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SAFE WORKING CONDITIONS IN HOT MINE ENVIRONMENT – THE ANALYSIS OF DIFFERENT INDICES

BEZPIECZNE WARUNKI PRACY W GORĄCYM ŚRODOWISKU KOPALNI – ANALIZA RÓŻNYCH WSKAŹNIKÓW

The article presents the discussion and practical examples relating to the interpretation of the notion of safe working areas in hot environment based on various indices (American Effective Temperature (ATE), climate equivalent temperature (t_{zk}) and the Silesian temperature (TS)). The first, theoretical part includes an analysis of the allowable dry bulb temperatures in line with the threshold values for the specified indices in case of various relative humidity and airflow velocity values. Also, the variability of the studied allowable working areas was exhibited for hypothetical extreme cases (such as an airflow of 0 m/s or the relative humidity of φ = 0%) as well as for actual conditions registered in headings. The second part consisted in the analysis of the allowable full-time working conditions for two selected cases of driving roadways. The analysis was conducted for two indices applied in the first part and complemented with an appraisal considering the dry bulb temperature (t_s) and the wet kata thermometer units (K_w). It has been exhibited that while regulating the airflow and the dry bulb temperature in the heading, significant differences in the interpretations (ranges) of safe working areas occur depending on the index that is being used. The conducted works indicate that by applying air cooling in the heading (decreasing the psychrometric temperatures considering the thermodynamic process corresponding to sensible air cooling) or by increasing the airflow, the requirements of the microclimate indices are fulfilled in the following order: ATE, t_{zk}, TS.

Keywords: underground mining; thermal hazard; microclimate index

W artykule przedstawiono dyskusję oraz przykłady praktyczne dotyczące interpretacji obszarów pracy bezpiecznej w środowisku gorącym według różnych wskaźników (Amerykańska temperatura efektywna ATE, temperatura zastępcza klimatu t_{zk}, temperatura śląska *TS*). W pierwszej, teoretycznej części dokonano analizy dopuszczalnych wartości temperatury suchej według wartości granicznych dla wymienionych wskaźników dla różnych przypadków wilgotności względnej i prędkości powietrza.

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Wykazano także zmienność badanych obszarów pracy dopuszczalnej dla hipotetycznych przypadków skrajnych (np. prędkość powietrza w = 0 m/s lub wilgotność względna φ = 0%) jak i rzeczywistych, odnotowanych w wyrobiskach górniczych. W drugiej części przeprowadzono analizę warunków pracy dopuszczalnej w pełnym wymiarze godzin dla dwóch wybranych przykładów, dotyczących drążonych wyrobisk korytarzowych. Analizę prowadzono dla wskaźników zastosowanych w części pierwszej i uzupełniono je o ocenę według temperatury suchej (t_s) i katastopni wilgotnych (K_w). Przedstawiono, że przy regulacji zarówno prędkości powietrza jak i temperatury suchej w wyrobisku występują znaczne różnice w interpretacji (zakresie) obszarów pracy bezpiecznej w zależności od wykorzystanego wskaźnika. Z przeprowadzonych prac wynika, że stosując w wyrobisku schładzanie powietrza (zmniejszanie temperatur psychrometrycznych według przemiany termodynamicznej odpowiadającej chłodzeniu jawnemu powietrza) lub zwiększanie prędkości powietrza wymagania stawiane przez wskaźniki mikroklimatu spełniane są w następującej kolejności ATE, t_{zk}, TS.

Słowa kluczowe: górnictwo podziemne, zagrożenie cieplne, wskaźniki mikroklimatu

1. Introduction

The Faculty of Mining and Geology of the Silesian University of Technology was coordinating the works within the scientific project named „Opracowanie zasad zatrudniania pracowników w warunkach zagrożenia klimatycznego w podziemnych zakładach górniczych" (development of rules for employing workers in climatic hazard conditions in underground mining plants) which is one of the tasks of the „Poprawa bezpieczeństwa pracy w kopalniach" (improvement of work safety in mines) strategic programme (Drenda et al., 2014a). The partners in the project were the AGH Academy of Science and Technology, Faculty of Mining and Geoengineering, EMAG – Institute of Innovative Technologies, Institute of Occupational Medicine as well as the CEN-MED company. The consortium also included three Polish mining companies: Kompania Węglowa, S.A, Jastrzębska Spółka Węglowa S.A. and Katowicki Holding Węglowy S.A.

The studies were conducted in 24 Polish mines in the region of the Upper-Silesian Coal Basin.

The main purpose of the project was to develop methods for employing persons for work in hot mining environments and one of the partial aims was to determine the thermal conditions in underground mines. The purpose was achieved by measuring physical parameters of air and determining the microclimatic indices.

The article presents the results of considerations over the appraisal of thermal conditions according to microclimatic indices, namely the ATE, t_{zk} and TS indices. The ATE index is one of the oldest and was used in USA. Currently it is still applied in Germany. The t_{zk} index will become obligatory in line with the polish provisions regarding the hazards in underground mining plants from 01.01.2018 (Ordinance, 2013). The TS index is a new proposal resulting from the works within the previously mentioned project (Drenda et al., 2014 a, b). The indices are based on the same physical parameters but each of them exhibits separate threshold values which are decisive for the allowable time of safe work. The appraisal giving consideration to these indices is different to the currently applied assessment based partially on the intensity of cooling index.

2. Thermal hazard in underground mining plants

The problem of assessing the thermal hazard in underground mining plants is the subject of many conducted studies (e.g. Wacławik et al., 1995; Wacławik, 2009; Yang & Innoue, 2012; Drenda, 1993). The works concern:

– The heat transfer between human and environment in hot environments (Knechtel, 2001; Bottomley et al., 1987),
– The practical solutions for reducing the hazard (Ramsden & Von Glehn, 2012),
– The appraisal of thermal conditions (Brake & Bates, 2002; Mitchel, 1971; Wacławik et al., 2013; Strumiński & Turkiewicz, 2003; Drenda, 2012).

Currently, approximately 60 microclimatic indices are applied worldwide (Brake & Bates, 2002). Several selected indices that are applied in countries where underground mining activity is or was conducted have been presented below.

In line with the provisions that are binding in Poland (Ordinance, 2002), the assessment of thermal hazard in the Polish underground mining plants is based on the dry bulb temperature values t_s and the intensity of air cooling K_w. In headings where self-propelled Diesel engine machines are applied, the assessment is conducted in line with the Polish Standard (PN-G-03100) based on the climate equivalent temperature t_{zk}. Since January 1st 2016, the assessment of climatic conditions is conducted based on the t_{zk} index in all mining plants (Ordinance, 2013).

Globally, various indices are used to assess the microclimate and thermal conditions. In Germany, for example, the assessment is conducted based on the TEF index, known in Poland as the American Effective Temperature – ATE. In Bulgaria and in the most countries of the former Soviet Union, the appraisal is conducted based on the dry bulb temperature value and the air humidity. In Belgium, Netherlands and France, an index called the Belgian Effective Temperature, BTE is applied. The Thermal Work Limit (TWL) index is used in Australia and United Arab Emirates. In USA, the air temperature, metabolism and the WBGT index are assessed. In Czech Republic the appraisal is conducted by determining the dry bulb and wet bulb temperatures, relative air humidity and the airflow velocity. In South Africa, the temperature of radiation of environment is measured besides the psychrometric temperatures.

2.1. The Analyzed Microclimate Indices

The American Effective Temperature (ATE), the climate equivalent temperature (t_{zk}) and the Silesian Temperature (TS) were selected for a detailed analysis.

The indices are easy to determine (the simplest method of psychrometric measurement), based on the same parameters – dry bulb t_s, and wet bulb t_w temperatures and the air velocity (relative humidity in calculation of TS is indirectly dependent on t_s and t_w).

a) American Effective Temperature, according to Yaglou

ATE is interpreted as the temperature of saturated still air characterized by the same cooling power as air in the given measurement point. ATE is determined based on the sample monogram shown in Fig. 1.

The threshold values for ATE are as follows (Frycz, 1981):

- When ATE is lower than 28°C – allowable working time is 8h,
- When ATE is within the range from 28°C to 32°C – the allowable working time is 6h,
- When ATE exceeds 32°C – the work is forbidden.

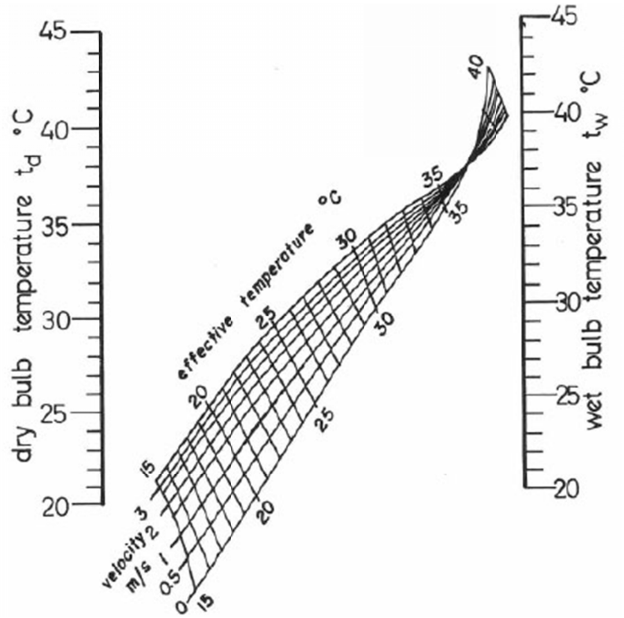

Fig. 1. An example of a monogram used in the determination of ATE for persons in typical working clothes. *Source:* Mc Pearson, 1993

b) Equivalent climate temperature (t_{zk})

The t_{zk} index is calculated using the formula (1). It depends on the psychrometric temperatures (t_s, t_w) and the air velocity (w).

$$t_{zk} = 0{,}4 \cdot t_s + 0{,}6 \cdot t_w - w \tag{1}$$

When t_{zk} is higher than 26°C, 3 levels of thermal hazard are introduced.

The 1st level of climatic hazard includes working posts at which the equivalent climate temperature is not higher than 30°C. The 2nd level includes working posts at which the equivalent climate temperature is higher than 30°C and does not exceed 32°C. The 3rd level of climatic hazard includes working posts at which the climate equivalent temperature is higher than 32°C or the wet bulb temperature is higher than 34°C or the air temperature measured with a dry bulb thermometer is higher than 35°C.

c) Silesian equivalent temperature (TS)

The TS index was developed as a result of analyses of impact of high velocities of air on the working conditions (Drenda et al., 2014a). TS is determined using the formula (2). It depends on the psychrometric temperatures (t_s, t_w), the air velocity (w) and the relative humidity (φ).

$$TS = 0{,}3 \cdot t_s + 0{,}7 \cdot t_w - (1{,}7 - \varphi) \cdot \varphi \cdot w \tag{2}$$

The obtained TS values have been presented below (Drenda, 2012):

(1) When TS is lower than 26°C – the allowable working time is 8h.

(2) When TS is higher than 26°C and lower than 30°C – the allowable working time is 6h.
(3) When TS is higher than 30°C – work is forbidden with the exception of rescue operations.
(4) In case of air velocities exceeding 5 m/s, the air velocity shall be assumed to be 5 m/s.

2.2. The analysis of safe working areas in line with ATE, t_{zk} and TS

While analyzing the dimensions of fields corresponding to the safe working areas in line with the above indices, one may note certain discrepancies. Below, an analysis of these discrepancies has been conducted for various air parameters, giving consideration to various relative air humidity and velocity values. It must, however, be stressed that references to low relative humidity values (φ = 0%) and air velocity of w = 0 m/s are purely hypothetical and in mining (especially hard coal and copper) such values are not observed in underground headings. The following characteristic values of parameters have been assumed in the considerations:

a) Air velocity
- 0 m/s – hypothetical value, may occur in case of ventilation failure,
- 0.3 m/s – minimal air velocity value resulting from the mining provisions binding in Poland (in roadway headings driven in fields of the 2nd, 3rd and 4th categories of methane hazard and in headings ventilated using streamlined air in methane fields),
- 1.0 m/s – minimal air velocity in headings with electric traction in methane fields,
- 3.0 m/s – maximal air velocity in headings registered within the project (Drenda et al. 2014a).

b) Relative humidity
- 0% – hypothetical extreme case,
- 80% – a value often measured in headings during the works conducted within the project (Drenda et al. 2014),
- 100% – extreme case occurring in underground mining.

The following is a comparative analysis of TS/ATE, t_{zk}/ATE, and TS/t_{zk} areas for previously mentioned cases, taking into account the resulting dry bulb temperature which should be observed at the excavation site so that the allowable values of the microclimate index are not exceeded. Figures 2, 3, and 4 show safe working areas in shifts reduced to 6h in accordance with the subsequent indices assuming the minimal airflow velocity as defined in the mining regulations equal to 0.3 m/s. For higher airflow velocity these areas will be larger. Figures 2, 3, and 4 only show their ranges as lines.

Tables 1-3 show the allowable values of dry bulb temperature in accordance with Fig. 2.

Table 1 presents the allowable values of dry bulb temperature for variable airflow velocity and relative humidity for the threshold value of t_{zk} = 32°C. Red colour indicates values unallowable due the limitation of dry bulb and wet bulb temperatures. Table 1 shows that for t_{zk} = 32°C, the lowest dry bulb temperature would be 32.0°C and it would correspond to w = 0 m/s and φ = 100%. The highest dry bulb temperature would be 34.9°C and would correspond to w = 1.0 m/s and φ = 80%. If there was no temperature limitation, the highest allowable temperature would be 57°C.

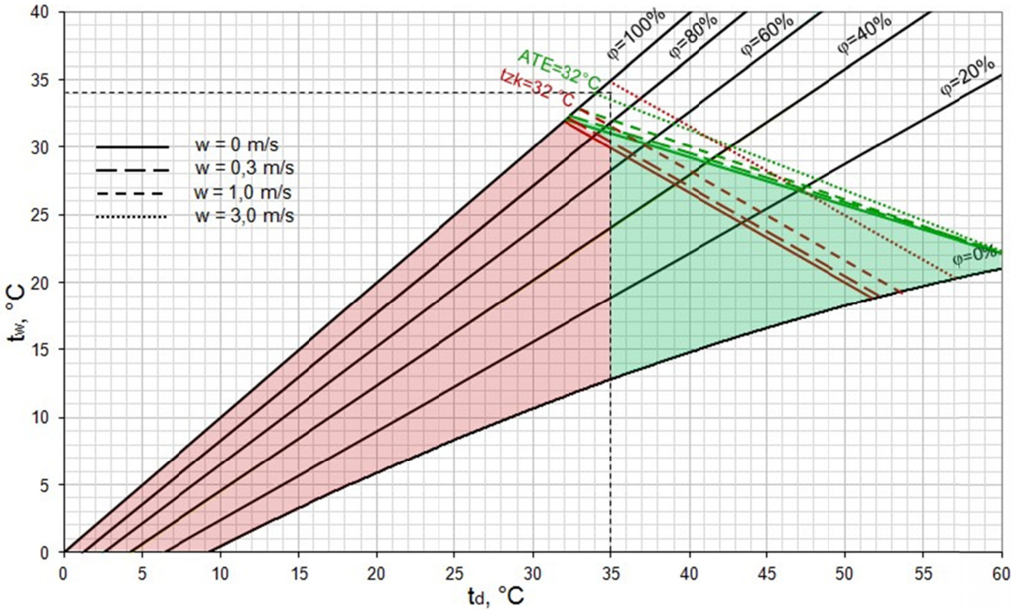

Fig. 2. Comparison of the allowable working conditions areas in time reduced to 6h in accordance with ATE (the sum of red and green cells) and t_{zk} (red cells) indices for airflow velocity of 0.3 m/s

TABLE 1

Allowable t_s values for variable airflow velocity (w) and its relative humidity (φ) for the threshold value of t_{zk} = 32°C

	w = 0 m/s	**w = 0.3 m/s**	**w = 1.0 m/s**	**w = 3.0 m/s**
φ = 0%	51.6°C	52.0°C	53.5°C	57.0°C
φ = 80%	33.9°C	34.2°C	34.9°C	37.0°C
φ = 100%	32.0°C	32.3°C	33.0°C	35.0°C (t_w = 35°C)

TABLE 2

Allowable values of t_s for variable airflow velocity (w) and relative air humidity (φ) for the threshold value of ATE =32°C

	w = 0 m/s	**w = 0.3 m/s**	**w = 1.0 m/s**	**w = 3.0 m/s**
φ = 0%	over 60°C	over 60°C	over 60°C	over 60°C
φ = 80%	34.2°C	34.4°C	34.9°C	35.8°C
φ = 100%	32.0°C	32.3°C	32.7°C	33.8°C

Table 2 presents the allowable values of dry bulb temperature for variables – airflow velocity and relative humidity – for the threshold value of ATE = 32°C. Table 2 indicates that for ATE = 32°C the lowest dry bulb temperature would be 32.0°C and it would correspond to w = 0 m/s and φ = 100% (the same as for t_{zk}). Figure 2 indicates a significant difference in the size of areas corresponding to safe working conditions resulting from the use of ATE and t_{zk} indices.

Dry bulb temperature of 35.8°C would correspond to w = 3.0 m/s and φ = 80%. The comparison of the highest allowable t_s values (Tables 1 and 2) shows that the ATE index allows for work at temperatures higher by 0.9°C than the t_{zk} suggests.

Figure 3 shows a similar comparison for ATE and TS indices.

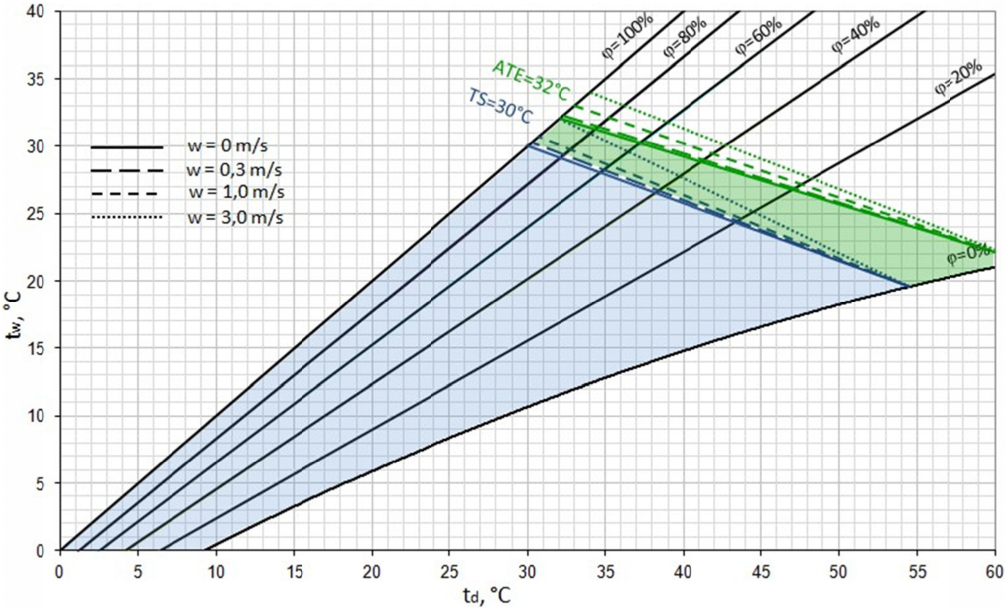

Fig. 3. Comparison of allowable working areas in shifts reduced to 6 h in accordance with ATE and TS indices for airflow velocity equal to 0.3 m/s

TABLE 3

Allowable values of t_s for variable airflow velocity (w) and relative air humidity (φ) for the threshold value of TS = 30°C

	w = 0 m/s	**w = 0.3 m/s**	**w = 1.0 m/s**	**w = 3.0 m/s**
φ = 0%	54.2°C	54.2°C	54.2°C	54.2°C
φ = 80%	32.0°C	32.1°C	32.8°C	34.0°C
φ = 100%	30.0°C	30.2°C	30.9°C	32.2°C

Table 3 presents the allowable values for dry bulb temperatures for airflow velocity and relative humidity for the threshold value of TS = 30°C. For the relative humidity of 0% a high allowable dry bulb temperature equal to 54.2°C has been observed. As highlighted in section 2.3, the assumption of a relative humidity value so low is only a hypothetical. While Table 2 shows that in the high relative humidity range of 80-100% (corresponding to mining conditions) for TS = 30°C the lowest dry bulb temperature would be 30.0°C and would correspond to w = 0 m/s and φ = 100%. The highest dry bulb temperature would be 34.0°C and would correspond to w = 3.0 m/s and φ = 80%. It follows that according to TS index a dry bulb temperature equal to 35°C would not be exceeded.

Based on the analysis of Fig. 4, a significant difference between allowable working areas in accordance with TS and t_{zk} indices has been found. The area to the right of the isoline t_s = 35°C and under the isoline TS = 30°C for w = 0 m/s indicates that the TS index could allow for working in headings with a dry bulb temperature lower than 35°C but at low relative humidity levels.

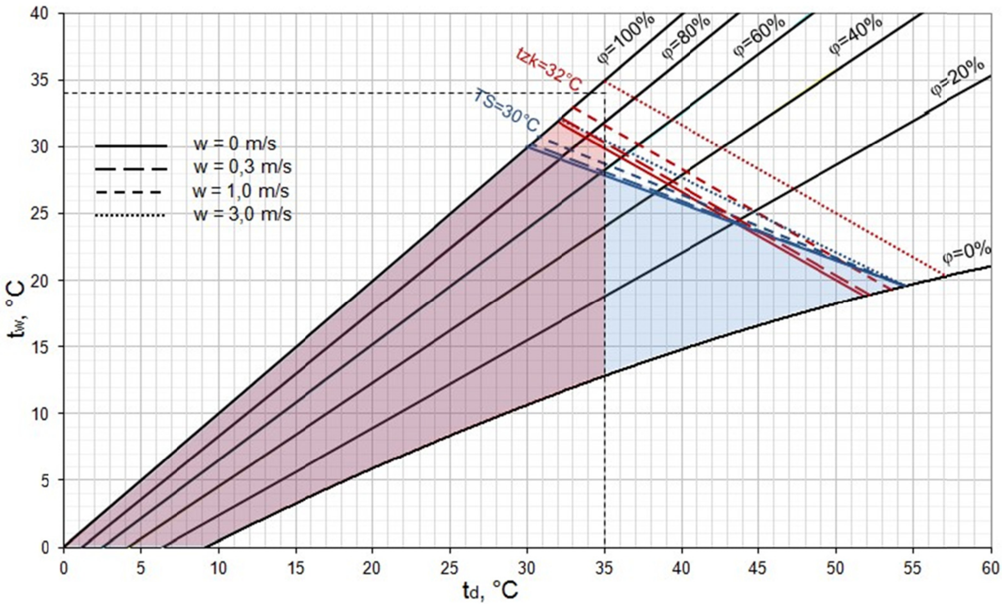

Fig. 4. Comparison of allowable working conditions areas in shifts reduced to 6 h in accordance with t_{zk} and TS indices for airflow velocity equal to 0.3 m/s

3. Examples of interpretation of safe working areas

Two cases were selected from the measuring stations in the driven headings for the analysis of interpretation of safe working areas resulting from the regulation of dry bulb temperature and airflow velocity. The measurement data has been summarised in Table 4. In the first case a variant regulation of t_s has been conducted at constant airflow velocity, and in the second case the variant regulation has been conducted at a constant dry bulb temperature.

TABLE 4

Examples of measurements in two selected driven roadway headings in one of the hard coal mines

t_d °C	t_w °C	w m/s	φ %	p hPa	K_w mcal/cm^{2}s	t_{zk} °C	TS °C	ATE °C	Comments
(1) Conveyor incline to 1100, depth 791m., primary rock mass temperature 50°C									
30.6	27.0	0.81	75.3	1080	10.7	27.6	27.5	27.5	heading I
(2) Excavation level 1050, depth 1118 m, primary rock mass temperature 41°C									
31.0	27.4	0.51	75.3	1115	9.4	28.3	28.1	28.2	heading II

The characteristic values of these parameters under consideration were so as to allow for full-time operation for the index values of ATE < 28°C, t_{zk} < 26°C, and TS < 26°C. Additionally, values of t_s i K_w valid until the end of 2015 were examined.

The analysis results are presented in subsections 3.1-3.2.

3.1. Example 1 – Conveyor incline to 1100, depth 791 m, primary rock mass temperature: 50°C

According to Table 4, the dry bulb temperature for 8 h working shift was exceeded by 2.6°C, while the cooling intensity was 0.3 wet kata thermometer unit lower than the required value. Measured t_{zk} and TS values exceeded the threshold by 1.6°C and 1.5°C respectively. The following are the characteristic values of t_s (variants 1 and 3) and w (variants 2 and 4). When these values are met, full-time working is permitted for the indices values of ATE < 28°C, t_{zk} < 26°C, and TS < 26°C. Reference to t_s and K_w has been included as additional information.

a) Heading I, Variant 1 – sensible cooling

TABLE 5

Variant 1 – effect of decrease in temperature on thermal conditions in heading I

No.	(1) Conveyor incline to 1100, depth 791 m., primary rock mass temperature 50°C								
	t_s °C	t_w °C	w m/s	p hPa	K_w mcal/cm^{2}s	t_{zk} °C	TS °C	ATE °C	Comments
1	30.6	27.0	0.81	1080	10.9	27.6	27.5	27.5	measured conditions
2	28.0	26.4	0.81	1080	11.5	26.2	26.3	26.1	condition met t_s and K_w
3	27.5	26.3	0.81	1080	11.7	26.0	26.1	25.5	condition met t_{zk}
4	27.4	26.2	0.81	1080	11.8	25.9	25.9	25.4	condition met TS

Green area – allowable state; red area – unallowable state

Changes in dry bulb temperature and the resulting shift of subsequent characteristic points have been shown in Figure 5.

In the heading I the values of t_s = 30.6°C, t_w = 27.0°C, and K_w = 10.9 wet kata thermometer units were measured. In accordance with the current regulations it is necessary to reduce working shifts in the heading from 8 h to 6 h. In order to make the operations allowed on the full-time basis it is necessary to lower t_s to 28°C, which – according to Table 5 – will increase the value of K_w to 11.5. The t_{zk} threshold value will be achieved after lowering t_s to 27.5°C, and the threshold value TS requires a decrease of wet bulb temperature to 27.4°C. The same effect can be achieved by increasing the airflow velocity in a heading (variant 2 – Table 6).

b) Heading I, Variant 2 – increase in airflow velocity

In case of adjusting the indices by changing the velocity of air stream in the heading, the constant value t_s will be maintained. Due to regulations in force, the working time will not be extended and the ATE index allows for full-time work regardless of the adjustments conducted. However, the values of t_{zk} and TS may be adjusted to match the threshold values of 8h working shift. In case of t_{zk} this involves the increase in the airflow velocity to 2.45 m/s, and TS to 2.92 m/s.

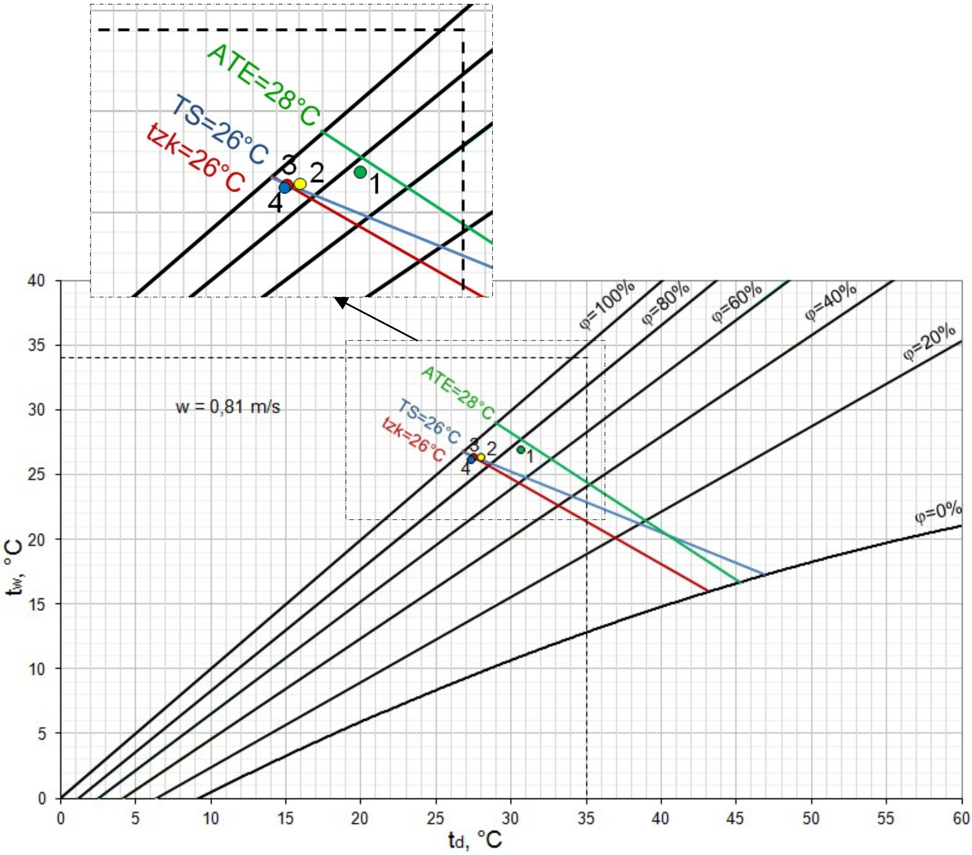

Fig. 5. Air cooling in accordance with variant 1 (w = 0.81 m/s)

TABLE 6

Variant 2 – the effect of velocity increase on the thermal conditions in the heading I (1)

No.	(1) Conveyor incline to 1100, depth 791m, primary rock mass temperature 50°C								
	t_s °C	t_w °C	w m/s	p hPa	K_w mcal/cm^{2}s	t_{zk} °C	TS °C	ATE °C	Comments
1	30.6	27.0	0.81	1080	10.9	27.6	27.5	27.5	measured conditions
2	30.6	27.0	0.85	1080	11.0	27.6	27.5	27.5	condition met t_s and K_w
3	30.6	27.0	2.45	1080	15.0	26.0	26.3	25.9	condition met t_{zk}
4	30.6	27.0	2.92	1080	15.9	25.5	25.9	25.6	condition met TS

3.2. Example 2 – Drift at level 1050, depth 1118 m, primary rock mass temperature: 41°C

In this case, the allowable dry bulb temperature was exceeded by 3.0°C, while the cooling intensity was lower by 1.6 kata thermometer units than the required level. Designated values

t_{zk} and TS exceeded the allowable values by 2.3°C and 2.1°C respectively. On the basis of the obtained results it may be stated that the thermal conditions in the excavation are more difficult than in the incline from Example I.

a) Heading II, Variant 1 – sensible cooling

TABLE 7

Variant 1 – effect of decrease of temperature on thermal conditions in heading II (2)

No.	(2) Excavation level 1050, depth 1118m, primary rock mass temperature 41°C								
	t_s °C	t_w °C	w m/s	p hPa	K_w mcal/cm^{2}s	t_{zk} °C	TS °C	ATE	Comments
1	31.0	27.4	0.51	1115	9.4	28.3	28.1	28.2	measured conditions
2	28.0	26.6	0.51	1115	10.2	26.6	26.6	26.5	condition met t_s
3	26.8	26.3	0.51	1115	10.5	26.0	26.1	25.6	condition met t_{zk}
4	26.6	26.3	0.51	1115	10.5	25.9	25.9	25.6	condition met TS
5	25.8	25.8	0.51	1115	11.0	25.3	25.4	24.9	condition met K_w

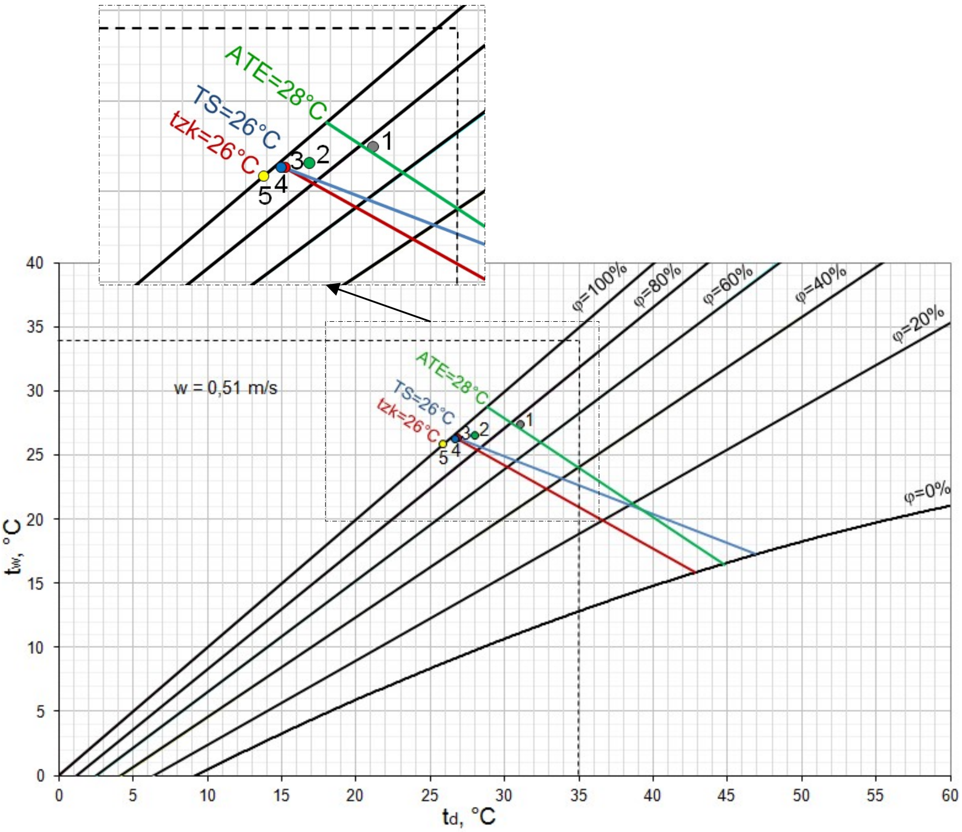

Fig. 6. Air cooling in accordance with variant 2 (w = 0.51 m/s)

An 8 h working time, in accordance with the current regulations, would require lowering the dry bulb temperature to 25.8°C as then the requirement of cooling intensity $K_w \geq 11.0$ would be met. Threshold value of t_{zk} would be achieved for $t_s = 26.8$°C, and the threshold value of TS for $t_s = 26.6$°C. ATE, for measured conditions only, exceeds the allowable value of 28°C.

b) Heading II, Variant 2 – increase of airflow velocity

TABLE 8

Variant 2 – effect of increase of airflow velocity on thermal conditions in heading II (2)

No.	(2) Excavation level 1050, depth 1118 m, primary rock mass temperature 41°C								
	t_s °C	t_w °C	w m/s	p hPa	K_w mcal/cm^{2}s	t_{zk} °C	TS °C	ATE °C	Notes
1	31.0	27.4	0.51	1115	9.4	28.3	28.1	28.2	measured conditions
2	31.0	27.4	1.03	1115	11.0	27.8	27.7	27.7	condition met K_w
3	31.0	27.4	2.85	1115	15.1	26.0	26.4	26.1	condition met t_{zk}
4	31.0	27.4	3.5	1115	16.1	25.3	25.9	25.7	condition met TS

Similarly to example 1, it is not possible to achieve $t_s = 28$°C, but the t_{zk} and TS threshold values would be achieved at the velocity of 2.85 m/s and 3.5 m/s respectively. ATE, for measured conditions only, exceeds the allowable value of 28°C.

Notes:

It should be noted that the air cooling intensity (K_w) depends significantly on the airflow velocity and in practice the attempt to increase K_w by lowering the dry bulb temperature is not common. However, the first example demonstrates such a case. The increase of K_w amounted only to 0.1.

4. Conclusions

Adjustment of air parameters in a mining excavation influences the classification of the site in terms of the thermal hazard, but there are significant differences in the interpretation of this hazard depending on the indices used.

1. At low relative humidity values (especially at $\varphi = 0\%$) the effect of airflow velocity on the value of TS and ATE indices is negligible and grows along the increase of φ (Fig. 3). However, the velocity isolines for t_{zk} are parallel, e.g. for $t_{zk} = 32$°C, as shown in Fig. 4, which results in the same increase in velocity, regardless of φ.

2. When comparing ATE and t_{zk} indices, the safe working area is larger for ATE (Fig. 2). The limitation due to t_s £ 35°C and t_w £ 34°C introduced in the regulations (Ordinance 2013) additionally reduces the safe working area determined for the t_{zk} index.

3. In relation to the origin of the $t_s - t_w$ coordinate system, threshold isolines for ATE are further from TS isolines for any identical velocities (Fig. 3). It follows that the safe working area is larger when employing ATE than when using TS.

4. When comparing the t_{zk} and TS indices (Fig. 4) isolines for threshold of TS (if the relative humidity exceeds 20%) are closer to the origin of the $t_s - t_w$ coordinate system. For relative

humidity below 20% this relation is reversed. However, because of limitations due to t_s and t_w (for t_{zk} index) this cannot be taken into account.

5. In accordance with the TS index, safe work could be allowed in excavations with a dry bulb temperature above 35°C but low values of relative humidity.

6. According to Tables 1-3 (assumption of threshold values for tested indices) the effect of velocity on the allowable values of t_s (for stable, allowable values of relative humidity) is the highest for t_{zk}, leading to excessive dry bulb and wet bulb temperatures, hence the necessity to limit them, which is inappropriate for environments with air humidity lower than 80%.

7. The threshold value of the Silesian temperature TS = 30°C was adopted on the basis of miners' climatic safety analysis based on the threshold of thermal discomfort index value of $\delta = 1$, taking into account the average energy expenditure of workers of various occupations and wearing lightweight work clothing. Adopting threshold temperatures such as t_{zk} and ATE equal to 32°C may pose a risk of thermal stress and heat stroke, especially for personnel who is non-acclimated and over 45 years of age (Drenda et al., 2014).

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