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ESTIMATION OF MICROCLIMATE CONDITIONS AT LONGWALL EXCAVATIONS IN HARD COAL MINES

1. Introduction

The depletion of shallow deposits in underground mines results in a systematic increase in mining depth, at the same time leading to a greater intensity of natural hazards [1]. Virgin rock temperature increases along with the depth which has an inevitable influence on the microclimate of the work places. The negative influence of microclimate conditions is mainly caused by high coal output concentration, increased power to underground extraction machinery and haulage equipment as well as high air humidity in excavation areas. In the near future it may be necessary to mine in rock masses with a temperature of 50°C where climate threat will be the main decisive element regarding the safety of miners, and this factor could even affect the possibility of extracting coal effectively at depth.

Hard microclimate conditions not only decrease efficiency, but more alarmingly, such conditions can endanger the health and even the lives of the workers themselves due to overheating of the human organism. Obtaining thermal equilibrium happens as a result of body thermoregulation. The body can detect changes in its surrounding temperature as well as its inner temperature thanks to thermo receptors located in different parts of the body, mainly in skin. High temperature surroundings cause physiological reactions to occur, such as dilating blood vessels of skin, increasing blood flow to the body surface and sweat secretion through sweat glands on the skin.

Individual psychophysical factors, such as age, body structure, general health condition, acclimatization, mental immunity and personal predispositions also have a great impact on the human organism's reaction to hard climate conditions in hot surroundings. At about 30°C in relatively high humidity, people with limited thermal tolerance, are already prone to heat exhaustion or overheating, particularly during a great physical effort [2, 3]. These tough climate conditions can be observed at longwall mine excavations.

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This paper aims at estimating microclimate conditions on the basis of research conducted in hard coal mines. On the basis of the results obtained, microclimates at longwall mine excavations can be estimated, taking into consideration well-known heat indexes.

2. Methodology of microclimate measurements at longwall mine excavations

Determining a suitable methodology of research is of key significance when conducting an analysis, based on real changes in microclimate conditions, in a longwall mine excavations. It was necessary to measure the climatic parameters at the headgate and tailgate of a longwall mine to obtain a complete set of results. In underground mine workings, the most important parameters include: temperature, measured by a dry thermometer t_s, temperature measured by a wet thermometer t_m, relative humidity φ and airflow rate v at the longwall. Measurements were taken at sampling stations at underground excavations in 5 hard coal mines at 22 longwalls. The longwalls were mined at depths from 650 to 1070 m and were ventilated by U and Y ventilation systems.

Figure 1 presents measurement schemes of air parameters. The U ventilation system is used most frequently in Polish hard coal mines, however, this system's disadvantage is poor operation in unfavorable climate conditions [4]. In longwall excavations ventilated by the U system, measurements were taken at the head entrance, about 10 m before the gate to the longwall, as well as in a tail entrance, no more than 10 m behind the tail gate (Fig. 1a). In longwall excavations ventilated by the Y system the measurements were taken in the entrance about 10 m before the headgate as well as in an entry with return air along goaf at no more than 10 m behind the tailgate (Fig. 1a). The latter system is more favorable during temperature hazard [4]. Sampling stations reflect work places in headgates and tailgates.
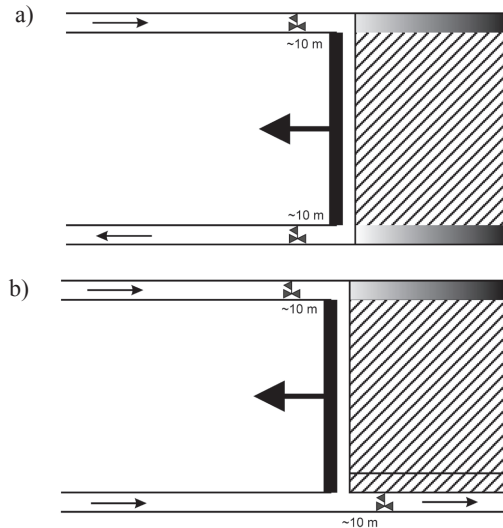

Fig. 1. Scheme of ventilating a longwall with: a) U ventilation system; b) Y ventilation systems

3. Results of microclimate measurements

The results of conducted measurements are presented in Table 1.

TABLE 1

Data sheet from measurements in longwalls

Mine	Longwall	Ventilation system / air cooling	Headgate				Tailgate			
			t_s, [°C]	t_m, [°C]	φ, [%]	v, [m/s]	t_s, [°C]	t_m, [°C]	φ, [%]	v, [m/s]
B-Z	1	U / air cooling	23.2	19.0	67	1.33	26.8	24.0	79	1.60
			24.0	21.8	83	1.95	29.8	28.4	90	2.30
	2	U / air cooling	22.6	18.0	64	0.97	27.0	25.0	85	1.15
			21.0	16.8	66	1.05	25.8	22.8	78	1.27
	3	Y / air cooling	24.0	20.0	69	1.05	28.4	25.8	81	2.33
			24.4	20.4	70	1.12	26.0	22.4	73	2.60
	4	U / air cooling	22.8	18.2	64	0.87	29.0	24.0	66	0.90
			21.6	17.8	69	1.53	27.2	25.6	88	2.38
	5	Y / air cooling	26.0	22.0	71	1.25	31.0	28.8	85	1.58
			25.0	21.4	73	1.33	26.6	26.6	86	1.73
P	6	Y / air cooling	18.2	14.2	63	2.40	25.2	21.2	69	2.30
	7	Y / air cooling	18.2	15.4	74	2.15	24.2	21.8	81	6.25
	8	Y / air cooling	22.4	17.0	57	5.90	31.4	28.2	78	2.03
	9	Y / air cooling	20.8	18.0	76	1.70	28.4	26.2	84	2.10
	10	Y / air cooling	23.0	19.6	72	1.30	31.2	27.8	77	1.20
	11	Y / air cooling	22.2	20.0	81	0.78	25.6	23.8	86	1.11
J-M	12	U / air cooling	22.4	18.8	70	1.16	28.2	26.8	89	1.15
	13	U / air cooling	27.8	26.0	86	1.09	31.8	30.6	92	1.03
	14	Y / air cooling	23.6	17.4	52	3.81	31.2	28.6	82	4.39
	15	U / air cooling	22.2	19.4	76	1.25	31.4	27.8	75	1.43
B	16	Y / air cooling	18.4	16.0	77	2.45	26.6	24.2	82	2.45
	17	Y / air cooling	19.8	17.2	77	2.18	25.6	23.4	83	2.18
	18	Y / air cooling	20.2	17.8	79	1.98	26.6	24.4	83	1.98
K	19	U / without cooling	19.2	16.2	73	3.75	20.4	19.0	88	3.67
	20	U / air cooling	24.4	20.6	70	2.52	27.8	25.6	84	2.58
	21	U / air cooling	17.4	14.0	68	3.19	23.4	20.6	77	3.20
	22	U / air cooling	24.0	21.6	81	3.24	23.6	23.0	95	2.94
Average values			22.2	18.7	71.4	2.00	27.4	25.1	82.1	2.20
Standard deviation			2.6	2.6	7.7	1.20	2.9	2.8	6.7	1.2

Volumetric air streams in the intake airways ranged from 600 to 1640 m³/min. In longwall excavations with a Y ventilation system, the participation of air in the face ranged from 40.3% to 82.4% of total intake air. Air cooling was used to improve climate conditions due to the depth of mining in longwalls.

4. Microclimate indexes at longwall excavations under research

The value of basic air parameters and microclimate indexes, which take into consideration the joint influence of a few basic air parameters were used to determine microclimate. The best-known microclimate indexes include: relative index of air cooling power K_w [5], equivalent French temperature TFR [6], equivalent temperature of climate t_{zk} [7], wet-bulb globe temperature index [8]. Table 2 presents the definitions of heat indexes and methods for their determination. On the basis of those indexes, microclimate conditions in excavations were estimated.

TABLE 2

Microclimate indexes

Index	Symbol	Unit	Determination method	Remarks	Explanations for equations
Relative index of air cooling power K_w	K_w	Wet Kata	measurement by wet katatermometer	K_w<11 Wet Kata part-time work	t_m – temperature measured by wet thermometer [°C], t_s – temperature measured by dry thermometer [°C], v – air velocity [m/s]
Equivalent French temperature TFR	TFR	°C	$TFR = 0.7\,t_m + 0.3\,t_s - v$	– $TFR \leq 28°C$ – normal work conditions, – TFR ranging from 28 to 34°C – work harmful to health, – $TFR > 34°C$ – dangerous work conditions	
Equivalent temperature of climate t_{zk}	t_{zk}	°C	$t_{zk} = 0.6\,t_m + 0.4\,t_s - v$	– permissible boundary values of equivalent temperature of climate are as follows: – for light work $t_{zk} < 30°C$, – for moderate work $t_{zk} < 28°C$, – for hard work $t_{zk} < 26°C$, – for very hard work $t_{zk} < 25°C$ (work time should be shortened if temperature t_{zk} is greater than boundary values: • work not allowed $t_{zk} > 32°C$	
Wet-bulb globe temperature index ($WBGT$)	$WBGT$	°C	$WBGT = 0.67\,t_m + 0.33\,t_s$	Norm PN-EN 272443:2005	

The measurements obtained determined the microclimate indexes. On the basis of the calculations carried out it can be concluded that the microclimate parameters were as follows:

— at headgate:
- relative index of air cooling power ranged from 12.9 to 41.1 Wet Kata (on average it was 24.7 Wet Kata, but in no case was it lower than 11 Wet Kata),
- equivalent French temperature ranged from 11.8 to 25.5°C (on average it was 17,8°C),

- equivalent temperature of climate ranged from 12.2 to 26.6°C (on average it was 18.1°C),
- wet-bulb globe temperature index ranged from 15.1 to 26.6°C (on average it was 19.8°C),

— at tailgate:
- relative index of air cooling power ranged from 7.1 to 31.4 Wet Kata (on average it was 17.2 Wet Kata and in one case it was lower than 11 Wet Kata),
- equivalent French temperature ranged from 15.8 to 29.9°C (on average it was 23.5°C),
- equivalent temperature of climate ranged from 15.9 to 30.1°C (on average it was 23.8°C),
- wet-bulb globe temperature index ranged from 19.5 to 31.0°C (on average it was 25.8°C).

Figures 2–4 present changes in indexes in the function of air temperature measured by a dry thermometer.
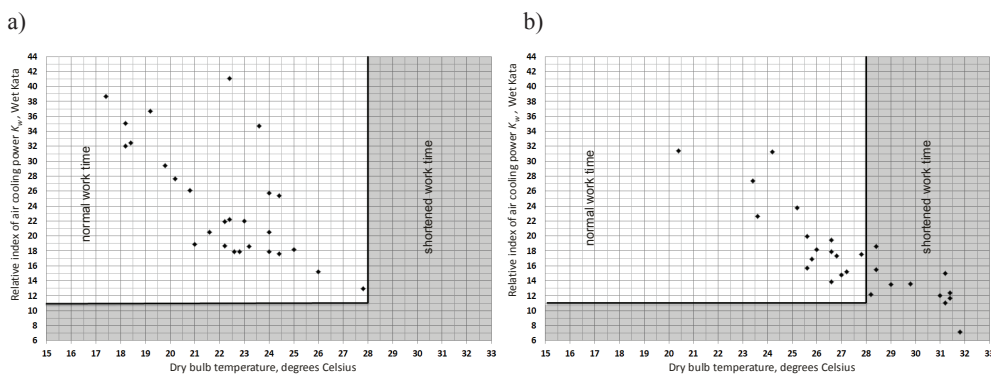
a)   b)

Fig. 2. Relative index of air cooling power K_w as a function of air temperature:
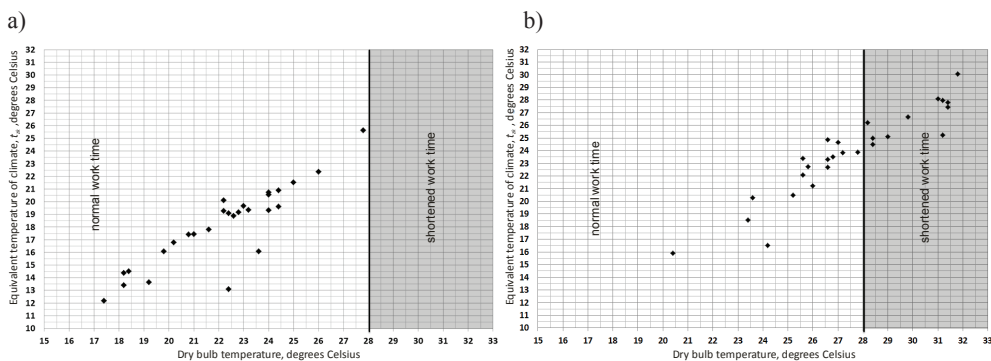a) the headgate of the longwalls; b) the tailgate of the longwalls

a)   b)

Fig. 3. Equivalent temperature of climate t_{zk} as a function of air temperature:
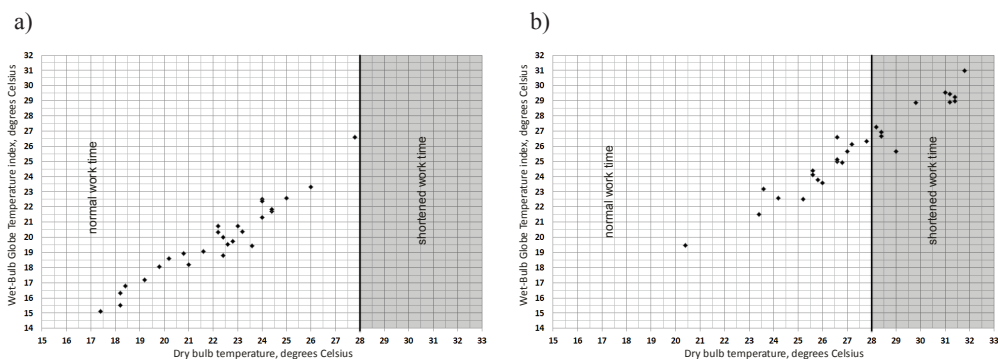a) headgates; b) tailgates

a)

b)

Fig. 4. Wet Bulb Globe Temperature Indicator *WBGT* as a function of air temperature:
a) the headgate of the longwalls; b) the tailgate of the longwalls

Mining regulations requirements [9] for air parameters at the headgate of longwalls were not exceeded; therefore there was no shortened work time. Air cooling in the longwall excavation was sufficient to maintain required parameters. At the outlet from longwall excavation, permissible air parameters were exceeded in 11 cases, the first of which being taken on a dry thermometer. In each case air cooling was used. People working in such conditions worked in short stints. These indexes indicate hard working conditions at a longwall excavation outlet. However, it must be emphasized that for miners working there, microclimate conditions are connected not only with air parameters, but also with the nature of the work, the thermal insulation of the miners clothing and their acclimatization to the given conditions. These are the deciding factors associated with heat stress. Heat comfort indicators and the factors mentioned above should be used to estimate microclimate conditions.

5. Estimation of thermal comfort in longwalls under research

Thermal comfort is a state in which a man does not feel either cold or heat [10]. Clothing is one of the main elements which should ensure a man's thermal comfort in various thermal environments at different levels of physical activity. As far as thermal comfort is concerned, the human organism's thermal equilibrium is balanced. To estimate thermal comfort, different indexes (criteria) of estimating thermal work conditions need to be applied, none of which are currently obligatory in Polish hard coal mines.

Results were used and calculations made using the following two indexes: American effective temperature *ATE* and thermal discomfort indicator. The explanations for these indexes can be found in Table 3.

American effective temperature is one of the indexes used for determining microclimates in the work place. American effective temperature is used to determine climate norms and is currently used, among others, in the American and German mining industries. Nomograms for the varying thermal insulation of clothing can be found in literature [6, 9]. As there was no data concerning thermo insulation of workers of longwall excavations under research,

the *ATE* index was calculated on the assumption that the thermo insulation of a workers' clothing was 1 clo (miner's normal work clothing [10]) and 0 clo (unclothed workers). Figure 5 presents a graphic interpretation of the changes in the *ATE* index, the temperature being measured using a dry thermometer.

TABLE 3

Microclimate index *ATE* and indicator δ

Index	Symbol	Unit	Determination method	Remarks
American effective tempera- ture [6]	*ATE*	°C	read from nomograms	According to German norm: $ATE < 25°C$ or $t_s < 28°C$ – normal work time, $ATE > 25°C$ and $ATE < 30°C$ or $t_s > 28$ – short- ened work time, $ATE > 32°C$ – work not allowed
Thermal discomfort indicator [6]	δ	–	read from nomograms	$δ < 0$ cool environment, $δ = 0$ thermal comfort, $0 < δ < 0.2$ – favourable climatic conditions, $0.2 ≤ δ < 0.5$ – satisfactory climatic conditions, $0.5 ≤ δ < 0.8$ – hard climatic conditions, $0.8 ≤ δ < 1$ – very hard climatic conditions, $δ ≥ 1$ – discomfort hazardous to health

The results were compared to *ATE* permissible values according to German regulations. The values obtained were compared to *NDN* value used in the German mining industry. According to these regulations [6] if *ATE* remains in the range between 25–30°C and at the same time the dry temperature is above 28°C, a German miners' work time should be shortened and if *ATE* is greater than 30°C work is not allowed. When comparing data in Figures 2–4 to data in Figure 5 it can be concluded that thermal working conditions were un- favorable at the outlet from longwalls, at the points were the test measurements were taken.
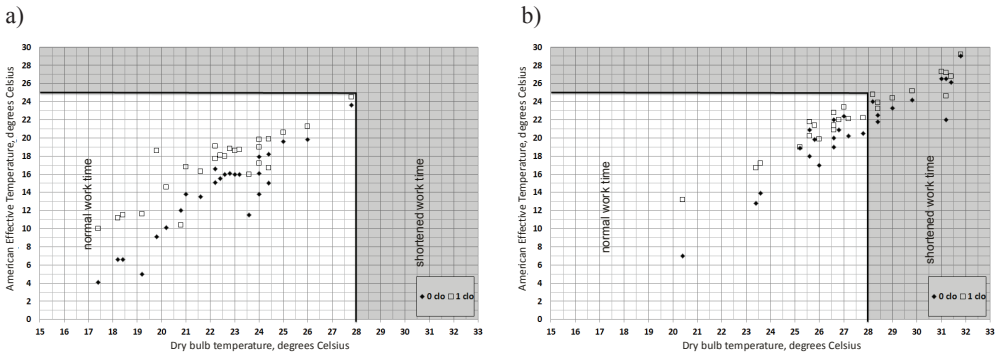
a)   b)

Fig. 5. American effective temperature *ATE* as a function of air temperature (thermal insulation of clothing 0 and 1 clo): a) the headgate of the longwalls; b) the tailgate of the longwalls

Conditions of thermal comfort for workers can also be determined by a thermal discomfort indicator δ [6]. This indicator not only helps to estimate work climate conditions, but also to analyze the influence of microclimate parameters, clothing and metabolic rate according to conditions in the work environment. If indicator δ is equal or greater than unit, work in a given environment should not be allowed due to a worker's heat stress or heat stroke [6].

To calculate indicator δ it was assumed that workers at longwall excavations wear protective clothing with an insulation of 1 clo or 0 clo at tailgate. Calculations were carried out for both acclimatized and non-acclimatized workers for three different values of metabolic rate: 100, 165 and 230 W/m². Nomograms for air relative humidity of 60%, 80%, 100% were used for calculations [11].

Figures 6e, f present an interpretation of the thermal discomfort indicator in the function of temperature measured by a dry thermometer for acclimatized workers wearing insulated clothing of 1 clo or 0 clo while Figures 6e, f for non-acclimatized workers wearing insulated clothing of 1 clo.

On the basis of the Figures it can be concluded that the harder a miner works (in clothing with 1 clo thermo insulation) the more exposed to the negative influence of microclimate parameters he is. Non-acclimatized workers find climatic conditions much worse. When acclimatized and non-acclimatized workers at the headgate and tailgate from longwall excavations were compared, there were more cases when δ indicator exceeded a boundary value, in other words, where thermal discomfort is hazardous to health (δ > 1).

Thermo insulation of clothing has a great impact on the values of a thermal discomfort indicator. When comparing the results of the determined indicator for different thermo insulations for workers at tailgates and those working at longwall excavations it can be concluded that climate conditions for thermo insulation of clothing with 1 clo could be much better. When tests were carried out, acclimatized miners working hard in clothing would have suffered discomfort hazardous to health in 11 cases, and for clothing with thermo insulation of 0 clo with the same parameters would have been breached in only one case.

Taking former assumptions into consideration, Figure 7 presents the percentage distribution of thermal discomfort for moderate work ($M_{sr} = 165$ W/m²). It can be observed that at the headgate of the longwall excavation, hard climate conditions ($0.5 \leq \delta < 0.8$) prevail. In such thermal conditions when the thermo insulation co-efficient is 1 clo, a worker will generally feel uncomfortable. At the tailgates hard or very hard climate conditions prevail. For 26% of work places at the tailgate, climate conditions would be described as too warm if the thermal resistance of clothing was 1 clo with metabolic rate $M_{sr} = 165$ W/m². In such conditions the level of discomfort is described as hazardous to health [6].

Indexes proved that it is necessary to improve climate conditions by using available methods of controlling climate hazards. Air-conditioning systems used in longwalls did not have a beneficial effect for miners working at the tailgate. To improve work conditions, thermo insulation of clothing should be as little as possible, and workers should be acclimatized.
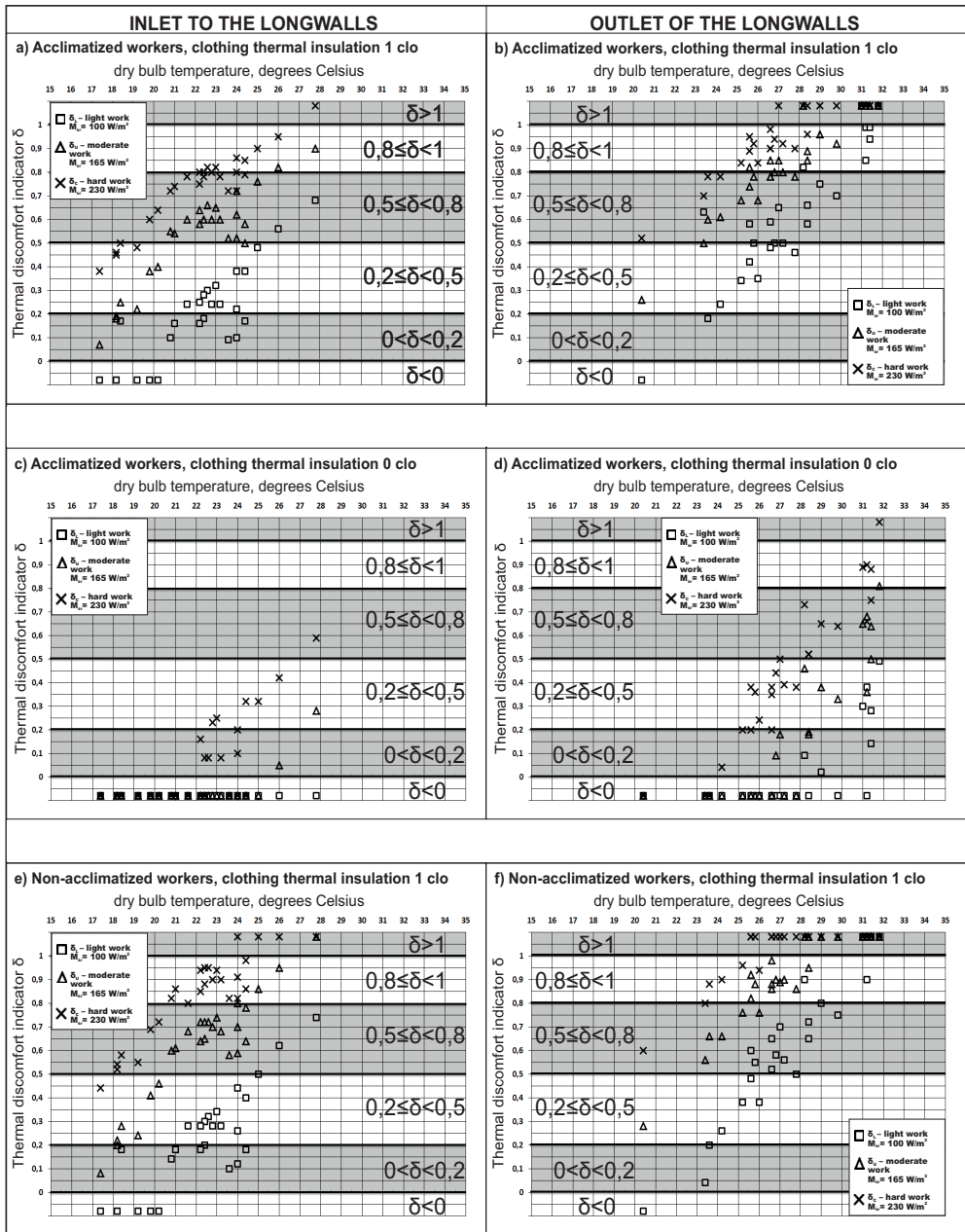
Fig. 6. Thermal discomfort indicator δ as a function of air temperature for:
variable metabolic rate of worker, non-acclimatized and acclimatized workers,
thermal insulation of clothing 0 and 1 clo (a, c, e) the headgate
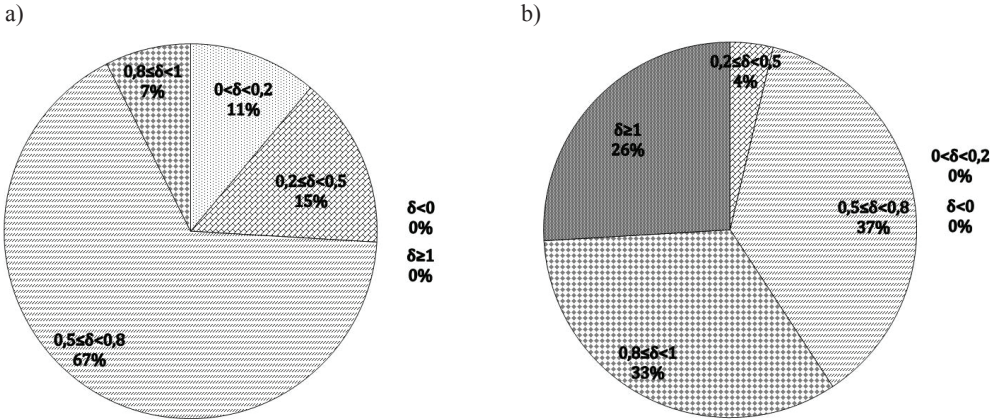of the longwalls (b, d, f) the tailgate of the longwalls

a)   b)

Fig. 7. Percentage distribution of thermal discomfort indicator for acclimatized workers, thermal insulation of clothing 1 clo and moderate work: a) the headgate of longwalls; b) the tailgate of the longwalls

Degrees of climate hazard were determined on the basis of the thermal discomfort indicator [11]. Putting climatic conditions into a given degree consists in determining a value of indicator δ and classifying it according to the following conditions:

— ZKG-I – 1st degree of climate hazard ($\delta_C > 1$, $\delta_U < 1$, $\delta_L < 1$); in environments belonging to 1st degree of climate hazard work can be conducted in a shortened, six-hour work time with frequent or continuous control of thermal discomfort indicator,

— ZKG-II – 2nd degree of climate hazard ($\delta_U > 1$, $\delta_L < 1$), in environments belonging to 2nd degree of climate hazard work can be conducted in a shortened, six-hour work time including a planned relaxation break every hour of a work day,

— ZKG-III – 3rd degree of climate hazard ($\delta_L > 1$), in environments belonging to the third degree of climate hazard, work should not be allowed, except for rescue operations.

In order to conduct the classification of degrees of climate hazards, it was assumed that workers were acclimatized, wore clothing with a thermo insulation of 0 clo or 1 clo and worked at the tailgate of the longwall. Table 4 presents classifications of longwalls according to work time or degrees of climate hazard (the tailgate of the longwall). When comparing microclimate indexes, it can be concluded that both the French temperature and equivalent temperature of climate are least restrictive. According to those indexes normal work time can be applied for most of the longwalls under research. However, Polish regulations, American effective temperature and degrees of climate hazard (1 clo) are stricter as more longwalls are classified as requiring a shortened work time. The main difference is the consideration given to the thermo insulation of clothing and how hard work is. The differences appear in environments where there is high temperature and humidity. The two tailgates from the longwalls were classified as 3rd degree climate hazards, where work should be forbidden. Norms were exceeded for acclimatized people wearing clothing with thermo insulation of 1 clo. Reducing the thermo insulation of clothing to 0 clo results in reducing the degree of climate hazard.

TABLE 4

Classification of excavations according to work time or climate hazard degrees (at the tailgate of longwalls)

Work time / work forbidden	Polish regulations, [%]	French temperature, [%]	Climate equivalent temperature, [%]		American effective temperature according to German norms, [%]		Miners' climate hazard degrees		
			moderate work	hard work	1 clo	0 clo	hazard degree	acclimatized workers, [%]	
								0 clo	1 clo
Forbidden	0	0	0	0	0	0	ZKG-III	0	7.4
Shortened	40.7	3.7	11.1	22.2	40.7	40.7	ZKG-II	0	18.5
							ZKG-I	3.7	14.8
Normal	59.3	96.3	88.9	77.8	59.3	59.3	not included	96.3	59.3

6. Summary

The measurements and calculations of microclimate indexes presented showed that measures taken to ensure the required working conditions remained safe (air conditioning in a longwall) were not effective for all of the longwalls being researched. Keeping the air temperature at the tailgate of longwalls at a required level is very difficult when using the U ventilation system due to a considerable inflow of heat from goaf.

At the headgate of longwall, thermal working conditions allowed for full-time work, in most cases mainly thanks to an air conditioning system in an intake airway. In about 41% of the tailgates under research, a temperature of 28°C was exceeded or the cooling intensity was below 11 Wet Kata, which means a shortened work time in those excavations.

The analysis of microclimate indexes conducted showed that the French temperature and the equivalent temperature of climate are least restrictive. At a similar level, Polish regulations, American effective temperature climate hazard degrees (1 clo) classify excavations for normal work time. There are differences for high temperatures and high relative air humidity.

Non-acclimatized workers should not be employed for work in hard microclimate conditions. Each time after a holiday or a longer break from work a miner should be gradually acclimatized at a given work place, especially in the case of miners working in a face of longwall or in the tailgates.

The authors are aware that the conclusions above refer to the specific longwalls under research and cannot be generalized for all the work of a longwall. Research should also be conducted over a longer period of time due to the changing character of air parameters during mining a panel of a longwall. It is also essential that workers should be examined with regard to their time exposure to microclimate conditions. In such cases, conclusions could be

generalized. However, it is necessary carry out research with regard to changing the regulations concerning employment and work organization in environments with very hard microclimate conditions.

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