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TWO STAGE ASSESSMENT OF THERMAL HAZARD IN AN UNDERGROUND MINE

DWUSTOPNIOWA OCENA ZAGROŻENIA CIEPLNEGO W PODZIEMNEJ KOPALNI

The results of research into the application of selected thermal indices of men's work and climate indices in a two stage assessment of climatic work conditions in underground mines have been presented in this article. The difference between these two kinds of indices was pointed out during the project entitled "The recruiting requirements for miners working in hot underground mine environments". The project was coordinated by The Institute of Mining Technologies at Silesian University of Technology. It was a part of a Polish strategic project: "Improvement of safety in mines" being financed by the National Centre of Research and Development.

Climate indices are based only on physical parameters of air and their measurements. Thermal indices include additional factors which are strictly connected with work, e.g. thermal resistance of clothing, kind of work etc.

Special emphasis has been put on the following indices – substitute Silesian temperature (*TS*) which is considered as the climatic index, and the thermal discomfort index (δ) which belongs to the thermal indices group.

The possibility of the two stage application of these indices has been taken into consideration (preliminary and detailed estimation). Based on the examples it was proved that by the application of thermal hazard (detailed estimation) it is possible to avoid the use of additional technical solutions which would be necessary to reduce thermal hazard in particular work places according to the climate index. The threshold limit value for *TS* has been set, based on these results. It was shown that below $TS = 24°C$ it is not necessary to perform detailed estimation.

Keywords: climate index, thermal index, thermal hazard, climatic safety of a human

W artykule przedstawiono wyniki badań nad stosowaniem wybranych wskaźników cieplnych pracy człowieka i wskaźników klimatu w dwustopniowej ocenie klimatycznych warunków pracy w kopalniach podziemnych. Różnicę pomiędzy tymi wskaźnikami wykazano podczas realizacji zadania kierowanego przez Instytut Eksploatacji Złóż Politechniki Śląskiej pt. „Opracowanie zasad zatrudniania pracowników w warunkach zagrożenia klimatycznego w podziemnych zakładach górniczych". Zadanie było częścią

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projektu strategicznego „Poprawa bezpieczeństwa pracy w kopalniach" finansowanego przez Narodowe Centrum Badań i Rozwoju.

Wskaźniki klimatu oparte są jedynie na pomiarach parametrów fizycznych powietrza, natomiast wskaźniki cieplne dodatkowo uwzględniają inne czynniki związane z wykonywaną pracą, np. rodzaj odzieży oraz ciężkość wykonywanej pracy.

Podczas realizacji projektu pod szczególną uwagę wzięto dwa wskaźniki, temperaturę śląską (*TS*), która należy do grupy wskaźników klimatycznych oraz wskaźnik dyskomfortu cieplnego (δ), należącego do wskaźników cieplnych pracy człowieka.

Pod dyskusję poddano możliwość dwustopniowego stosowania tych wskaźników (ocena podstawowa i szczegółowa), a także wykazano na przykładach, że za pomocą stosowania wskaźnika cieplnego (jako oceny szczegółowej) można uniknąć wprowadzania dodatkowych środków technicznych i organizacyjnych by zmniejszyć zagrożenie cieplne w danym miejscu pracy. Na podstawie wyników badań ustalono także graniczną wartość wskaźnika TS = 24°C poniżej, której nie ma konieczności stosowania szczegółowego stopnia oceny zagrożenia klimatycznego.

Słowa kluczowe: wskaźnik klimatu, wskaźnik cieplny, zagrożenie cieplne, bezpieczeństwo klimatyczne człowieka

1. Introduction

The results of the research into the two stage estimation of climate conditions in the work place in underground mines are presented in this article. The main emphasis was put on differences between two types of indices – the climate index and the thermal index. The research has been conducted in the framework of the project „The recruiting requirements for miners working in hot underground mine environments" which was coordinated by The Institute of Mining Technologies at Silesian University of Technology. It was part of a Polish strategic project: "Improvement of safety in mines" being financed by The National Centre of Research and Development.

The other members of the consortium were: the other participants who were selected from among the following major Polish mining and medical research units: AGH – University of Science and Technology – Faculty of Mining and Geo-engineering, EMAG – Institute of Innovative Technologies, Institute of Occupational Medicine and Environmental Health and CEN-MED – Professional Medical Research Center. The consortium also included the Polish Mining Companies – JSW S.A., KW S.A and KHW S.A.

The research covered 24 Polish coal mines owned by the supporting mining companies and they are located within The Upper Silesia Coal Basin (USCB). 98 longwalls and 224 headings have been analyzed. In the framwork of current Polish regulations (during the duration of the project) (*Polish Regulations*) worktime should be reduced to 6h when dry bulb temperature is higher than t_d = 28°C or wet Kata cooling power is lower than 11 K_w. Such a situation has been noticed in 35 longwalls (36% of all the longwalls). The lowest value of dry bulb temperature in longwall was 18,8°C,and the highest was 32,6°C (Drenda, 2013b; Drenda et al., 2013).

Considering the headings it was noted that t_d exceeded 28°C in 50 cases (22% of all the headings). The lowest value of dry bulb temperature was 18,0°C and the highest was 32,6°C (Drenda, 2013b; Drenda et al., 2013; Wrona & Pach 2013).

Sufficient data are presented in Table 1.

About 60 different microclimate indices are in use in the world (Brake & Bates, 2002a; Epstein & Moran, 2006). A lot of them are based on simple measurements of air parameters, e.g. dry bulb temperature, cooling intensity. (Szlązak et al., 2008; Knechtel, 2011). On the other hand, part of them can be considered as connected to human work parameters, e.g Thermal Work Limit index (Brake & Bates, 2002b), WBGT, cooling power index (Lambrecht, 1972) or thermal discomfort index (Drenda 1993, 2012).

TABLE 1

The range of detected values of dry bulb temperature in longwalls and headings

The number of longwalls/ headings	**The range of t_s, °C**	**$t_{s\,min}$, °C longwalls / headings**	**$t_{s\,max}$, °C longwalls / headings**
22/82	18-25	18,8/18,0	32,6/32,6
41/92	25-28		
14/30	28-30		
21/20	30-33		

The following indices are the best known among Polish mining engineers: substitute Silesian temperature, American effective temperature according to Yaglou (t_{ef}, ATE) (Mc Phearson, 1993), French temperature (t_r), Belgian effective temperature (BTE) and WBGT (Hartman et al., 1997). There are proper nomograms or equations for their estimation. WBGT has not been introduced as compulsory in underground mines according to complex measuring methodology (Epstein, 2006).

The legal aspects of thermal hazard estimation in underground mines in selected countries are presented below:

a) Germany
Microclimate assessment is based on the effective temperature index (t_{ef}) which in Poland is known as ATE (Słota, 2013; *German Regulations*).

b) Former USSR countries and Bulgaria
In those countries the assessment is based on dry bulb temperature and humidity measurements. When relative humidity is higher than 90%, dry bulb temperature should be lower than 26°C.

c) Belgium, Nedtherlands, France
The assessment is based on BTE index.

d) Australia, UAE
Thermal Work Limit (TWL) is in use (Brake & Bates 2002b).

d) USA
The criteria of thermal assessment are compiled in the document published by NIOSH (National Institute of Occupational Safe and Health): “Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments. They are based on temperature,the metabolism rate of a worker and WBGT index.

e) Czech Republic
There is a set of tables for the regulation of thermal conditions according to the results of psychrometric air parameters and air velocity.

f) South Africa
The results of psychrometric results are combined with the document entitled: Guideline for the Compilation of a Mandatory Code of Practice for an Occupational Health Programme on Personal Exposure to Thermal Stress Ref. No. DME 16/3/2/4-A2 (*South African Regulations*).

After the analysis of world indices, the entire group has been divided into three groups:
- group 1 – simple results of air parameters measurements,
- group 2 – climatic indices –calculations based only on air parameters values,
- group 3 – human thermal indices – calculations based on air parameter values as well as on additional (work) factors, e.g. metabolism rate, thermal resistance of clothing, acclimatization.

After analyzing the results obtained during the project, it was stated that the assessment of thermal hazard in an underground working situation can be divided into two stages:
- preliminary (basic) – based on indices from among group 2,
- detailed – based on human thermal indices (group 3).

The two stage assessment based on the indices calculated in Silesian University of Technology has been presented in the following chapters. TS has been proposed as a basic index and δ index as a detailed one.

According heat exchange occurring between rockmass and the air (Wacławik, 2005), suitable examples have been selected for further analysis. A two stage estimation of thermal hazard has been applied and interpreted for selected working stands in underground conditions. The results allowed the limit value of *TS* to be set, below which it is not necessary to perform the second stage of the assessment.

2. Silesian substitute temperature (*TS*) – climatic index for basic microclimate assessment

Silesian substitute temperature *TS* can be an index for principal assessments for thermal hazard evaluation in underground mines. It includes dry and wet bulb temperatures t_d, t_w, air velocity v and its relative humidity φ (equation 1) (Drenda, 2013a):

$$TS = 0{,}7 \cdot t_W + 0{,}3 \cdot t_d - (1{,}7 - \varphi) \cdot \varphi \cdot v \tag{1}$$

where:

t_w — wet bulb temperature, °C;
t_d — dry bulb temperature, °C;
φ — relative humidity, -;
v — air velocity, m/s.

The construction of the equation (1) gives a similar course of ATE nad TS isolines in the range 28-32°C. TS should be evaluated as follows:

TS < 26°C – full time work,
26 ≤ TS < 30°C – reduction of time work or improvement of thermal conditions,
TS ≥ 30°C – work forbidden except rescue operations.

For example, in German coal mines *ATE* = 30°C is also the limit value for work.

3. Thermal discomfort index (δ) – thermal index for detailed microclimate assessment

Thermal discomfort index (δ) is a tool for thermal hazard assessment in every environment. That is the reason why it could be applied in coal mines as well as in other mines (e.g. copper mines). Easy interpretation of the result obtained is the great advantage of this index. The result is dimensionless, therefore the values can be from among the set ($-\infty < \delta < +\infty$). In practice only values of zero and one are crucial. If $\delta = 0$ there is thermal comfort. If $\delta \neq 0$, the values give the information about discomfort. The result $\delta \geq 1$ indicates that conditions are dangerous for humans (heat rash or heat stroke are possible).

Detailed assessment should be based on (Drenda, 1993):

$0 \leq \delta < 0,2$ – favourable climate conditions,
$0,2 \leq \delta < 0,5$ – satisfactory climate conditions,
$0,5 \leq \delta < 0,8$ – hard climate conditions – measures for the improvement of conditions should be applied,
$0,8 \leq \delta < 1,0$ – very hard climate conditions.

The index depends on factors connected with climate and humans. Climate parameters are:

- temperature,
- humidity,
- air velocity.

Additional parameters: average radiant temperature (temperature of sidewalls in the case of a mine).

Human parameters are:

- metabolism ratio,
- thermal insulation of clothes,
- acclimatization.

These parameters can be presented as an empirical function:

$$\delta = f(t_d, \varphi, \mathrm{v}, t_r, M, I_{cl}, A) \tag{2}$$

where:

t_d — dry bulb temperature, °C,
φ — relative humidity, %,
v — air velocity, m/s,
t_r — average radiant temperature, °C,
M — metabolism ratio, W/m^{2},
I_{cl} — thermal insulation of clothes, clo,
A — acclimatization, (yes or no).

Sufficient nomograms are presented for assessment of this index (Figs 1-5).

Following nomograms are created for particular values of relative humidity φ = 20%, 40%, 60%, 80% and 100%. The left part is designed for a non – clothed human, and the right for clothed. The example of the application is shown in Fig. 4. For different input data it is necessary to make proper interpolations.

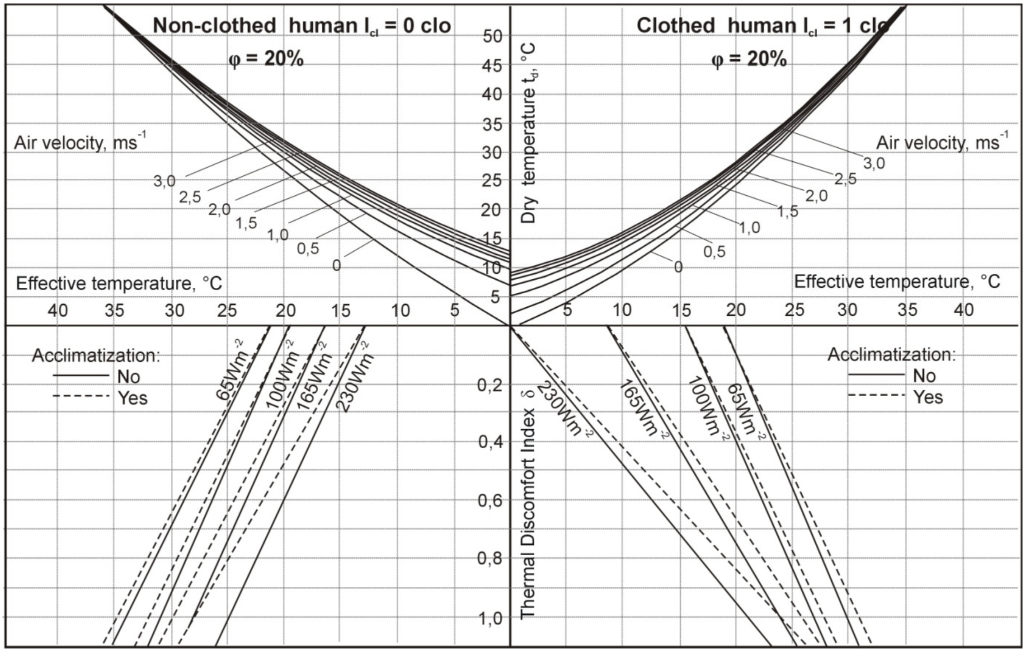

Fig. 1. The nomogram for thermal discomfort assessment, relative humidity φ = 20%

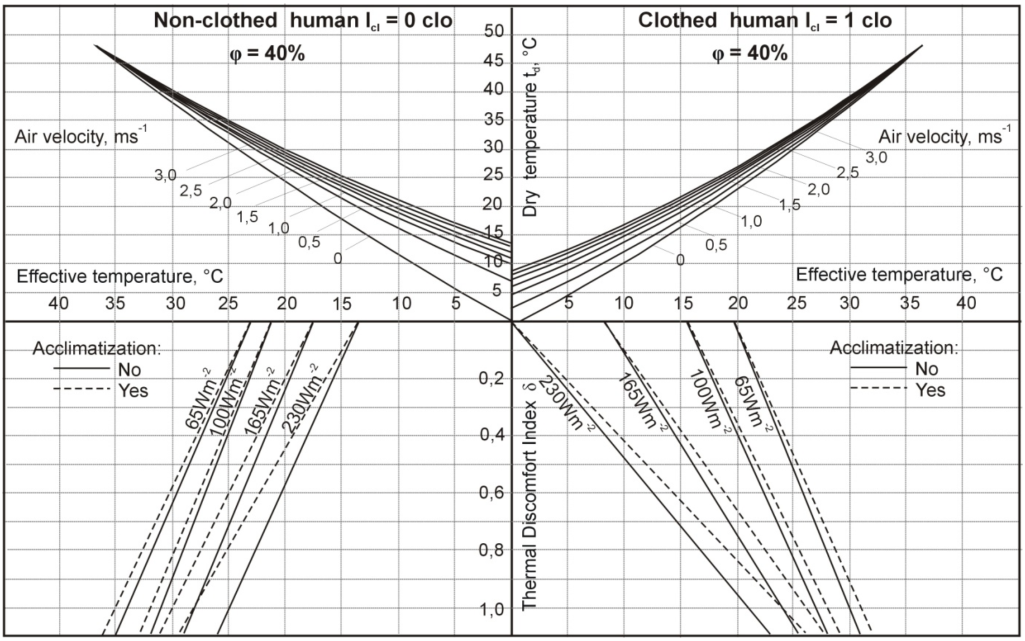

Fig. 2. The nomogram for thermal discomfort assessment, relative humidity φ = 40%

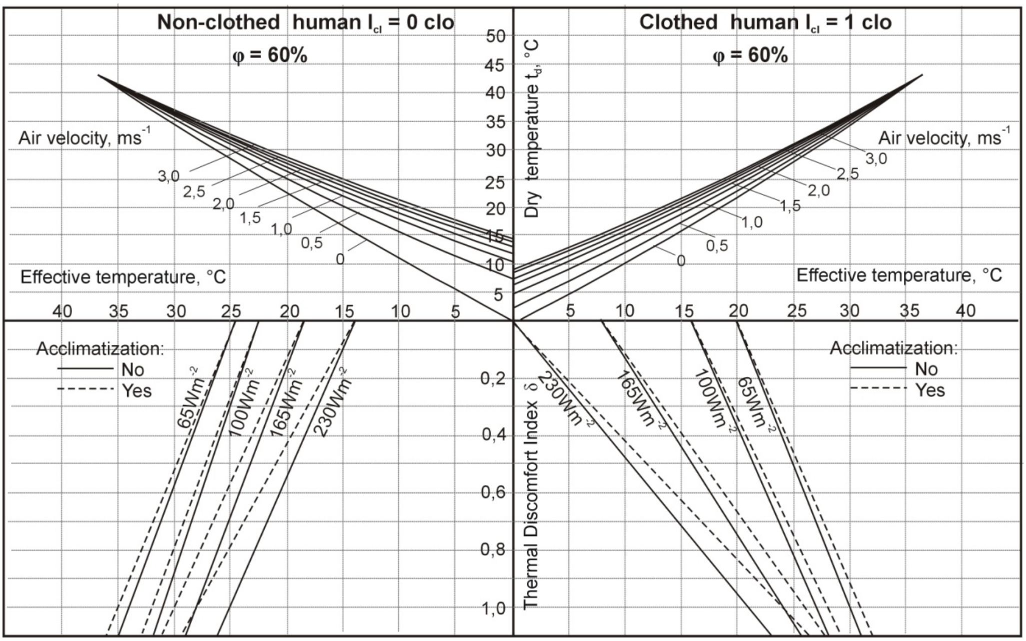

Fig. 3. The nomogram for thermal discomfort assessment, relative humidity φ = 60%

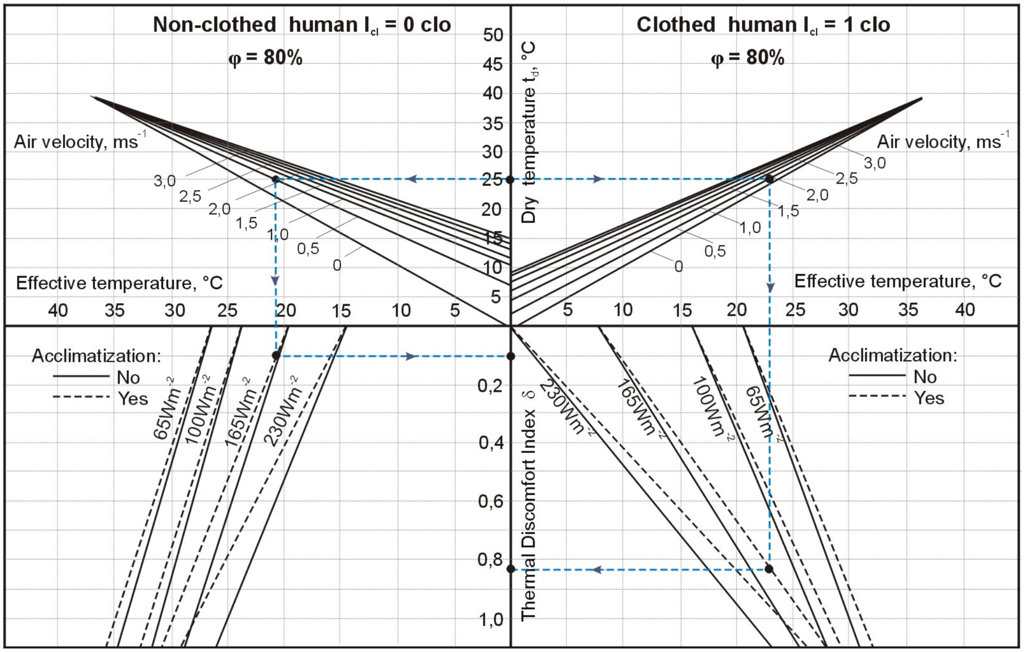

Fig. 4. The nomogram for thermal discomfort assessment, relative humidity φ = 80%

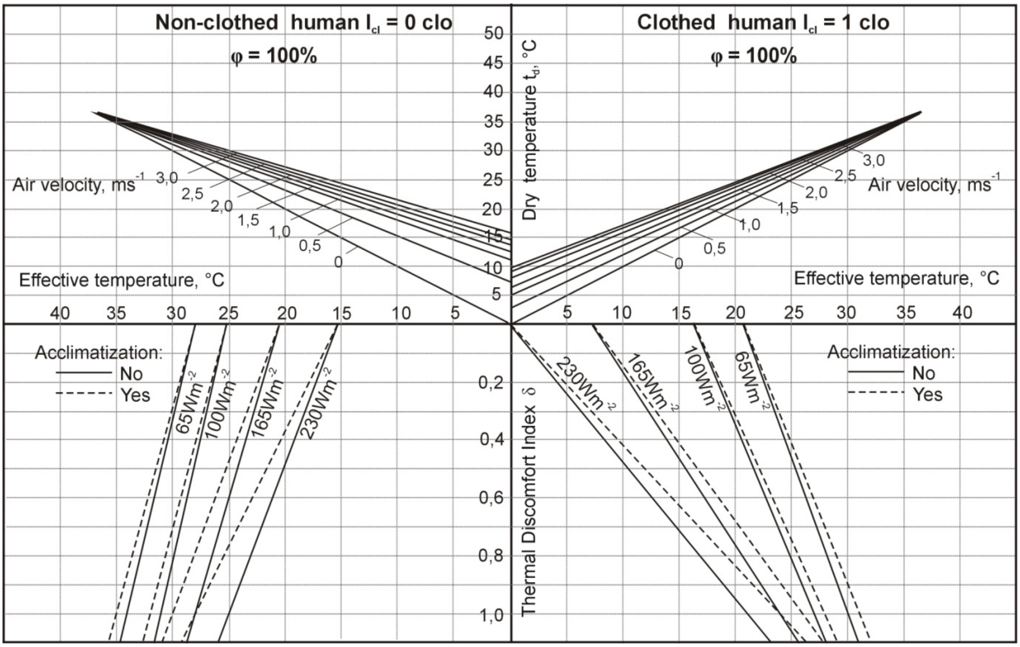

Fig. 5. The nomogram for thermal discomfort assessment, relative humidity φ = 100%

4. The assessment of thermal conditions

Examples of the application of the above mentioned two stage assessment of thermal hazard are presented in this chapter.

4.1. Methodology

Many series of measurements of air parameters have been undertaken in the framework of the project. Generally, data from 98 longwalls and 224 headings were collected (total number 322). For the further two stage assessment of microclimate (basic – *TS*, and detailed δ) the following parameters have been measured:

- dry bulb temperature t_d and wet bulb temperature t_w – by Assmann's psychrometer,
- air velocity v – by vane anemometer,
- pressure p – by portable barometer.

Then relative humidity has been calculated with psychrometric charts.

Measurements have been carried out on following points (Fig. 6):

- intake to a longwall,
- outlet from a longwall,
- the beginning of heading,
- blind end.

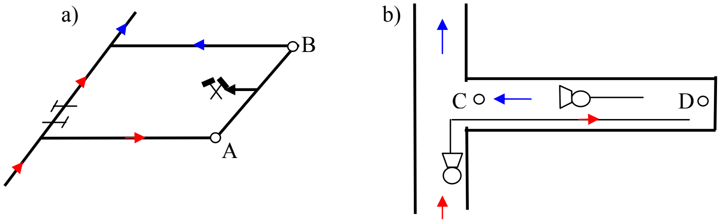

Fig. 6. Location of measuring points in: a) a longwall, b) a heading.

4.2. The results

The analysis has been based on many climate and thermal indices but special emphasis has been put on the proper layout of a two stage assessment with the application of $TS - \delta$ indices. Ten different examples have been selected from 644 measuring points. The examples are given with worse climate conditions, considering the parameters (t_d, t_w, v, K_w and φ) The examples are given in Table 2.

TABLE 2

The selected examples for the analysis of the two stage assessment of thermal hazard

Air parameter	The number of an example and its location									
	1	2	3	4	5	6	7	8	9	10
	A	C	B	B	C	A	D	B	D	B
t_d, °C	22,0	25,8	25,2	25,6	28,2	28,2	29,6	31,8	31,4	32,6
t_w, °C	17,4	19,8	23,8	24,4	23,2	26,2	25,4	29,0	28,6	31,0
v, m/s	2,16	1,11	0,84	0,73	0,69	1,46	0,56	2,0	0,36	1,48
φ, %	62,5	56,4	88,8	90,5	64,8	85,1	70,8	80,8	80,7	89,0
K_w	29,1	20,7	14,6	13,5	14,6	13,9	11,7	11,1	7,5	7,4

(A – inlet to a longwall, B – outlet from a longwall, C – inlet to a heading, D – dead end)

4.3. The analysis

Based on the examples 1-10 (Tab. 2) a two stage assessment of hazard has been performed. In the framework of the detailed research the thermal discomfort index has been taken into considerations (Tab. 3) with the option of the acclimatized human and three variants of clothes and five variants of working activity.

According to the results and observations (heart rate tests for the workers) moderate work is the most common among the miners (Drenda et al., 2013). Hard work was being done intermittently. That is the reason why further discussion is based on this kind of work and relative metabolic heat production. Additional assumption – δ cannot exceed 1,0.

TABLE 3

TS and *δ* for 10 examples

		The example									
		1	2	3	4	5	6	7	8	9	10
		TS, °C									
		17,3	20,9	23,6	24,2	24,2	25,7	26,3	28,4	29,2	30,4
Kind of work, metabolic heat production, W/m²	**Thermal resistance of clothing, clo**	*δ*									
Light, 100	0 clo	–1,27	–0,4	–0,50	–0,38	–0,01	–0,18	0,21	0,27	0,56	0,67
	0,5 clo	–0,79	–0,08	–0,03	0,07	0,29	0,21	0,49	0,57	0,81	0,91
	1,0 clo	0,01	0,43	0,58	0,63	0,71	0,75	0,87	**1,00**	**1,10**	**1,20**
Less than moderate, 130	0 clo	–1,00	–0,22	–0,23	–0,12	0,15	0,04	0,36	0,43	0,69	0,80
	0,5 clo	–0,53	0,09	0,18	0,26	0,43	0,38	0,61	0,69	0,89	0,98
	1,0 clo	0,22	0,57	0,70	0,74	0,81	0,84	0,94	**1,05**	**1,13**	**1,22**
Moderate, 165	0 clo	–0,68	–0,01	0,08	0,17	0,35	0,29	0,54	0,62	0,85	0,95
	0,5 clo	–0,22	0,3	0,42	0,49	0,6	0,58	0,75	0,83	**1,00**	**1,08**
	1,0 clo	0,46	0,73	0,84	0,87	0,92	0,95	**1,02**	**1,11**	**1,17**	**1,23**
Less than hard, 200	0 clo	–0,43	0,16	0,28	0,36	0,49	0,46	0,67	0,75	0,95	**1,04**
	0,5 clo	–0,02	0,43	0,56	0,61	0,7	0,69	0,84	0,91	**1,06**	**1,13**
	1,0 clo	0,57	0,81	0,90	0,93	0,98	**1,00**	**1,06**	**1,14**	**1,20**	**1,25**
Hard, 230	0 clo	–0,21	0,31	0,45	0,52	0,62	0,61	0,78	0,86	**1,03**	**1,12**
	0,5 clo	0,15	0,55	0,67	0,73	0,79	0,79	0,92	0,98	**1,11**	**1,18**
	1,0 clo	0,67	0,88	0,96	0,99	**1,02**	**1,04**	**1,1**	**1,17**	**1,22**	**1,26**

Example 1

In the example 1 values of δ are lower than zero (cold environment) and *TS* = 17,3°C (far from limit *TS* = 26°C). Only for hard work do these values reach 0,15 and 0,67 respectively, for thermal resistance of clothing 0,5clo and 1,0clo. The conclusion is that only during hard work (which can be done periodically) can a worker regulate his thermal comfort by temporarily removing part of his clothing. In addition, having a full set of clothing (*clo* = 1,0) a worker can perform light work in thermal comfort (*δ* = 0,01). In this case TS is not exceeded and according to the present law (t_d and K_w) work is allowed up to 8h (Tab. 2).

Examples 2 and 3

The examples 2 and 3 indicate that when *TS* is between 20,9 and 23,6°C even hard work in full clothing (I_{cl} = 1,0 *clo*) does not cause thermal discomfort which could be life threatening (*δ* values lower than 1,0). Although less than moderate work produced *δ* = 0,57 and 0,70, which indicates the necessity of additional technical improvement of conditions or working time reduction, nevertheless, it could be improved by decreasing thermal clothing resistance and the values of *δ* would be 0,09 and 0,18 respectively.

Considering these statements and Figures 7-9 it was pointed out that there is no case when *δ* = 1,0 is exceeded if *TS* is lower than 24,0°C. That is the basis for the conclusion that *TS* = 24°C is the limit value, and for the lower values it is not necessary to introduce detailed assessment. According to t_d and K_w full time work is allowed, too.

Examples 4 and 5

Comparing the results from the examples 4 and 5 it is very important that the value *TS* = 24,2°C is the same for both cases and beside this there is a significant difference in t_d. In the example 4 t_d = 25,6°C, while in the example 5 t_d = 28,2°C. There is also a relative humidity difference – approx. 26%. It was found that in spite of having equal TS values, there are different *δ* values. For hard work the values of δ were 0,99 (example 4) and 1,02 (example 5). Considering possible measuring inaccuracy it was proved that *TS* = 24°C should be stated as the limit for basic assessment. In examples 4 and 5 *TS* = 26°C is not exceeded, either. According to present regulations for example 4 full time work is allowed but for example 5 technical solutions or time reduction should be applied.

Example 6

In the example 6 (*TS* = 25,7°C) it was stated that for moderate work in full clothes value *δ* would be 0,95. Therefore it would be necessary to make a detailed selection and analysis of the intensity of work and kind of clothes at this stand. It would be possible to regulate thermal hazard by application of *δ*.

In spite of the *TS* value being lower than 26°C, according to present regulations technical solutions or time reduction should be applied.

Example 7

Example 7 has been selected because it exceeds *TS* = 26°C. It is 26,3°C. For moderate work a miner is in dangerous thermal conditions. Considering dry bulb temperature equal 29,6°C it is necessary to apply conditions improvement. It also conforms to present regulations.

Examples 8 and 9

That is the case when t_d is higher in example 8 than in example 9, however *TS* is lower. Dry bulb temperature exceeds 28,0°C, and *TS* equal 28,4°C and 29,2°C respectively.

The difference is caused by significant velocity influence in example 8. In both cases *δ* is higher than the limit value for every kind of work in full clothing. Therefore, at first it is necessary to apply lighter clothing /and/or reduce worktime or/and turn on the cooling system.

According to present regulations worktime should be reduced or a technical solution should be introduced.

Example 10

In this example *TS* = 30°C is exceeded and equals 30,4°C. Hard work in full clothing is dangerous. *δ* equals 1,0 or is higher than 1,0 during light work when fully clothed. Probably only cooling would be a proper solution. It is consensual with current regulations.

Relation between *TS* and *δ* is shown in Figures 7-9. It is computed on the basis of the entire collection of results and analysis in framework of the project. The diagrams (Fig. 7-9) confirm the value *TS* = 24°C as a limit for basic thermal assessments.

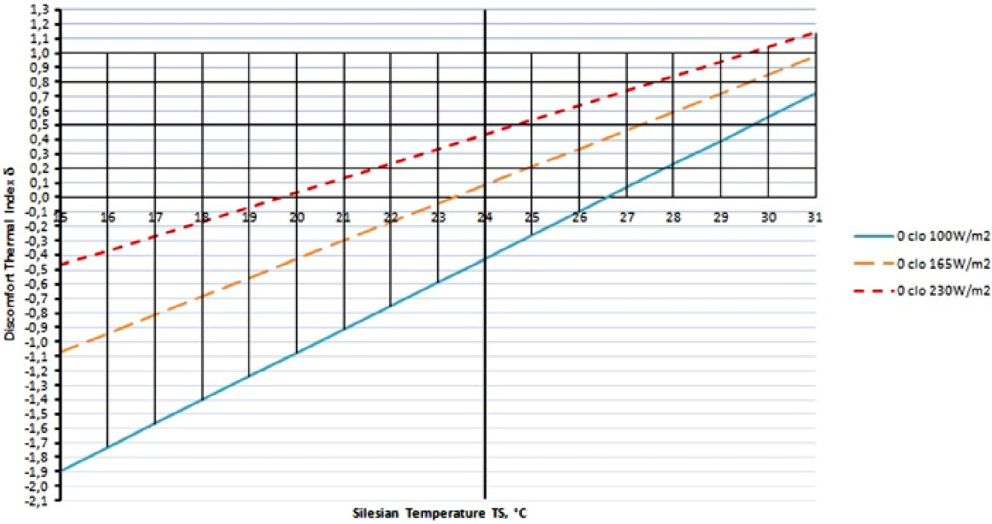

Fig. 7. The dependence of thermal discomfort index *δ* and average *TS* values for unclothed and acclimatized people

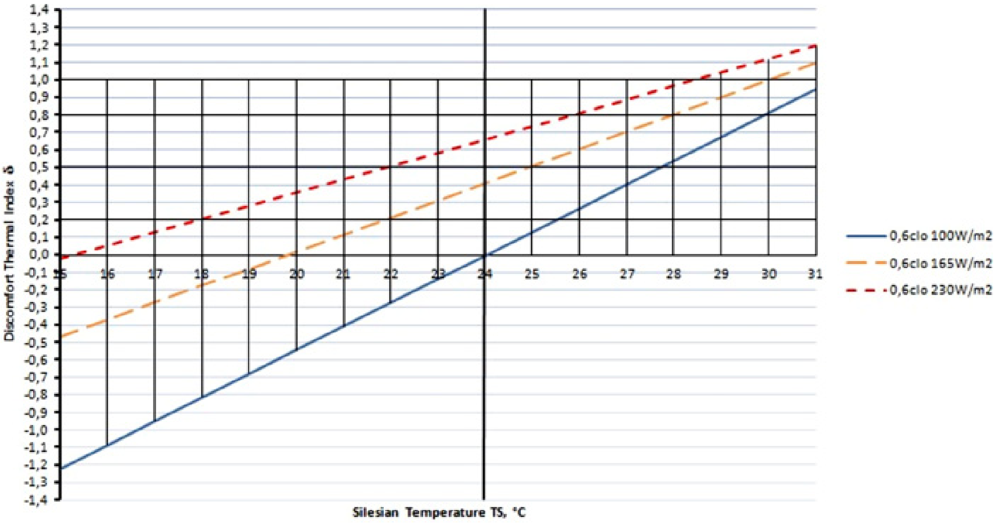

Fig. 8. The dependence of thermal discomfort index *δ* and average *TS* values for lightly clothed and acclimatized people

The top line in Figure 9 refers to the most difficult illustration of given variants of the type of work and clothing. Values of δ will be lower when the intensity of work and/or clothing is lighter. After analyzing Figure 9, it is clear that for TS < 24°C δ cannot be higher than 1,0. Thermal discomfort in such a case is acceptable. Although when TS is higher than 24°C, thermal discomfort could be dangerous, e.g for hard work in full clothing.

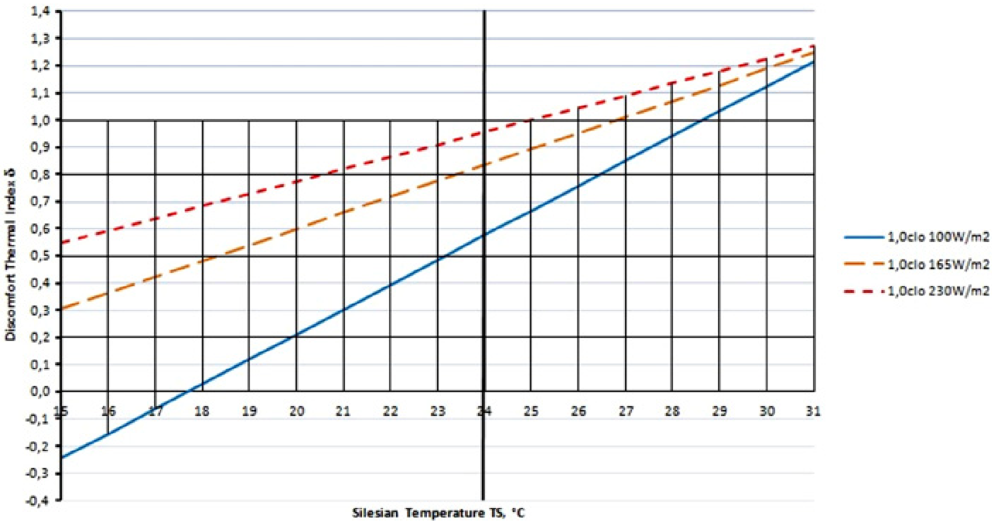

Fig. 9. The dependence of thermal discomfort index δ and average *TS* values for completely clothed and acclimatized people

Another conclusion which can be drawn from Figure 9 is that for moderate work (the most common for miners) δ is higher than 1,0 for a *TS* higher than 26°C. This is the reason for this value being the limit for *TS*, when thermal condition improvement should be applied.

The examples give the general view that a two stage assessment of thermal hazard (including intensity of work and clothing) will allow a reduction in thermal discomfort by individual regulations (periodical rest, decrease of metabolism ratio, decrease of clothing thermal resistance) without radical solutions (e.g. turning on the cooler) (Table 3).

5. Conclusions

1) In underground mines, a two stage assessment of microclimate conditions (thermal hazard) is possible with the application of climate and thermal indices. Silesian substitute temperature index (*TS*) could be applied at the principal (basic) stage and thermal discomfort index (δ) at the detailed phase. TS is based on air parameter measurements, δ also includes human factors, e.g. thermal resistance of clothing, type of work.
2) It was proved that when the *TS* is lower than 24°C it is impossible to exceed $\delta = 1{,}0$. Therefore $TS = 24$°C should be set as the threshold limit value for the principal assessments.
3) The introduction of a two stage assessment of thermal hazard would allow the employer to conduct a more detailed analysis of microclimate conditions at working stands and more efficient management of heat reduction in his plant (a mine). Instead of activating expensive air cooling systems, sometimes it would be enough simply to apply periodical rest periods for the miners, decrease their average metabolism ratio or decrease their clothing thermal resistance.

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