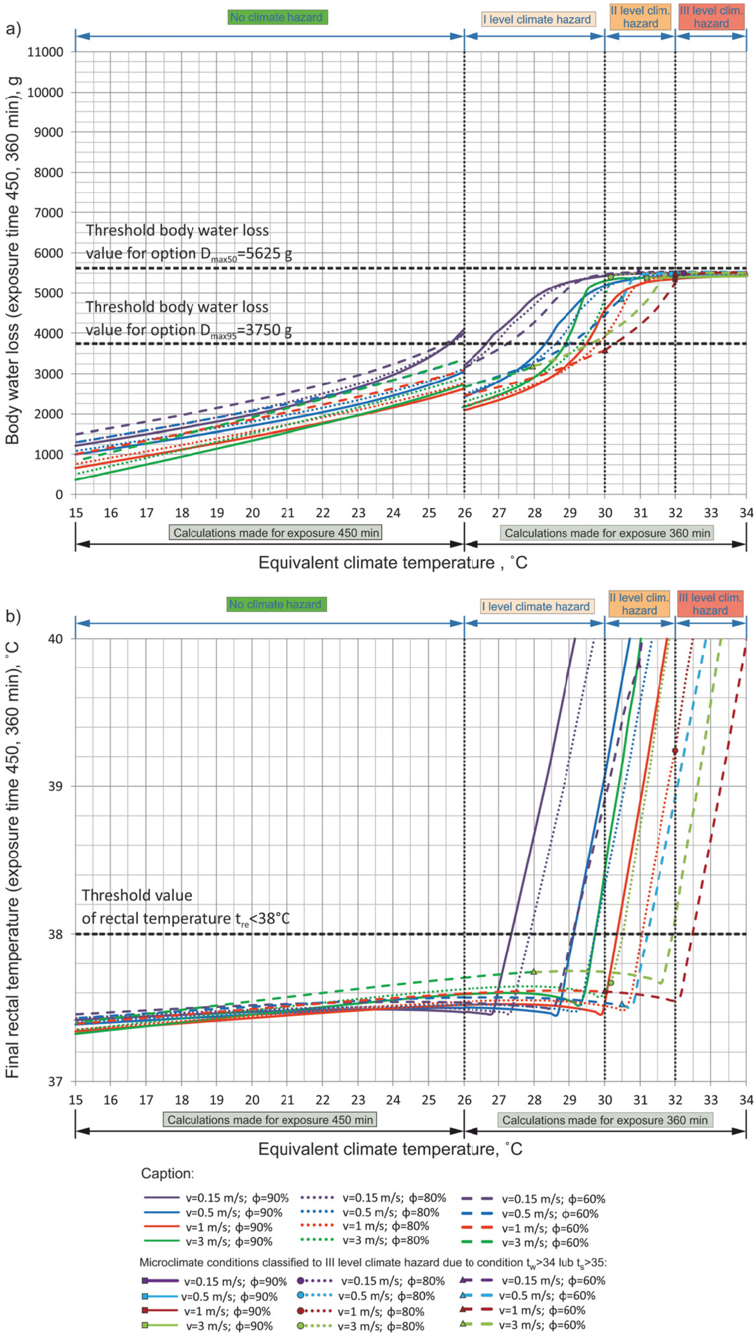

Fig. 5.2. Change in value of physiological parameters defining heat strain for clothing insulation equal 0,6 clo and metabolic rate equal 165 W/m^2 in function of equivalent climate temperature: a) body water loss for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C), b) rectal temperature, calculation results for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C)

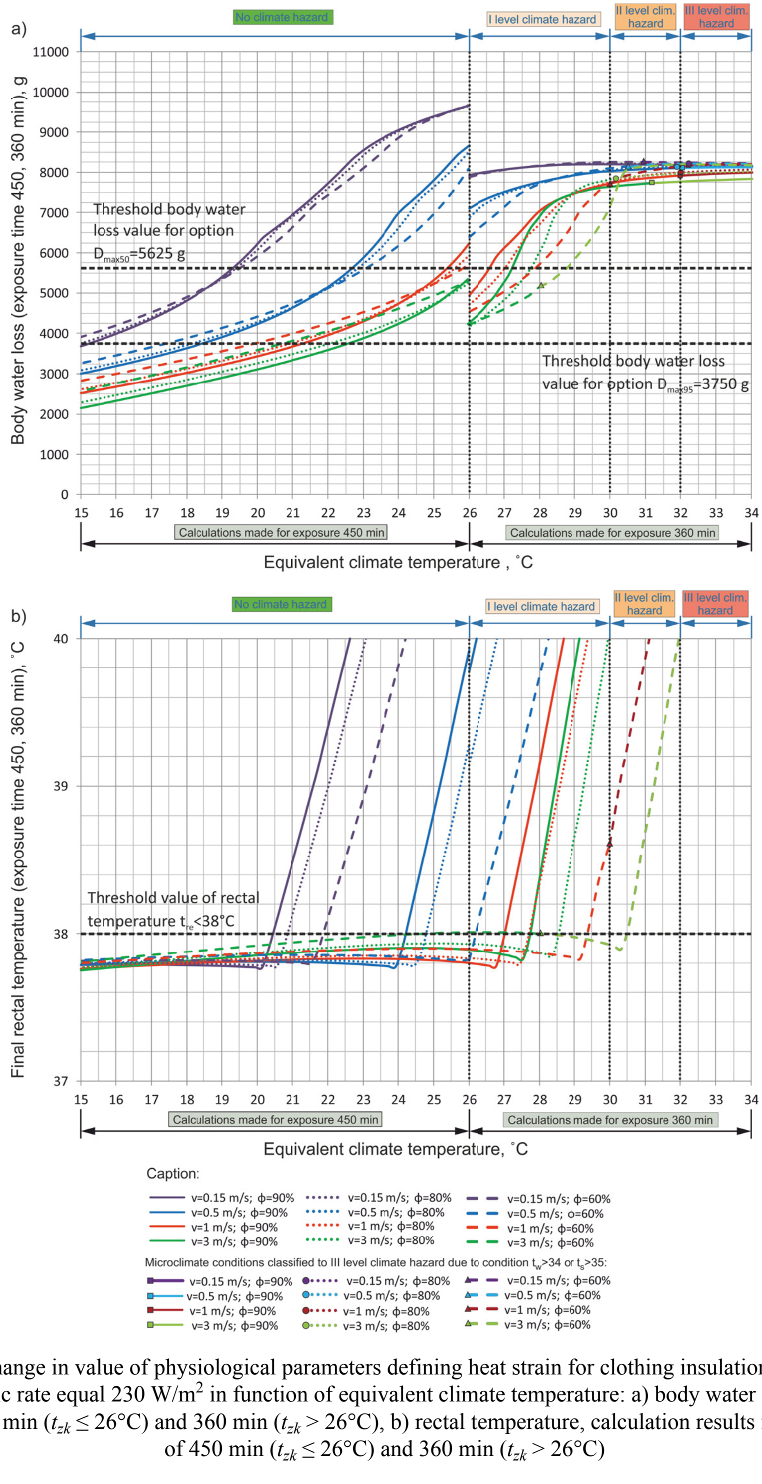

Fig. 5.3. Change in value of physiological parameters defining heat strain for clothing insulation equal 1 clo and metabolic rate equal 230 W/m^2 in function of equivalent climate temperature: a) body water loss for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C), b) rectal temperature, calculation results for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C)

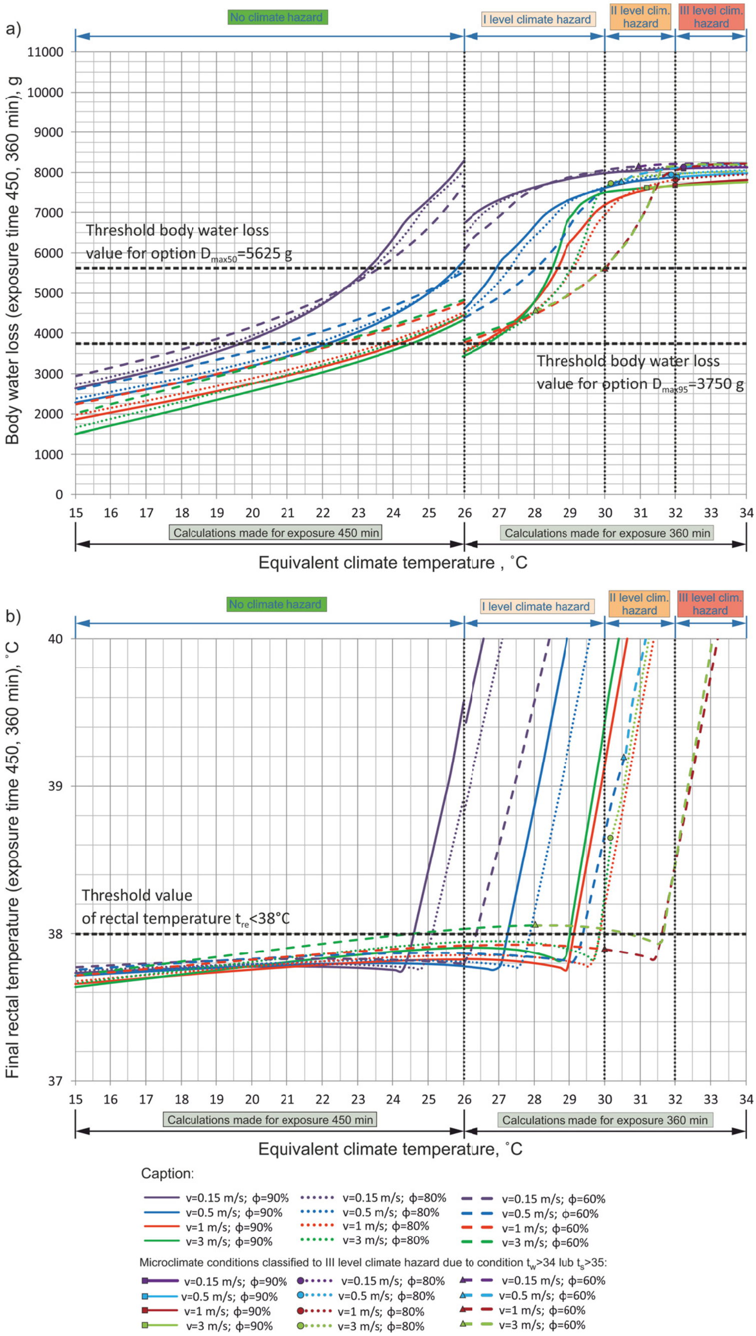

Fig. 5.4. Change in value of physiological parameters defining heat strain for clothing insulation equal 0,6 clo and metabolic rate equal 230 W/m^2 in function of equivalent climate temperature: a) body water loss for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C), b) rectal temperature, calculation results for exposures of 450 min ($t_{zk} \leq 26$°C) and 360 min ($t_{zk} > 26$°C)

mate hazard as one of the natural hazards. At present, the key criterion for assessment of climate hazard is equivalent climate temperature. Method of analytical determination and interpretation of heat stress experienced by employees in hot environment was used to verify effectiveness of equivalent climate temperature.

Researches were carried out with assumption that worker spends full-time or short-time working hours in microclimate conditions described in research methodology and work is performed with average metabolic rate. Researches have demonstrated that the equivalent climate temperature does not provide correct description of heat strain in a hot environment with low air velocity and high relative humidity. Reduced working time does not allow to provide safe working conditions in workplaces qualified to II and III climate hazard levels. Greatest difficulties occur in assessment of heat strain when metabolic rate equals 230 W/m^2.

Determination of working time in climate hazard conditions is a complicated issue. There are many factors determining heat strain experienced by the worker. The most important are air parameters, metabolic rate and clothing insulation. Current regulations only take into account the air parameters in the determination of working time. Assessment of the climate hazard based on the equivalent climate temperature does not consider impact of metabolic rate and clothing insulation. Analysis of the research results led to the formulation of the following conclusion: evaluation of microclimate conditions in underground mining operations should be based on a comprehensive evaluation of environmental and working parameters. Working time shall be determined for every workplace, taking into account parameters of the air, clothing insulation and metabolic rate. Determination of the working time should also include the itinerary on the way to the workplace.

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